An exploration of the key factors influencing the success and failure of small-scale anaerobic digestion programmes in Bangladesh



BIRMINGHAM CITY University

School of Engineering and The Built Environment
Faculty of Computing, Engineering and The Built Environment
Birmingham City University

Tania Islam (ID: 17152028)

Supervisors: Prof. Lynsey Melville
Dr Khondokar Mizanur Rahman

A thesis submitted in partial fulfilment of the requirements of Birmingham City University for the degree of

DOCTOR OF PHILOSOPHY

Submission Date: October/ 2025

Declaration

I declare that this thesis has been composed solely by myself and that it has not been submitted, in whole or in part, in any previous application for a degree, except where states otherwise by reference or acknowledgement; the work presented is entirely my own.

I also declare that, as I am not a native English speaker, portions of this thesis were reviewed using Grammarly, an automated grammar and language-checking tool. The software was used solely for improving grammar, punctuation, and clarity; no content, analysis, or interpretation was generated or altered by the tool.



Name: Tania Islam
Date: 08/10/25

Acknowledgements

First and foremost, I want to express my sincere gratitude to Prof. Lynsey Melville, my supervisor, whose steady support has carried me through the many stages of this PhD journey. Her patience, kindness, and deep knowledge have shaped not only my research but, in many ways, who I have become through the process. I often think I could not have asked for a better mentor.

I'm also deeply thankful to Dr. Khondokar Mizanur Rahman. Without his patience and quiet persistence, I doubt half of my research graphs would have seen the light of day. His thoughtful questions and gentle challenges pushed me to look at my work from different, sometimes uncomfortable, but always enlightening angles. And a special thanks to Professor Dr. Md Khalekuzzaman for his kind support.

To all the staff members and fellow PhD students at the Faculty of Computing, Engineering and Built Environment, thank you for the mix of intellectual company and emotional kindness that helped me stay afloat when things got tough. On those long, grey research days, many of you were the small but needed bit of colour that kept me going. I am also truly grateful to the Science and Technology Fellowship, Bangladesh, for their enormous support along the way.

My heartfelt thanks go to my family for their unshakable faith and spiritual strength. To my husband, Abdul Kadir Ibne Kamal, and our son, Abdullah Tayeeb Ayat, I love you both more than words can manage. This thesis belongs to you as much as it does to me.

And finally, to the **Almighty Allah**, who sustained me day after day, thank you.

List of Abbreviations

ABPP	= Africa Biogas Partnership Programme
AD	= Anaerobic Digestion
ADB	= Asian Development Bank
AEPC	= Alternative Energy Promotion Centre
BBDF	= Bangladesh Biogas Development Foundation
BCCTF	= Bangladesh Climate Change Trust Fund
BCSIR	= Bangladesh Council of Scientific & Industrial Research
BEPRC	= Bangladesh Energy and Power Research Council
BPDB	= Bangladesh Power Development Board
BSP-Nepal	= Biogas Sector Partnership Nepal
CLD	= Causal Loop Diagram
CH_4	= Methane
CSTR	= Continuous Stirred Tank Reactor
CO	= Carbon Monoxide
EIA	= Environmental Impact Assessment
EPRC	= Energy and Power Research Council
GCF	= Green Climate Fund
GDP	= Gross Domestic Product
GERBIO	= German Society for Sustainable Biogas and Bioenergy Utilisation
GHG	= Greenhouse Gas
GIZ	= German Corporation for International Cooperation (English meaning)
IDCOL	= Infrastructure Development Company Limited
IPCC	= Intergovernmental Panel on Climate Change
LGED	= Local Government Engineering Department (Bangladesh)
LPG	= Liquefied Petroleum Gas
MoDMR	= Ministry of Disaster Management and Relief (Bangladesh)
MoY&S	= Ministry of Youth and Sports (Bangladesh)
NBFIs	= Non-Banking Financial Institutions
NBMMP	= National Biogas and Manure Management Programme (India)
NDBMP	= National Domestic Biogas and Manure Program (Bangladesh)
ppb	= Parts per billion
ppm	= Parts per million
PPP	= Public-Private Partnership
PSMP	= Power System Master Plan
REP	= Renewable Energy Policy (Bangladesh)
SNV	= Stichting Nederlandse Vrijwilligers (SNV Netherlands Development Organisation)
SREDA	= Sustainable and Renewable Energy Development Authority
Toe	= Tonne of oil equivalent (toe)
WBA	= World Biogas Association

Table of Contents

Declaration		i
Acknowledgements		Ii
List of Abbreviations		iii
Contents		iv
List of Figures		x
List of Tables		xii
Abstract		xiv
Chapter 01: Introduction	--------	001
1.1 Introduction	--------	002
1.2 Statement of the problem	--------	005
1.3 Research question	--------	006
1.4 Aim	--------	006
1.5 Objectives	--------	006
1.6 Thesis outline	--------	006
1.7 Sustainable development goals (SDGs) and AD technology in rural Bangladesh	--------	009
1.8 Bangladesh context: anaerobic digestion	--------	014
1.9 Importance of anaerobic digestion for Bangladesh	--------	017
1.10 Anaerobic digestion or biogas system	--------	018
1.11 The predominant design of Level 1 AD used in rural Bangladesh: The Chinese Fixed-Dome Plant	--------	020
Chapter 02: Literature Review	--------	023
2.1 Energy use trends in Bangladesh	--------	024
2.2 Renewable energy trends in Bangladesh	--------	024
2.3 AD sector in Bangladesh	--------	025
2.3.1 The History of the AD Extension Programme in Bangladesh	--------	026
2.3.2 Biogas energy trends in Bangladesh	--------	029
2.3.3 AD technology or biogas in the renewable energy policy of Bangladesh	--------	033
2.3.4 AD technology and performance	--------	035
2.3.5 Prospects of AD technology in Bangladesh	--------	036
2.4 Comparison of AD sector with other neighbouring LMICs	--------	038
2.4.1 AD programmes across countries	--------	039
2.4.2 AD sector growth	--------	042
2.4.3 Policy context	--------	043
2.5 Barriers to AD sectors in third-world countries	--------	044
2.5.1 Technical barriers	--------	045
2.5.2 Economic barriers	--------	045
2.5.3 Market barriers	--------	046
2.5.4 Institutional barriers	--------	047
2.5.5 Socio-cultural barriers	--------	047
Chapter 03: Research Methodology	--------	049
3.1 Overview of methodology	--------	050
3.2 Methodology	--------	051
3.2.1 Philosophical stance	--------	053

3.2.2 Research approach -------- 053
3.2.3 Methodological choice -------- 054
3.2.4 Strategies -------- 054
3.2.5 Time horizons -------- 055
3.2.6 Technique and procedure -------- 055
3.3 Technique and procedure of PESTEL analysis (Section 1) -------- 058
3.3.1 Principles of first section (PESTEL analysis) -------- 058
3.3.2 PESTEL analysis -------- 062
3.3.3 Horizon scanning -------- 064
3.3.4 The Delphi method or estimate-talk-estimate (ETE) method -------- 066
3.3.4.1 Formulation of the questionnaire -------- 067
3.3.5 Likert scale and weighted scoring method -------- 069
3.3.6 Stakeholder mapping and selection of stakeholders for the survey -------- 072
3.3.7 Justification for the number of stakeholders -------- 074
3.3.8 Selection and description of pillars of PESTEL -------- 075
3.3.9 Potential impact, uncertainty, and Impact/Uncertainty grid analysis -------- 085
3.4 Technique and procedure for AD user survey (Section 2) -------- 088
3.4.1 Principle of the second section -------- 089
3.4.2 Study area -------- 089
3.4.3 Sampling unit -------- 090
3.4.4 Sample size calculation -------- 091
3.4.5 Key informants -------- 092
3.4.6 Survey tool (questionnaire) -------- 093
3.4.7 Data compilation -------- 093
3.4.8 Statistical analysis -------- 094
3.5 Systemic interrelationships among critical key factors: A causal loop diagram (CLD)–based systems thinking approach -------- 098
3.5.1. Identification and construction of FeedBack Loop -------- 098
3.5.2. Development of the causal loop diagram (CLD) -------- 099

Chapter 04: Results: PESTEL Analysis -------- 101
4.1 PESTEL analysis on macro environment -------- 102
4.1.1 Results from PESTEL analysis -------- 102
4.1.1.1 Potential impact and uncertainty of the key factors -------- 103
4.1.1.2 Potential impact of the key factors -------- 107
4.1.1.3 Uncertainty of the key factors -------- 111
4.1.1.4 The Impact/Uncertainty grid analysis -------- 112

Chapter 05: In-Depth Analysis of the Political Pillar of PESTEL -------- 117
5.1 Introduction -------- 118
5.2 Insights from expert stakeholder opinion on the political pillar of PESTEL -------- 118
5.2.1 P7: National coordination among stakeholders -------- 119
5.2.2 P5: Corruption at the national and individual level -------- 120
5.2.3 P6: Bureaucratic complication (the level of administrative obstacles) -------- 122
5.2.4 P2: Taxation policies on landfilling with waste -------- 123
5.2.5 P4: Stability of the political framework of Bangladesh government -------- 125
5.2.6 P1: Existing renewable energy and climate change policy of Bangladesh -------- 127
5.2.7 P3: Government support (incentives) and bank loan policy for the AD industries in Bangladesh -------- 128
5.3 Outcome of AD user survey (political point of view) -------- 130
5.3.1 Inconsistent government policies -------- 130
5.3.2 Bureaucratic delays and red tape -------- 131

5.3.3 Political instability -------- 131
5.3.4 Weak enforcement of environmental regulations -------- 132
5.3.5 Limited public-private partnerships (PPP) -------- 133
5.3.6 Insufficient foreign investment and international support -------- 133
5.3.7 Exclusion from policy-making processes -------- 134
5.4 SWOT Analysis: Political pillar of PESTEL -------- 134

Chapter 06: In-Depth Analysis of the Economic Pillar of PESTEL -------- 137
6.1 Introduction -------- 138
6.2 Insights from expert stakeholder opinion -------- 139
6.2.1 Ec7: Security on investment -------- 139
6.2.2 Ec4: New job opportunities -------- 140
6.2.3 Ec6: Labour costs -------- 141
6.2.4 Ec2: Biogas plant construction cost -------- 142
6.2.5 Ec1: Availability and price of feedstock -------- 143
6.3 Outcome of AD user survey (economic point of view) -------- 143
6.3.1 Impacts of AD plants on cooking fuel -------- 144
6.3.1.1 Conversion from traditional fuels to biogas -------- 144
6.3.1.2 Detailed savings breakdown -------- 145
6.3.2 Impacts of AD on the sustainability of agriculture -------- 146
6.3.3 Impacts of the production of biogas on the income of a family -------- 148
6.3.3.1 Cooking time -------- 149
6.3.3.2 Fuel cost -------- 151
6.3.3.3 Fuel wood consumption -------- 153
6.3.3.4 Time involvement for collecting fuel wood -------- 154
6.3.4 AD construction cost and IDCOL support -------- 156
6.3.4.1 Construction Costs by Plant Size -------- 156
6.3.4.2 IDCOL subsidy structure -------- 156
6.3.5 Cost-benefit analysis of level 1 household AD plant in Bangladesh -------- 157
6.3.5.1 Capital cost and subsidy -------- 157
6.3.5.1 Savings from cooking fuel -------- 158
6.3.5.2 Time savings -------- 158
6.3.5.3 Bio-slurry benefit -------- 158
6.3.5.4 Health cost savings -------- 158
6.3.5.5 Programme funding -------- 159
6.4 SWOT analysis: Economic pillar of PESTEL -------- 159

Chapter 07: In-Depth Analysis of the Social Pillar of PESTEL -------- 162
7.1 Introduction -------- 163
7.2 Insights from expert stakeholder opinion on the social pillar of PESTEL -------- 164
7.2.1 S2: Information dissemination and advertising -------- 164
7.2.2 S6: Social stigma (cultural and religious viewpoint) -------- 165
7.2.3 S4: Improvement of household welfare among the AD plant users -------- 166
7.2.4 S5: Vermin and malodour reduction -------- 168
7.3 Outcome of AD user survey (social point of view) 168
7.3.1 Status of the surrounding environment -------- 168
7.3.2 Status of social environment -------- 170
7.3.3 Time involvement for child education -------- 172
7.3.4 Time involvement for collecting fuel wood -------- 174
7.3.5 Social stigma related to religious and cultural perspectives in Bangladesh and its impact on sustainable AD growth -------- 176
7.4 SWOT analysis for the social pillar of PESTEL -------- 178

Chapter 08: Insights from the Technological Pillar of PESTEL -------- 182
8.1 Introduction -------- 183
8.2 Insights from expert stakeholder opinion on the technological pillar of PESTEL -------- 184
8.2.1 T6: Alternative source of highly efficient renewable energy (such as solar energy) -------- 184
8.2.2 T1: Planning and installation issues for the biogas plant in Bangladesh -------- 186
8.2.3 T5: New technology and research -------- 187
8.2.4 T3 : Biogas extraction technology in Bangladesh -------- 189
8.3 Outcome of AD user survey (technological point of view) -------- 191
8.3.1 Operation and maintenance of the biogas plant -------- 191
8.3.2 Plant size and seasonal variation impact on cooking hour -------- 194
8.4 SWOT analysis of the technological pillar of PESTEL -------- 204

Chapter 09: In-Depth Analysis of the Environmental Pillar of PESTEL -------- 207
9.1 Introduction -------- 208
9.2 Insights from expert stakeholder opinion on the environmental pillar of PESTEL -------- 210
9.2.1 En1: Reduction of GHG emissions -------- 210
9.2.2 En4: Climatic condition of Bangladesh -------- 212
9.2.3 En3: Indoor air pollution -------- 213
9.2.4 En2: Waste management -------- 215
9.2.5 En5: Access to adequate water for the biogas plant -------- 216
9.3 Outcome of AD user survey (Environmental point of view) -------- 218
9.3.1 Air pollution (in kitchen) -------- 218
9.3.2 Eye infection due to smoke -------- 219
9.3.3 Respiratory infection status due to smoke -------- 220
9.3.4 Abundance of mosquitoes/flies -------- 222
9.3.5 Cow shed management -------- 223
9.3.6 Fodder management status -------- 224
9.3.7 Environment friendly fuel -------- 226
9.3.8 Self-assessed household environment -------- 227
9.3.9 Self-assessed kitchen environment -------- 228
9.4 SWOT analysis of the environmental pillar of PESTEL -------- 229

Chapter 10: In-Depth Analysis of the Legal Pillar of PESTEL -------- 232
10.1 Introduction -------- 233
10.2 Insights from expert stakeholder opinion on the legal pillar of PESTEL -------- 233
10.2.1 L4: The range of requirements for anaerobic digestate / bio-slurry as fertiliser or quality protocol (Fertiliser Recommendation Guide 2018, Bangladesh) -------- 234
10.2.2 L5: Feed-in Tariffs for produced biogas -------- 236
10.2.3 L7: Local government law for setting up an AD plant in premises (range of requirements) -------- 238
10.2.4 L3: Biogas guidelines/legislation -------- 240
10.3 Outcome of AD user survey (legal point of view) -------- 243
10.3.1 Regulatory awareness and compliance -------- 243
10.3.1.1 Awareness of policies -------- 243
10.3.1.2 Clarity of legal requirements and compliance -------- 244
10.3.1.3 Official acceptance process for obtaining permission -------- 244
10.3.1.4 Compliance with environmental laws -------- 245
10.3.2 Legal framework for bio-slurry and fertiliser use -------- 245

10.3.2.1 Awareness of fertiliser guidelines -------- 245
10.3.2.2 Legal restrictions on bio-slurry use -------- 246
10.3.3 Feed-In tariffs and financial incentives -------- 246
10.3.3.1 Awareness of FiTs -------- 246
10.3.3.2 Sufficiency of financial incentives -------- 247
10.3.4 Local Government Regulations -------- 248
10.3.4.1. Challenges with Local Regulations -------- 248
10.4 SWOT analysis: Legal pillar of PESTEL -------- 248

Chapter 11: Systemic Interrelationships Among Critical Key Factors: A Causal Loop Diagram (CLD)–Based Systems Thinking Approach -------- 251
11.1 Systemic interrelationships among critical key factors: a causal loop diagram (CLD)–based systems thinking approach -------- 252
11.2 Reinforcing feedback loops (R1–R10) -------- 253
11.2.1 R1: Policy–economy loop -------- 253
11.2.2 R2: Technology–efficiency loop -------- 254
11.2.3 R3: Jobs and welfare Loop -------- 255
11.2.4 R4: Revenue–investment loop -------- 255
11.2.5 R5: Awareness and social adoption loop -------- 257
11.2.6 R6: Legal Incentives loop -------- 257
11.2.7 R7: Environmental public support loop -------- 258
11.2.8 R8: Education and literacy loop -------- 258
11.2.9 R9: Regulatory quality loop -------- 259
11.2.10 R10: Digestate utilisation loop -------- 259
11.3 Balancing feedback loops (B1–B11) -------- 259
11.3.1 B1: Social resistance loop -------- 260
11.3.2 B2: Corruption–planning loop -------- 260
11.3.3 B3: Renewable energy competition loop -------- 262
11.3.4 B4: Labour cost loop -------- 262
11.3.5 B5: Technical expertise gap loop -------- 263
11.3.6 B6: Environmental compliance loop -------- 263
11.3.7 B7: Environmental risk loop -------- 264
11.3.8 B8: National coordination gap loop -------- 264
11.3.9 B9: Technology obsolescence loop -------- 264
11.3.10 B10: Feed-in tariff absence loop -------- 265
11.3.11 B11: Bureaucratic barrier loop -------- 265
11.4. Strategic recommendations for sustainable anaerobic digestion development in Bangladesh -------- 265
11.4.1 Short-term recommendations -------- 266
11.4.1.1 Reforming the feed-in tariff (FiT) mechanism -------- 266
11.4.1.2 Streamlining permitting and licensing procedures -------- 266
11.4.1.3 Launching public awareness and education campaigns -------- 266
11.4.1.4 Supporting small-scale AD deployment in rural communities -------- 267
11.4.2. Medium-Term Recommendations -------- 267
11.4.2.1 Enhancing environmental enforcement and monitoring -------- 267
11.4.2.2 Strengthening inter-ministerial coordination -------- 268
11.4.2.3 Developing technical training and certification programs -------- 268
11.4.2.4 Promoting digestate valorisation and agricultural Integration -------- 268
11.4.3. Long-term recommendations -------- 269
11.4.3.1 Embedding AD within the national energy and climate strategy -------- 269
11.4.3.2 Transforming social norms through public education -------- 269
11.4.3.3 Establishing a national AD roadmap (2025–2040) -------- 270
11.5 Sector Analysis of the Bangladesh AD Extension Programme -------- 270

11.5.1 The Political Sector -------- 270
11.5.2 The Financial Sector -------- 271
11.5.3 The Agricultural Sector -------- 272
11.5.4 The Health Sector -------- 273
11.5.5 The Publicity and Communications Sector -------- 274
11.5.6 The Education and Research Sector -------- 274
11.5.7 The Environmental Sector -------- 275
11.6 Summary -------- 276

Chapter 12: Conclusion -------- 278
12 Conclusion -------- 279
12.1 Challenges -------- 279
12.2 Key opportunities -------- 280
12.3 Knowledge contribution -------- 280
12.3.1 Theoretical Contributions -------- 280
12.3.1.1 Extension of the PESTEL framework to small-scale renewable energy transitions in a low-income country context -------- 280
12.3.1.2 Integration of macro-environmental analysis with micro-level user experience -------- 281
12.3.1.3 Systems-theoretic understanding of AD sector stagnation -------- 282
12.3.2 Methodological contributions -------- 282
12.3.2.1 A novel integrated mixed-methods research design -------- 282
12.3.2.2 Development of a weighted scoring method for Delphi-derived PESTEL factors -------- 282
12.3.2.3 Application of paired statistical testing to before-and-after household technology adoption -------- 283
12.3.2.4 Empirical construction of a Causal Loop Diagram from primary mixed-methods data -------- 283
12.3.3 Practical contributions -------- 284
12.3.3.1 Identification of the operative barriers to Level 1 AD sector growth in Bangladesh -------- 284
12.3.3.2 Quantified evidence of household-level benefits -------- 284
12.3.3.3 A revised financial case for household AD -------- 284
12.3.3.4 Strategic recommendations structured by time horizon and system leverage -------- 285
12.3.3.5 A multi-sector implementation framework -------- 285
12.3.3.6 Transferability to comparable programme contexts -------- 285
Summary of Contributions -------- 286
12.4 Final Thoughts -------- 286
References -------- 288
Appendices -------- 318
Appendix 01: Ethical approval letter from BCU -------- 319
Appendix 02: Consent form for interviews -------- 320
Appendix 03: Project overview (participant information leaflet) -------- 321
Appendix 04: Field Locations -------- 326
Appendix 05: Questionnaire & Google Form -------- 332
Appendix 06: Statistical analysis -------- 345
Appendix 07: Anonymised raw data -------- 353

List of Figures

Flow chart 1:	Thesis outline.	----	008
Figure 1.1:	Sustainable Development Goals addressed by AD technology (WHO, 2020).	----	009
Figure 1.2:	Potential of biogas to contribute towards the SDGs (IPE Triple Line, 2018).	----	010
Figure 1.3:	Degradation steps in anaerobic digestion (Drosg, 2013)	----	019
Figure 1.4:	Diagram of Chinese fixed dome biogas plant model used in Bangladesh (Fulford, 2015, Rahman et al. 2017)	----	021
Figure 2.1:	Renewable energy installed capacity of Bangladesh (SREDA, 2020).	----	025
Figure 2.2:	Map shows the distribution of AD plants under IDCOL construction under IDCOL biogas construction under renewable energy (RE) program in Bangladesh (IDCOL, 2020).	----	031
Figure 2.3:	Performance of household Biogas plants (in %) in Bangladesh (Data from NDBMP-IDCOL, 2013)	----	032
Figure 2.4:	Livestock population of Bangladesh (in lakh number or in 1,00,000) in Bangladesh (DLS, 2020)	----	037
Figure 2.5:	Production of biogas for cooking in selected countries, 2014 and 2018 (REN21, 2020).	----	042
Figure 2.6:	Comparison of GDP per capita and small-scale AD plants among Nepal, Vietnam and Bangladesh (IDCOL, 2020; MoFE, 2021; SNV-Vietnam, 2020; World-Bank, 2020).	----	043
Figure 2.7:	Timeline of published policy papers related to AD/ Biogas technology in Nepal, Vietnam and Bangladesh.	----	044
Figure 3.1:	Research onion (Saunders et al., 2019).	----	052
Figure 3.2:	Outline of the different features of this research based on the research onion (Saunders et al., 2019).	----	056
Figure 3.3:	Summary of the method used in this study.	----	060
Figure 3.4:	Bibliometric networks (A) Network visualisation and (B) Density visualisation.	----	065
Figure 3.5:	Modified steps of Delphi methods used in this study.	----	067
Figure 3.6:	A 6-point Likert scale used in this study.	----	070
Figure 3.7:	Impact/ uncertainty grid and global average of the key factors.	----	088
Figure 3.8:	Location map of surveyed Biogas plant (small scale) in Bangladesh.	----	090
Figure 3.9:	Flow chart of development of the questionnaire and field survey	----	094
Figure 4.1:	Stakeholder Ratings on Impact and Uncertainty for the political pillar of PESTEL. Blue bars indicate impact scores, and orange bars indicate uncertainty scores.	----	104

Figure 4.2:	Stakeholder Ratings on Impact and Uncertainty for the economic pillar of PESTEL. Blue bars indicate impact scores, and orange bars indicate uncertainty scores.	----	105
Figure 4.3:	Stakeholder Ratings on Impact and Uncertainty for the social pillar of PESTEL.Blue bars indicate impact scores, and orange bars indicate uncertainty scores.	----	105
Figure 4.4:	Stakeholder Ratings on Impact and Uncertainty for the technological pillar of PESTEL. Blue bars indicate impact scores, and orange bars indicate uncertainty scores.	----	106
Figure 4.5:	Stakeholder Ratings on Impact and Uncertainty for the environmental pillar of PESTEL. Blue bars indicate impact scores, and orange bars indicate uncertainty scores.	----	106
Figure 4.6:	Stakeholder Ratings on Impact and Uncertainty for the legal pillar of PESTEL. Blue bars indicate impact scores, and orange bars indicate uncertainty scores.	----	107
Figure 4.7:	The results of the expert surveys regarding the potential impact of the elements (markings in Table 3.1). In the figure, the above green and below red horizontal lines represent the positive and negative potential impact zones, respectively (discussed in Table 3.4).	----	109
Figure 4.8:	The results of the expert surveys regarding the uncertainty of the elements (markings in Table 3.1).	----	112
Figure 4.9:	The outcomes of the expert surveys related to the uncertainty of the factors (as indicated in Table 3.4).	----	113
Figure 6.1:	Money and wood saved after using AD plants. Error bars are standard	----	144
Figure 6.2:	Percentages of the Use of Slurry in Agriculture (n=50)	----	147
Figure 6.3:	Estimating annual profit from biogas plants (£/year). Error bars are standard error bars.	----	149
Figure 8.1:	An example of a failed AD plant (due to a construction fault, after 1 month).	----	192
Figure 8.2:	Graphical representation of mean and standard deviation for each plant size and different seasonsß	----	196
Figure 8.3:	Boxplot for cooking hour in each plant size and season	----	196
Figure 8.4:	Normal Probability Plot	----	197
Figure 8.5:	The differences of cooking hours for different seasons.	----	201
Figure 8.6:	The differences among cooking hours for various size of plants	----	202
Figure 8.7:	The differences among plant sizes for the interaction of various plant sizes and seasons.	----	202
Figure 11.1:	Causal Loop Diagrams (CLDs)—offers a powerful lens through which to analyse the dynamic behaviour of the AD system in Bangladesh.	----	261

List of Tables

Table 2.1:	Summary of other NGOs active in the small-scale AD sector in Bangladesh	----	028
Table 2.2:	Total number of household small-scale AD plants constructed by different agencies in Bangladesh (BPDB, 2019; IDCOL, 2020)	----	030
Table 2.3:	Results of Technical Survey (TS) report of 2005, Biogas User Surveys (BUS) 2007 to 2011, and Biogas Audit Bangladesh Team (BAB) 2011-2012: Functioning status of biogas plants in Bangladesh (in % and [households])	----	036
Table 3.1:	General calculation for scoring of individual factors	----	071
Table 3.2:	Impact Range	----	072
Table 3.3:	Summary of stakeholder engagement strategies.	----	073
Table 3.4:	List of the key factors of PESTEL.	----	075
Table 3.5:	Statistical Methods, purpose, real-world application in this thesis	----	095
Table 5.1:	SWOT Analysis for the political pillar of PESTEL	----	134
Table 6.1:	A paired-samples t-test results for daily cooking time before and after AD plant installation	----	150
Table 6.2:	A paired-samples t-test results for fuel cost before and after AD plant installation	----	151
Table 6.3:	A paired-samples t-test results for fuel wood consumption before and after AD plant installation	----	153
Table 6.4:	A paired-samples t-test results for daily time spent collecting fuel wood before and after AD plant installation	----	154
Table 6.5:	SWOT Analysis for the economic pillar of PESTEL	----	159
Table 7.1:	McNemar-Bowker Test results for changes in surrounding environment status before and after AD Plant Installation	----	169
Table 7.2:	McNemar-Bowker Test results for changes in social environment status before and after AD Plant Installation	----	170
Table 7.3:	A paired samples t-test results for daily time spent on child education before and after AD plant installation	----	172
Table 7.4:	A paired samples t-test results for daily time spent on collecting fuel wood before and after AD plant installation	----	174
Table 7.5:	SWOT Analysis: Social pillar of PESTEL	----	178
Table 8.1:	Descriptions of model parameters or variables	----	195
Table 8.2:	Descriptive Statistics for each plant size and different seasons	----	195
Table 8.3:	ANOVA Table	----	199

Table 8.4:	Pairwise comparison test (season)	----	200
Table 8.5:	Pairwise comparison test (plant sizes)	----	200
Table 8.6:	SWOT Analysis: Technological pillar of PESTEL	----	204
Table 9.1:	McNemar-Bowker Test results showing significant reduction in kitchen air pollution before and after AD plant installation	----	218
Table 9.2:	McNemar-Bowker Test results show the difference in eye infection status before and after AD plant installation	----	220
Table 9.3:	McNemar-Bowker Test results show the difference in respiratory infection status before and after AD plant installation	----	221
Table 9.4:	McNemar-Bowker Test results show the difference in abundance of mosquitoes or flies status before and after AD plant installation	----	222
Table 9.5:	McNemar-Bowker Test results show the difference in cow shed management status before and after AD plant installation	----	223
Table 9.6:	McNemar-Bowker Test results show the difference in fodder management status before and after AD plant installation	----	225
Table 9.7:	McNemar-Bowker Test results show the difference in environmental friendliness of fuels before and after AD plant installation	----	226
Table 9.8:	McNemar-Bowker Test results show the difference in self-assessed household environment status before and after AD plant installation	----	227
Table 9.9:	McNemar-Bowker Test results show the difference in self-assessed kitchen environment status before and after AD plant installation	----	228
Table 9.10:	SWOT analysis: Environmental pillar of PESTEL	----	230
Table 10.1:	SWOT Analysis of Legal pillar of PESTEL	----	249
Table 11.1:	Reinforcing Feedback Loops (R1–R10) and Balancing Feedback Loops (B1–B11)	----	256
Table 12.1:	Summary of the theoretical, methodological, and practical contributions of this research	----	286

Abstract

This doctoral research examines the key factors that influence the success and failure of small-scale anaerobic digestion (AD) programmes in Bangladesh, a country facing rapid urbanisation, energy insecurity, and waste management challenges. The study adopts a comprehensive, interdisciplinary methodology that integrates systems thinking, stakeholder analysis, and empirical research. It employs tools such as PESTEL analysis, SWOT, Delphi elicitation, Likert-scale, and extensive field-level surveys. Central to the study is the development of a Causal Loop Diagram (CLD), which models the dynamic interactions among political, economic, social, technological, environmental, and legal key factors affecting the AD sector. The CLD identifies 21 key feedback loops—10 reinforcing and 11 balancing—that illustrate how interventions may trigger self-reinforcing improvements or encounter counterbalancing resistance.

Key challenges identified in this study include institutional fragmentation, bureaucratic inefficiencies, policy inconsistency, financial and investment barriers, cultural stigma around waste and biogas, technological limitations, and inadequate legal enforcement mechanisms.

Despite these obstacles, the study reveals significant opportunities to advance the sector. Bangladesh's warm tropical climate, abundant labour force, and access to water are ideal for efficient biogas production. The integration of AD into national renewable energy, waste management, and climate action plans could unlock synergies and attract international financing. Furthermore, the global momentum around the Sustainable Development Goals (SDGs), particularly Clean Energy (SDG 7), Sustainable Cities (SDG 11) and Climate Action (SDG 13), makes AD a strategic tool for inclusive sustainable development.

The research contributes conceptually by extending the application of systems thinking to small-scale AD programmes in the Global South, where AD growth is struggling to expand. Methodologically, this study pioneers a replicable framework that synthesises qualitative policy tools with dynamic system modelling. Empirically,

it bridges the gap between policy design and field-level realities by capturing user experiences, institutional challenges, and implementation outcomes across multiple regions.

A significant output of the study is a strategically phased roadmap for AD sector development, outlining short-, medium-, and long-term policies. The roadmap offers actionable insights for policymakers, development agencies, and practitioners seeking.

In conclusion, small-scale anaerobic digestion, supported by coherent policy frameworks, institutional collaboration, and community empowerment, can play a transformative role in Bangladesh's transition toward a circular, resilient, and sustainable future energy. The findings have broader implications for other developing countries seeking organic waste-to-energy solutions.

Chapter 01: Introduction

1.1 Introduction

Energy used by human civilisation has transformed through time from wood to coal, coal to oil and gas and now to new renewable forms of energy source (Ekwurzel et al., 2017; McCrone et al., 2019). Fire was essential for primitive humans to survive by burning readily available timber for cooking, heating and self-defence. After technological advancements, coal became a major source of energy because of its higher energy density and high availability (REN21, 2020; Zou et al., 2016). After the Industrial Revolution (after 1750), large amounts of carbon dioxide (CO_2) were released into our atmosphere due to the burning of large quantities of fossil fuels for development (Davis, 2017; Ekwurzel et al., 2017). Thus, CO_2 as a heat-trapping gas is increasing in the atmosphere, which causes the earth's climate to become warmer (Davis, 2017).

For over ten thousand years, atmospheric carbon dioxide (CO_2) concentrations have been between 200 and 300 ppm (parts per million)(UNEP, 2019a). In recent years, the global scientific community have agreed that excessive use of fossil fuel has caused increasing levels of CO_2 and other Green house gases (GHGs) in the Earth's atmosphere. The use of coal and other fossil fuels caused fog in London in the early 20th century and photochemical smog in China (Davis, 2017). So, burning fossil fuel creates local and global environmental problems. Now, using the alternative, cleaner energy to protect the environment has become necessary. The new energy transformation aims to build a low-carbon society (UNEP, 2021; WBA, 2022).

In addition, methane (CH_4) has been identified as another major potent GHG and has a global warming potential about 86 times higher than CO_2 over 20 years (Aksyutin et al., 2019; WBA, 2022). After the industrial revolution, the atmospheric CH_4 concentration has doubled and is now considered to be the second most global warming potential (Aksyutin et al., 2019; Dean et al., 2018; UNEP, 2021). According to a recent UN report, a significant percentage of CH_4 emissions (more than 50 %) can be attributed to anthropogenic activities. Three primary anthropogenic sources are responsible for more than 90% of CH_4 emissions, which include fossil fuel consumption and production (35%), improper organic waste management (20%), and agriculture (40%) (UNEP, 2021).

The rate of CH_4 emission has rapidly increased since 1980, if the global community fails to act now with new policies, the emission of CH_4 will continue to increase. According to Intergovernmental Pannel on Climate Change (IPCC's) 2013 assessment, methane concentration is now above 2° C scenarios, which already jeopardises the Paris Agreement's (1.5° C target by reducing 40 to 45% of CH_4 emissions by 2030) (UN, 2015). In addition to that, tropospheric harmful ozone pollution increases with increasing CH_4. Tropospheric ozone accounts for approximately 0.5 million premature deaths yearly and ecosystem destruction (UNEP, 2019b).

It is possible to combat the lowering anthropogenic CH_4 emissions. World Biogas Association (WBA) has stated that anthropogenic activities generate 80 billion tons of organic waste, and by processing this waste with anaerobic digestion (AD), it could meet 50% of the global methane pledge (WBA, 2022). Reduction of CH_4 emissions not only hinders global warming but also improves global human health (reducing ground-level ozone) and the global economy. In addition to that, the UN agencies have set up Sustainable Development Goals (SDGs) for a better future of the planet and lowering CH_4 emissions can help to achieve several SDGs, such as climate action (SDG 13), and good health and well-being (SDG3). In the "Global Methane Assessment: Benefits and Costs of Mitigating Methane Emissions" report by UNEP (2021), several recommendations have been made to combat global warming by reducing CH_4 emissions and among them, management of organic materials (livestock manure, agricultural residue and household organic waste) through AD technology has been recommended (UNEP, 2021).

Before proceeding to the statement of the problem and research objectives, it is important to clarify the scale and level at which this research is positioned, where 'level' refers to the scale of operation, the type of feedstock used, the end use of the biogas produced, and the population served by the technology. This distinction has direct implications for the analysis, findings, and recommendations presented throughout the thesis. Three broad levels of AD application are therefore distinguished, as follows.

At Level 1 (small-scale AD plant), small-scale domestic AD systems are built for individual farming households that keep a small number of cattle, or chickens. Animal dung is fed into an underground fixed-dome or floating-drum digester; the biogas produced is used primarily for domestic cooking, and the effluent slurry is applied to agricultural land as an organic soil conditioner. These systems are economically viable in tropical climates without the need for insulation or heating. In Bangladesh, this is the level at which the National Domestic Biogas and Manure Programme (NDBMP), operated by IDCOL and its partner organisations, functions. Critically, it is also the level at which all fieldwork, household surveys, and plant assessments reported in this thesis were conducted.

At Level 2, basic commercial AD systems convert organic materials, including agricultural and food processing residues and sewage, into raw biogas, which is used in static engines to generate electricity for the national grid or a local network. Some such plants have been established in Bangladesh on a limited scale. Although Level 2 lies outside the scope of the primary research reported in this thesis, it represents an important and realistic direction for future development of the AD sector in Bangladesh. The experience gained by technicians, extension workers, and programme managers through years of working on the Level 1 household programme, in plant construction, digester management, feedstock handling, and community engagement, provides a valuable foundation from which Level 2 activity can grow. In particular, the skills developed within the Level 1 programme are directly transferable to the processing of a wider range of organic materials at commercial scale, especially agricultural and food processing residues, which are abundant in Bangladesh and represent a largely untapped resource for biogas production.

At Level 3, advanced commercial AD systems process organic materials into biomethane, biogas from which carbon dioxide has been removed, which can be compressed and injected into a national gas grid or used as a vehicle fuel. This level requires substantially greater capital investment, advanced infrastructure, and a high level of technical support. It is primarily relevant to more developed countries and is not a subject of this thesis.

In this thesis, the survey results, user experiences, and PESTEL findings reported throughout this thesis all relate to Level 1 small-scale domestic AD. References to

programmes in more developed countries, Germany, Denmark, the United Kingdom, and the United States are included only where they illuminate a specific policy or institutional question relevant to the Bangladesh context. Technical innovations designed for Levels 2 or 3 are not advocated as solutions to the challenges identified in this research, and references to advanced commercial programmes are clearly framed as context rather than comparators.

1.2 Statement of the problem

There are significant opportunities for AD implementation (availability of abundant biomass resources, clear and proven benefits of waste management practices, and reduction of the environmental impact of waste and economic growth through new business opportunities) in Bangladesh. However, AD requires wider adoption at the national and regional levels to meet the country's targets for SDG goals and the energy crisis. In 2012, NDBMP-IDCOL reported failures related to technical aspects in biogas plant sub-systems (Zifu et al., 2013); but within the last decade, changes in the technology and raw material in the biogas sector have also created new challenges in Bangladesh. However, based on expert opinion, Hasan et al., (2020) briefly reported the drivers and barriers to setting up biogas plants in Bangladesh. It is clear that a knowledge gap exists to address the key factors of the macro environment for sustainable growth of AD sectors in Bangladesh, emphasising small-scale AD plants. Again, no evidence has been recorded about the problems faced by the small-scale (level 1) AD plant owner/ user (micro level). So, it is also essential to understand the challenges to make recommendations to support the sector and promote wider adoption.

1.3 Research question

1. What are the key indicators of success and failure of small-scale biogas plants in Bangladesh?
2. What are the barriers to sustainable growth of the small-scale AD sector in Bangladesh, and how can these be overcome?

1.4 Aim

The research aims to identify and explore the barriers and opportunities to the sustainable growth of the small-scale AD sector in Bangladesh, with recommendations for supporting the sector.

1.5 Objectives

1. To identify the macro-environment factors and broad challenges to promote the sustainable growth of the small-scale AD sector in Bangladesh.
2. To identify the key indicators (actual or perceived) of success and failure of small-scale biogas plants in Bangladesh at the micro-scale.
3. To determine and critically evaluate the root causes of the success and failure of small-scale biogas plants in Bangladesh.
4. To provide recommendations to improve the performance and operation of small-scale AD technologies and promote wider deployment and success of the AD sector in Bangladesh.

1.6 Thesis outline

This thesis is divided into twelve chapters that collectively examine the barriers and prospects surrounding the sustainable growth of small-scale AD in Bangladesh.

The opening chapter sets the stage by outlining the background, problem statement, research questions, and objectives. It also focuses the study within broader global and national contexts by addressing issues related to energy, climate change, and biogas technology.

Chapter 2 follows with a review of existing literature, tracing energy use patterns, renewable energy development, and the evolution of Bangladesh's AD sector. It also looks outward, comparing these trends with neighbouring low- and middle-income countries to pinpoint both shared and country-specific challenges.

Chapter 3 explains the methodology used in conducting the research. It describes the mixed-methods framework that brings together PESTEL analysis, Delphi

consultation, SWOT, horizon scanning, and a field-level user survey. The chapter also notes how statistical techniques and systems-thinking tools were applied to analyse data and eventually construct the Causal Loop Diagram (CLD).

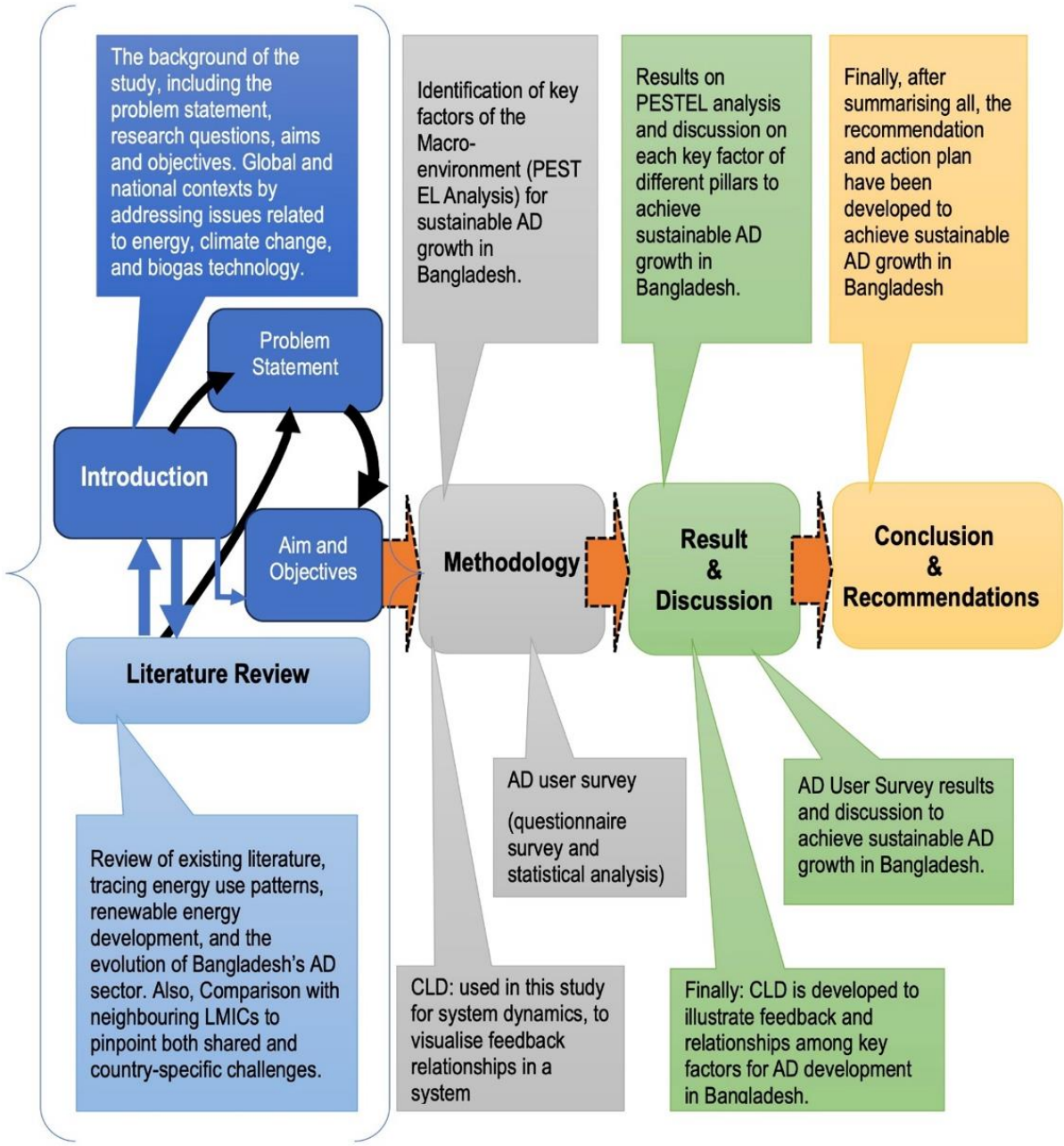
The results begin in Chapter 4, which presents the outcomes of the PESTEL analysis and highlights the macro-environmental factors most likely to shape the AD sector's sustainability, those with the highest impact or uncertainty.

Chapters 5 to chapter 10 provide a closer examination of each pillar of the PESTEL framework, including Political, Economic, Social, Technological, Environmental, and Legal. Each section draws on stakeholder insights, Delphi findings, SWOT reflections, and, where relevant, comparisons with field data from AD user surveys. Collectively, these chapters provide a layered understanding of how various key factors interact to either empower or hinder AD development.

Chapter 11 then ties everything together through a systems-thinking lens. It introduces the CLD, which visualises the feedback loops and interconnections that seem to drive the sector's performance, sometimes reinforcing progress and at other times constraining it.

The final chapter, Chapter 12, offers the main conclusions along with policy and practical recommendations. It closes with reflections on what these findings may suggest for future research and for those working to expand AD systems in Bangladesh.

The following flow chart 1 explains the thesis outline :



Flow chart 1: Thesis outline.

1.7 Sustainable development goals (SDGs) and AD technology in rural Bangladesh

At the general assembly of the UN on 25th September 2015 (General Assembly resolution A/RES/70/1), all member countries approved the Sustainable Development Goals (SDGs). The aim of this SDG is to "end all forms of poverty, fight inequalities, and tackle climate change while ensuring that no one is left behind by 2030", and SDGs contain 17 goals (WHO, 2020).



Figure 1.1: Sustainable Development Goals addressed by AD technology (WHO, 2020).

Energy production and consumption patterns are key drivers for SDGs. Among all the processes of bioenergy production, biogas production through anaerobic digestion has substantial benefits (Figure 1.1) (Panwar et al., 2011; M. A. Rahman et al., 2019). Production of biogas based on anaerobic digestion is one of the most efficient and clean energy (Obileke et al., 2021; Weiland, 2010). Biogas can be generated through several methods, and different raw materials can be used in this process. Different biogas plants with different raw materials have different potential to produce biogas. The raw materials vary from household organic waste to industrial organic waste (Börjesson and Berglund, 2006). Figure 1.2 shows the related SDGs to AD.

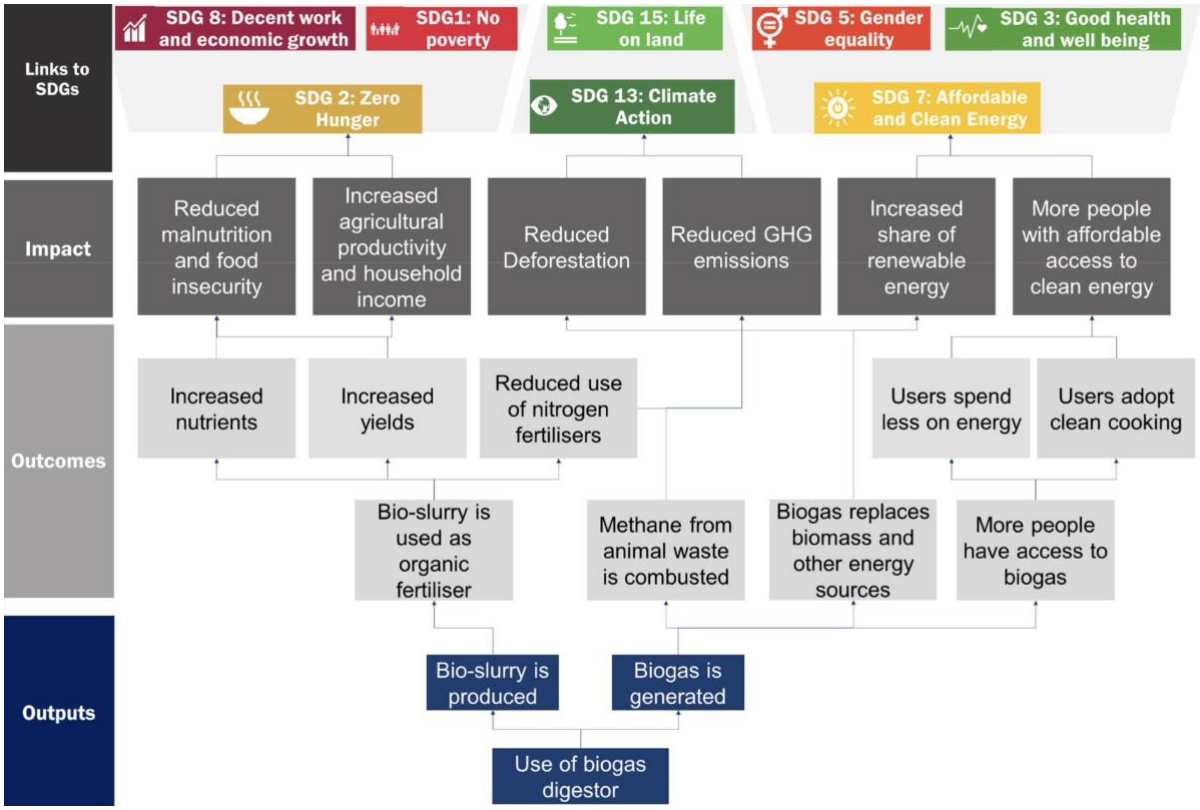


Figure 1.2: Potential of biogas to contribute towards the SDGs (IPE Triple Line, 2018).

Addressing Goals 3 and 5: Reducing indoor air pollution

At present, in many parts of the world, women and marginalised communities are still vulnerable to indoor air pollution, and biogas as a fuel in cooking can be a solution to this problem (Puzzolo and Pope, 2017; Quinn et al., 2018). For example, in Bangladesh, more than 41% of families still depend on traditional fuel (firewood and dried cow dung) as their primary cooking fuel, and almost 100% of cooking responsibilities are performed by women. However, the legal system of Bangladesh recognises the right to clean air for everyone, but the execution of this right is still a challenge (UNEP, 2019c).

Addressing Goal 7: Renewable energy generation

In anaerobic conditions, microbes decompose organic materials and generate biogas, which is a source of renewable energy (Martínez-Gutiérrez, 2018; Obileke et al., 2021). These biogas have the potential to run engines and a dynamo to convert mechanical energy or electricity (Obileke et al., 2021; Thiruselvi et al., 2020). After

treatment and compression, biogas can also be used in vehicle fuel and can also replace natural gas for similar applications (Karmaker et al., 2020).

In the context of Bangladesh, however, the most immediate and significant contribution of AD to Goal 7 is not electricity generation but the provision of a clean, locally produced cooking fuel for rural farming households. More than 41% of rural households in Bangladesh still depend on firewood or dried cattle dung as their primary cooking fuel (UNEP, 2019c). A household biogas plant fed with cattle dung provides a renewable energy source that directly replaces these traditional fuels without requiring the household to purchase LPG from commercial suppliers. The savings on fuel costs form the economic basis for repaying the low-interest agricultural loan used to finance the plant, making biogas a self-sustaining energy solution at the household level.

Addressing Goal 11: Diversion of organics from city landfills

At present, all over the world, municipal solid waste (MSW) is one of the biggest challenges for sustainable cities and separated organic materials from the municipal solid waste (MSW) stream can be used as feedstock in an anaerobic digester (Elizabeth Funmi et al., 2021). In addition to that, nutrient leaching from landfill sites contaminates the stream and groundwater (Elizabeth Funmi et al., 2021).

In Bangladesh, this challenge is particularly acute. Dhaka city alone generates more than 5,000 tons of solid waste each day, of which 62–73% is organic kitchen or food residues, and almost all collected waste is currently dumped in landfills surrounding the city (Ahsan et al., 2014; Islam, 2018). The diversion of this organic fraction to AD plants would not only reduce the volume of waste entering landfills but would also generate biogas and bio-slurry, converting a waste management burden into a productive resource. At the Level 1 household scale that is the focus of this research, animal dung rather than municipal waste is the primary feedstock; however, the potential to process urban organic waste through Level 2 commercial AD represents an important future direction for Bangladesh's growing cities.

Addressing Goal 13: CH_4 emissions reduction

As CH_4 is a potent greenhouse gas, anaerobic digestion systems capture CH_4 and prevent it from escaping into the atmosphere (Elizabeth Funmi et al., 2021; Sharma et al., 2019; Somanathan and Bluffstone, 2015; UNEP, 2021). Avoiding organic waste from landfills by managing with AD plants is beneficial for the ecosystem because if they are decomposed in landfills, CH_4 and CO_2 can be discharged into the atmosphere, which enhances the global warming process (Elizabeth Funmi et al., 2021; Sharma et al., 2019; Somanathan and Bluffstone, 2015).

Bangladesh is particularly vulnerable to the consequences of global warming, as a low-lying delta nation, it faces increasing threats from sea level rise, flooding, and extreme weather events (BPDB, 2019; MoPEM, 2017). At the same time, the management of animal dung through household AD plants directly prevents the open decomposition of manure, which is a significant source of uncontrolled CH_4 and CO_2 emissions in agricultural settings. The capture of this methane as biogas for cooking thus contributes to Bangladesh's national climate commitments under the Paris Agreement while simultaneously addressing the household energy challenge.

Addressing Goal 14: Prevention of eutrophication

Landfill leachate contains a significant amount of high organic and inorganic pollutants, and this is very toxic to the ecosystem. (Environment Agency, 2003). Organic wastes have traditionally been decomposed in landfills, but this can often lead to adverse environmental impacts, such as the leaching of nutrients into groundwater and potential eutrophication in surface water (Environment Agency, 2003; Melville et al., 2014; Naveen et al., 2018). It is possible to prevent eutrophication by diverting the organic waste and treating it with AD plants.

In Bangladesh, where rivers, wetlands, and coastal water bodies are central to both the ecosystem and the livelihoods of millions of people, the risk of nutrient leaching from poorly managed organic material is a significant concern. The uncontrolled disposal of animal dung near water bodies, a common practice in rural areas of Bangladesh where AD plants are absent, contributes to nutrient runoff and localised eutrophication in ponds and rivers used for drinking water, fishing, and irrigation

(BPDB, 2019; MoPEM, 2017). The adoption of Level 1 AD plants, by channelling animal dung into a sealed digestion system, reduces this risk and protects the water quality on which rural communities depend.

Addressing Goal 15: Soil health benefits

Maintaining fertile and resilient soils is central to sustaining food production at local and global scales. One pathway that has attracted attention is the use of digestate, the nutrient-rich by-product of anaerobic digestion. Digestate can be applied to farmland as both a fertiliser and a soil amendment (Jared et al., 2016; Wagaw, 2016). Evidence suggests it may enhance soil organic matter, reduce dependence on synthetic inputs, and contribute to healthier plant growth. At the same time, its application appears to lessen erosion, mitigate compaction, and improve water retention capacity which can lower irrigation demand (Jared et al., 2016; Wagaw, 2016). While these outcomes are promising, the extent of benefits may vary depending on soil type, management practices, and local conditions, reminding us that digestate use is not a one-size-fits-all solution.

Bio-slurry, the liquid effluent that exits an AD system after the digestion process is rich in plant-available nitrogen, phosphorus, and potassium (Siddiki et al., 2021; Khan and Martin, 2016). Unlike undigested animal dung applied directly to the soil, bio-slurry has undergone microbial processing that makes these nutrients more immediately available to crop plants (Jared et al., 2016; Wagaw, 2016). When the slurry is properly composted before application, and particularly when it is processed through vermiculture, where earthworms further digest and enrich the material, the resulting product is an exceptionally effective soil conditioner (Möller and Müller, 2012; Li et al., 2021). Evidence from Bangladesh and comparable South Asian agricultural settings consistently shows that regular application of properly processed bio-slurry can match or exceed the performance of commercial chemical fertilisers in improving crop yields, while simultaneously improving soil structure, increasing water retention capacity, and supporting the microbial biodiversity that underpins long-term soil health (Bond and Templeton, 2011; Svensson et al., 2004; Islam, 2018).

It is important to note that household organic residues, animal dung that serves as the primary feedstock for Level 1 AD plants in Bangladesh, are not 'waste' in any meaningful sense. They are organic materials that retain intrinsic value as sources of energy and as soil nutrients (Rahman et al., 2018; Siddiki et al., 2021). The AD process extracts the energy value of the material as biogas, while the residual bio-slurry retains and in some respects enhances its nutrient value (Mezzullo et al., 2013; Chakrabarty et al., 2013). Describing these materials as 'agricultural waste' obscures their value and implies a disposal framing that is both inaccurate and unhelpful for policy purposes (Muradin and Foltynowicz, 2014; Islam, 2018). Throughout this thesis, the term 'agricultural residues' is used instead.

For Bangladesh, a country where agricultural land is intensively farmed, where soil degradation is a recognised and growing concern, and where chemical fertiliser costs represent a significant burden on smallholder farming households, the systematic promotion of bio-slurry use could have considerable economic and environmental benefits (Siddiki et al., 2021; Kabir and Endlicher, 2011; Rahman et al., 2022). Agricultural extension services in Bangladesh have a critical role to play in communicating the agronomic value of properly composted bio-slurry to farming households and in advising on appropriate application methods (BARC, 2018; Akter et al., 2021). At present, this knowledge is not systematically transmitted through the national agricultural extension system, and the full potential of bio-slurry as a contribution to Goal 15 is largely unrealised (Ahmmed et al., 2018; Khan and Martin, 2016).

1.8 Bangladesh context: anaerobic digestion

Despite the progress in economic growth, Bangladesh is still a lower-middle-income country (LMIC) with substantial poverty, inequality, and poor access to sustainable, affordable energy (World Bank, 2021). Bangladesh is experiencing growth in industry, commerce, and population size, resulting in an increase in energy demand (BPDB, 2019; MoPEM, 2017). The total installed electricity generation capacity of Bangladesh has reached 20,383MW (BPDB, 2019), but at present, renewable energy sources (excluding hydropower generation) have a meagre share of the total generation (<1.5%)(Islam and Khan, 2017; SREDA, 2020). Bioenergy can offer a

vital resource to address the energy demand in Bangladesh (Iqbal et al., 2014; Siddiki et al., 2021). The generation of biogas from anaerobic digestion (AD) systems has clear advantages over other types of bio-energy generation. It is also an energy-efficient, clean and sustainable technology (Panwar et al., 2011; Sárvári Horváth et al., 2016).

Bangladesh remains a predominantly rural country, with approximately 60 per cent of its population living in rural areas and a significant proportion of rural households engaged in smallholder agriculture (World Bank, 2021; Asif and Barua, 2011). The daily life of a rural farming household in Bangladesh is shaped by dependence on locally available resources: cattle or goats for agricultural work and dairy production, small plots of land for crop cultivation, and a mixture of biomass fuels for cooking (Hossain, 2020; Power Division, 2018). For the majority of such households, the primary cooking fuel remains firewood, dried cattle dung, or crop residues, fuels that are free or low in cost at the point of use but carry heavy hidden costs in the form of indoor air pollution, health impacts on the women and children who cook and spend most time near the fire, and environmental pressure on local wood resources (Puzzolo and Pope, 2017; Quinn et al., 2018; UNEP, 2019c).

It is within this rural context that Level 1 small-scale anaerobic digestion becomes most directly relevant. The primary feedstock for household AD plants in Bangladesh is cattle dung, a resource that smallholder farming households with cattle generate daily and in consistent quantities (Siddiki et al., 2021; Rahman et al., 2014). A household with two or three cattle produces sufficient dung each day to feed a standard 2 m^3 fixed-dome digester, generating enough biogas for the household's daily cooking needs (Power Division, 2018; NDBMP-IDCOL, 2013). The level 1 AD plant simultaneously addresses the household energy problem and returns processed nutrients to the soil through bio-slurry, representing an integrated contribution to both SDG 7 (energy generation) and SDG 15 (soil health and land management) (Bond and Templeton, 2011; Svensson et al., 2004; Power Division, 2016).

This emphasis on animal dung as the key feedstock for Level 1 AD is important because it differentiates the technology from Level 2 commercial AD, which

processes a wider range of organic materials including agricultural and food processing residues, and from the framing of urban organic waste management that appears in some of the broader AD literature (Islam, 2018; Alam and Qiao, 2020). The management of organic residues from food processing and agriculture, while valuable and worth considering as a direction for Level 2 programme development in Bangladesh, is not the focus of the extension programme that this research examines (Hossain, 2020; Sarker et al., 2020).

Both the government of Bangladesh and the private sector are encouraging the installation of new (level 1) biogas plants by providing low-interest loans across the country (IDCOL, 2020). Since December 2017, IDCOL (Infrastructure Development Company Limited, established in 1997 by the Government of Bangladesh) has financed the construction of 61,000 biogas plants (out of 1,07,353 plants) all over Bangladesh (IDCOL, 2020). Despite the Bangladesh government's new initiatives, the AD sector's growth remains negligible compared to that of other LMICs (Hasan et al., 2020; IDCOL, 2020; Sarker et al., 2020).

In practice, the efficacy of biogas production is affected by several challenges; these include feeding intervals, temperature (inside the digester) due to the climatic conditions, ammonia or hydrogen sulphide production (inhibition), antibiotics and pesticides in feedstocks reduce the gas production (Drosg, 2013; Mushtaq et al., 2016). In addition, it has been well reported globally that suboptimal design and low-quality construction products of a subsystem (physical components and biogas plant appliances) of biogas plants may also impact performance and lead to decreased biogas production (Drosg, 2013; Mushtaq et al., 2016). The ambient temperature may be reduced during the winter months, and gas production may decrease by 10%-15%. Gas production decreases if the temperature of the digester falls below 15°C (IDCOL, 2020). As a result, the faulty or underperforming biogas plant is no longer economically viable because of high maintenance costs (Iqbal et al., 2014; IRENA, 2017; Quinn et al., 2018). As Bangladesh is a low-lying country, it is often inundated with floodwater, which can also lead to flooding of digesters and problems with biogas production (Iqbal et al., 2014; IRENA, 2017; Quinn et al., 2018). From Bangladesh's national-level biogas survey in 2012, only 50 % of the biogas plant operators have been trained in the operation and maintenance of AD plants

(NDBMP-IDCOL, 2013). Socio-economic issues often hinder progress toward sustainable AD development, and analysis is required to gain a greater understanding of these issues (e.g., support of communities) (Iqbal et al., 2014; IRENA, 2017; Quinn et al., 2018).

1.9 Importance of anaerobic digestion for Bangladesh

AD technology is one of the key renewable energy sources with a lesser environmental impact, and Bangladesh possesses an exceptionally strong resource base for its adoption (Elizabeth Funmi et al., 2021; Sharma et al., 2019; UNEP, 2019a). According to one estimate, Bangladesh generated approximately 486.77 million tons of animal waste products annually in 2019, with the theoretical potential to produce 27,923.72 million m^3 per year of biogas equivalent to 50 TWh per year of electric power, alongside approximately 29.232 million tons per year of organic fertiliser from the resulting bio-slurry (Siddiki et al., 2021). Agricultural residues in village areas add a further 9,693 million m^3 per year of biogas potential, calculated at 223 PJ per year under optimal conditions (Rahman et al., 2018). Together, these figures indicate a resource base that is, in principle, capable of meeting the cooking energy needs of tens of millions of rural households while simultaneously contributing to SDG 7 (energy access), SDG 13 (climate action), and SDG 15 (soil health) (Power Division, 2016; UNEP, 2021).

The significance of AD for Bangladesh goes beyond energy production. It represents a convergence of the country's agricultural traditions, its rural energy challenges, environmental vulnerabilities, and aspirations for sustainable development (Asif and Barua, 2011; Iqbal et al., 2014). AD technology was first introduced in Bangladesh at Bangladesh Agricultural University in 1972 (Khan and Martin, 2016; SREDA, 2020). Over the following decades, this early demonstration evolved into a structured national extension programme serving rural farming households across the country (IDCOL, 2020; Hossain, 2020). Systematic efforts to extend household biogas plants to rural farming communities gained momentum during the 1980s and 1990s, led principally by NGOs working at the grassroots level (Hossain, 2020; NDBMP-IDCOL, 2013).

Among the key figures in Bangladesh's biogas history, MA Gofran is widely recognised as a pioneer of household biogas extension, demonstrating that sustainable adoption depends on training users rather than simply installing hardware (Khan and Martin, 2016; Surendra et al., 2014). Grameen Shakti, the energy wing of the Grameen Bank founded by Professor Muhammad Yunus, further advanced the sector by providing low-interest loans to rural farming households that conventional banks would not serve (IDCOL, 2020; Power Division, 2018). At the institutional level, the Netherlands Development Organisation SNV was instrumental in establishing IDCOL as the coordinating and financing body for the National Domestic Biogas and Manure Programme (NDBMP) (IDCOL, 2020; Dao et al., 2020; SNV-Vietnam, 2020). The NDBMP, launched with World Bank and ADB support in 2006, was built on the principle of capacity development, strengthening local human and organisational capability for the long term rather than depending on ongoing international assistance (Ubels, Acquaye-Baddoo and Fowler, 2010; Surendra et al., 2014). By December 2020, these combined efforts had resulted in approximately 107,353 household biogas plants installed across Bangladesh (IDCOL, 2020; BPDB, 2019; SREDA, 2020). The full history of the programme is discussed in Section 2.3.1 of the Literature Review.

1.10 Anaerobic digestion or biogas system

According to guidelines on biogas technology for energy, Bangladesh, “Biogas is a type of biofuel (gas) that is naturally produced from the decomposition of organic matter. When organic matter, such as food scraps and animal waste, break down in an anaerobic environment (absence of oxygen) they produce a blend of gases, consisting of methane, carbon dioxide and a small quantity of hydrogen sulphide, water vapour, as well as a liquid slurry” (Power Division, 2018). As decomposition occurs in an anaerobic environment, the process of producing biogas is commonly known as anaerobic digestion (Power Division, 2018).

Usually, biogas consists of CH_4 (40–70%), CO_2 (30–60%), and other gases (1–5%.) It has been well-recorded that the calorific values of biogas vary from 16 to 20 MJm^{-3} (Kurchania et al., 2010)**.**

In an anaerobic digestion process (shown in Figure 1.3), there are four consecutive biological processes: (1) Hydrolysis; (2) Acidogenesis; (3) Acetogenesis and (4) Methanogenesis.

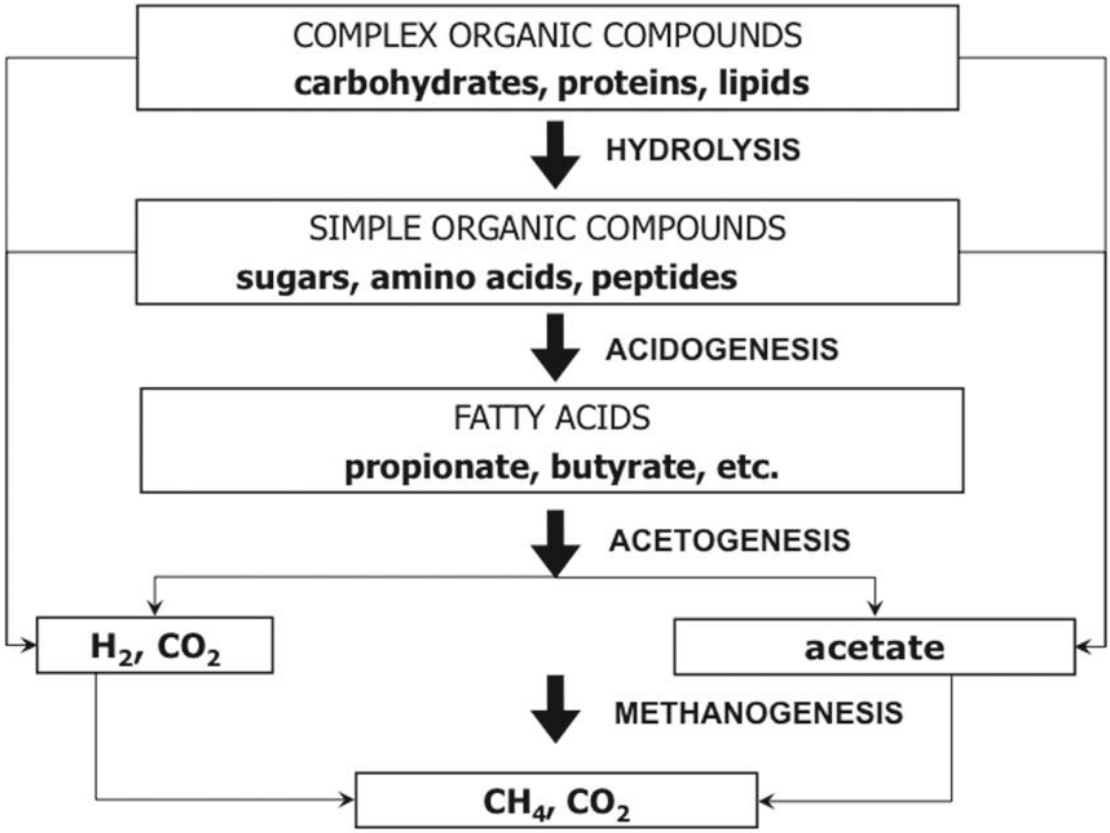


Figure 1.3: Degradation steps in anaerobic digestion (Drosg, 2013)

Anaerobic digestion begins with hydrolysis, where complex organic materials such as fats, proteins, and carbohydrates are fragmented down into smaller, soluble molecules as simple sugars, amino acids, and fatty acids, which microbes can easily process (Drosg, 2013; Melville et al., 2014; Sárvári Horváth et al., 2016). This led to acidogenesis, where bacteria fermented to produce volatile fatty acids, alcohols, hydrogen, carbon dioxide, and ammonia (Drosg, 2013; Melville et al., 2014; Sárvári Horváth et al., 2016). From there, acetogenesis starts, further refining the volatile fatty acids and alcohols into acetic acid, H_2, and CO_2. After that, these compounds are converted into CH_4 and CO_2 by specialised microorganisms; this process is known as methanogenesis.

This final step produces biogas, which can be used as a cooking fuel and can also be converted into electricity, making AD a renewable energy technology (Drosg, 2013; Melville et al., 2014; Sárvári Horváth et al., 2016).

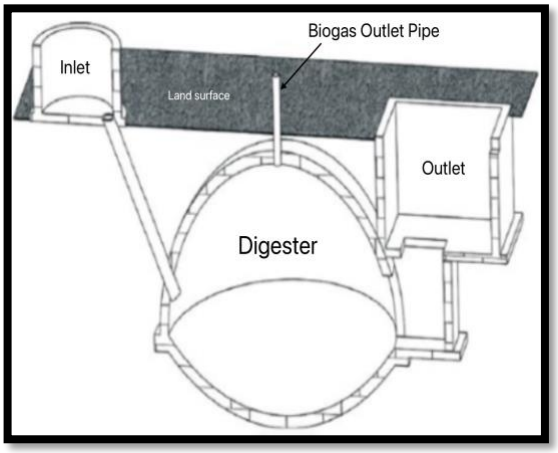
1.11 The predominant design of Level 1 AD used in rural Bangladesh: The Chinese Fixed-Dome Plant

The Chinese fixed-dome biogas plant is one of the most widely used anaerobic digestion systems in the world, particularly in rural areas of developing countries (Sasse, 1988; Seadi et al., 2008; IRENA, 2017). It is designed to convert organic materials, such as animal manure, crop residues, kitchen waste, and other biodegradable materials, into useful biogas and nutrient-rich organic fertiliser (Power Division, 2018; Fulford, 2015). The plant consists of an underground digester with a fixed masonry or concrete dome that serves as the gas storage chamber (Fulford, 2015; Sasse, 1988).

The operation of the plant begins when organic material is mixed with water to form a slurry and introduced into the digester through the inlet chamber (Power Division, 2018; Fulford, 2015). Inside the sealed digester, anaerobic microorganisms decompose the organic matter in the absence of oxygen (Drosg, 2013; Mushtaq et al., 2016). During this biological process, biogas, primarily composed of CH_4 and CO_2 is produced and accumulates beneath the fixed dome (Kurchania et al., 2010; Power Division, 2018). As more gas is generated, pressure builds up within the digester, causing the digested slurry to move into the outlet chamber. When biogas is withdrawn for use, the pressure decreases and the slurry flows back into the digester (Fulford, 2015; Sasse, 1988).



Digester during construction



Basic design of an AD plant

Figure 1.4: Diagram of Chinese fixed dome biogas plant model used in Bangladesh (Fulford, 2015; Rahman et al., 2017)

The primary function of the Chinese fixed-dome plant is to produce renewable energy in the form of biogas. This gas can be used for cooking, heating, lighting, and even electricity generation, thereby reducing dependence on conventional fuels such as firewood, kerosene, and fossil fuels (Puzzolo and Pope, 2017; Quinn et al., 2018; Power Division, 2018). In addition to energy production, the plant plays an important role in organic waste management by safely treating biodegradable materials that would otherwise contribute to environmental pollution (Paolini et al., 2018; Elizabeth Funmi et al., 2021).

Another significant function of the system is the production of high-quality biofertiliser. The digested slurry that leaves the plant contains valuable nutrients, including nitrogen, phosphorus, and potassium, which can be applied to agricultural land to improve soil fertility and crop productivity (Bond and Templeton, 2011; Svensson et al., 2004; Siddiki et al., 2021). This contributes to nutrient recycling and supports sustainable agricultural practices (Islam, 2018; Jared et al., 2016; Wagaw, 2016).

The Chinese fixed-dome biogas plant also provides important environmental benefits. By capturing methane generated during the decomposition of organic matter, the system reduces greenhouse gas emissions and helps mitigate climate change (Sharma et al., 2019; UNEP, 2021; Panwar et al., 2011). Furthermore, the controlled treatment of organic material reduces unpleasant odours, limits the

breeding of flies and disease vectors, and improves overall sanitation and public health conditions (Zaman et al., 2019; Hossain, 2020).

Because the plant has no moving gas-holder parts and is constructed underground, it is durable, requires relatively low maintenance, and can operate for many years (Fulford, 2015; Sasse, 1988; Power Division, 2018). In Bangladesh, the Chinese fixed-dome design has been adopted as the standard plant type under the NDBMP-IDCOL programme, with some local modifications to suit construction practices and material availability (Power Division, 2018; NDBMP-IDCOL, 2013). Overall, the system serves multiple functions, renewable energy generation, organic material treatment, fertiliser production, environmental protection, and the promotion of sustainable rural development, making it an appropriate and well-proven technology for rural farming households in Bangladesh (Sarker et al., 2020; Karim et al., 2019; IDCOL, 2020).

Chapter 02: Literature Review

2.1 Energy use trends in Bangladesh

Bangladesh is a developing country, and at present, the total demand for electricity is about 34,000 MW, but the existing capacity is only about 18,753 MW (BPDB, 2019). The International Trade Administration (2018) estimates that two-thirds of the country's population will have access to electricity by 2030 (Masud et al., 2020). Most of Bangladesh's electricity is generated by natural gas-based power plants. However, as the national natural gas reserve is depleted, the government has taken the initiative to generate at least half of its electricity from coal (BPDB, 2019; Power Division, 2016). In 2018, 15,953 MW of electricity was distributed at the consumer level and among this, 1745 MW was generated by diesel and furnace oil based on rented power plants and 660 MW of electricity was imported from neighbouring countries (BPDB, 2019; Power Division, 2016). In total, BPDB generated 62,677.91 GWh in 2018, which is 9.43 % higher than the previous year. Approximately 65% of the total electricity is generated from natural gas-based power plants, while only 0.1% comes from renewable sources (BPDB, 2019).

2.2 Renewable energy trends in Bangladesh

The government of Bangladesh aimed to generate 5 % (in 2015) and 10 % (by 2020) of its total energy from renewable energy sources. (IDCOL, 2020; SREDA, 2020). To promote the renewable energy sector, the Government of Bangladesh has established the Sustainable and Renewable Energy Development Authority (SREDA). One of the aims of SREDA is to generate 1800 MW, which is 10% of the total generated electricity by 2020, however, the reality is, only 730.32 MW (off-grid and on-grid) has been generated (SREDA, 2020).

The government of Bangladesh is now focusing more on solar (496.39 MW) and hydro (230 MW) resources rather than AD plants (only 1.4 MW on the grid) (BPDB, 2019; IDCOL, 2020; SREDA, 2020). In addition, SREDA also took the initiative to produce 31.08 MW of electricity by the end of 2021 from biogas (AD system) (SREDA, 2020).

Renewable Energy Installed Capacity: 730.32 **MW**

Techlology	Off-grid (MW)	On-grid (MW)	Total (MW)
Solar	346.6	149.8	496.39
Wind	2	0.9	2.9
Hydro	0	230	230
Biogas to Electricity	0.63	0	0.63
Biomass to Electricity	0.4	0	0.4
Total	**349.63**	**380.7**	**730.32**

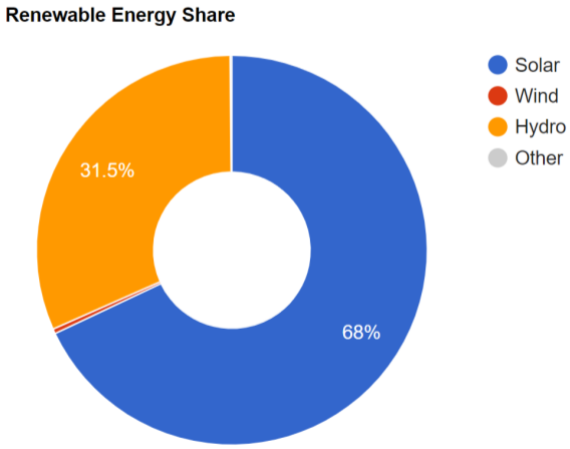


Figure 2.1: Renewable energy installed capacity of Bangladesh (SREDA, 2020).

2.3 AD sector in Bangladesh

This section of the literature review provides an overview of the biogas or AD sectors in Bangladesh. A full understanding of the current state of the small-scale AD sector in Bangladesh requires engagement with the history of the extension programme described in “2.3.1 The History of the AD Extension Programme in Bangladesh: The SNV-IDCOL “ — a history that has been shaped by the work of specific individuals, the sustained involvement of international development organisations, and a series of deliberate institutional choices about how to structure a national programme that can outlast any single project or source of external funding. Then "Biogas Energy Trends in Bangladesh" (2.3.2), which outlines the stages of evolution and development, as well as the challenges it still faces in achieving growth. After that, “AD Technology or Biogas in the Renewable Energy Policy of Bangladesh” (2.3.3) explains how the AD sector is enclosed within the current national policy, the incentives or support structures, and its alignment with the country’s broader renewable energy goals. Following this, “AD Technology and Performance” (2.3.4) provides an overview of how AD systems are functioning in the field, as well as the reported technical and operational challenges. Finally, the section “Prospects of Biogas or AD Technology in Bangladesh” (2.3.5) examines the opportunities for the

AD sector's growth and the potential role of biogas that could play in enhancing energy security, improving rural livelihoods, and supporting the achievement of the SDGs.

2.3.1 The History of the AD Extension Programme in Bangladesh

Bangladesh's growth in small-scale anaerobic digestion has been shaped not by government mandates alone, but by a collaborative framework uniting international development agencies, local NGOs, and private enterprises (Hasan et al., 2020; IDCOL, 2020). This market-oriented, commercially driven strategy has earned widespread international recognition, and its development can be traced through the contributions of specific key players and institutions (Surendra et al., 2014; REN21, 2020).

Early foundations (1970s–1990s)

AD technology was first demonstrated in Bangladesh at Bangladesh Agricultural University in 1972, marking the beginning of what would become a decades-long effort to translate the country's vast resource potential into a functioning national programme (Khan and Martin, 2016; SREDA, 2020). Systematic efforts to extend household biogas plants to rural farming communities gained momentum during the 1980s and 1990s, led principally by NGOs working at the grassroots level (Hossain, 2020; NDBMP-IDCOL, 2013). These early efforts established the community-level relationships, practical construction knowledge, and user awareness that later national programmes would build upon (Khan and Martin, 2016; Surendra et al., 2014).

SNV's entry in 2006

In 2006, SNV Netherlands Development Organisation entered Bangladesh with a capacity-building philosophy focused on strengthening local institutions rather than direct implementation (Ubels, Acquaye-Baddoo and Fowler, 2010; Surendra et al., 2014). To create a viable commercial biogas sector, SNV identified three prerequisites: appropriate technology, trained local providers, and accessible financing. These were pursued through the National Domestic Biogas and Manure Programme (NDBMP), launched that same year with the support of the World Bank

and the Asian Development Bank (ADB) (IDCOL, 2020). Crucially, SNV partnered with IDCOL, a government-owned but independently managed finance company already proven in solar energy, to channel subsidies and credit to rural households (IDCOL, 2020; Power Division, 2018). By leveraging IDCOL's existing infrastructure rather than building a parallel system, SNV established the conditions for a programme capable of scaling to national reach (Hossain, 2020; Sarker et al., 2020).

IDCOL's central role (shaped by SNV)

IDCOL was formed by the Government of Bangladesh in 1997 and began executing AD programmes in 2006 (IDCOL, 2020). The NDBMP implementation framework formally designated IDCOL as the main implementing partner, responsible for overall programme management and sector coordination, a role SNV had deliberately engineered (IDCOL, 2020; Hasan et al., 2020). IDCOL acted as the central intermediary between international donors, partner organisations (POs), and rural households. Its key functions included administering subsidies of Taka 7,000 per plant, facilitating credit through refinancing mechanisms, enforcing quality assurance including five-year structural guarantees and three-year maintenance requirements, and overseeing the network of POs responsible for plant construction and community engagement (Power Division, 2018; NDBMP-IDCOL, 2013). By 2012, among 26,311 NDBMP-registered AD plants, the programme had demonstrated the capacity to aggregate demand across multiple partners while enforcing standardised technical protocols, though it also revealed that approximately 24.7% of plants were only partially functioning and 7% had failed, highlighting the persistent challenge of maintaining quality at scale (NDBMP-IDCOL, 2013; Zifu et al., 2013).

Key Players: M. A. Gofran and Grameen Shakti

Grassroots legitimacy and reach in Bangladesh's small-scale biogas expansion were driven by key individuals and organisations. M. A. Gofran is widely recognised as a pioneer of household biogas extension in Bangladesh, bridging activism, research, and policy practice (Khan and Martin, 2016; Surendra et al., 2014). His farmer-centred approach demonstrated that sustainable adoption depends on training users rather than merely installing hardware, and his model of community-level engagement influenced the design of subsequent national programmes (Khan and Martin, 2016; NDBMP-IDCOL, 2013). Grameen Shakti, the energy arm of the

Grameen Bank, founded by Professor Muhammad Yunus, extended the Grameen Bank's established micro-finance model to household renewable energy, including small-scale biogas plants (IDCOL, 2020; Power Division, 2018). By enabling rural households to afford plant installation through low-interest loan repayment plans, and by drawing on its deep rural network and trust capital built over years of micro-credit work, Grameen Shakti became a natural and trusted partner for SNV and IDCOL in reaching remote communities that formal banking structures would not serve (IDCOL, 2020; Hossain, 2020; Mwirigi et al., 2014).

Other notable NGOs and their specialised niches

Beyond the major players, a range of smaller NGOs and research institutes have carved out specific niches within the sector, contributing to urban waste innovation, regional coverage, and community-based models (Hossain, 2020; Islam, 2018). Table 2.1 summarises the roles of key organisations operating alongside IDCOL and its partner organisations.

Table 2.1: Summary of other NGOs active in the small-scale AD sector in Bangladesh

Organisation	**Type**	**Key Focus / Activities**	**Geographic Context**
Kazi Shahid Foundation (KSF)	Rural Development	Women-led dairy-biogas model; portable fibre-glass plants with accessible repayment systems	Panchagarh District
Practical Action	Waste to biogas	Piloted municipal kitchen waste as feedstock; developed training manuals and educational films; advocates for Technology Justice to ensure clean energy access for marginalised groups	Gaibandha Municipality
Waste Concern	Research / Consultancy	Urban waste management; designs AD systems for municipal solid waste; promotes 3R principles (Reduce, Reuse, Recycle)	Dhaka and Urban Areas
Bangladesh Centre for Advanced Studies (BCAS)	Policy / Research	Assesses waste-to-energy potential; promotes biogas in commercial establishments	Khulna and Dhaka

Organisation	**Type**	**Key Focus / Activities**	**Geographic Context**
SDRS	IDCOL Partner	Implements household biogas plants as a partner organisation within the national IDCOL programme	Gaibandha, Bogura, Gazipur, Cumilla, Lakshmipur
C4RE Services Ltd	Consulting / Research	Pilots renewable energy projects; promotes an integrated agro-solar model	National
NGO Forum for Public Health	Public Health	Pilots Anaerobic Baffled Reactors (ABR) for wastewater treatment in humanitarian settings	Cox's Bazar (Refugee Camps)

NGOs have served as the backbone of Bangladesh's AD sector, with their roles expanding from plant installation to encompass market creation, urban waste innovation, rural financing, and applied research (Hossain, 2020; Islam, 2018; Alam and Qiao, 2020). Through partnerships with government and financial institutions, they have contributed to transforming a proven basic technology into a practical tool for poverty alleviation, energy access, and environmental sustainability across rural and urban Bangladesh (IDCOL, 2020; Karim et al., 2019; Rahman et al., 2019).

2.3.2 Biogas energy trends in Bangladesh

AD technology was introduced in Bangladesh in 1972 by Bangladesh Agricultural University (Khan and Martin, 2016; SREDA, 2020). Although the Bangladesh government formed IDCOL in early 1997 to promote the renewable energy initiative, it has been executing AD programs since 2006, supported by the World Bank, ADB (Asian Development Bank), and SNV Netherlands Development Organisation (IDCOL, 2020). IDCOL financed 61,000 small-scale AD plants with the help of 38 partner organisations (up to December 2020).

Table 2.2: Total number of household small-scale AD plants constructed by different agencies in Bangladesh (BPDB, 2019; IDCOL, 2020)

Agency (in Bangladesh)	**Number**
IDCOL	61000
GIZ	1500
BCSIR	24774
MoDMR	79
MoY&S	5000
LGED	7000
Others (personal and local NGOS)	8000 (approx.)
Total	1,07,353 (approx.)

At present, approximately 1MW of electricity has been generated from 10 medium-sized AD plants. In addition, another 50,000 biogas plants (medium and small scale) were built by both private organisations and NGOs; however, the total number of working small-scale AD plants is approximately 1,07,353 units (Table 2.2) (Hossain, 2020; SREDA, 2020). Bangladesh is a country with the potential for 3 million biogas plants (Rahman et al., 2014). During the last 40 years, more than one hundred thousand biogas plants of different sizes have been installed in different areas of Bangladesh (SREDA, 2020). Figure 2.2 shows the distribution of AD plants in Bangladesh (IDCOL, 2020).

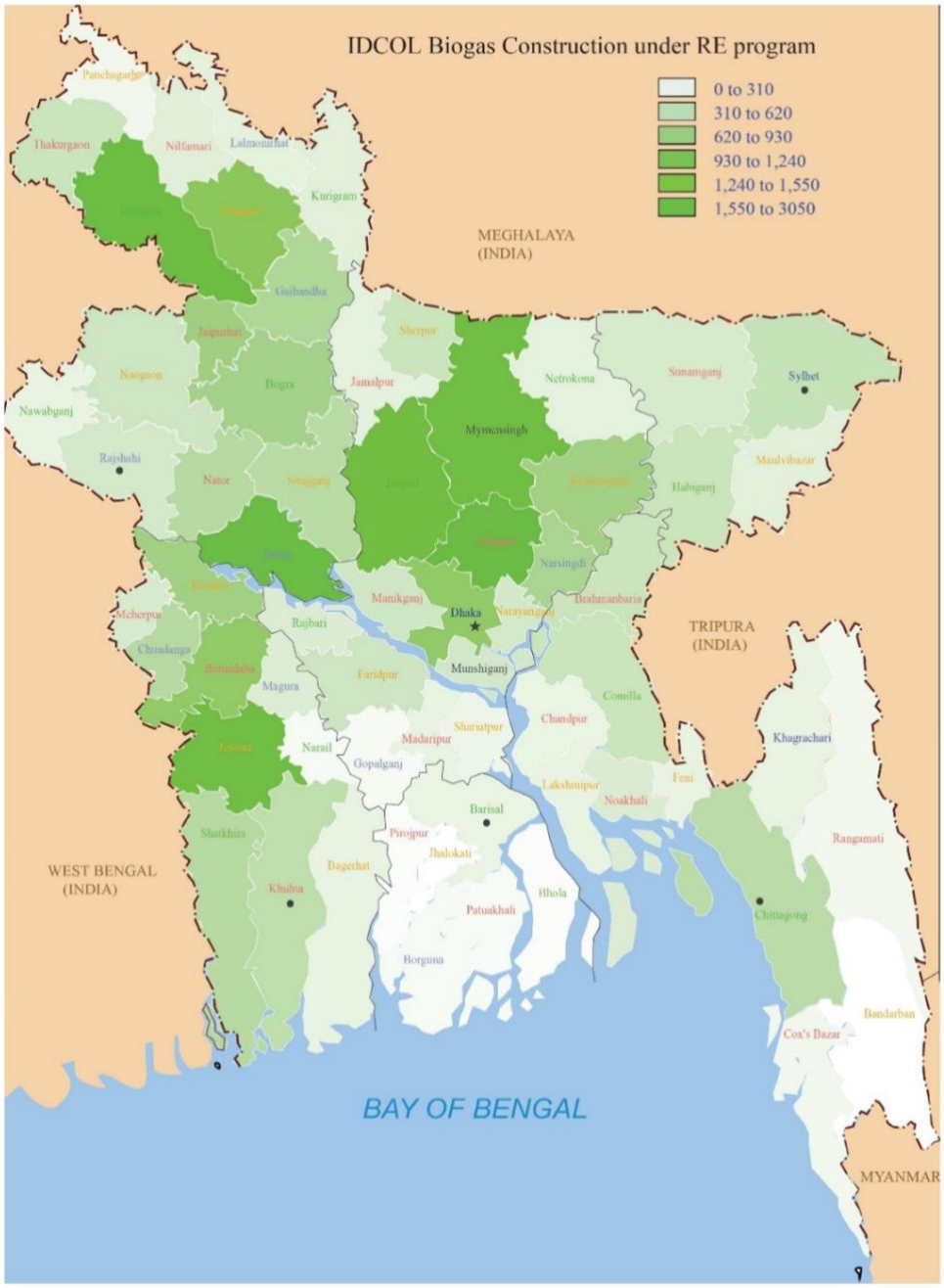


Figure 2.2: Map shows the distribution of AD plants under IDCOL construction under IDCOL biogas construction under renewable energy (RE) program in Bangladesh (IDCOL, 2020).

Figure 2.3 shows the data on the performance of biogas plants surveyed by NDBMP-IDCOL (2013) in Bangladesh. The figure portrays scenarios from 11 years back, where several AD plants of Bangladesh are not functioning properly; however, many of these plants (non-functioning) are demolished or remain inactive (Hossain, 2020;

Khan and Martin, 2016; NDBMP-IDCOL, 2013). There is a deficit of data on the current status of AD sectors in Bangladesh.

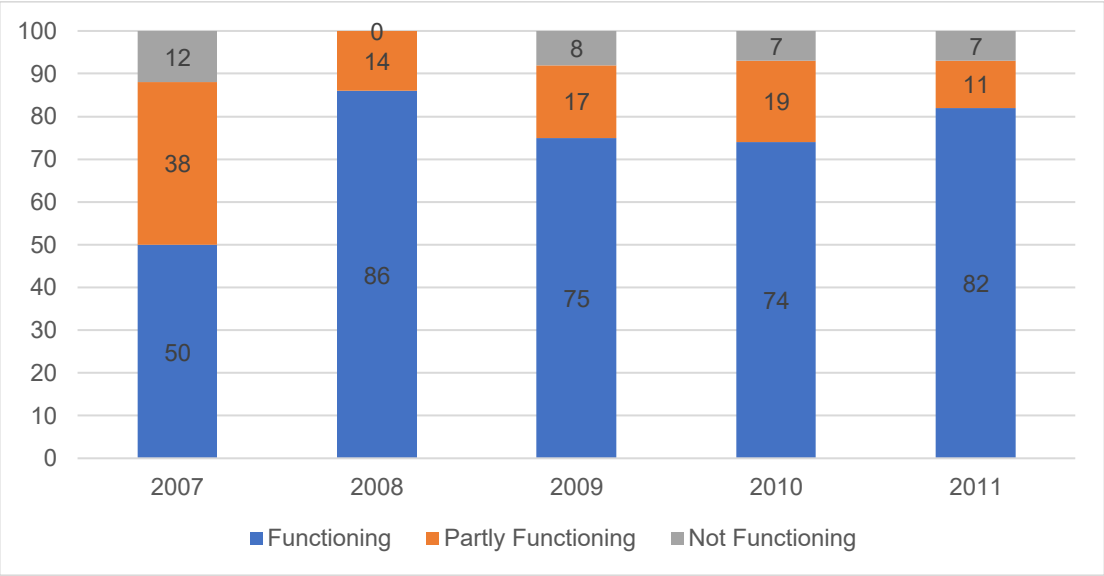


Figure 2.3: Performance of household Biogas plants (in %) in Bangladesh (Data from NDBMP-IDCOL, 2013)

After reviewing the literature, several studies have been summarised, and some suggested causes or factors that influence poor operation and failures of these AD plants in Bangladesh are given below:

- Poor design and low-standard construction practices, including the use of low-quality materials, have been identified as a barrier to AD sector growth (Khan and Martin, 2016; NDBMP-IDCOL, 2013). Insufficient design leads to structural faults, cracks, or faulty sealing, which increases the risk of leaks resulting in the loss of CH_4. Poor construction also allows for water seepage or air intrusion, which spoils the anaerobic condition required for a stable AD system. In addition, contamination from external sources or corrosion due to the use of inappropriate lining materials also affects the AD system (Khan and Martin, 2016; NDBMP-IDCOL, 2013). All these factors play a significant role in hindering AD growth in Bangladesh.
- Poor operation process hinders biogas production. Underfeeding is an example of a poor operation process. The reasons behind underfeeding include low

availability of feedstock, unbalanced feeding, and a lack of user education (Khan and Martin, 2016; NDBMP-IDCOL, 2013; Salam et al., 2020).

- Ineffective maintenance, non-availability of spare parts, and clogging of gas pipes due to the entry of slurry are also identified as key points of failure for these AD plants in Bangladesh (Khan and Martin, 2016; Mang et al., 2017; NDBMP-IDCOL, 2013).
- Studies show that one-third of AD plants experience gas leakages in their distribution pipelines during their lifetime (NDBMP-IDCOL, 2013).
- During the rainy season, rainwater and high water levels cause problems for biogas production in Bangladesh (Khan and Martin, 2016; Salam et al., 2020).
- Gas stoves used for cooking with biogas are not easy to maintain, as they experience clogging and a lack of expert mechanics for repair (Khan and Martin, 2016; NDBMP-IDCOL, 2013).

2.3.3 AD technology or biogas in the renewable energy policy of Bangladesh

In this section, we will discuss the policy and action plan related to Biogas in Bangladesh by focusing on three documents: " Renewable Energy Policy of Bangladesh (2008")," "Power System Master Plan (PSMP) 2016 Summary," and "Final Draft: Guidelines on Biogas Technology for Energy (2018)."

In 2008, the Bangladesh government developed the "Renewable Energy Policy (REP) of Bangladesh", and very few recommendations have been made related to biogas. Article 1.3.3 of REP described biomass as follows. "Biomass: Bangladesh has strong potential for biomass gasification-based electricity. More common biomass resources available in the country are rice husk, crop residue, wood, jute sticks, animal waste, municipal waste and sugarcane bagasse. This technology can be disseminated on a larger scale for electricity generation." Article 1.3.4 of REP described Biogas as follows. "Biogas, mainly from animal and municipal wastes, may be one of the promising renewable energy resources for Bangladesh. Presently, there are tens of thousands of households and village-level biogas plants throughout the country. It is a potential source to harness basic biogas technology for cooking

and rural and peri-urban electrification to provide electricity during periods of power shortfalls."

Following an eight-year interval, the Government of Bangladesh formulated the Power System Master Plan (PSMP) in 2016, aiming to realign national energy strategies with the global Sustainable Development Goals (SDGs), particularly SDG 7, which advocates for universal access to affordable, reliable, sustainable, and modern energy services (Power Division, 2016). While the PSMP places significant emphasis on the expansion of solar energy technologies, it also acknowledges the untapped potential of biogas as a viable alternative energy source, particularly for household cooking applications in rural settings. The high cost and limited accessibility of liquefied petroleum gas (LPG) in many parts of the country underscore the importance of biogas as a cost-effective and environmentally sustainable substitute (Power Division, 2016).

The master plan highlights the role of biogas in supporting rural energy resilience, emphasising its potential contribution to achieving SDG 7. It proposes a phased approach for scaling up domestic biogas production, with a target of achieving 790,000 m^3/day, including an incremental addition of 600,000 m^3/day by 2031 and reaching 3 million m^3/day by 2041(Power Division, 2016). To realise this vision, the government has outlined a strategic roadmap encompassing regulatory, infrastructural, and financial interventions.

In the short term (2016–2021), the removal of import duties and levies on glass-fibre biogas digesters and related materials was proposed to reduce initial deployment costs. In the medium term (2016–2035), the development of domestic manufacturing capacity for glass-fibre digesters is prioritised, ensuring technology adaptation, affordability, and supply chain resilience. Finally, in the mid- to long-term period (2021–2035), the plan envisions the large-scale roll-out of these digesters through financing mechanisms such as the Infrastructure Development Company Limited (IDCOL) loan scheme, thereby promoting access and adoption at the grassroots level (Power Division, 2016).

Despite the outlined potential, the implementation of this strategy is contingent upon resolving several enabling factors, including policy support, capacity-building, and stakeholder coordination. A lead time is required to develop domestic expertise and infrastructure, harmonise regulatory frameworks, and build consumer awareness and trust in the technology.

In "Final Draft: Guidelines on Biogas Technology for Energy" (2018), the Bangladesh government primarily focused on the 2016 scenario of AD technology in Bangladesh, noting the lack of integration observed in the PSMP 2016. In PSMP, the authority focused on glass-fibre biogas digesters, but very little information has been reported in the Final Draft guidelines on Biogas Technology for Energy. In addition to that, they also focused on financial support rather than technological issues. According to the guideline, the average subsidy rate is fixed at Taka 7,000 (approximately £ 65) per plant, regardless of size and location, which is very low. In addition to that, there are two funding support windows from Bangladesh Bank (i) “Refinance Scheme for Green Products/Green Initiatives (BDT 2.00 billion)”; (ii) “Refinance Scheme for Green Products/Green Initiatives by Shariah-Based Banks and Non-Banking Financial Institutions (NBFIs). 51 green products are eligible under these schemes, of which 6 are biogas products”. The guideline also recommended that VAT (15%) be exempted for all equipment and related materials for renewable energy generation (Power Division, 2018). Reviewing the renewable energy policy has become highly important, and more efforts must be invested in a master plan to promote AD technology in Bangladesh.

2.3.4 AD technology and performance

Minimal information is available at the national level regarding the success and failure of AD plants in Bangladesh. A technical survey report in 2005 stated that 66 biogas plants were studied from eight administrative districts of Bangladesh and observed that 31 (47%) plants were performing properly, 21 (32%) plants were performing partially, and rest of the 14 (21%) plants were not performing at the time of field investigation (Ghimire, 2005). In 2012, among 26,311 small-scale biogas plants (NDBMP-registered AD plants), about 6,500 plants (24.7 %) were partially

functioning, and 1,841 plants (7%) failed (NDBMP-IDCOL, 2013). A joint study by BBDF and GERBIO showed that among 70 agro-industrial biogas plants (size 6 to 49 m^3) in Bangladesh, 14 (20%) plants were not in operation, 17 (24%) of responses from operators were incomplete during the study and 19 (27%) plants could not be included into the final data analysis due to not existing slurry management (Mang et al., 2017). Again, “Final Draft: Guidelines on Biogas Technology for Energy" for Bangladesh reported that "between 25% and 50% of operational plants experience problems during lifetime" based on the Biogas user survey (BUS) 2007, 2008, 2009, 2010, 2011 report by IDCOL summarised in the table (Table 2.2) (NDBMP-IDCOL, 2013; Power Division, 2018).

Table 2.3: Results of Technical Survey (TS) report of 2005, Biogas User Surveys (BUS) 2007 to 2011, and Biogas Audit Bangladesh Team (BAB) 2011-2012: Functioning status of biogas plants in Bangladesh (in % and [households])

	Functioning	**Partly Functioning**	**Not Functioning**
2005 (TS)	47	32	21
2007 (BUS)	50	38	12
2008 (BUS)	86	14	0
2009 (BUS)	75	17	8
2010 (BUS)	74	19	7
2011 (BUS)	82	11	7
2011-2012 (BAB)	80	12	8

At present (after 2012), no data or information are available regarding the underperforming or failed small-scale biogas plants in Bangladesh.

2.3.5 Prospects of AD technology in Bangladesh

Feedstock:

Based on the physical, chemical, and biological properties of feedstock, their potential for biogas production can vary. Among commonly utilised biomass, cow dung has exhibited a biogas yield of 148 to 216 L CH_4/kg VS depending on its age, poultry litter have a biogas yield of 266 to 272 L CH_4/kg VS and town cattle market

straw has a biogas yield of 0.142 m^3/kg (Abdallah et al., 2018; Achinas et al., 2019; Fen et al., 2017; K. M. Rahman et al., 2018). For Bangladesh, it has been estimated that the potentiality of biogas energy from the above types of feedstock is 240×10^6 MJ (240TJ) per day, or 66.7×10^6 kWh, which in total has the potential to meet the energy demand of cooking of more than 30 million people of Bangladesh (Rahman et al., 2014). Figure 2.4 shows the livestock population of Bangladesh to understand its potentiality for AD sector. Again, Bangladesh has very high potential to set up around 2 million small-scale (household), 340,000 medium-scale, 19,000 large-scale, and 500 industrial-scale AD plants (Rahman et al., 2014).

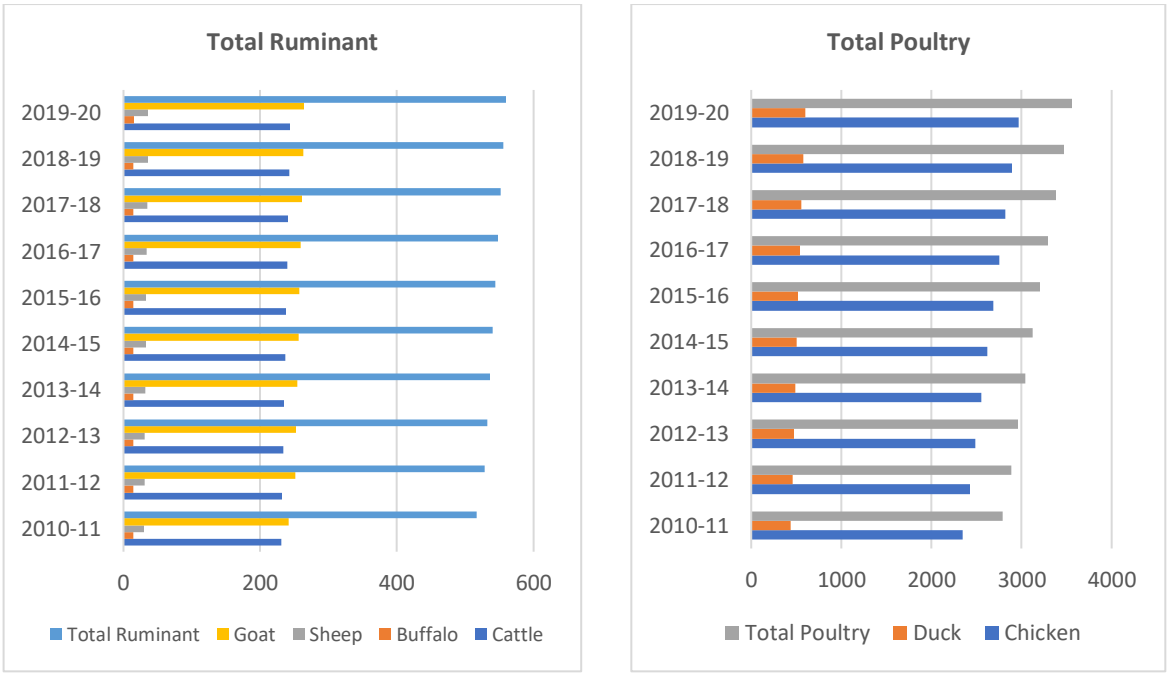


Figure 2.4: Livestock population of Bangladesh (in lakh number or in 1,00,000) in Bangladesh (DLS, 2020)

In the most recent study based on livestock research Siddiki et al., (2021), it is reported that about 486.77 million tons $year^{-1}$ of animal waste are produced in Bangladesh and have the potential to generate 27,923.72 million m3 $year^{-1}$ biogas, which can be converted to 50 TW h $year^{-1}$ of electric power in 2018–2019. In addition to that, produced slurry or digestate can be converted into 29.232 million tons $year^{-1}$ of organic fertiliser (Siddiki et al., 2021). In addition to that, solid waste (organic) from municipal waste is a great source for biogas production (Hanafi et al., 2016; Islam, 2018). Again, the organic portion of solid waste varies between 65% to 75% because

citizens use raw food for cooking rather than processed food in Bangladesh (Alam and Qiao, 2020; Habib et al., 2021). Alone, Dhaka city generates more than 5000 tons of solid waste each day, and almost all collected waste is dumped in landfills surrounding the city (Ahsan et al., 2014; Alam and Qiao, 2020)

Geographical position and climatic condition:

Bangladesh is a tropical country (Straddling the Tropic of Cancer) with a mild winter from October to March and a hot, humid summer from March to June, and this makes this environment suitable for AD industries in Bangladesh (Hossain, 2020; Sarker et al., 2020).

Energy demand:

Demand for energy, especially for cooking, is very high in Bangladesh, and small-scale AD plants can be a key component for solving this demand (Hossain, 2020; Power Division, 2018)

SDGs and Bangladesh:

One of the key ways for Bangladesh to achieve the United Nations Sustainable Development Goals is to promote the use of renewable energy resources (IDCOL, 2019; Rahman et al., 2019). Bangladesh's Biogas production is considered a viable option to combat climate change and waste management problems (Karim et al., 2019; Power Division, 2016).

Available material for AD construction:

Unlike other renewable energy devices, small-scale AD construction requires less skill, and general building construction material is sufficient to construct a small-scale traditional (Chinese fixed-dome plant) AD plant (Power Division, 2018; Sarker et al., 2020).

2.4 Comparison of AD sector with other neighbouring LMICs

This section comprises a comparative outline of Bangladesh’s AD sector with other neighbouring low- and middle-income countries (LMICs), focusing first on the AD

growth pattern (2.4.2) and then on policy contexts (2.4.3). This comparison highlights the shared opportunities and constraints, as well as the differences in policy orientation and sectoral development, which can provide a pathway for the successful growth of the AD sector in Bangladesh.

2.4.1 AD programmes across countries

In examining Bangladesh's AD sector by comparison with programmes in other countries, it is important to situate each comparator within its appropriate scale, context, and institutional history. Not all AD programmes are equivalent; they differ in the level at which they operate, in the feedstocks they use, in the populations they serve, and in the institutional frameworks through which they are delivered. Comparisons that do not account for these differences risk generating misleading conclusions (Surendra et al., 2014; Rupf et al., 2015). The following framework distinguishes between country comparisons that are directly relevant to the Bangladesh Level 1 programme, those that are partially relevant, and those that are of limited relevance to the research reported in this thesis.

Directly relevant comparators: Nepal, Vietnam, and African ABPP countries

The most directly relevant international comparators for Bangladesh's NDBMP-IDCOL programme are the national Level 1 household biogas extension programmes supported by SNV in Nepal and Vietnam, and those developed through the Africa Biogas Partnership Programme (ABPP) in Kenya, Uganda, Burkina Faso, Ethiopia, and Tanzania (Surendra et al., 2014; REN21, 2020).

Nepal's Biogas Sector Partnership (BSP-Nepal), established in 1992 with SNV support and subsequently managed by the Alternative Energy Promotion Centre (AEPC), was the model on which Bangladesh's programme was explicitly based (IDCOL, 2020, SNV-Vietnam, 2020). It targets rural smallholder farming households, uses cattle dung as the primary feedstock, finances plants through low-interest agricultural loans with repayments funded by fuel savings, and operates through a network of partner organisations under national institutional coordination (Surendra

et al., 2014). Comparisons with Nepal are therefore not merely analogical; they reflect a direct programme lineage.

Vietnam's national biogas programme, developed with SNV support from 2003, similarly targets rural farming households with cattle and pig dung as the primary feedstocks, and is structured through a comparable institutional framework (Dao et al., 2020; SNV-Vietnam, 2020). As Figure 2.6 in this thesis shows, both Nepal and Vietnam have significantly more small-scale AD plants per household than Bangladesh, despite having lower or comparable GDPs, a comparison that directly motivates the research questions of this thesis (IDCOL, 2020; MoFE, 2021; SNV-Vietnam, 2020; World-Bank, 2020).

The ABPP countries, Kenya, Uganda, Burkina Faso, Ethiopia, and Tanzania, host Level 1 domestic biogas programmes developed through SNV and subsequently continued by HIVOS. These programmes similarly target smallholder farming households, primarily with cattle dung as feedstock, and have generated significant bodies of evidence on the socio-technical and socio-economic factors that influence household biogas adoption and sustained use (Mwirigi et al., 2014; Rupf et al., 2015; Roopnarain and Adeleke, 2017). Lessons from these programmes are directly relevant to the Bangladesh context.

Relevant comparators: India and China

India and China have had national Level 1 small-scale domestic biogas programmes for several decades, predating the Bangladesh programme (REN21, 2020). India's National Biogas and Manure Management Programme (NBMMP) and China's national biogas programme have both reached a much larger scale than Bangladesh's, providing valuable experience in quality control, programme management at national scale, and the challenges of sustaining performance over time (Mittal et al., 2018; Li et al., 2015; Chen and Liu, 2017). These comparisons are relevant and informative, and are retained in this thesis as appropriate. It should be noted, however, that both India and China also have substantial Level 2 and Level 3 commercial AD activity, and references to those aspects of their programmes are

less directly applicable to Bangladesh's Level 1 household programme (REN21, 2020).

Partially relevant comparators: Brazil and Latin America

Brazil and Latin American countries are primarily engaged in Level 2 commercial AD, applying the technology at industrial scale to agricultural residues from large livestock operations (REN21, 2020). While some financial and policy lessons from these programmes, particularly regarding carbon credits, off-take agreements, and electricity grid integration, may be instructive for the future development of Level 2 commercial AD in Bangladesh, the operational context differs substantially from Bangladesh's Level 1 household programme (Hoo et al., 2018; Lönnqvist et al., 2018). References to Brazil and Latin America are included in this thesis only where they offer specific relevant insights, and they are clearly framed as Level 2 comparators rather than as direct models for the extension programme.

Limited relevance: USA, Denmark, and other developed countries

The United States and Denmark host primarily Level 2 commercial AD programmes, including sewage-based biogas and agricultural residue-based systems, with very limited Level 1 small-scale domestic activity (Seadi et al., 2008; IRENA, 2017). This is largely because the economics of household biogas are not viable in temperate climates without additional heating, and because rural households in these countries have access to gas grids and electricity networks that make household digestion unnecessary (Christensen and Bach, 2015; Lönnqvist et al., 2018). References to these countries' AD sectors are therefore of limited relevance to the Bangladesh Level 1 programme and are included in this thesis only where specific policy questions, such as feed-in tariff design or regulatory frameworks, warrant illustration from an advanced economy context (Christensen and Bach, 2015; Lönnqvist et al., 2018).

Germany and the broader Scandinavian region are primarily engaged in Level 3 advanced commercial AD, generating biomethane from agricultural residues and energy crops, removing carbon dioxide from the gas stream, and injecting the

resulting biomethane into national gas grids or using it as a compressed vehicle fuel (Seadi et al., 2008; IRENA, 2017). This level of activity requires an order of magnitude greater capital investment than Level 1 or Level 2 programmes, a highly skilled technical workforce, and an advanced regulatory and infrastructure environment (Igliński et al., 2015; Muradin and Foltynowicz, 2014). References to Level 3 programmes in Germany or Scandinavia are therefore not applicable to the Bangladesh programme as it currently exists or as it is likely to develop in the near to medium term. Where such references appeared in earlier drafts of this thesis, they have been reviewed and either removed or reframed to make clear that they do not represent models for emulation in the Bangladesh context.

2.4.2 AD sector growth

Despite the vast potential of the AD sector in Bangladesh, growth is currently limited and falling far behind that of other similar Asian LMICs, such as Nepal and Vietnam (Figure 2.5).

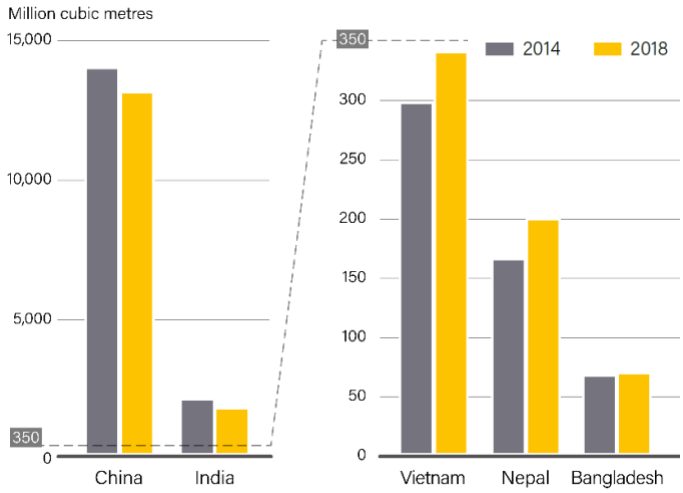


Figure 2.5: Production of biogas for cooking in selected countries, 2014 and 2018 (REN21, 2020).

According to the Figure 2.5 about 15,000 million m^3 of biogas was used for in 2018, and China alone generated and used 13100 million m^3, the nearest user in India (1600 million m^3) (REN21, 2020). However, compared to 2014 and 2018 data, a decline is observed in China and India, but Bangladesh, Nepal, and Vietnam show upward trends (REN21, 2020).

The figure below (Figure 2.6) compares Bangladesh with other LMICs like Nepal and Vietnam for small-scale (≤ 5 m^3) AD plants along with gross domestic products (GDPs) in 2020. Nepal has 75% more small-scale AD plants, and Vietnam has more than 65% of its small-scale AD plants compared to Bangladesh. In terms of biogas production, Vietnam produces significantly more biogas than Nepal and Bangladesh, as shown in Figure 2.5 (REN21, 2020).

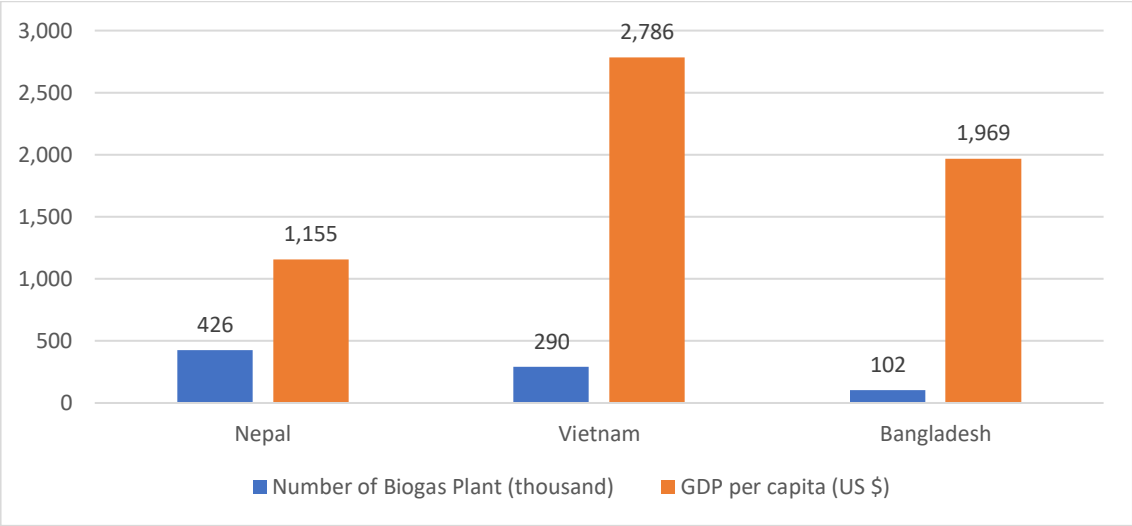


Figure 2.6: Comparison of GDP per capita and small-scale AD plants among Nepal, Vietnam and Bangladesh (IDCOL, 2020; MoFE, 2021; SNV-Vietnam, 2020; World-Bank, 2020).

GDP is a measure of the size and health of a country's economy for some time (usually one quarter or one year) (World-Bank, 2020). Though Bangladesh has a higher GDP than Nepal, AD growth is insignificant. It is clear from Figures 2.5 and 2.6 that there are significantly fewer AD plants in Bangladesh than in other countries.

2.4.3 Policy context

The Government of Bangladesh published a "Renewable energy policy" in 2008, mainly focused on solar and wind power (Power Division, 2008). In contrast, in 2006, the Government of Nepal published a detailed plan on the small-scale AD sector in its "Rural Energy Policy-2006" (Power Division, 2008). Vietnam also elaborated its strategy regarding AD in 2011 (Dao et al., 2020; SNV-Vietnam, 2020). However, to date, the "Guideline on Biogas Technology" has not been published in Bangladesh

(Power Division, 2018). Figure 2.7 shows the timeline of published policy papers related to AD sector in Nepal, Vietnam and Bangladesh.

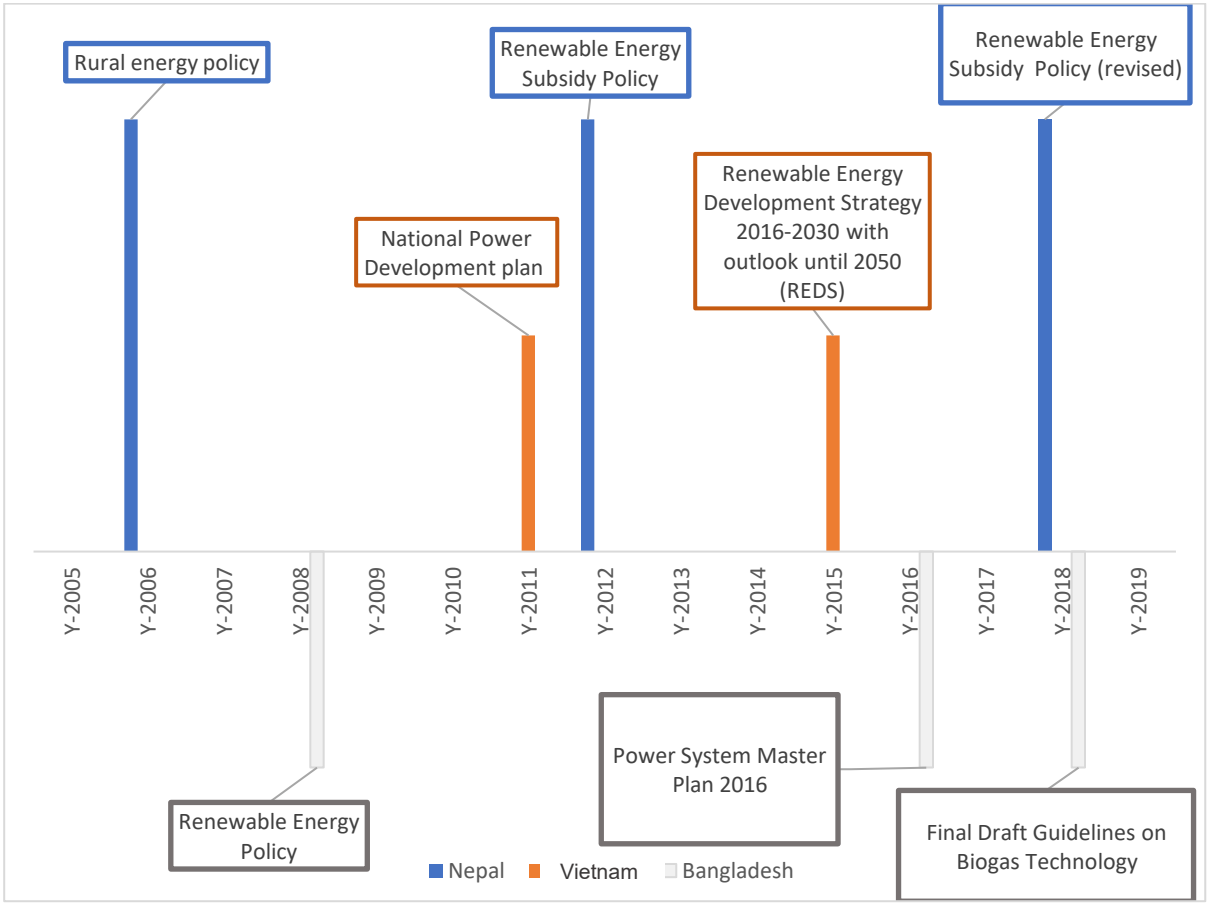


Figure 2.7: Timeline of published policy papers related to AD/ Biogas technology in Nepal, Vietnam and Bangladesh.

2.5 Barriers to AD sectors in third-world countries

There is a significant deficit in detailed data on the barriers and limitations of the AD sector in Bangladesh. It is difficult to target actions and recommendations to support the sector's growth without clear data and information on the barriers and limitations. This section will focus on the well-documented barriers and limitations of third-world countries to understand the areas where Bangladesh needs to emphasise. Significant barriers in third-world countries are discussed below.

2.5.1 Technical barriers

The performance and biogas production of AD plants rely on the knowledge and experience of the operator and support personnel. In developing countries, the adoption of AD technology becomes challenging because of a lack of specialised construction firms, qualified experts, construction businesses, and technicians with expertise in designing and constructing AD plants (Dhar et al., 2017; Kumar Ghosh and Mandal, 2018; Kumaran et al., 2016; Li et al., 2015; Malahayati and Masui, 2018). A successful biogas plant encourages others to adopt the technology. On the contrary, technically faulty biogas plants can cause trust issues among prospective users. Biogas programs run with the defective design of AD plants create a negative impression on the community for the further adoption of AD technology (Amuzu-Sefordzi et al., 2018; Kelebe, 2018; Mittal et al., 2018; Sovacool et al., 2015)

The frequent necessity of repair and low maintenance of biogas plants causes significant obstruction to the growth of the AD sector (Shen et al., 2015; Sovacool et al., 2015; Surendra et al., 2014). In third-world countries, the lack of expert engineers for AD installation and maintenance also causes a negative impact on prospective investors (Surendra et al., 2014). Ghafoor et al., (2016) identified unskilled or lack of technical knowledge of AD constructors led to the collapse of AD plants in the long run. In another study in Pakistan, the author concluded that lack or improper maintenance for one year caused the complete shutdown of AD plants (Yasar et al., 2017). Improper management and insufficient technical knowledge of AD constructors endanger the AD programmes because this creates a depraved impression of the programme (Dahlin et al., 2015; Ghafoor et al., 2016; Surendra et al., 2014; Tiwary et al., 2015).

2.5.2 Economic barriers

A lack of adequate financial incentives is one of the most persistent economic barriers hindering the growth of the AD sector in developing countries (Hossain, 2020; Power Division, 2018). The absence of required subsidies, limited governmental financial support programs, and restricted access to bank loans collectively deters potential investors from adopting AD projects (Chen and Liu, 2017;

Christensen and Bach, 2015; Lönnqvist et al., 2018; Roopnarain and Adeleke, 2017). In low-income countries where high capital cost is a substantial burden, economic barriers are particularly acute.

For instance, in sub-Saharan Africa, the deployment of household-scale biogas plants has been significantly constrained by affordability issues. Due to the absence of comprehensive and sustained financial support schemes, such technologies remain financially inaccessible for a large proportion of the rural population, especially among low-income households (Mwirigi et al., 2014; Rupf et al., 2015). Similarly, in Bangladesh, the implementation of community-based biogas initiatives has encountered substantial setbacks owing to insufficient financial backing. Several pilot projects failed to reach operational sustainability, mentioning the crucial role of structured financial interventions in confirming the long-term feasibility of such schemes (Hossain, 2020; Power Division, 2018).

Moreover, the expansion of the AD sector is further undermined by the continued provision of government subsidies to conventional fossil fuel industries in many developing nations. These subsidies distort market dynamics by artificially lowering the cost of fossil fuels, thereby reducing the relative competitiveness of renewable energy technologies such as biogas (Hoo et al., 2018; Surendra et al., 2014). A notable example is Bolivia, where the government has historically subsidised fossil fuels to support industrial growth and economic development. However, attempts to withdraw these subsidies have triggered widespread public dissent and civil unrest, demonstrating the political sensitivities surrounding energy price reforms (Lönnqvist et al., 2018).

2.5.3 Market barriers

Traditional solid biomass competes with biogas because it is a comparatively cheaper alternative and is available in village areas (Mittal et al., 2018). Digestate-based products (fertilisers) face competition with existing fertilisers and face legal issues with existing fertiliser legislation (Dahlin et al., 2015; Kumaran et al., 2016)

2.5.4 Institutional barriers

Lack of political support and bureaucratic issues still need to be overcome to enhance the AD programme (Igliński et al., 2015; Msibi and Kornelius, 2017; Muradin and Foltynowicz, 2014). Too many prerequisites and administrative complexity delay the entire process of new AD plant installation (Chen et al., 2017; Pazera et al., 2015). In rural China, AD plant installation under the Clean Development Mechanism project takes 12–18 months (Chen et al., 2017). New AD plant owners and investors would like complete policies and support from the administration (Martin, 2015).

Both internal and external political uncertainty also hinder the growth of AD sectors. This circumstance hampers entrepreneurial actions and suspends investment from the private sector. For example, conflicts with Eritrea and Somalia make Ethiopia vulnerable to the AD programme. Many countries face significant geopolitical risks due to their conflict with other countries (e.g., Sudan, South Sudan, and Somalia) (Kamp and Bermúdez Forn, 2016). Lack of coordination among the public and the private sectors and lack of private sector participation challenge the growth of the AD sector (Mahachi et al., 2015; Mittal et al., 2018). The private sector plays a vital role in the AD sector's growth and promotes biogas to the market (Msibi and Kornelius, 2017).

2.5.5 Socio-cultural barriers

A lack of community engagement and user interest hinders the expansion of the AD sector. In Ghana, rural communities were unfamiliar with AD technology and also unwilling to accept AD technology (Arthur et al., 2011; Mengistu et al., 2015). In Malaysia, people prefer low-price options for their waste disposal, and community awareness is missing in rural parts of the country, hindering the prospects of the AD sectors (Chien Bong et al., 2017).

In sub-Saharan Africa, different religious communities have strong guidelines regarding hygiene. People in that area consider the AD process unhygienic, which hinders the growth of AD technology in that region (Gebreegziabher et al., 2014). Even many households in Kenya showed adverse concerns regarding the

cleanliness of the gas from AD plants (Sovacool et al., 2015). Muslim communities or countries have strict rules regarding ‘Halal’ (acceptability) and ‘Haram’ (unacceptability) of gas produced from pig manure; this creates a barrier in the export of gas produced in other countries to the Muslim nations (Dahlin et al.,2015).

Potential AD clients are often unaware of the AD system, and sometimes they do not see the difference between natural gas and biogas (Ammenberg et al., 2018; Hoppe and Sanders, 2014; Nethengwe et al., 2018). Researchers studied the knowledge level of prospective clients regarding the AD system and concluded that farmers have a lack of knowledge (Amuzu-Sefordzi et al., 2018; Cheng et al., 2017). Lack of knowledge on AD plants, selection of materials for AD plants, and economic feasibility evaluation of AD technology hinders the growth of this sector (Amuzu-Sefordzi et al., 2018; Cheng et al., 2017). In sub-Saharan Africa, the adoption of biogas technologies is hindered by low literacy levels (Mwirigi et al., 2014).

In this research, all prospects and barriers are considered as indicators of the success and failure of the small-scale AD sector.

Chapter 03: Research Methodology

3.1 Overview of methodology

This section of the research presents the detailed methodological steps to allow other researchers to regenerate or compare with other studies. It will also enable other researchers to evaluate the reliability and validity of this study. Chapter 1 summarises the research gap, research question, and research objectives of this study. Consequently, this chapter describes and discusses the methodology used to pursue a goal - the research objective(s), and the quest for a solution to the problem - the research question. Furthermore, this section elaborates on the research methodology, discussing the underlying research philosophy and detailing the approach, strategy, methods, and data collection and analysis techniques utilised in the study.

The study is divided into two major sections (1) Assessment of the key factors of the macro environment for sustainable growth of AD sectors in Bangladesh based on integrated approaches (combination of PESTEL, SWOT, ETE (Delphi), Horizon scanning and Likert scale) and (2) Evaluation of the present scenario and assessing the success and failure of small-scale biogas plants in Bangladesh via questionnaire survey and field investigation on existing biogas plants (micro-scale). The first component of the study explores the macro-level factors which are impacting the stability/ growth of the AD sector (looking at national-level factors) in Bangladesh. Then, the second part of the study explores the micro-scale factors with operators/ AD owners to assess the socio-technical and socio-economic reasons for the underperformance and failure/ inhibited growth of the AD sector in Bangladesh.

The first section of the study (at the policy and institutional level) has been designed as an integrated approach that includes several tools like PESTEL, SWOT, Delphi, and Horizon scanning for assessing the sustainable growth of the AD sector in Bangladesh. In this section, several key factors of the macro environment for the success and failure of the AD sector in Bangladesh have been identified for each of the six pillars of PESTEL through the literature review process (horizon scanning) and stakeholders selected (a part of Delphi approach), with major 7 key factors for each pillar. The Likert scale (scoring methods) was applied to the selected key factors of PESTEL for the stakeholder's responses (via Google form) to understand their

views on these key factors. Finally, PESTEL is analysed. Then, Strengths, Weaknesses, Opportunities and Threats (SWOT) are also identified as the key factors of the macro-environment for the success and failure of AD plants in Bangladesh. The second section of the study (at the operator/user level) comprises a detailed questionnaire survey among the small-scale AD plants to assess the problem and prospect for sustainable growth of AD plants in Bangladesh. This study provides a real scenario of the AD sector and can identify the reasons for the success and failure of the AD sector in Bangladesh. All raw data have been processed and analysed by statistical software.

To translate the empirical findings into a coherent, dynamic, and systemically informed framework, this study employed a Causal Loop Diagram (CLD) grounded in the principles of systems thinking. The CLD served as a conceptual tool to visualise and analyse the complex web of interactions among the variables (key factors) identified in both the macro-level (policy and institutional) and micro-level (operational and practical) components of the study. Key factors extracted from the PESTEL-based policy analysis and the field-level survey data were systematically translated into a network of interconnected feedback loops. These loops capture the recursive, non-linear, and dynamic interdependencies among critical factors such as political stability, financial incentives, technological capability, stakeholder awareness, and institutional coordination. The resulting CLD offers a structured representation of how these elements co-evolve over time, either reinforcing system growth or constraining it through feedback mechanisms. Finally, recommendations have been made for sustainable AD growth in Bangladesh.

3.2 Methodology

Methodology can be thought of as the broad framework that ties together a study's design, methods, and procedures, the overall plan for addressing the research objectives (Kivunja and Kuyini, 2017; Melnikovas, 2018; Willis, 2007). It typically involves practical elements, such as how data will be collected, who will be included, which tools will be chosen, and how the findings will be analysed. Each of these pieces plays into the larger methodological process (Kivunja and Kuyini, 2017; Melnikovas, 2018; Willis, 2007). Rather than just a checklist, methodology appears

to describe the logical structure and sequence of steps through which research moves toward generating new insights. Methodology is fundamentally concerned with how researchers acquire knowledge and understand various aspects of the world or a specific area of inquiry (Khatri, 2020; Willis, 2007). When designing the methodology, researchers must identify the most appropriate strategies for obtaining the data, knowledge, and insights necessary to answer the research question and contribute meaningfully to the existing body of knowledge (Khatri, 2020; Willis, 2007).

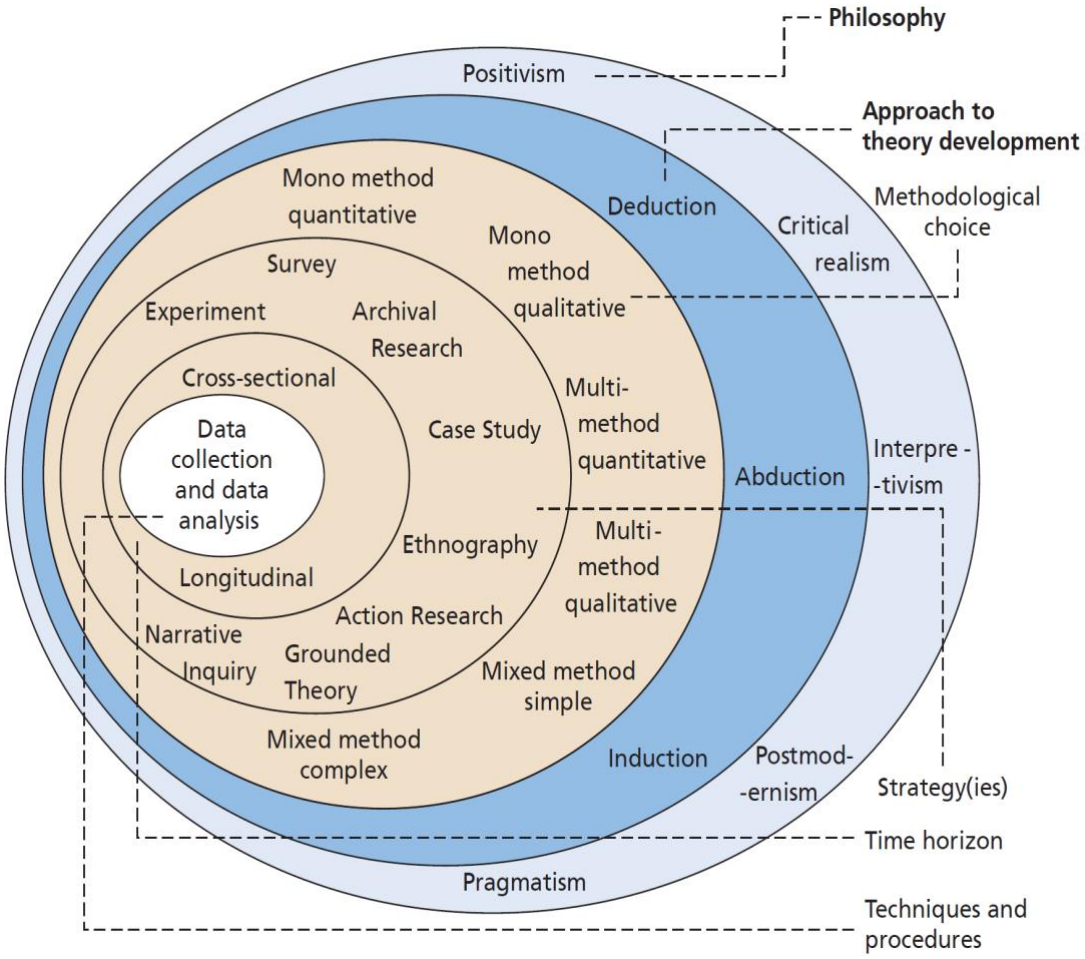


Figure 3.1: Research onion (Saunders et al., 2019).

A widely recognised framework for developing a research methodology is the theoretical concept of the "research onion," introduced by Saunders et al. (2016). The research onion comprehensively depicts the key layers or stages that must be addressed to design a robust and effective methodology (Khatri, 2020; Willis, 2007). According to Saunders et al. (2019), "*A well thought-out and consistent set of assumptions will constitute a credible research philosophy, which will underpin the researcher's methodological choice, research strategy and data collection*

techniques and analysis procedures. These will allow the researcher to design a coherent research project, in which all elements of research fit together" (Saunders et al., 2019).

3.2.1 Philosophical stance

Recognising several realities and combining objectivist and subjectivist approaches, the research embraces pragmatism as its guiding philosophy (Kaushik and Walsh, 2019; Maarouf, 2019; Park et al., 2020). Pragmatism uses hybrid approaches for dealing with challenging research topics, therefore resolving the "paradigm war" between positivism and interpretivism (Saunders et al., 2019; Ugwu et al., 2021). While epistemologically, it stresses flexibility in selecting approaches that best fit research objectives, ontologically, it implies a dynamic reality impacted by human activities (Kaushik and Walsh, 2019; Saunders et al., 2019). Combining stakeholder views using qualitative and quantitative approaches, the study looks at elements impeding Bangladesh's anaerobic digestion (AD) sector. Again, from an axiological perspective, a researcher's values, experiences, beliefs, and ideas should enhance the research process rather than hinder the pursuit of truth (Kivunja and Kuyini, 2017). Following the ethical guidelines (BCU guidelines) and COVID-19 protocols, the study aligns with the emphasis on pragmatic problem-solving and heterogeneous knowledge integration (BCU, 2010).

3.2.2 Research approach

An abductive approach was employed to conduct the study, which combines elements of deductive and inductive research approaches (Okesina, 2020; Saunders et al., 2019). Instead of moving step by step in a straight line, it circled back and forth, testing ideas against evidence and letting new evidence reshape them. In this case, the process involved surveying stakeholders, noticing recurring patterns, and using those outcomes to interpret, to find out the barriers or limitations for sustainable expansion of small-scale anaerobic digestion (AD) sectors in Bangladesh. Both qualitative and quantitative tools, particularly questionnaires, were used to collect data, and practical recommendations were derived from the findings to create a more sustainable path for the AD sector.

3.2.3 Methodological choice

This research used a mixed-methods strategy to solve the complex research questions, with a combination of qualitative and quantitative components. This type of research design appears better suited for capturing the different layers of the research questions (Kaushik and Walsh, 2019; Maarouf, 2019; Park et al., 2020). On the qualitative side, it gathers in-depth and often subjective views from stakeholders, which may shed light on the sociopolitical settings shaping their perspectives. On the quantitative side, data such as the number of AD plants, patterns in economic performance, and measurable environmental impacts provide a more structured basis for analysis.

Drawing on a mix of sources, including policy documents, interviews, survey data, and statistical datasets, also adds weight to the analysis. Overall, this mixed approach appears to offer a stronger foundation for generating recommendations that could guide the sustainable development of Bangladesh's anaerobic digestion sector.

3.2.4 Strategies

The study combines field surveys and the Delphi method (for PESTEL analysis) to investigate key factors affecting the anaerobic digestion (AD) sector in Bangladesh. The Delphi method, used here for the PESTEL analysis, brings key stakeholders (such as policymakers, industry leaders, and others) together to reflect on broader forces, including regulations, incentives, and economic shifts. This process appears especially useful during what may be a transitional stage for the sector (Mukherjee et al., 2015; Nelms and Porter, 1985; Riggs, 1983).

Field surveys, in contrast, ground the research in the everyday realities of AD plant operators and users, thereby addressing concerns such as technical problems, financial sustainability, and operational efficiency (Kaushik and Walsh, 2019; Maarouf, 2019; Park et al., 2020). This mix provides a whole understanding of systemic and operational constraints by combining qualitative insights with quantitative data. It helps create plans for the sustainable expansion of the AD sector.

3.2.5 Time horizons

The Ph.D research aims to capture the current operational processes and challenges faced by small-scale anaerobic digestion (AD) plants in Bangladesh. The primary evidence collected during the study, drawn from surveys, Delphi exercises, and interviews, offers only a snapshot in time (cross-sectional time horizon). Again, incorporating policy documents, economic statistics and other published documents from different years indicates that the research is not entirely about a single moment (longitudinal time horizon) (Melnikovas, 2018). This combined method enables this study to examine both historical trends and present conditions, thereby providing a comprehensive understanding of the AD sectors and offering informed suggestions for their sustainable growth.

3.2.6 Technique and procedure:

The last layer of the research onion, as outlined by Melnikovas, (2018) and Saunders et al. (2019), includes the techniques and procedures for data acquisition and analysis of data. At this point, the earlier methodological choices take shape in the practical steps to address the research questions (Saunders et al., 2019).

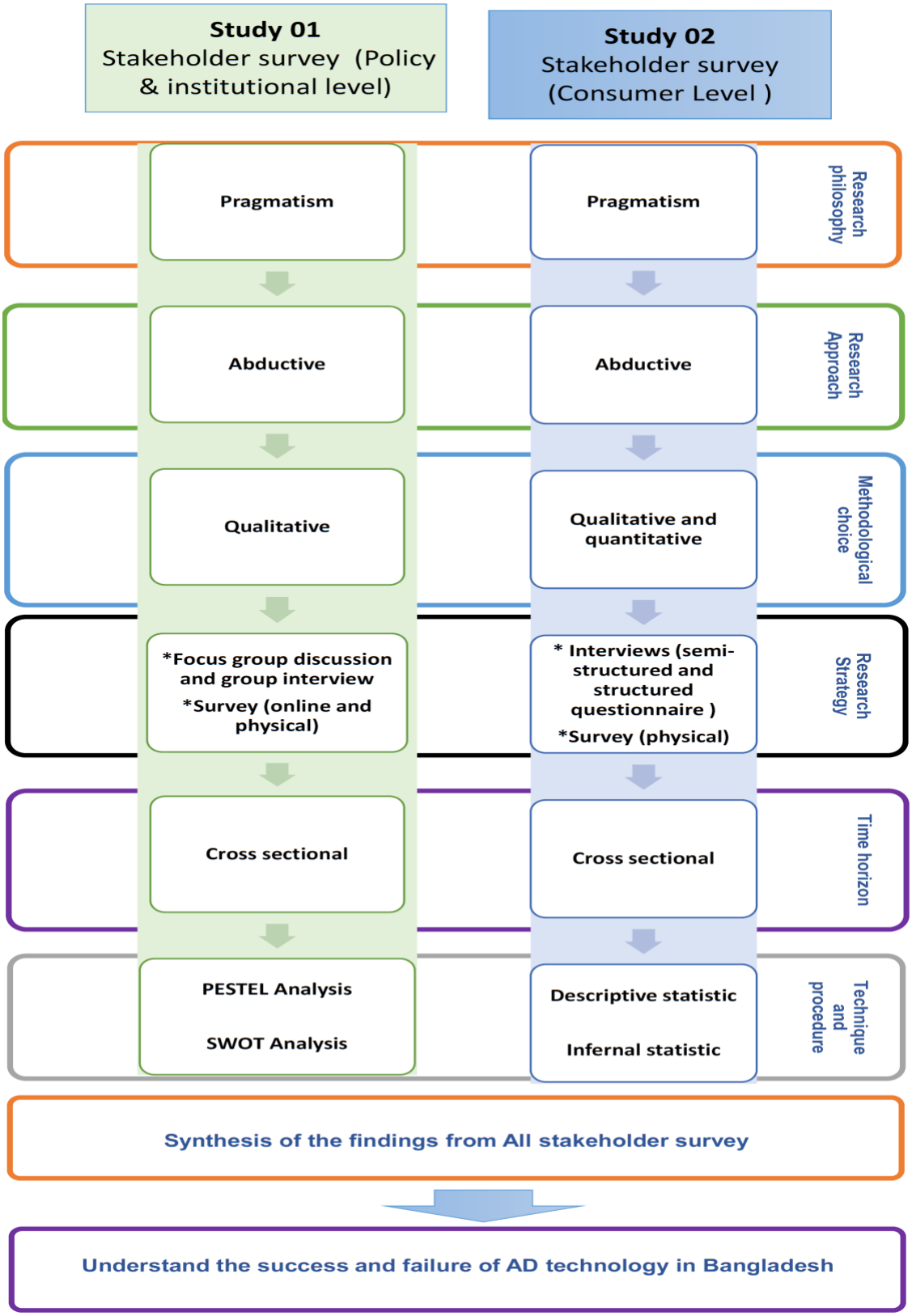


Figure 3.2: Outline of the different features of this research based on the research onion (Saunders et al., 2019).

The choice of techniques and procedures largely depends on the earlier decision regarding research philosophy, strategy, and overall approach (Okesina, 2020; Saunders et al., 2019). Those choices ultimately shape both the tools used to collect data and the way it is interpreted afterwards. It is crucial that the methods must align reasonably the research objectives to ensuring that the collected data addresses the research questions comprehensively (Okesina, 2020; Saunders et al., 2019).

In this research, as noted earlier in Section 3.1, two separate but complementary studies have been established to examine the sustainable development of the anaerobic digestion (AD) sector in Bangladesh. They can be outlined as follows:

> **Section 1:** This part of the study focuses on broader forces affecting the AD sector, such as government policies, regulatory practices, and overall economic trends. To investigate these issues, this study uses expert interviews and the Delphi method, are expected to gather insights from policymakers, regulators, and industry leaders. These are then complemented with reviewed policy documents and official reports, which provide additional context about the wider forces shaping the sector (further discussed in Section 3.3).
>
> **Section 2:** This study took a micro-level perspective, focusing on how small-scale AD plants actually performed in practice. Field surveys were carried out, using a mix of semi-structured and structured questionnaires with plant operators and users. The intention was to capture both measurable indicators, such as technical performance and financial outcomes, and the more subjective experiences of users. The surveys aim to gather quantitative and qualitative data related to technical performance, financial viability, and user satisfaction. This data will then be analysed statistically to identify patterns and correlations that can inform recommendations for improving the sustainability of small-scale AD plants (details discussed in 3.4).

By employing these techniques and procedures, the research ensures that data collection is robust and aligned with the study's goals, and that the subsequent analysis will be capable of addressing both macro- and micro-level factors influencing the AD sector in Bangladesh. This comprehensive approach will enable

the researcher to derive actionable insights and propose evidence-based recommendations for the sustainable growth of the sector.

3.3 Technique and procedure of PESTEL analysis (Section 1)

In this section, we assess the key factors of the macro environment for the sustainable growth of AD sectors in Bangladesh based on an integrated approach (a combination of PESTEL, SWOT, ETE (Delphi), Horizon scanning, and Likert scale).

3.3.1 Principles of first section (PESTEL analysis)

This study utilised a combination of PESTEL analysis (Political, Economic, Social, Technological, Environmental, Legal) (described in 3.3.2) and SWOT analysis (Strengths, Weaknesses, Opportunities, Threats) analyses to provide a comprehensive evaluation of the current status of the anaerobic digestion (AD) sector in Bangladesh.

The integration of both offers a comprehensive view of both the external factors and the internal dynamics of the sector, although they operate (Bull et al., 2016; Johnson et al., 2008). Effective strategies can be obtained from this dual study to promote the sustainable development of the AD sector in Bangladesh. PESTEL analysis helps identify the external factors that appear to influence the AD industry. SWOT then takes those insights a step further, translating them into practical strategies by weighing potential opportunities against the risks that might hold the AD sector back.

The first stage of the PESTEL study involved selecting and grouping the factors that could shape the future of Bangladesh's AD sector. For this, a panel of stakeholders was brought together, and the Delphi method was used to sort through the key factors. The technique was selected mainly because it lets expert opinions evolve through several rounds of feedback, rather than freezing them at first glance. This kind of back-and-forth seems particularly useful for complex issues like sustainability in the AD sector, where views do not stay fixed after one discussion. Again, Delphi is not flawless, but it does seem to reduce bias and push experts to think a little more carefully, which makes it a reasonable choice here.

In the first round of the Delphi process (described in Section 3.3.4), experts selected and classified important key factors into six groups based on the PESTEL pillars (Mukherjee et al., 2015; Nelms and Porter, 1985; Riggs, 1983). These key factors were refined through subsequent rounds of the Delphi process. The thorough description and categorisation of these pillars are discussed in Section 3.3.8. Additionally, key factors were identified through a rigorous literature search and horizon scanning approach (outlined in Section 3.3.3). This facilitated the determination of the most important and impactful key factors for the sustainable development of the AD sector. A total of seven key factors from each pillar, each representing a significant impact on the PESTEL pillar, were selected by stakeholders (as indicated in Table 3.4) as crucial to the sector's progress.

A six-point Likert scale (described in Section 3.3.5) was used to score these key factors, where 6 represented the most favourable and 1 the most negative for sustainable AD growth in Bangladesh (Rungson Chomeya, 2010; Taherdoost, 2019). The decision to use a six-point Likert scale rather than the more typical five- or seven-point scales was deliberate. This choice was made to avoid the neutral middle usually seen in odd-numbered scales, thereby encouraging respondents to make a definite choice and engage more seriously with the questions. This strategy was thought vital for generating more definitive and actionable data, particularly in the context of expert evaluations, where vagueness in responses could compromise the reliability of the findings.

The selection of the right stakeholders was crucial for ensuring that the findings would be both reliable and broadly representative (Bubela et al., 2016; Shostak et al., 2017). In this study, a panel of 60 experts was assembled, including academics, policymakers, NGO representatives, and AD builders (described in Section 3.3.6).

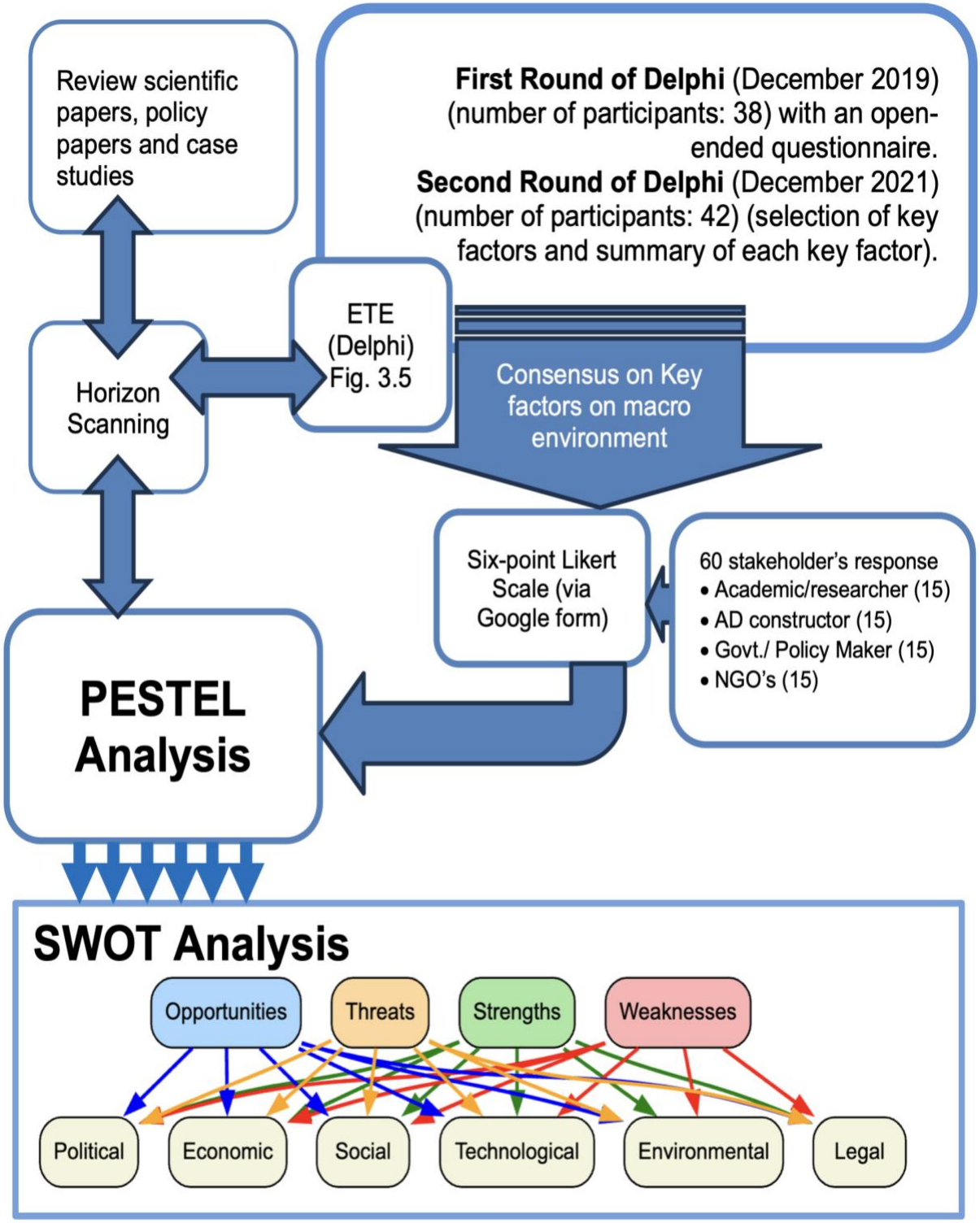


Figure 3.3: Summary of the method used in this study.

They were chosen primarily for their professional experience in the AD sector. The figure of 60 was intended to balance the diversity of perspectives with the practical limits of running the iterative Delphi process. In practice, this number appears

sufficient to capture the main spectrum of views within the sector while keeping the method manageable. The decision was guided by earlier work suggesting that such a sample size tends to provide reasonable coverage without drifting into unmanageable complexity.

The Delphi method consisted of several rounds of consultation. Feedback from the past round was incorporated into the next round, and participants were encouraged to adjust their opinions based on the general group response. This iterative procedure let important elements to be refined. A consensus was established after three rounds, thereby guaranteeing that the chosen elements reflected the group's experience (the exact number of rounds is reported in Section 3.3.4).

The arithmetic means of the ratings assigned by every expert were computed using Statistica software. These approaches, therefore, helped to ascertain the potential impact and uncertainty related to every essential key factor found in the PESTEL study.

Using the approach described by Wulf et al., (2010), further study included developing a Potential Impact vs. Uncertainty Grid (covered in Section 3.3.9). This grid helped clarify areas of high uncertainty, as well as positive and negative key factors that most significantly impact the continued growth of the AD sector in Bangladesh (Kordana and Słyś, 2020). This strategy instrument is essential for prioritising key factors that could either promote or impede sectoral development as a top priority. For the sustainable expansion of the AD industry, the grid also helps to identify driving forces (Ejdys et al., 2019; Kordana and Słyś, 2020).

Another round of brainstorming, this time using the Delphi method (described in Section 3.3.4), was carried out with experts and stakeholders to test and refine the earlier list of key factors. The intention was to let different viewpoints circulate and settle, so that the final set would reflect something closer to shared judgment rather than a single voice. Following this, participants received a Google Form survey where they were asked to weigh the potential impact and uncertainty of each factor, an attempt to make the results feel more grounded and less speculative.

From there, the study moved to identifying external opportunities (O) and threats (T) by feeding the PESTEL findings into a SWOT framework, which also surfaced

internal strengths (S) and weaknesses (W). The combined exercise appears to have offered a clearer basis for suggesting strategies—ones that could both support the sector's sustainability and confront the obstacles standing in the way of its growth in Bangladesh.

3.3.2 PESTEL analysis

Macro-environment

A macro-environmental assessment is essential for systematic strategic planning. This assessment involves analysing factors within the social, economic, technological, political, legal, and environmental domains to identify their potential changes and evaluate their impact on the organisation or industry (Bull et al., 2016; Johnson et al., 2008).

Organisations often have limited control over macro-environmental factors, which can either support or hinder their strategic efforts depending on the situation. However, macro-environmental analysis provides valuable insights into the strategic process for industry emergence, growth, and development. It identifies external factors that can positively or negatively affect market sustainability. Furthermore, organisational performance is closely tied to how effectively they respond to their external macro-environment (Bull et al., 2016; Johnson et al., 2008). In essence, understanding and analysing the macro-environment can significantly contribute to creating a competitive advantage. A comprehensive understanding of the macro-environment is crucial for organisations aiming to navigate the complexities of their external context. This section explores the significance of each macro-environmental segment and its implications for strategic planning.

Definition of PESTEL

PESTEL analysis is a strategic framework used to evaluate the macro-environmental factors which impact the organisation. The PESTEL stands for Political, Economic, Social, Technological, Environmental, and Legal factors. This analysis helps organisations understand the broader external environment in which they operate and identify potential opportunities and threats. By assessing these factors, businesses can develop strategies that align with external conditions and mitigate risks associated with environmental changes (Bull et al., 2016; Johnson et al., 2008).

Different approaches of PESTEL analysis

Over time, researchers have adapted the PESTEL analysis in various ways, depending on what they sought to understand. The traditional version adopts a straightforward approach, examining the six macro factors, but it often proves more descriptive than analytical. Some prefer an extended approach, adding new layers such as ethical, demographic, or global issues to capture what the basic model might miss (Bull et al., 2016; Johnson et al., 2008).

When combined with scenario planning, PESTEL becomes more forward-looking, helping to imagine different futures rather than predict a single one. A few studies take a quantitative approach, scoring each factor to facilitate easier comparisons, although these numbers still rely on subjective judgment.

There's also the integrated PESTEL–SWOT model, designed to merge external and internal views, although it can feel somewhat repetitive in practice. The Delphi method takes a more consultative path, seeking expert opinions over several rounds to reach a shared view, but consensus doesn't always mean accuracy (Mukherjee et al., 2015; Nelms and Porter, 1985; Riggs, 1983).

Some researchers narrow the focus by tailoring the industry-specific PESTEL framework to the realities of a single sector, while others move toward a digital PESTEL approach, utilising big data and AI tools to detect patterns more efficiently. These newer methods may appear more sophisticated, yet they still depend on thoughtful human interpretation to make sense of the results.

Selection of PESTEL analysis

This study uses a combined PESTEL–SWOT framework alongside the Delphi method. The PESTEL tool helps highlight the broader political, economic, social, technological, environmental, and legal factors that appear to shape how an industry performs (Iacovidou et al., 2017). While PESTEL on its own does not directly measure a project's sustainability, it can point to the intermediate steps that matter for such an assessment (Iacovidou et al., 2017; Tsangas et al., 2019; Zorpas, 2020). In practice, its findings may give policymakers a clearer sense of where to focus their efforts or how to steer future initiatives (Achinas et al., 2019).

The elaboration of SWOT analysis stands for Strengths (S), Weaknesses (W), Opportunities (O), and Threats (T) (Bull et al., 2016; UNICEF, 2015). Strengths and weaknesses are internal characteristics of the system; on the other hand, opportunities and threats are external factors of the system which affect the entire project or initiative (Bull et al., 2016; Islam and Mamun, 2017). In summary, Islam and Mamun, (2017) describe SWOT analysis as a tool (qualitative and quantitative) used in planning or policymaking for a project by policymakers.

Evidence of the combined use of PESTEL and SWOT in research

Most recently, this SWOT and PESTEL analysis has also been used in combination to assess the possibilities and the demonstration of renewable energy technologies (Islam and Mamun, 2017). Srdjevic et al., (2012) applied PESTEL into SWOT as a collective method to describe the exterior and interior barriers that affect Servia's water supply. Moreover, Tsangas et al., (2019) implement a SWOT in every individual pillar of PESTEL for the evaluation of the hydrocarbons sector in Insular communities. Zorpas, (2020) used PESTEL and SWOT tools to develop a strategic framework for waste management. In this study, it is assumed that stakeholder's concerns and perceptions are able to help the government to make decisions for the sustainable growth of AD sector in Bangladesh, which can be assessed by the PESTEL analysis. Consequently, new multidisciplinary, holistic and integrated models for stakeholder analysis, such as PESTEL, are gaining popularity in sustainability transformation initiatives and research.

3.3.3 Horizon scanning

According to the Organisation for Economic Co-operation and Development (OECD), horizon scanning is defined as a systematic method for detecting early indicators of potentially significant developments. It involves a structured examination of potential challenges and opportunities, with a particular focus on emerging technologies and their implications for the subject under investigation (OECD, 2020).

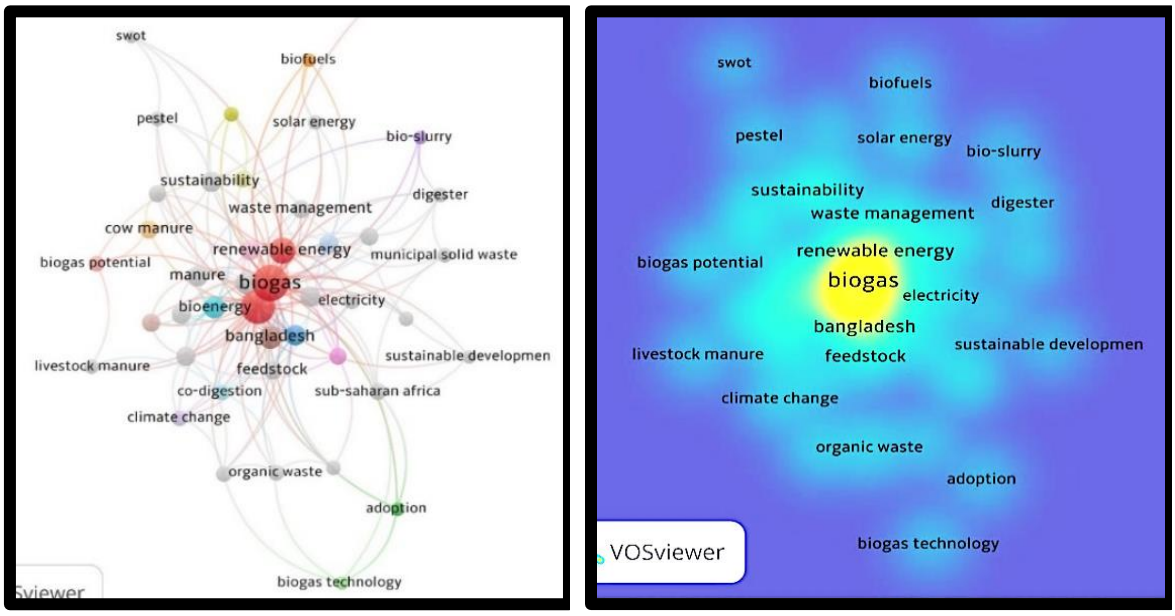


Figure 3.4: Bibliometric networks (A) Network visualisation and (B) Density visualisation.

In this study, a comprehensive literature review was conducted to understand the energy system in Bangladesh, the current status of biogas production, and factors influencing the biogas sector. Key search terms included 'biogas and drivers,' 'biogas and barriers,' 'biogas status in Bangladesh,' and 'energy system in Bangladesh,' along with other related topics. The scientific databases Web of Science and Scopus were utilised to retrieve relevant academic papers and sources. Initially, a broad search of scientific literature was performed, and the collected data were later categorised and prioritised based on relevance. Mendeley referencing software and VOSviewer (a tool for constructing and visualising bibliometric networks) were employed to organise and visualise the literature (Figure 3.4).

This horizon scanning, combined with the literature review, was instrumental in identifying key factors for each pillar of the PESTEL framework. Following this process, the participants of the first expert meeting held in December 2019 identified the seven most significant factors from each PESTEL pillar for further investigation (refer to Table 3.4) and a general description of these key factors is discussed in section 3.3.8. This structured approach ensured a focused and comprehensive analysis of the factors critical to the sustainable growth of the biogas sector in Bangladesh.

3.3.4 The Delphi method or estimate-talk-estimate (ETE) method

In essence, the Delphi method was set up as a structured communication technique originally developed for forecasting and resolving problems by relying on input from a panel of experts (Riggs, 1983). The fundamental idea behind the Delphi method is that the collective judgment of a carefully selected group of experts is generally considered than the opinions of unstructured groups or individuals. The method tends to work best when people are trying to reach an agreement on complicated questions, especially when specialist knowledge really matters (Mukherjee et al., 2015; Nelms and Porter, 1985; Riggs, 1983).

The Delphi method was carried out in several rounds of questionnaires, giving experts a chance to reconsider their opinions after seeing the anonymous feedback of others. This back-and-forth adjustment seems to be one of its strengths, even if it is not without limitations. In recent years, a slightly different version has gained ground in more interactive settings, known as the Estimate–Talk–Estimate (ETE) method (OECD, 2020). In practice, the ETE process starts with experts giving their initial views. These are then tested and refined through structured discussion before everyone makes a second round of estimates. It is essentially the Delphi idea reworked for face-to-face exchanges (Mukherjee et al., 2015; Nelms and Porter, 1985; Riggs, 1983).

The modified Delphi method used in this study is illustrated in Figure 3.5 and follows the principles of the ETE approach to ensure that expert input is systematically gathered, discussed, and re-evaluated to achieve a more precise and consensus-driven outcome.

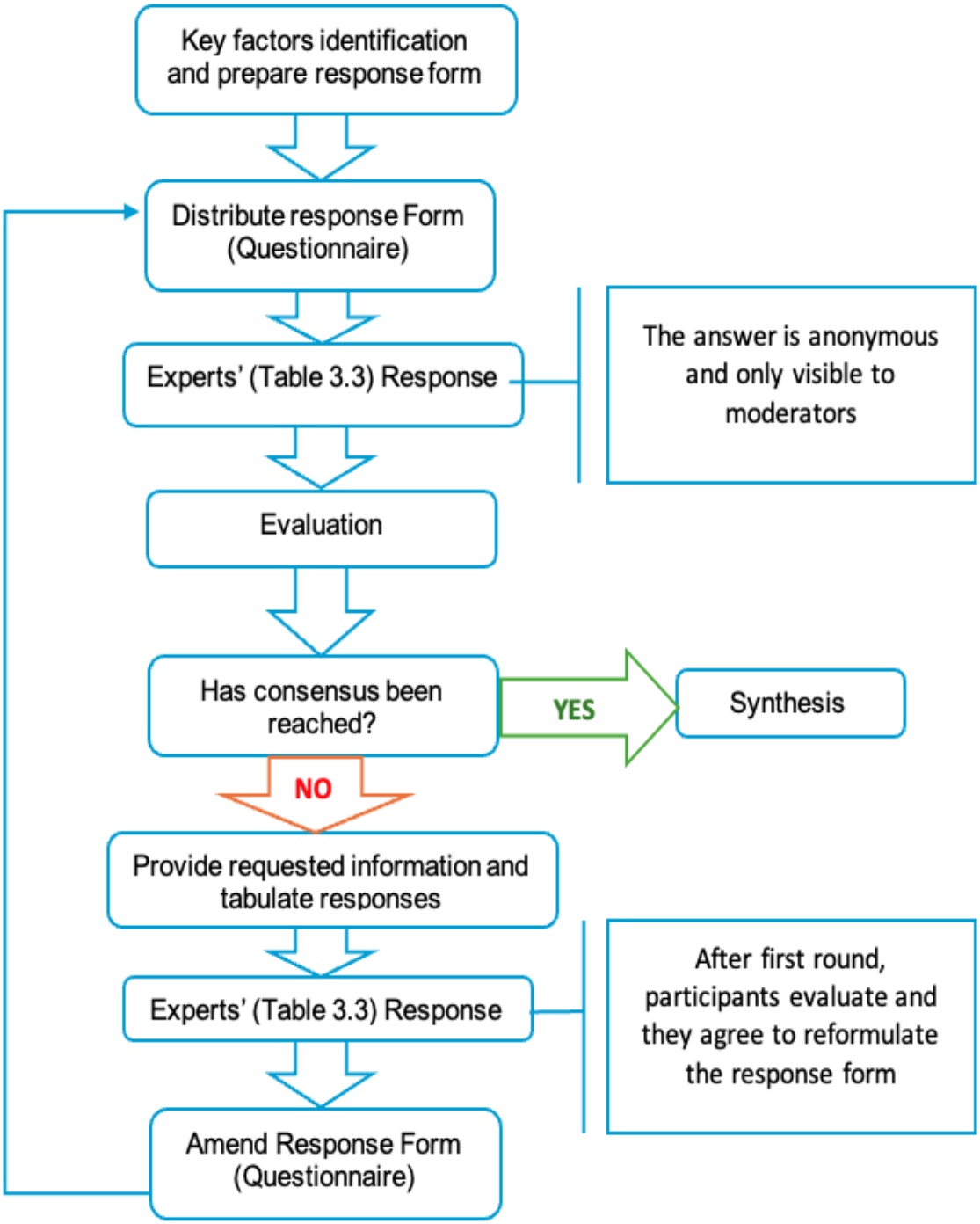


Figure 3.5: Modified steps of Delphi methods used in this study.

3.3.4.1 Formulation of the questionnaire

After reviewing the literature, several key factors of each pillar PESTEL have been identified and discussed in the stakeholder meeting (2019). Altogether, 38 experts (stakeholders) participated in a discussion during December 2019 on the intended research question to bring their own argued future views on AD sector in Bangladesh.



Meeting with Key Biogas Development Stakeholders in Bangladesh Biogas Development Foundation (BBDF) office December 2019



Distribution of Questionnaire to the Key Biogas Development Stakeholders in BBDF Meeting (December 2019)

After the meeting of 2019 and reviewing the literature, a questionnaire (Google Form) was developed with seven major key factors from each pillar (Table 3.4) relevant to Bangladesh. During the study, participants find out the important key factors for each pillar of PESTEL which they consider vital for sustainable AD plants in Bangladesh. With the selected key factors considering the sustainable growth of AD sectors in Bangladesh, the form was finally developed and disseminated among the stakeholders for the intensive data and 60 responses have been taken into consideration in this research (Stakeholder selection is discussed in section 3.3.6).



Final meeting with Key Biogas Development Stakeholders in BEPRC office December 2021.



Distribution of Questionnaire to the Key Biogas Development Stakeholders in final stakeholder meeting (December 2021)

The final round of Delphi was organised in Bangladesh (at BEPRC venue, December 2021), and 42 experts (EPRC, SREDA, Practical Action, and experts from various educational institutes) were present at the meeting. During the meeting, the experts

agreed on the final version of the response form as a Google form (questionnaire). Then, Google forms were sent to all the stakeholders for their response (see section 3.3.6). After receiving all the response forms from the stakeholders, the accumulated data have been analysed with a scoring method (3.3.5) to find out the impact and uncertainty of the key factors based on the participant's responses.

3.3.5 Likert scale and weighted scoring method

Rating scales are widely utilised as measurement tools in various academic and applied disciplines, such as sociology, psychology, information systems, political science, economics, and survey-based research (Rungson Chomeya, 2010; Taherdoost, 2019). Among these, the Likert scale is one of the most fundamental and commonly adopted scaling methods for quantifying attitudes, perceptions, or behaviours in survey research. Originally developed in 1932 as part of Rensis Likert's doctoral dissertation, the Likert scale has become a widely used psychometric tool for assessing respondents' levels of agreement or disagreement with specific statements related to the research hypothesis (Taherdoost, 2019).

The Likert scale is usually set up to capture how much someone agrees or disagrees with a series of statements, using options that run from "strongly agree" to "strongly disagree." The classic version had five evenly spaced points, but over time the format has been bent and stretched in different directions—sometimes pared down to just two choices, other times extended all the way to eleven (Simms et al., 2019). This study settled on a six-point version (illustrated Figure 3.6). The idea was to avoid giving people a middle ground where they could park a neutral response. That might sound a little restrictive, but it does nudge respondents toward taking a stand, either leaning positive or negative. In practice, this approach tends to sharpen the data, since it reduces the tendency for participants to slip into the safety of a "neutral" middle option. Whether that always improves reliability is open to debate, but it generally produces responses that feel more decisive.

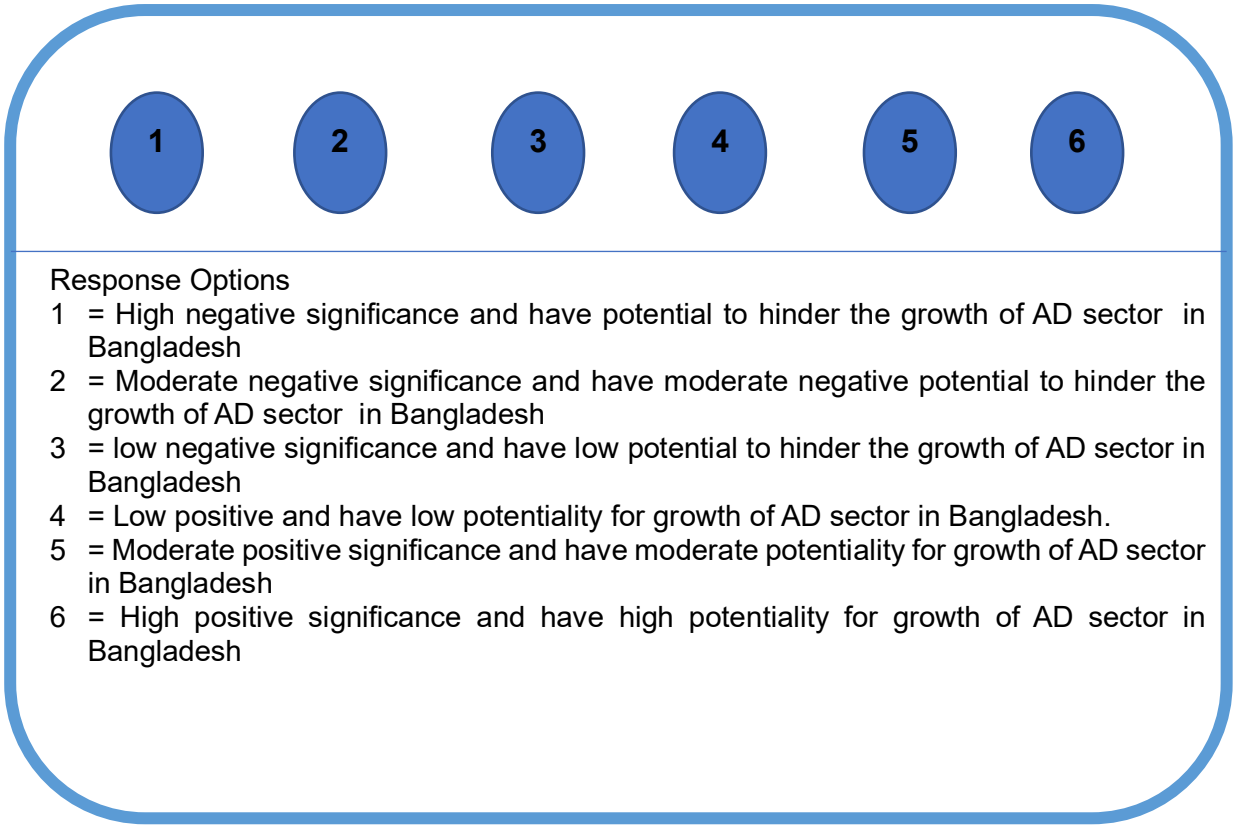


Figure 3.6: A 6-point Likert scale used in this study.

In this study, alongside the Likert scale, a weighted scoring approach has been applied to gauge the significance of each key factor. In practice, this meant assigning numerical values to the different criteria so that their relative priority could be factored in (Pluye et al., 2009). Once the weights were applied, the scores could be added up, giving a clearer sense of which components stood out when measured against the standards under review. This method enables a more refined analysis by considering both the relative importance and the ability of each component to meet the specific standards established by the research objectives. The calculation for scoring individual factors is presented in Table 3.1.

This combined approach of using a Likert scale with a weighted scoring method enables a comprehensive analysis of respondents' subjective attitudes and the objective prioritisation of key factors, ensuring that the research findings are robust and meaningful.

Table 3.1: General calculation for scoring of individual factors

Response option	Number of responses (Total Number N)	Percentage of respondents (Per)	Score assigned	Score calculation (S)
1	N1	Per 1=(N1/N) × 100	**1**	(N1× 1) ÷ N = S1
2	N2	Per 2= (N2/N) × 100	**2**	(N2 × 2) ÷ N = S2
3	N3	Per 3 = (N3/N) × 100	**3**	(N3 × 3) ÷ N = S3
4	N4	Per 4 = (N4/N) × 100	**4**	(N4 × 4) ÷ N = S4
5	N5	Per 5 = (N5/N) × 100	**5**	(N5 × 5) ÷ N = S5
6	N6	Per 6 = (N6/N) × 100	**6**	(N6 × 6) ÷ N = S6
TOTAL	**N** = N1+N2+N3+N4+N5+N6	100		**S** = S1+S2+S3+S4+S5+S6

Note: Response Options

1 = High negative significance and have potential to hinder the growth of AD sector in Bangladesh
2 = Moderate negative significance and have moderate negative potential to hinder the growth of AD sector in Bangladesh
3 = Low negative significance and have low potential to hinder the growth of AD sector in Bangladesh
4 = Low positive and have low potentiality for growth of AD sector in Bangladesh.
5 = Moderate positive significance and have moderate potentiality for growth of AD sector in Bangladesh
6 = High positive significance and have high potentiality for growth of AD sector in Bangladesh

Determination of the range

Calculation of range by the following equation (CQC UK, 2015):

Range difference

= (Total number of response option - 1) / Total number of response option.

For the Six-point Likert scale, the range difference is [(6-1)/6] = 0.83.

Table 3.2: Impact Range

	RANGE	Impact Range
High negative significance and have high potential to hinder the growth of AD industries in Bangladesh	1.00 to 1.83	Negative Impact (1 to 2.66)
Moderate negative significance and have moderate potential to hinder the growth of AD industries in Bangladesh	1.84 to 2.66	
Low negative significance and have low potential to hinder the growth of AD industries in Bangladesh	2.67 to 3.49	No impact / moderate impact (2.67 to 4.32)
Low positive significance and have a low potential for sustainability of AD industries in Bangladesh.	3.50 to 4.32	
Moderate positive significance and have moderate potential for sustainability of AD industries in Bangladesh	4.33 to 5.15	Positive Impact (4.33 to 6)
High positive significance and have a high potential for sustainability of AD industries in Bangladesh	5.16 to 6.00	

Table 3.2 shows the range for results where each range is 0.83. The total score for the individual factor (S) is then compared with the range (Table 3.2) to confirm the impact of the factor on the sustainability of AD growth in Bangladesh.

3.3.6 Stakeholder mapping and selection of stakeholders for the survey

Stakeholder mapping is a strategic tool used in project management, business, and organisational settings to identify, categorise, and understand the key individuals or groups that have an involvement in a particular project, initiative, or decision. This process helps ensure that the concerns, needs, and impacts on various stakeholders are considered for the success of any project (Bernstein et al., 2020; Ginige et al., 2018).

Three primary criteria have been considered in the selection process of stakeholders for the survey : (1) experience in the biogas sector, (2) proficiency in technical knowledge related to AD system, and (3) involvement in biogas or renewable energy policy development within governmental or relevant organisations (Bernstein et al., 2020; Ginige et al., 2018). Based on these criteria, four distinct groups of stakeholders were identified for participation: policymakers, NGO representatives,

AD constructors, and researchers/academics. In this study, a brainstorming session helps to list all possible stakeholders.

For each group, 15 respondents were randomly selected to ensure a balanced and unbiased representation. This anonymous random selection process was designed to eliminate any potential bias in both the selection of participants and their responses, thereby enhancing the reliability of the findings. Table 3.3 outlines the stakeholder selection process, ensuring transparency and rigour in the survey design.

Table 3.3: Summary of stakeholder engagement strategies.

Stakeholder	Power	Interest	Engagement Strategy
Policymakers	High	High	Regular consultations, policy briefs, public-private partnerships
NGOs	Low	High	Capacity building, pilot projects, advocacy, Monitoring and evaluation
AD Constructors	High	Low	Incentivize sustainability, compliance standards, public recognition
Researchers/ Academics	Medium	High	Collaborative research, data sharing, funding for R&D, capacity building

This stakeholder mapping helps ensure that each stakeholder group is effectively managed and that their concerns, needs, and influences are integrated into the sustainable AD development efforts in Bangladesh. The overall initiative can move forward more efficiently and inclusively by aligning their roles and interests with appropriate engagement strategies.

In this survey, the stakeholder's working experience was considered as a minimum of 5 years, except for the government policy organisations. For example, policymaker stakeholders have been selected from the Sustainable Renewable Energy Development Authority (SREDA), the Infrastructure Development Company of Bangladesh (IDCOL), the Bangladesh Energy and Power Research Council (BEPRC) and the Ministry of Power, Energy and Mineral Resources (MPEMR). For NGO, we have considered SNV, Practical Action, BBDF, RDA and researchers from reputed universities.

3.3.7 Justification for the number of stakeholders

In research involving experts, it is generally accepted that the minimum number of participants should range between 6 and 10 to ensure a diversity of opinions and expertise (Kordana and Słyś, 2020). However, in more complex studies, where a larger number of variables or key factors are being evaluated, the number of stakeholders should be proportional to the number of elements being assessed (Bubela et al., 2016). In this study, 42 key factors are being evaluated, and therefore, it is essential that the number of stakeholders exceeds this minimum threshold to enhance the reliability and comprehensiveness of the findings.

A number of experts (N experts) can be determined by taking into account the acceptable margin of error (ε) (Shostak et al., 2017). The necessary sample size for expert consultation can be calculated using the following formula (Equation 3.1), which incorporates the desired precision level and error rate:

$$\textbf{N experts} = 0.5 \times \left[\left(3/\varepsilon\right) + 5\right] \quad \text{---------- [3.1]}$$

As part of the research, the required number of experts was determined, assuming the error value ε = 3%. This gives a value of 53. In this research, it is determined that the minimum number of stakeholders must be 53. To account for this, 60 stakeholders were selected in this research.

This approach ensures that the number of experts selected is sufficient to achieve statistically reliable results, minimising the margin of error and ensuring that the findings are robust and reflective of a wide range of expert opinions. In this research, based on the complexity of the factors involved and the need to achieve a low margin of error, a larger pool of stakeholders (60 in total) was chosen, with representation across four key groups (policymakers, NGOs, AD constructors, and researchers/ academicians). The justification for selecting this number of stakeholders is rooted in the goal of maximising the reliability and validity of the data, while also adhering to established standards for expert consultation. This balance between statistical precision and practical feasibility ensures that the research outcomes are both meaningful and actionable.

3.3.8 Selection and description of pillars of PESTEL

After horizon scanning and the first round of Delphi, the following key factors have been identified for PESTEL analysis, as given in the table,

Table 3.4: List of the key factors of PESTEL.

Pillar	Selected key factors	
Political	P1	Existing Renewable Energy and Climate Change policy of Bangladesh
	P2	Taxation policies on landfilling with waste (in Bangladesh).
	P3	Government support (incentives) and bank loan policy for the AD industry in Bangladesh.
	P4	Stability of political framework of Bangladesh government.
	P5	Corruption at the national and individual level.
	P6	Bureaucratic complication (The level of administrative obstacles)
	P7	National coordination among stakeholders
Economical	Ec1	Availability and price of feedstock.
	Ec2	Biogas plant construction cost.
	Ec3	Level of maintenance costs for the biogas plant.
	Ec4	New job opportunities
	Ec5	Revenue from biogas and digestate.
	Ec6	Labour costs.
	Ec7	Security on investment
		.
Social	S1	Knowledge and awareness about the Biogas plant.
	S2	Level of information dissemination and advertising.
	S3	Level of literacy rate among the mass population in Bangladesh.
	S4	Improvement of household welfare among the AD plant users.
	S5	Vermin and malodour reduction (especially of poultry firm).
	S6	Level of social stigma (cultural and religious viewpoint).
	S7	Unwillingness to accept new technology (Biogas system).
Technological	T1	Planning and installation issues for the biogas plant in Bangladesh.
	T2	Efficiency/ Performance of existing biogas plants (AD technology) in Bangladesh.
	T3	Biogas extraction technology in Bangladesh.
	T4	Post-Treatment technology to improve the efficiency of digestate.
	T5	New technology and research
	T6	Alternative source of highly efficient renewable energy (such as solar energy).
	T7	Availability of expert technicians for biogas plant construction and maintenance.
Environmental	En1	Reduction of GHG emissions (SDG agenda).
	En2	Waste management.
	En3	Reduction of indoor air pollution.
	En4	Climatic condition of Bangladesh.
	En5	Access to adequate water for the biogas plant.
	En6	Eutrophication or groundwater contamination.
	En7	Flooding and other natural disasters.

Pillar		Selected key factors
Legal	L1	National 3R Strategy for waste management (2010), Bangladesh.
	L2	Bangladesh Standards and Guideline for sludge management (2016).
	L3	Biogas guidelines/ legislation.
	L4	The range of requirement for anaerobic digestate / bio-slurry as fertiliser or quality protocol (Fertilizer Recommendation Guide 2018, Bangladesh)
	L5	Feed-in Tariffs for produced biogas.
	L6	Environmental Law for setup and operation biogas plant.
	L7	Local government law for setup AD plants in premises (range of requirements).

1. Description of political pillar:

The political pillar is the first pillar of PESTEL, and it illustrates an overview of the key factors and the perceived importance of the sustainability of AD plants in Bangladesh from a political perspective.

P1: Renewable Energy and Climate Change Policy of Bangladesh

P2: Taxation policies on landfilling with waste (in Bangladesh).

P3: Government support (incentives) and bank loan policy for the AD industries in Bangladesh.

P4: Stability of the political framework of Bangladesh government.

P5: Corruption at the national and individual level.

P6: Bureaucratic complication (The level of administrative obstacles).

P7: National coordination among stakeholders.

In the renewable energy and climate change policy (**P1**), the Bangladesh government pledged to increase energy production from renewable sources to achieve SDG (Power Division, 2008). In addition to that, energy security is highly emphasised in Bangladesh's political agenda, but no clear policy has been stated related to the AD sector compared to other renewables (MoEF, 2009; Power Division, 2008).

The taxation policy on landfilling with waste (**P2**) is another key factor because people and industries dump food waste and other organic waste into landfills without paying any landfill tax (Shuvo, 2022). This policy has been a key factor for the adoption of AD technology for the management of organic waste, but in Bangladesh, there are no landfill taxes (except in Dhaka (capital))(DoE, 2019). All developed

countries have landfill taxes, and for this reason, companies and individuals who produce organic waste consider AD plants to be a recycling option for their waste (GOV.UK, 2016).

Bangladesh government has set an incentive and low-interest bank loan (**P3**) policy for new AD plant owners (IDCOL, 2020; Power Division, 2018). The Government of Bangladesh provides incentives (only 7000 tk) for constructing a new AD plant as a part of renewable energy subsidies and also adopts a renewable energy strategy to overcome the barriers to up-taking the technologies (IDCOL, 2020; Power Division, 2018).

Like many other LMICs, the stability of the political framework of the Bangladesh government (**P4**) is of concern, especially in the long term. However, the policy of minimum governmental interference in the economic affairs of the private sector has maintained economic growth at an impressive rate (GOV.UK, 2022). The nominal GDP of Bangladesh is $325bn and GDP per capita is $2010 higher than India's (GOV.UK, 2022; World-Bank, 2020). In addition to that, the new trade relationship between China and Bangladesh in 2020 will help AD industries to grow as China is the leader in the AD sector (Dhaka Tribune, 2020).

Bangladesh faces corruption (**P5**) at the national and individual levels, like many other LMICs (Iacovidou et al., 2017; Kamp and Bermúdez Forn, 2016). Bribery and corruption are entrenched in Bangladesh and pervade daily life, and widespread corruption is a barrier to the effective development of both the government and private sectors (GOV.UK, 2022).

Institutional barriers and a narrow business horizon of individual bodies involved in the AD sector constitute significant obstacles to developing innovative solutions and progress (Igliński et al., 2015; Mittal et al., 2018; Nevzorova and Kutcherov, 2019). The owners of small and large animal farms and agricultural and food processing industries consider biogas plants as a solution to utilising their organic waste, but these potential investors are discouraged by prolonged bureaucracy (**P6**), which leads to high costs and a long investment period.

In many LMIC a lack of national coordination among stakeholders (**P7**) has been observed in implementing projects (Buysman and Mol, 2013; Hasan et al., 2020; Mengistu et al., 2015). This phenomenon (lack of national coordination among stakeholders) hinders the sustainable growth of undertaking projects/sectors.

2. Description of economic pillar

The economic pillar is one the most important sections of PESTEL analysis

Ec1: Availability and price of feedstock.
Ec2: Biogas plant construction cost.
Ec3: Level of maintenance costs for the Biogas plant.
Ec4: New Job opportunities
Ec5: Revenue from biogas and digestate.
Ec6: Labour costs.
Ec7: Security on investment

The availability and cost of feedstock (**Ec1**) are the most essential factors in the sustainable growth of AD sectors. Bangladesh had an estimated 486.77 million tons of animal waste products per year to produce 27,923.72 million m^3/year of biogas (2018–2019) (Siddiki et al., 2021). Along with animal waste, the available agricultural residues in the rural areas of Bangladesh have the potential to produce 9693 million m^3/year of biogas and are calculated to be 223 PJ/year, equivalent to 7075 MW under optimal conditions (M. A. Rahman et al., 2018). It is crucial to have a profitable, sustainable, and environment-friendly agricultural system to ensure long-term food security for people where AD plants can contribute.

The AD construction cost **(Ec2)** differs considerably based on design, size, geographical position and technology, but costs are relatively easy to determine. In Bangladesh, the construction costs are comparatively lower than in other first-world countries because of low labour costs (Sarker et al., 2020). The small-scale (Household) AD plants in Bangladesh are not costly and are affordable (Power Division, 2018).

Maintenance cost (**Ec3**) is one of the significant issues in the operation of a successful AD plant. For example, AD plants are affected by the rise of H_2S levels during biogas production because of their corrosive nature (Esposito et al., 2012; Zaman et al., 2019).

The existing government have a high priority to create a new job (**Ec4**) for its population and AD industries can offer a large number of employment opportunities in every stage of AD operation (plant operator, construction and delivery of AD equipment, service and maintenance) in Bangladesh (Power Division, 2018). In the first-world country like the United Kingdom, more than 50,000 people are directly or indirectly working related to AD industries (McDermott, 2012).

Revenue from biogas and digestate (**Ec5**) (Mezzullo et al., 2013) is the most significant contribution toward AD plants' whole-life cycle; AD output results in consequential savings in replacing fossil fuel and inorganic fertiliser. Digestate can be used or sold as fertiliser if it complies with organic fertilizer /compost standards. Otherwise, it is considered waste, which increases management costs (Chakrabarty et al., 2013; Sarker et al., 2020). AD plant operation costs can also be minimised while biogas is transformed into cooking gas or generator gas (for electricity) (Zaman et al., 2019).

Labour costs (**Ec6**) are linked with the processing of raw materials and the operation of AD plants. In Bangladesh, labour costs are relatively low compared to other countries (ILO, 2022). Insecurity (**Ec7**) on investment for a project often creates hesitation among new potential investors or users due to some failure reports of the previous project and slow returns (Nevzorova and Kutcherov, 2019).

3. Description of social pillar

The key factors of the social pillar of PESTEL have been identified are given below,

S1 : Knowledge and awareness about the Biogas plant.

S2 : Level of information dissemination and advertising.

S3 : Level of literacy rate among the mass population in Bangladesh.

S4 : Improvement of household welfare among the AD system user.

S5: Vermin and malodour reduction (especially of poultry firm).

S6 : Level of social stigma (cultural and religious viewpoint).

S7 : Unwillingness to accept new technology (Biogas system).

Although the biogas plants were introduced in Bangladesh a long time ago (1972), knowledge and awareness about the biogas plant (**S1**) among the people are still not enough (Power Division, 2018)**.** Compared to other renewable energy (i.e. solar energy) the dissemination of information (**S2**) related to AD technology is negligible. Also, the literacy rate in Bangladesh is not up to the mark (around 62%) (**S3**) (BPDB, 2019)**.** AD plants have the capacity to change the everyday lives of poor families, especially children and women, because they do not need to spend any time on fuelwood collection in the village area (Hossain, 2020). Poor households benefit (**S4**) from the government's skim to improve their lifestyle (Power Division, 2018). In addition, vermin and malodour are reduced by constructing AD plants (**S5**). As the waste materials (organic waste, cow dung, poultry litter) (Zaman et al., 2019) are used as feedstock in the AD plants, people of the village area sometimes refuse to use the biogas for cooking purposes (**S6**) (Hossain, 2020). In addition to those, stakeholders also consider that people are unwilling to accept new rather than traditional methods (**S7**).

4. Description of technological pillar

The key factors of the technological pillar of PESTEL have been identified are given below,

T1: Planning and installation issues for the biogas plant in Bangladesh.

T2: Efficiency/ Performance of existing Biogas plants (AD) in Bangladesh.

T3: Biogas extraction technology available in Bangladesh.

T4: Post-Treatment technology to improve the efficiency of digestate.

T5: New technology and research.

T6: Alternative source of highly efficient renewable energy (such as solar energy).

T7: Availability of expert technicians for biogas plant construction and maintenance.

The key factor, planning and installation issues for the biogas plant (**T1)** is considered in this analysis. The availability of the area for the construction of individual systems

is very important because certain AD systems require a considerable amount of available space (Iqbal et al., 2014; Paglini et al., 2022). At some point, space is required for feedstock storage and process. In the case of restricted land availability, especially in cities, proper planning is needed.

The efficiency/ performance of existing Biogas plants (AD technology) (**T2**) is one of the key factors because this background information will help policymakers ensure sustainable growth of the AD sector (Iqbal et al., 2014; Paglini et al., 2022). A 2005 survey of 66 plants (level 1) found that only 47% were functioning satisfactorily (Ghimire, 2005), a finding reinforced by the 2012 national survey in which 24.7% of 26,311 NDBMP-registered plants were only partially functioning and 7% had failed entirely (NDBMP-IDCOL, 2013; Power Division, 2018), underscoring the persistent challenge of maintaining plant performance that this research seeks to address. A joint study by BBDF and GERBIO showed that among 70 agro-industrial biogas plants (AIBP) (size 6 to 49 m3) in Bangladesh, 14 (20%) plants were not in operation, 17 (24%) of responses from operators were incomplete during the study and 19 (27%) plants could not be included into the final data analysis due to not existing slurry management (Mang et al., 2017). Again, “Final Draft: Guidelines on Biogas Technology for Energy” for Bangladesh reported that “between 25% and 50% of operational plants experience problems during lifetime” based on the Biogas User Survey (BUS) 2007, 2008, 2009, 2010, 2011 report by IDCOL summarised in the table (Table 2.2) (NDBMP-IDCOL, 2013; Power Division, 2018). At present (after 2012), no data or information is available regarding the underperforming or failed small-scale (level 1) biogas plants in Bangladesh.

Again, produced biogas from the AD system contains methane (60%) and carbon dioxide (40%) as its principal constituents (Kurchania et al., 2010). Excluding methane, other gases contained in biogas are considered as contaminants. Removal of these impurities, especially carbon dioxide, will increase the biogas quality for further use. So, Biogas extraction technology (**T3**) is another key factor of AD growth. Biogas extraction technology is available, but it is limited in AD plants due to the cost reported in many third-world countries (Godin et al., 2015). Furthermore, the digestate after the AD process add great value to agriculture practice, but it requires proper treatment for complex feedstock (Angouria-Tsorochidou et al., 2022). Post-

Treatment technology to improve the efficiency of digestate (**T4**) needs to be adopted in AD plants for better use of the digestate; otherwise, it will become a problem (waste).

New technology and research (**T5**) is one of the key factors to the success of the AD sector worldwide (Obileke et al., 2021). Many new technologies and systems have been developed related to small-scale AD all over the world; however, these technologies face problems when applied in a new country or different geographical region. In 2016, the Bangladesh government published the Power System Master Plan and in it, the government wants to roll out a new type (glass fibre) of biogas digester (Power Division, 2016).

Alternative sources of highly efficient renewable energy (such as solar energy) (**T6**) are another key factor for choosing between AD technology and other renewable energy sources. This choice also affects the policy of the government and the government of Bangladesh published a “Renewable energy policy” in 2008, mainly focusing on solar and wind power (Power Division, 2008).

For every project/product/construction, during and after-sales service is very important, or skilled manpower is required for the maintenance of the project/ product. Thus availability of expert technicians for biogas plant construction and maintenance (**T7**) contribute to the AD growth.

5. Description of environmental pillar

The key factors of the environmental pillar of PESTEL have been identified are given below,

En1: Reduction of GHG emissions (SDG agenda).
En2: Waste management.
En3: Reduction of indoor air pollution.
En4: Climatic condition of Bangladesh.
En5: Access to adequate water for the Biogas plant.
En6: Eutrophication or groundwater contamination.
En7: Flooding and other natural disasters.

Greenhouse gas emission (**En1**) from organic wastes can be reduced by AD operation rather than traditional treatment methods and have less potential for GHG emission from AD plants (Panwar et al., 2011; Sárvári Horváth et al., 2016). In addition to that, biogas from the AD system reduces fossil fuel consumption (Paolini et al., 2018). Waste management (**En2**) is another key factor of the environmental pillar, and AD plants help reduce organic waste and have the potential to convert it into fertiliser (Paolini et al., 2018). At present, in many parts of the world, women in marginalised communities are still vulnerable to indoor air pollution and the key factor, reduction of indoor air pollution (**En3**), is possible by using biogas as a fuel in cooking (Puzzolo and Pope, 2017; Quinn et al., 2018). Successful AD operation depends on weather/ climatic conditions (**En4**) and is vital because favourable temperature helps to grow bacteria inside the digester. AD plants do not perform well or stop at extreme temperatures (winter or hot).

AD system requires a large amount of water depending on size and feed material, thus requiring (**En5**) access to adequate water for the Biogas plant. The groundwater level is accessible by using a shallow tube well. Bangladesh is a tropical riverine country, and the groundwater level is accessible by using shallow tube wells. There are risks of eutrophication (surface water) and groundwater contamination (**En6**) by leaching of nutrients from unmanaged digestate and faulty or old AD plants or unmanaged feed stock plants or unmanaged feedstock and unmanaged digestate (Vu et al., 2015). In addition to that, agricultural runoff containing pesticides and some metals (nickel(Ni), beryllium (Be), cobalt (Co) and vanadium (V)) from fertilisers also find their way to the water body during the cultivation of fodder crop (Drosg, 2013; Melville et al., 2014). Again, Bangladesh is a flood and natural disaster-prone country (**En7**) and is at the top of the index, but government initiatives like flood zoning maps and early flood warning systems can play a role for AD growth (MoDMR, 2017).

6. Description of legal pillar

The legal pillar is the final pillar of PESTEL, and it illustrates an overview of the key stability of the political framework of Bangladesh government factors and the

perceived importance of the sustainability of AD plants in Bangladesh from a legal perspective.

L1: National 3R Strategy for waste management (2010), Bangladesh.
L2: Bangladesh Standards and Guideline for Sludge Management (2016)
L3: Biogas guidelines/ legislation.
L4: The range of requirements for anaerobic digestate / bio-slurry as fertiliser or quality protocol (Fertilizer Recommendation Guide 2018, Bangladesh)
L5: Feed-in Tariffs for produced biogas.
L6: Environmental Law for setup and operation of Biogas plant.
L7: Local government law for setting up an AD plant on premises (range of requirements).

National 3R Strategy for Waste Management (2010) (**L1**) and Slurry management in Bangladesh Standards and Guideline for Sludge Management (2016) (**L2**) are two very significant key factors for the sustainable growth of AD industries in Bangladesh (Department of Environment, 2015; MoEF, 2018) and but very less have been discussed about AD in these. Again, the proposed biogas guideline (**L3**) is incomplete, and the fertiliser act (**L4**) also failed to clarify the standard of digestate (MoFL, 2015; Power Division, 2018).

The feed-in tariff (**L5**) is significant for AD sectors because it is related to small-scale electricity production and has a substantial influence on the feasibility of the technology (Power Division, 2016). Although the feed-in tariff depends on the economic feasibility of the electricity production from AD sectors, it is essential to set clear guidelines related to the feed-in tariff. In Bangladesh, the feed-in tariff has not yet been set.

AD plants are subjected to the environmental law (**L6**) of Bangladesh described in the legislation; no clear information is there in the Environmental Law of Bangladesh (DoE, 2s019; MoEF, 2018). Local government law for setting up AD plants on-premises (range of requirements) (**L7**) is absent, but it is essential to follow a set of standard rules for the installation and operation of any AD plant within the residential area (DoE, 2019).

3.3.9 Potential impact, uncertainty, and Impact/Uncertainty grid analysis

The scenarios provide a framework for evaluating how key factors may influence the sustainable growth of the Anaerobic Digestion (AD) sector in Bangladesh and assess the associated uncertainties. Critical uncertainty of individual key factors is a significant driver in shaping future developments, yet its trajectory is highly unpredictable (Jäger et al., 2008; Rikkonen and Tapio, 2009). Conversely, potential impact analysis evaluates the effect of each key factor on projects, categorising impacts as positive, moderate/low, or negative. The Impact/Uncertainty Grid is instrumental in visualising and structuring the exhaustive list of key factors that potentially influence project success or failure (Jäger et al., 2008; Rikkonen and Tapio, 2009; Speziale and Geneletti, 2014; Wulf et al., 2010).

Impact and uncertainty

Impact refers to the extent to which a particular factor can influence the outcomes of a project or the overall growth and sustainability of an industry. In this context, the impact can be positive, leading to favourable outcomes, moderate/low, having a limited effect, or negative, causing adverse consequences. Understanding the impact of key factors is crucial because it helps organisations prioritise their strategic responses and allocate resources effectively to leverage positive impacts or mitigate negative ones (Wulf et al., 2010).

Uncertainty denotes the degree to which the future development of a key factor is unpredictable. High uncertainty implies that the factor's future state or evolution is difficult to foresee, while low uncertainty indicates a more predictable trajectory. Assessing uncertainty is vital as it helps organisations identify potential risks and opportunities, allowing them to develop flexible strategies that can adapt to various future scenarios (Speziale and Geneletti, 2014; Wulf et al., 2010).

Methodology of Impact/Uncertainty grid analysis

After reviewing the literature following steps are taken develop Impact/Uncertainty Grid Analysis (Jäger et al., 2008; Rikkonen and Tapio, 2009; Speziale and Geneletti, 2014; Wulf et al., 2010).

1. Evaluation of Key Factors: Each key factor is considered individually, and the range of possible evolutions is assessed.
2. Assessment of Uncertainty: The degree of uncertainty for each key factor is determined based on stakeholder responses. This involves gauging the variability in possible future developments and identifying whether there is significant uncertainty or minimal variability.
3. Impact and Importance Evaluation: The relative impact or importance of each driver is considered for the future. The analysis focuses on whether the evolution of these factors will significantly affect the overall vision for the future or have a minor influence .
4. Plotting on the Grid: Each key factor, scored by stakeholders, is plotted on the chart of impact/importance versus uncertainty.
5. Segmentation of the Grid: The Impact/Uncertainty Grid is divided into six sections:
    - Trends: Positioned in the bottom left (between the negative point (Red line; from table 3.2) and below the uncertainty global average) and bottom right (between the positive point (Green line; from table 3.2) and below the uncertainty global average) sections (Figure 3.7). These factors have a comparatively high impact (negative or positive) and are relatively predictable, thus important for setting recommendations for the broader adoption of sustainable AD plants
    - Critical Uncertainties: Located in the upper right and upper left corners of the grid (Figure 3.7), these factors have a high-performance impact and a high degree of future uncertainty.
    - Secondary Elements: Factors in the middle section (impact range between 2.66 and 4.33 for both above and below the global average of uncertainties) (Figure 3.7). These factors have a relatively low-performance impact and are not prioritised in recommendations.

Global average

The global average provides a standard reference point, aiding in the clear categorisation of factors. Those with uncertainty levels above this average are deemed to have significant unpredictability, thus impacting strategic planning more profoundly (Jäger et al., 2008; Wulf et al., 2010). Differentiating factors based on this average allows organisations to prioritise resources and attention towards those with higher uncertainty and potential impact, ensuring a more focused and effective approach to managing risks and opportunities (Jäger et al., 2008; Wulf et al., 2010). Incorporating the global average enhances the visual representation of the grid, facilitating the interpretation and understanding of the distribution and significance of various factors (Jäger et al., 2008; Wulf et al., 2010).

Methodology of the global average

The global average serves as a benchmark in the Impact/Uncertainty Grid, facilitating the differentiation between high and low uncertainty factors (Speziale and Geneletti, 2014; Wulf et al., 2010). This average represents the mean to the level of uncertainty derived from all assessed key factors in the study. By plotting each factor relative to this global average, it becomes easier to identify which factors exhibit above-average uncertainty (thus being more unpredictable) and which fall below this threshold (considered more predictable).

Methodology of the Impact/Uncertainty grid and the global average of key factors

This analysis identified key factors that belong to specific groups and have the greatest impact on the sustainable growth of the AD sector in Bangladesh. Based on survey results regarding the impact assessment and uncertainty of these key factors, a dependency structure matrix for impact and uncertainty parameters was subsequently developed. Figure 3.7 illustrates this matrix, with dark blue indicating key uncertainties.

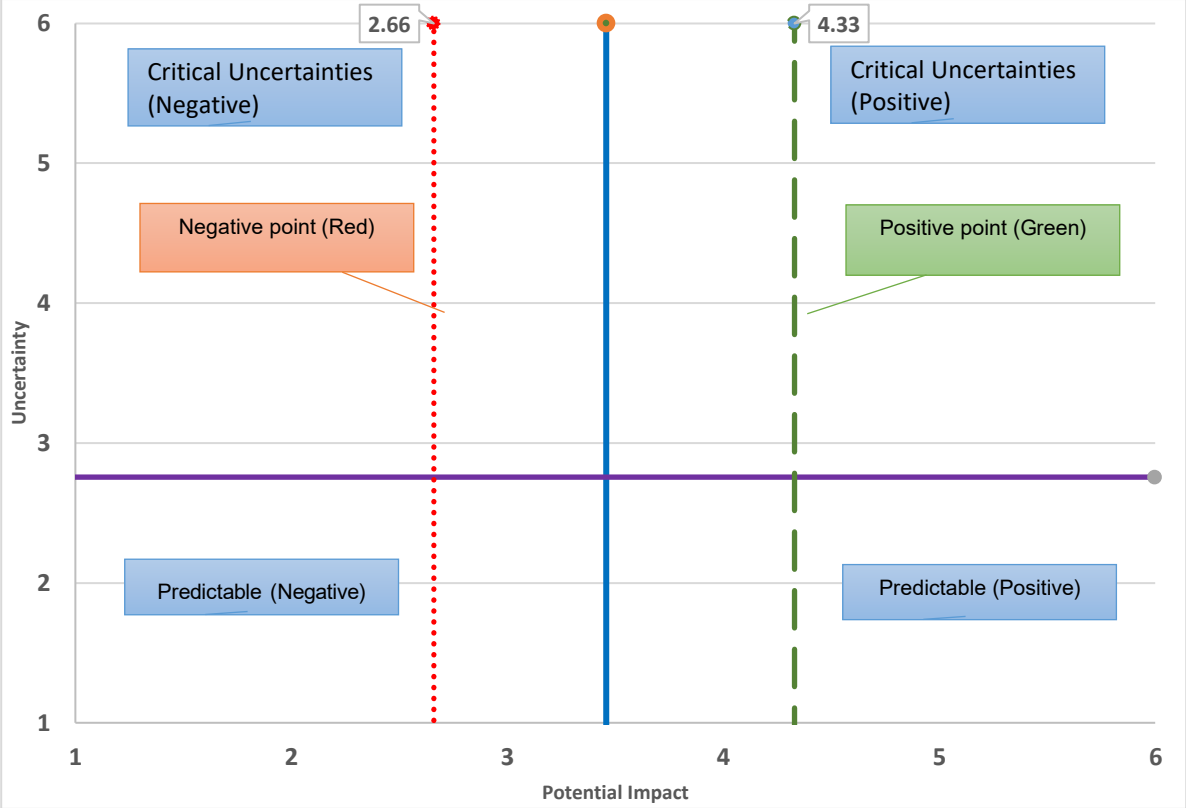


Figure 3.7: Impact/ uncertainty grid and global average of the key factors.

The application of the Impact/Uncertainty Grid in this study elucidates the critical factors that must be addressed to ensure the sustainable growth of the AD sector in Bangladesh. By identifying and analysing both predictable trends and critical uncertainties, the grid provides a structured approach to strategic planning and decision-making, assisting stakeholders in prioritising actions and allocating resources effectively.

3.4 Technique and procedure for AD user survey (Section 2)

The second section aims to evaluate the current status of small-scale biogas plants in Bangladesh from the perspective of both existing and potential AD users, assessing their successes and failures. This evaluation is carried out through a combination of questionnaire surveys and field investigations of existing biogas plants and potential AD users

3.4.1 Principle of the second section

The second study comprises a detailed questionnaire survey among the small-scale biogas plant owners. Secondary sources of data for AD plants in Bangladesh are insufficient to understand the present scenario; thus, field surveys allow us to monitor better and evaluate the present status of existing small-scale (level 1) AD plants in Bangladesh.

3.4.2 Study area

This study was conducted across Bangladesh, a tropical monsoon country with pronounced wet (June–October) and dry (November–May) seasons that shape feedstock availability and digester performance. From the national frame of 64 districts, ten districts (clusters) were randomly selected to capture variation in agro-ecological zones, livestock density, and rural energy use patterns. Within these clusters, a total of 50 small-scale biogas plants were surveyed (Figure 3.8).

The inclusion criteria focused on household–to–community systems with an installed digester volume ≤ 4.8 m^3 (available plant sizes 1.25 m^3, 2 m^3, 2.4 m^3, 3.2 m^3, 4.8 m^3). Plants were further stratified by primary feedstock into three categories: (i) cow dung, (ii) poultry litter, and (iii) mixed substrates (e.g., cow dung with kitchen residue or crop waste). The selected sites predominantly span rural and peri-urban settings, where cattle and poultry rearing are common, and where biogas is typically used for cooking and limited lighting. This distribution enables the sample to reflect differences in feedstock supply chains, water access, and user practices across Bangladesh's major administrative regions, while maintaining technology type and scale as broadly comparable as possible.



Figure 3.8: Location map of surveyed Biogas plant (small scale) in Bangladesh.

3.4.3 Sampling unit

The method of random sampling was adopted to ensure that the survey captured a representative cross-section of household biogas users across Bangladesh. In this approach, the sampling unit was defined as an individual biogas plant owner or

operator aged 18 years or older, thereby ensuring that respondents were legal adults and directly responsible for managing the plant.

A total of 65 plants were included in the sample, comprising 50 active plants and 15 inactive plants. The active plants provided valuable insights into current operational practices, feedstock utilisation, and the challenges faced in sustaining biogas production. Meanwhile, the inclusion of inactive plants helped capture reasons for failure, discontinuation, or neglect, which are equally critical for understanding the long-term viability of small-scale biogas technology in Bangladesh.



Picture: Observing the Biogas plant



Picture: Surveying with a questionnaire



Picture: Observing the Biogas plant



Picture: Surveying with a questionnaire

3.4.4 Sample size calculation

In this study, the sample size refers to the number of AD plants selected for data collection. More generally, sample size is a statistical idea that deals with how many observations or replicates of an experimental condition are needed to capture the variability of a phenomenon (Ejdys et al., 2019; Kordana and Słyś, 2020).

Choosing an appropriate sample size is crucial. Any empirical study that hopes to draw conclusions about a larger population from a smaller set of observations depends on it. In practice, a sample serves as a representation of the population, and the choice of how large it should be is rarely trivial. To calculate it, this research considered the margin of error, ε, which represents the maximum amount by which an estimate from the sample might differ from the true population value. Put simply, we worked with the confidence interval equation, set the term after the ± sign equal to the chosen margin of error, and solved for the required sample size, n. The formula (Equations 3.2 and 3.3) used is given below.

$$Unlimited\ population: n = \frac{z^2 \times \hat{p}(1-\hat{p})}{\varepsilon^2} \quad \text{---------- [3.2]}$$

$$Finite\ population: n = \frac{n}{1+\frac{z^2 \times \hat{p}(1-\hat{p})}{\varepsilon^2}} \quad \text{---------- [3.3]}$$

Where,

z is the z score
ε is the margin of error
N is the population size
p̂ is the population proportion

In this study, determining the sample size is crucial to estimate the proportion of biogas plants (from existing biogas plants) in Bangladesh that are identified as small-scale biogas plants (≤ 4.8 m³) with 95% confidence and a margin of error of 4%. It is assumed that the population proportion (The population proportion is the anticipated percentage of the total population to have the characteristic assessed from the survey) is ≥ 98% because, in Bangladesh, more than 98% of biogas is considered a small-scale biogas plant and the population size is 101000 (till 2019) (IDCOL,2020). Again, the z value for a 95% confidence level is 1.96. So, the sample size for a finite population, according to the equation, is 48. This means that a minimum of 48 measurements/surveys (sample size) are needed to have a 95% confidence level that the real value is within ±4% of the measured/surveyed value.

3.4.5 Key informants

During the interview with the biogas plant owner/operator, the AD plants were carefully observed and pictures were taken of both the plant and participants for

photographic evidence. Before the questionnaire survey, we took consent from the interviewee.

3.4.6 Survey tool (questionnaire)

A structured questionnaire was designed for the survey. [Annexe “1” and “2”, ethical permission from BCU (Islam /3546 /R(A) /2019 /Dec /CEBE FAEC) and a consent form from AD were used]. These questions were divided into 14 sections. These sections include,

- Personal Information of AD plant owner
- Basic Information on AD plant and related matter
- Source of raw materials for AD plant
- Physical features of AD plant
- Installation and Functioning of AD plant
- Institutional Information and cost for AD construction
- Institutional aspects of Biogas plant
- Socio-economic condition of biogas production on the energy situation
- Health and sanitation
- Gender
- Bio-slurry management and potentiality.
- Agriculture aspect
- Environment aspect
- Biogas consumers on payment

3.4.7 Data compilation

Primary and secondary sources were used for the collection of required data. Preliminary data for the study were gathered through a questionnaire survey of selected households, discussions with key informants, and self-observation techniques.

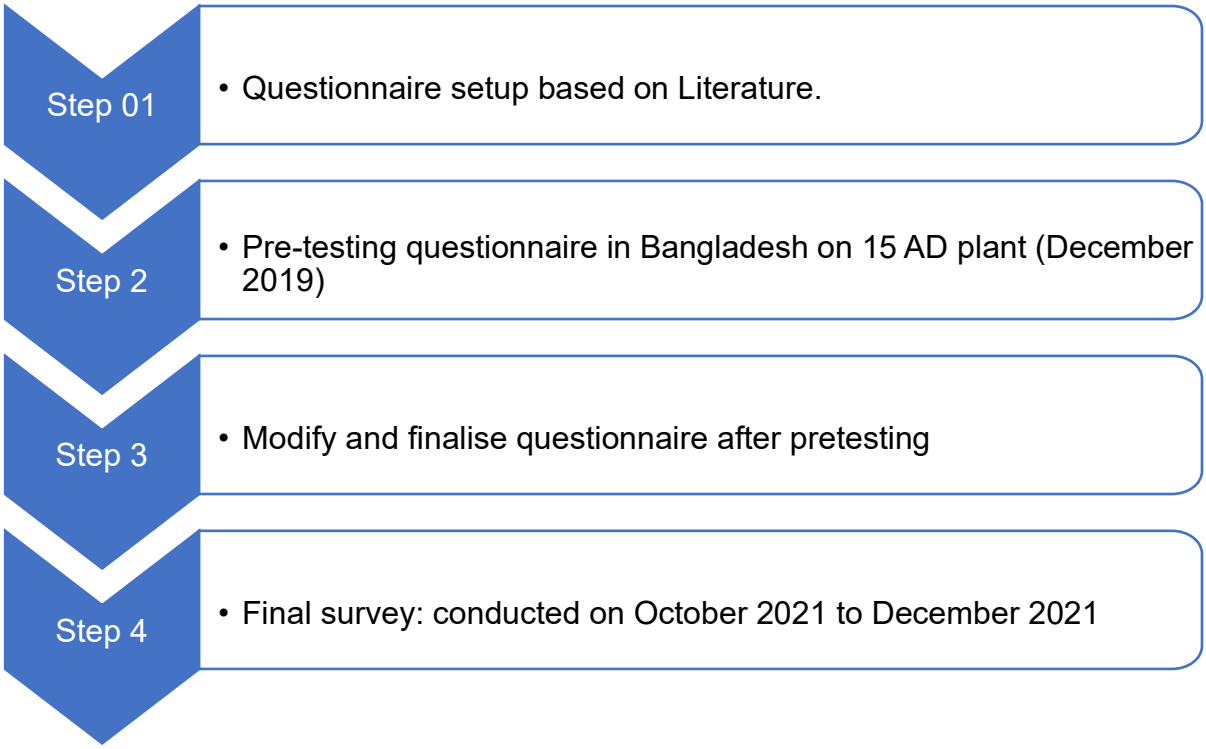


Figure 3.9: Flow chart of development of the questionnaire and field survey

3.4.8 Statistical analysis

Analysis and interpretation were made through SPSS version 27.0. Data gathered through questionnaires (quantitative data) were analysed in terms of frequency, percentage, and standard deviation.

Overview

This appendix provides a concise summary of the statistical methods applied in Section 3.4.8 of Chapter 3 to analyse the data collected from the AD user survey (Section 2 of the study). All statistical analyses were performed using SPSS version 27.0. The survey data, collected from 50 small-scale biogas plant owners and operators across the study area, were quantitative and qualitative in nature and were analysed in terms of frequency, percentage, and standard deviation, alongside a range of inferential statistical techniques. The purpose of each method, the conditions under which it was applied, and its specific relevance to the research objectives are summarised below in Table 3.5.

Table 3.5: Statistical Methods, purpose, real-world application in this thesis

Statistical Method	**Purpose in this Study**	**Real-World Application in the Thesis**
McNemar-Bowker Test (Appendix 6)	Compares paired categorical before-and-after responses from the same respondents to test whether the distribution of answers changed significantly between two time points.	**Applied to five environmental outcome variables to assess change before and after biogas plant installation:** • Kitchen air pollution → significant improvement ($p < 0.05$): households reported cleaner air after switching to biogas cooking • Eye infections from smoke → significant reduction ($p < 0.05$): fewer cases of smoke-related eye irritation reported • Respiratory infections from smoke → significant reduction ($p < 0.05$): measurable health gain from cleaner cooking fuel • Mosquito/fly abundance → significant reduction ($p < 0.05$): sealed digestion eliminated open dung, reducing insect breeding • Cow shed management → NO significant change ($p = 0.2482$): plant installation alone does not change farm hygiene behaviour, explicit training is needed
Paired Sample T-Test (Appendix 6)	Compares the mean of a continuous variable measured at two time points for the same group, to determine whether the change before and after is statistically significant.	**Applied to four continuous household variables:** • Daily cooking hours: fell from 5.16 to 3.70 hrs/day — saving 1.46 hrs daily ($t=11.367$, $p<0.001$); women gain nearly 1.5 hrs per day for other activities • Monthly fuel cost: fell from BDT 2,290 to BDT 955/month — saving BDT 1,335/month ($t=11.256$, $p<0.001$); direct economic relief for rural households • Monthly firewood use: fell from 459 kg to 78 kg/month — saving 381 kg/month ($t=7.451$, $p<0.001$); equivalent to ~4.5 tonnes per year per household • Daily firewood collection time: fell from 1.09 to 0.29 hrs/day — saving 0.63 hrs daily ($t=7.282$, $p<0.001$); time returned to women and children
Two-Way Analysis of Variance (ANOVA) (Appendix 6)	Tests whether a continuous dependent variable differs significantly across the levels of two categorical independent variables, and whether there is an interaction effect between them.	**Applied to examine the effect of plant size and season on daily cooking hours:** • Plant size effect: statistically significant — larger plants produce more gas and enable more cooking hours per day; households with 4.8 m^3 plants cook significantly longer than those with 1.2 m^3 plants • Seasonal effect: statistically significant — winter months produce measurably less biogas due to lower soil temperature, reducing available cooking hours

Statistical Method	Purpose in this Study	Real-World Application in the Thesis
		• Practical implication: users must be informed at installation that winter will reduce gas output, and plant size must be matched to actual livestock numbers to maximise performance
Tukey's HSD Post-Hoc Test (Appendix 6)	Identifies which specific pairs of group means differ significantly from each other following a significant ANOVA result, while controlling for the risk of false positives across multiple comparisons.	**Applied after significant ANOVA results for plant size:** • Identified that the 4.8 m³ plant group was significantly different from the 1.2 m³ group in daily cooking hours and monthly savings • Middle-sized groups (2.4 m³, 3 m³) were not significantly different from each other • Practical implication: the biggest performance gains come when households step up from the smallest to the largest plant size — confirming the value of installing an appropriately sized plant from the outset rather than under-specifying
Pearson's Coefficient of Correlation (Appendix 6)	Measures the strength and direction of the linear relationship between two continuous variables, with values ranging from -1 (perfect negative) through 0 (no relationship) to +1 (perfect positive).	**Applied to examine associations between plant size and household benefit variables:** • Plant size and monthly financial saving: strong positive correlation — larger plants save more money each month • Plant size and monthly firewood saved: strong positive correlation — larger plants displace more firewood, benefiting both the household and local forests • Practical implication: confirms that the decision about plant size at installation is the single most controllable factor in determining the economic and environmental benefit a household will receive from the programme
Cross Tabulation (with Chi-Square Test) (Appendix 6)	Displays the joint frequency distribution of two categorical variables to reveal patterns of association, tested for statistical significance using the chi-square test.	**Applied to several categorical variable pairs:** • Supplementary fuel type during peak demand (festivals): 72% of respondents used LPG and 28% used firewood when biogas was insufficient — revealing a gap the programme should address through user guidance on managing peak demand • Bio-slurry use by land ownership: 44% of respondents used bio-slurry on their fields, but only 20% could use all of it — those with less land wasted a valuable resource; suggests need for community composting or slurry-sharing schemes • Regulatory awareness by district: all respondents (100%) reported no knowledge of a dedicated AD policy framework in Bangladesh

Statistical Method	Purpose in this Study	Real-World Application in the Thesis
Categorical Data Analysis and Bivariate Analysis (Appendix 6)	Examines statistical relationships between categorical or ordinal variables using frequency tables, hypothesis tests, and association measures.	**Applied across survey sections to describe patterns of fuel use, plant performance, and user behaviour:** • 94% of respondents switched from firewood to biogas as their primary cooking fuel after installation • 82% had experienced cooking fuel supply interruptions at least once per week before installation; 8% reported no change after • 88% of respondents reported making financial savings after installation; 12% reported no savings pointing to the need to investigate why a minority do not benefit (plant underfeeding, substandard construction, or insufficient livestock)
Shapiro-Wilk Test (Appendix 6)	Tests whether a variable is normally distributed — a required assumption before applying parametric tests such as the paired t-test or two-way ANOVA.	**Applied to all continuous variables before parametric testing:** • Cooking hours, fuel cost, firewood consumption, and firewood collection time all satisfied the normality assumption ($p > 0.05$), confirming that the paired t-test was statistically appropriate for these variables • Practical implication: the significant results reported for these variables, the reductions in cost, time, and firewood use, are based on statistically valid tests, strengthening confidence in the findings
Levene's Test for Homogeneity of Variances (Appendix 6)	Tests whether the variance of the dependent variable is equal across the groups being compared — a required assumption before interpreting two-way ANOVA results.	**Applied before the two-way ANOVA on cooking hours by plant size and season:** • Confirmed that the variance in cooking hours was sufficiently equal across plant size groups and seasons for the ANOVA to proceed without adjustment • Practical implication: the significant seasonal and plant-size effects on cooking hours identified by the ANOVA are based on a statistically sound test, the assumption checks support the reliability of these findings for programme planning

Note: Mathematical formulas and full assumption-check outputs for each test are provided in Appendix 6. Results are reported in the relevant results chapters (Chapters 6, 8, 9, 10) with full statistical tables.

3.5 Systemic interrelationships among critical key factors: A causal loop diagram (CLD)–based systems thinking approach

Addressing the systemic barriers to sustainable anaerobic digestion (AD) growth in Bangladesh requires a methodological framework that can capture complexity, feedback dynamics, and interdependencies across multiple policy, economic, social, technological, environmental, and legal domains. This study adopts a qualitative systems thinking methodology supported by feedback loop analysis and causal mapping (Barbrook-Johnson and Penn, 2022; Brereton and Jagals, 2021; Newberry and Carhart, 2024; Tobin et al., 2022; Veldhuis et al., 2025).

This approach allows for the diagnosis of feedback structures, the visualisation of causal relationships, and the strategic prioritisation of interventions based on their potential to influence systemic behaviour (Barbrook-Johnson and Penn, 2022)
The methodology is structured in two integrated phases:

1. Identification and construction of feedback loops
2. Development of a Causal Loop Diagram (CLD)

Below, each phase outlines the data sources, analytical procedures, and theoretical rationale behind the study's design.

3.5.1. Identification and construction of FeedBack Loop

Feedback loops are fundamental tools in systems thinking, used to represent the causal processes by which key factors influence one another over time. In a feedback loop, the effect of a change in one key factor propagates through the system and ultimately feeds back to influence the original variable. Loops can be reinforcing (positive), leading to growth or escalation, or balancing (negative), promoting stability or resistance to change (Barbrook-Johnson and Penn, 2022; Veldhuis et al., 2025).

Methodology of Feedback Loops
System variables were identified through a multi-source qualitative synthesis, drawing from (Newberry and Carhart, 2024; Tobin et al., 2022):

- Literature review (discussed in section 3.3)

- Semi-structured expert interviews were conducted with stakeholders from different sectors (as discussed in section 3.3.6)
- Stakeholder survey (AD user) in Bangladesh (is discussed in section 3.4)

From this data, key factors were extracted across the PESTEL categories. These were then grouped thematically and examined for their interrelationships.

Loop formation procedure

Causal relationships among key factors were structured into loops using diagrammatic causal mapping techniques. For each relationship, a polarity was assigned:

- (+) indicating a reinforcing or amplifying effect
- (–) indicating a balancing or counteracting effect

Each loop was tested for internal consistency and logical closure. These loops became the foundational units for the development of the Causal Loop Diagram.

3.5.2. Development of the causal loop diagram (CLD)

The Causal Loop Diagram serves as a systemic visualisation tool, revealing dynamic complexity and cross-sectoral interactions. It enables researchers and policy-makers to trace the structural causes of stagnation, feedback-driven amplification, or policy resistance within the AD system in Bangladesh (Barbrook-Johnson and Penn, 2022; Veldhuis et al., 2025).

Methodology of CLD

The CLD was constructed using the Graphviz DOT language, chosen for its ability to support clear, colour-coded, and polarity-sensitive diagramming. Key design features included:

- Green arrows for reinforcing relationships and red arrows for balancing ones
- PESTEL-coded nodes to visually differentiate domains of influence
- Grouping of feedback loops into clusters (e.g., policy-financial, environmental-social)

The diagram was iteratively refined through cycles of expert review and empirical consistency checks (Barbrook-Johnson and Penn, 2022; Veldhuis et al., 2025).

To ensure analytical integrity, the CLD was validated through:

- Cross-checking against published literature and national plans
- Peer review from experts in sustainable energy and waste management
- Internal consistency testing for loop completeness and directional logic

This ensured that the final CLD provided a coherent and grounded representation of the AD system's structure and behaviour.

Chapter 04: Results: PESTEL Analysis

4.1 PESTEL analysis on macro environment

In this initial section of the study, we conduct a thorough assessment of the critical macro-environmental factors influencing the sustainable growth of anaerobic digestion (AD) sectors in Bangladesh. This evaluation is grounded in an integrated approach, encompassing the political, economic, sociological, technological, legal, and environmental (PESTEL) dimensions. Through a meticulous analysis of the political landscape, we examine the implications of governmental policies, regulatory frameworks, and political stability on the development and expansion of AD technologies. The economic assessment delves into market dynamics, investment climate, financial incentives, and economic barriers that impact the viability and scalability of AD projects. The sociological dimension explores societal attitudes, cultural factors, community engagement, and the overall acceptance of AD systems among various stakeholders. Technological analysis focuses on the state of technological advancements, innovation capabilities, infrastructure, and technical support available for AD implementation. Legal factors are scrutinised to understand the legal frameworks, compliance requirements, and regulatory challenges that govern the AD sector. Lastly, the environmental evaluation addresses the ecological benefits, sustainability metrics, and environmental impact of AD systems, highlighting their role in mitigating climate change and promoting renewable energy.

By integrating these multifaceted perspectives, this section aims to provide a comprehensive understanding of the macro-environmental context that shapes the sustainable growth of anaerobic digestion sectors in Bangladesh. The insights derived from this analysis will inform the strategic planning and policy formulation necessary to foster a conducive environment for the proliferation of AD technologies in the region.

4.1.1 Results from PESTEL analysis

To encourage the broader adoption of any project or development program, it is essential to analyse the key trends (both positive and negative) and the uncertain critical factors (Jäger et al., 2008; Rikkonen and Tapio, 2009; Speziale and

Geneletti, 2014; Wulf et al., 2010). This analysis is sometimes divided into two phases, as outlined by Schoemaker: 'Identify potential impact' and 'Identify Key Uncertainties', or combined into a single step, 'Data Analysis'. The identified factors are then ranked based on their uncertainty and their importance, as well as their potential impact on the project's success, in order to highlight the most essential ones for ensuring sustainable growth (Jäger et al., 2008; Rikkonen and Tapio, 2009; Speziale and Geneletti, 2014; Wulf et al., 2010). In this study, seven key factors were identified from the analysis of each PESTEL pillar. These factors were evaluated according to the survey responses. Since this research focuses on assessing the macro environment and identifying significant challenges for promoting sustainable growth in Bangladesh's AD sectors, the decisions made are necessarily subjective.

4.1.1.1 Potential impact and uncertainty of the key factors

The response from the required number (relatively low error rate, ε = 3%) of stakeholders are from recognised organisations and have experience in the relevant areas in the AD sector of Bangladesh, allowing this work to obtain reliable outcomes concerning the potential impact and uncertainty of the selected key factors (Table 3.4).

The study shows that, according to the judgement of the expert panel, key factors of economic (4.23, average) and environmental (4.47, average) pillars of PESTEL (above the global average of 3.46) have the most positive impact on the implementation or acceleration of the sustainable growth of AD sector in Bangladesh. Social (3.45, average) and Legal (3.08, average) pillars were also found to be close to the global average (3.46) and considered to have less potential impact on the sustainable growth of the AD sector in Bangladesh. According to the panel, the political (2.76) and technological (2.77, average) pillars play a negative role, and the panel recognised that these pillars hinder the growth of the AD sector of Bangladesh (Figure 4.7).

Slightly more substantial differences were noted in assessing the uncertainty of the key factors analysed. The highest uncertainty has been recorded in the Economic (3.46, average), Technological (3.12, average) and Political (2.95, average) pillars,

and these are above the global average scores. Environmental (2.04, average), Social (2.40, average) and Legal (2.46, average) are below the global average and more predictable (Figure 4.8). Figures 4.7 and 4.8 demonstrate the mean impact and uncertainty assessments of individual key factors for the sustainable growth of AD sectors in Bangladesh for the upcoming years. In Figure 4.7 a green and red horizontal line represents the positive and negative potential impact zone (discussed in Table 3.2). Again, in Figure 4.8, the horizontal blue line shows the global mean value obtained from all the key factors.

The bar charts (Figure 4.1 to 4.6) display the stakeholder ratings on Impact and Uncertainty for each pillar of PESTEL, as shown below (scoring calculations have been discussed in the methodology chapter)

Political Pillar

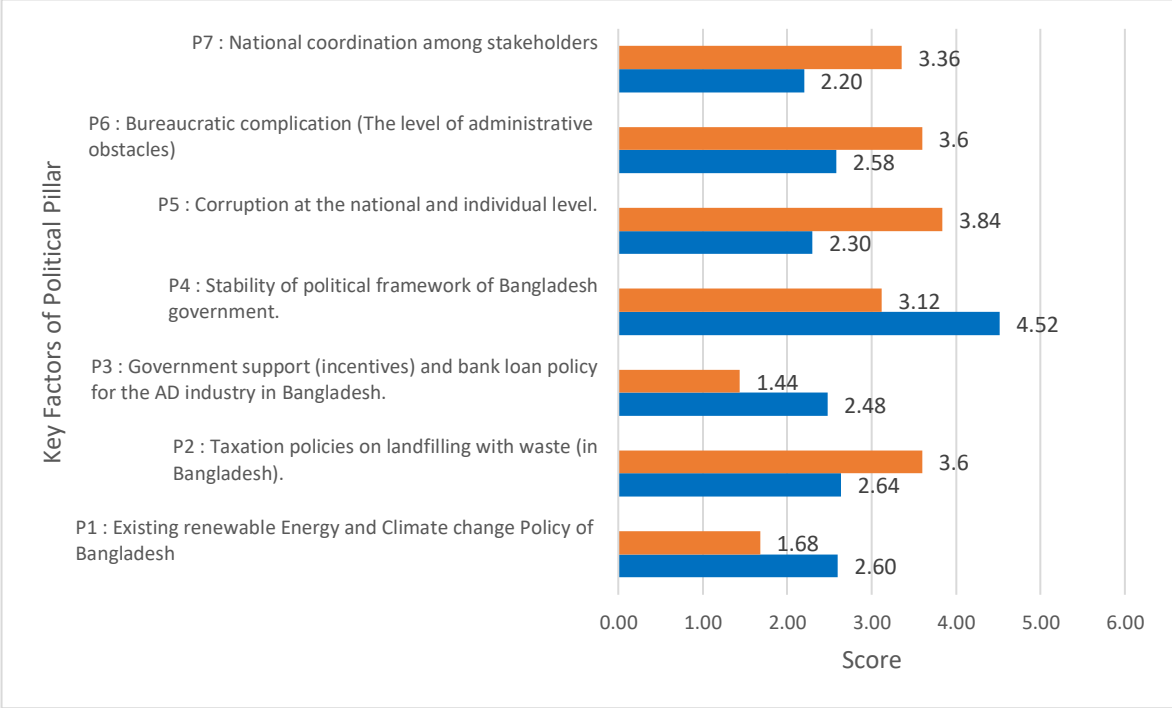


Figure 4.1: Stakeholder Ratings on Impact and Uncertainty for the political pillar of PESTEL. Blue bars indicate impact scores, and orange bars indicate uncertainty scores.

Economic Pillar

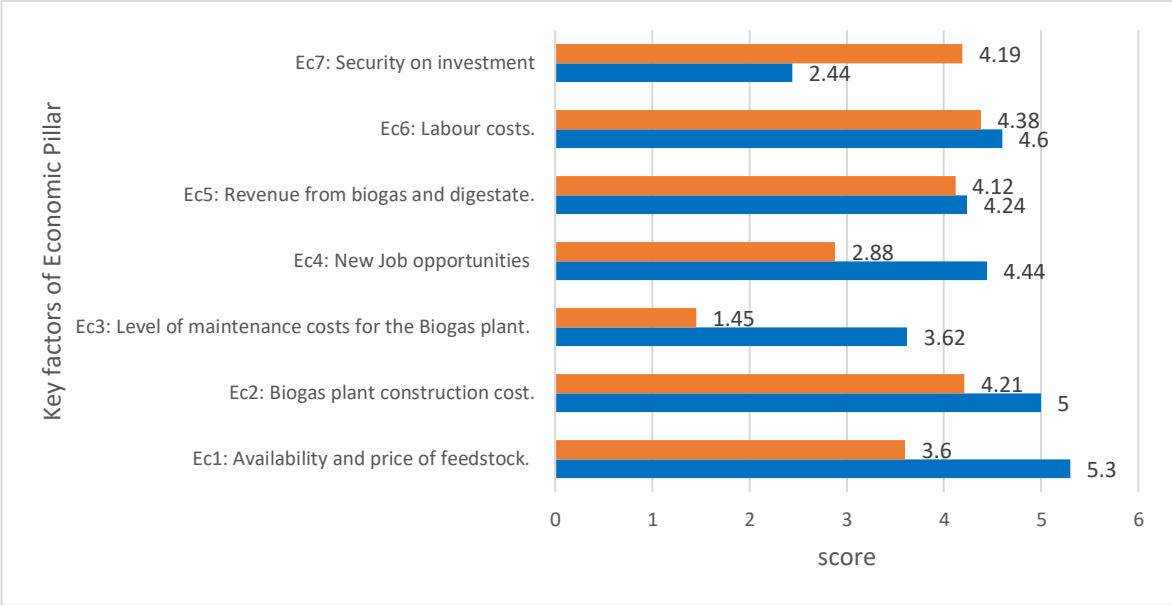


Figure 4.2: Stakeholder Ratings on Impact and Uncertainty for the economic pillar of PESTEL. Blue bars indicate impact scores, and orange bars indicate uncertainty scores.

Social Pillar

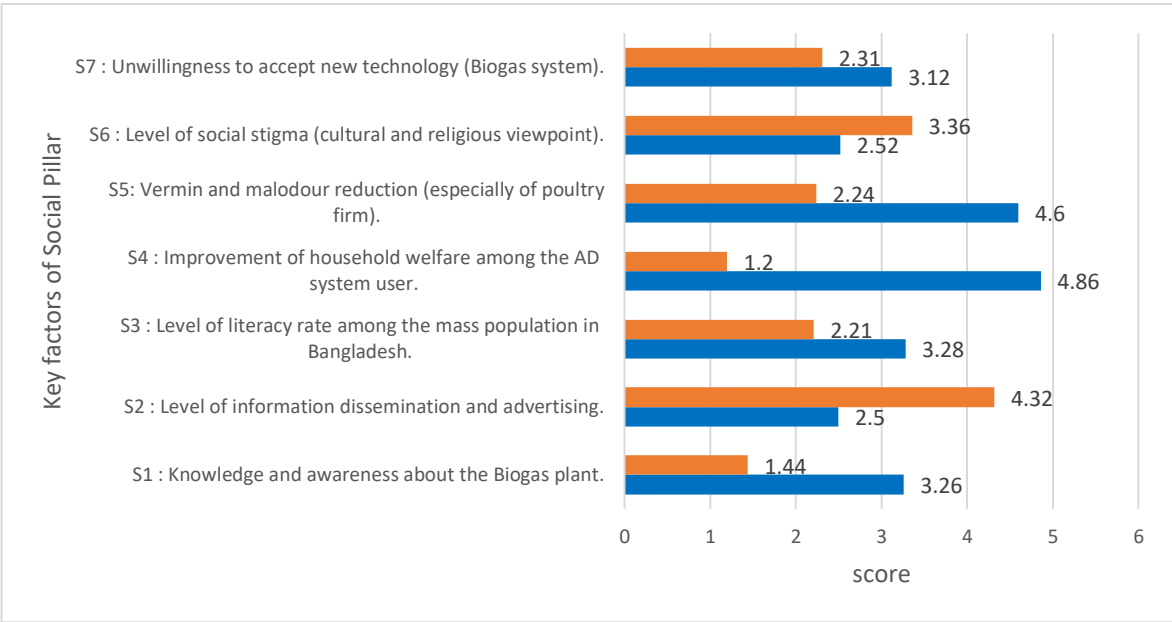


Figure 4.3: Stakeholder Ratings on Impact and Uncertainty for the social pillar of PESTEL.Blue bars indicate impact scores, and orange bars indicate uncertainty scores.

Technological Pillar

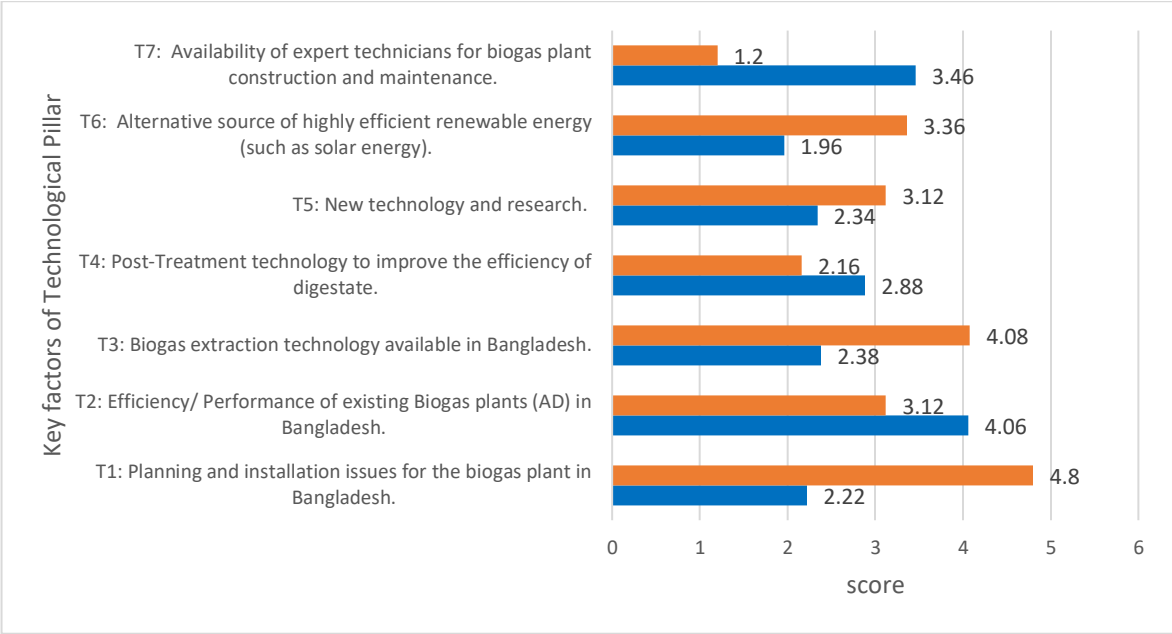


Figure 4.4: Stakeholder Ratings on Impact and Uncertainty for the technological pillar of PESTEL. Blue bars indicate impact scores, and orange bars indicate uncertainty scores.

Environmental Pillar

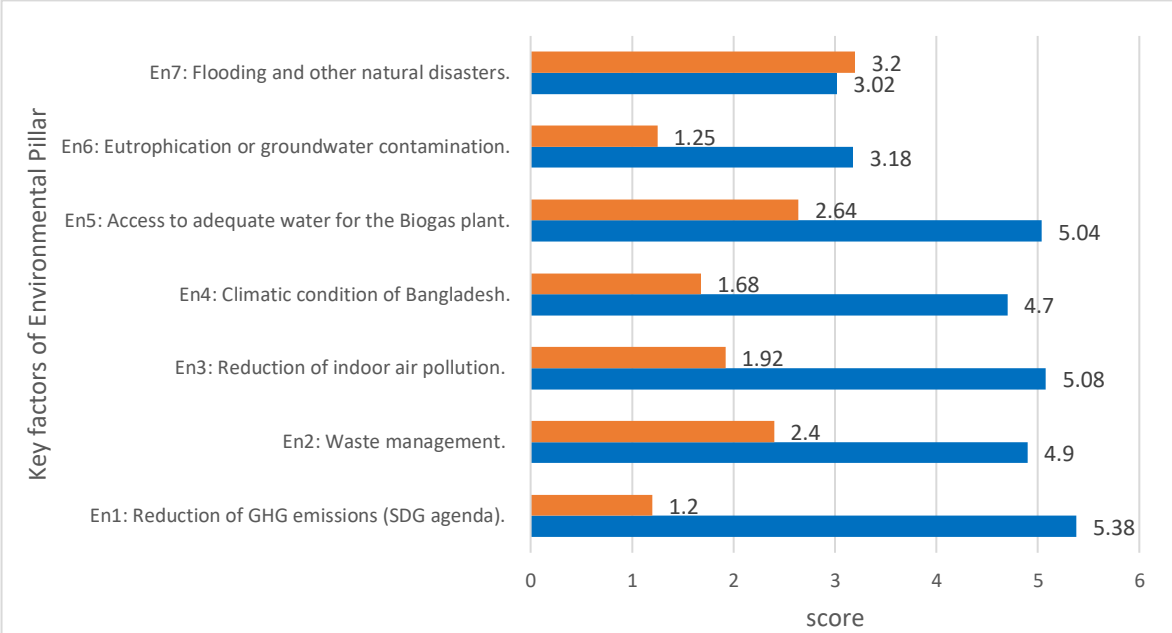


Figure 4.5: Stakeholder Ratings on Impact and Uncertainty for the environmental pillar of PESTEL. Blue bars indicate impact scores, and orange bars indicate uncertainty scores.

Legal Pillar

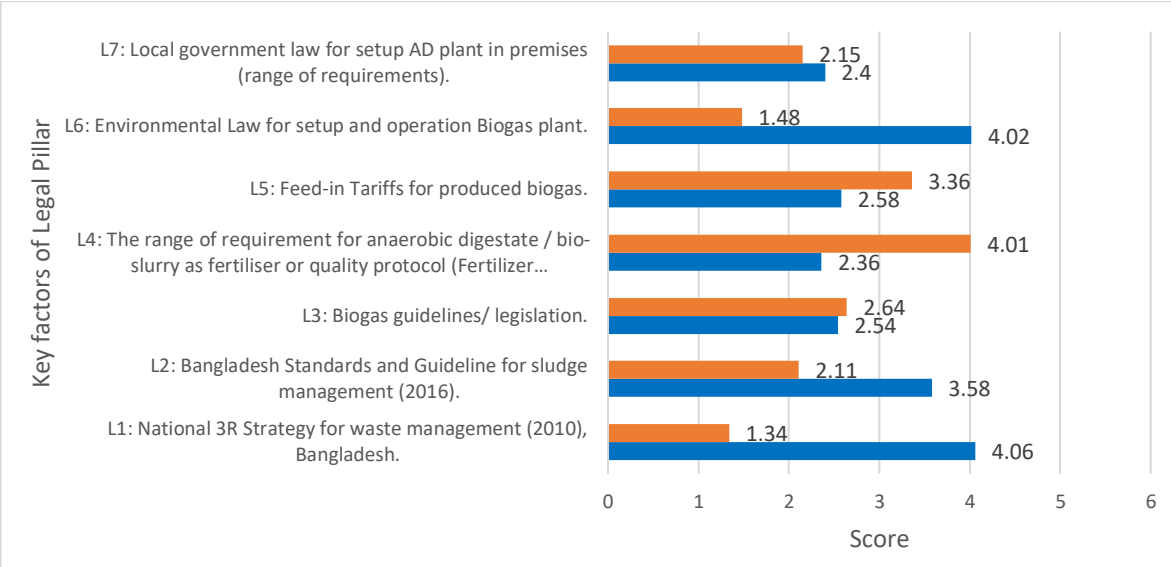


Figure 4.6: Stakeholder Ratings on Impact and Uncertainty for the legal pillar of PESTEL. Blue bars indicate impact scores, and orange bars indicate uncertainty scores.

4.1.1.2 Potential impact of the key factors

The results indicate a considerable variation within the mean impact assessments obtained in the survey. Among the forty-two key factors analysed, the high positive (highest ratings) were given to the following 12 key factors,

1. En1: Reduction of GHG emissions (SDG agenda) (score: 5.38).
2. Ec1: Availability and price of feedstock (score: 5.3).
3. En3: Reduction of indoor air pollution (score: 5.08).
4. En5: Access to adequate water for the biogas plant (score: 5.04).
5. Ec2: Biogas plant construction cost (score: 5.00).
6. En2: Waste management (score: 4.9).
7. S4 : Improvement of household welfare among the AD plant users (score: 4.86).
8. En4: Climatic condition of Bangladesh (score: 4.7).
9. Ec6: Labour costs (score: 4.6).
10. S5: Vermin and malodour reduction (especially of poultry firm) (score: 4.6).
11. P4: Stability of political framework of Bangladesh government (score: 4.53).
12. Ec4: New Job opportunities (score: 4.44)

The individual mean assessment (above 12 key factors) obtained in the survey exceeded 4.33 (discussed in Table 3.2), which is considered to have a positive impact on the sustainable growth of AD sectors of Bangladesh and more than 50 % of the experts assessed these issues above 5.

The following factors score between 4.34 and 2.67 and are considered to have less potential impact (discussed in Table 3.2).

1. Ec5: Revenue from biogas and digestate (score:4.24).
2. T2: Efficiency/ Performance of existing biogas plants (AD) in Bangladesh (score: 4.06).
3. L1: National 3R Strategy for waste management (2010), Bangladesh (score: 4.06).
4. L6: Environmental Law for setup and operation of biogas plant (score: 4.02).
5. Ec3: Level of maintenance costs for the Biogas plant (score: 3.62).
6. L2: Bangladesh Standards and Guideline for Sludge Management (2016) (score: 3.52).
7. T7: Availability of expert technicians for biogas plant construction and maintenance (score: 3.46)
8. S3: Level of literacy rate among the mass population in Bangladesh (score: 3.28).
9. S1: Knowledge and awareness about the Biogas plant (score: 3.26).
10. En6: Eutrophication or groundwater contamination (score:3.18).
11. S7: Unwillingness to accept new technology (Biogas system) (3.12).
12. En7: Flooding and other natural disasters (score: 3.02).
13. T4: Post-Treatment technology to improve the efficiency of digestate (score: 2.88).

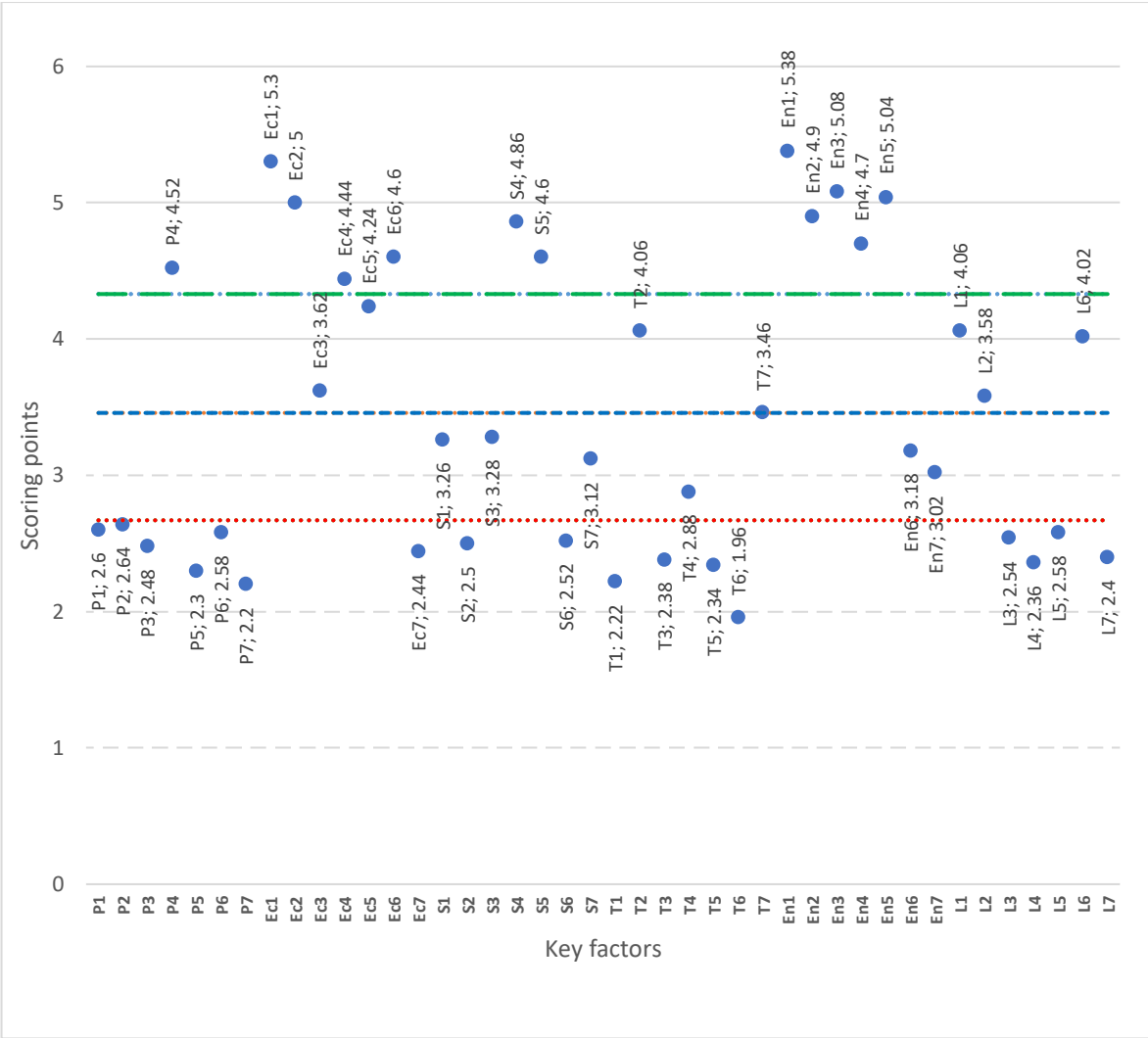


Figure 4.7: The results of the expert surveys regarding the potential impact of the elements (markings in Table 3.1). In the figure, the above green and below red horizontal lines represent the positive and negative potential impact zones, respectively (discussed in Table 3.4).

The stakeholders identified 17 key factors as negative potential which hinder the AD growth in Bangladesh. The mean assessment obtained in the survey below is 2.67 (discussed in Table 3.2), which is considered to have a negative potential impact and hinders the sustainable growth of AD sectors of Bangladesh and more than 50% of the experts assessed these issues above 5.

1. P2: Taxation policies on landfilling with waste (in Bangladesh) (score: 2.64).
2. P1: Existing Renewable Energy and Climate Change Policy of Bangladesh (score: 2.6).

3. P6: Bureaucratic complication (The level of administrative obstacles) (score: 2.58).
4. L5: Feed-in Tariffs for produced biogas (score: 2.58).
5. L3: Biogas guidelines/ legislation (score: 2.54).
6. S6: Level of social stigma (cultural and religious viewpoint) (score: 2.52).
7. S2: Level of information dissemination and advertising (score: 2.5).
8. P3: Government support (incentives) and bank loan policy for the AD industries in Bangladesh (score: 2.48).
9. Ec7: Security on investment (score: 2.44).
10. L7: Local government law for setup AD plant in premises (range of requirements) (score: 2.4).
11. T3: Biogas extraction technology available in Bangladesh (score: 2.38).
12. L4: The range of requirement for anaerobic digestate / bio-slurry as fertiliser or quality protocol (Fertilizer Recommendation Guide 2018, Bangladesh) (score: 2.36)
13. T5: New technology and research (score: 2.34).
14. P5: Corruption at the national and individual level (score:2.3).
15. T1: Planning and installation issues for the biogas plant in Bangladesh (score: 2.22).
16. P7: National coordination among stakeholders (score: 2.2)
17. T6: Alternative source of highly efficient renewable energy (such as solar energy) (score: 1.96).

The results indicate a considerable variation within the individual groups (pillar). Six key factors were assessed below the negative impact line within the political pillar. The stakeholders considered this a highly negative pillar that hinders the sustainable growth of AD sectors in Bangladesh. After that, the four key factors of the technological pillar and four key factors of the legal pillar are in the second position. Two key factors of the social pillar, one key factor from the economic pillar, and no key factor from the environmental pillar fall within the negative impact zone (Figure 4.7).

On the other hand, the highest positive key factors (above 4.33) have been selected for the environmental pillar (five key factors) and then the economic pillar (four key

factors). Only two positive key factors have been identified for the social pillar and one for the political pillar, but no positive key factors have been identified from the technological and legal pillars. In addition, key factor scores between 2.67 to 4.32 are considered factors for low impact on the sustainable growth of AD sector in Bangladesh. In this category, no key factors for the political, two key factors for the economic, three key factors for the social, three key factors for the technological, two key factors for the environmental and three key factors for the legal pillar have low impact.

4.1.1.3 Uncertainty of the key factors

In the case of uncertainty regarding key factors, an apparent discrepancy can be seen between individual key factors' assessments and individual experts' opinions. To sum up, in the critical analysis, it is identified that environmental and social factors do not constitute strategic areas (Figure 4.7 and Figure 4.8) because these are predictable factors considerably, though they have a high impact on the sustainable growth of AD sector in Bangladesh. However, attention should be paid to factors of the Political, Economic, Technological and Legal pillars of PESTEL.

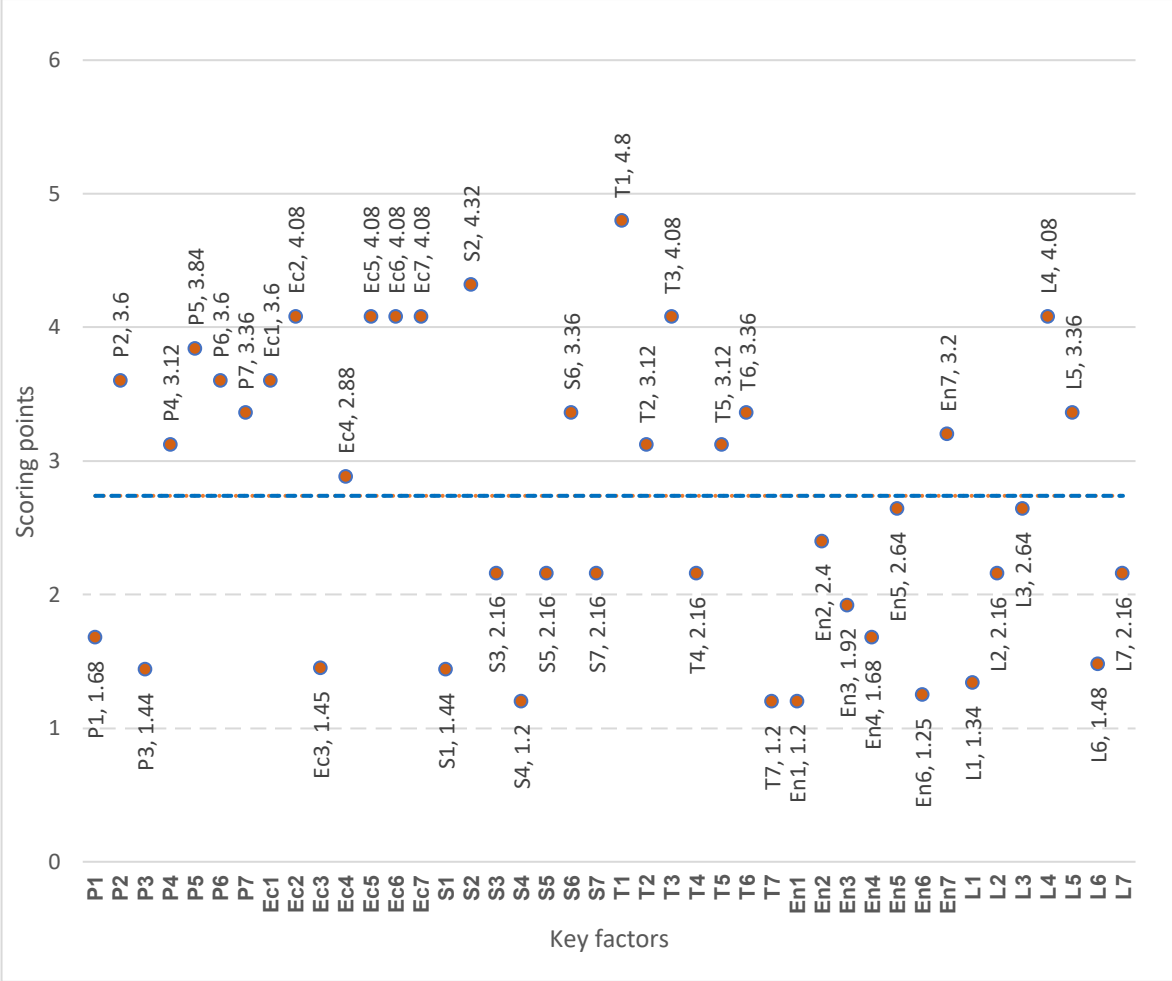


Figure 4.8: The results of the expert surveys regarding the uncertainty of the elements (markings in Table 3.1).

The analysis of the results for both assessed categories (Potential Impact and Uncertainty) illustrates that the key factors assigned to these groups have a substantial impact on the sustainable growth of the AD sector in Bangladesh, and at the same time, they are challenging to foresee.

4.1.1.4 The Impact/Uncertainty grid analysis

The Impact/Uncertainty Grid serves as a tool to organise and visualise a comprehensive list of factors that could potentially affect the success or failure of small-scale anaerobic digestion programs in Bangladesh. This matrix categorises all identified factors based on their potential impact on performance and the degree of uncertainty regarding their future influence. Factors with higher uncertainty are

placed higher on the grid, with positive factors positioned on the right and negative factors on the left (Figure 4.9).

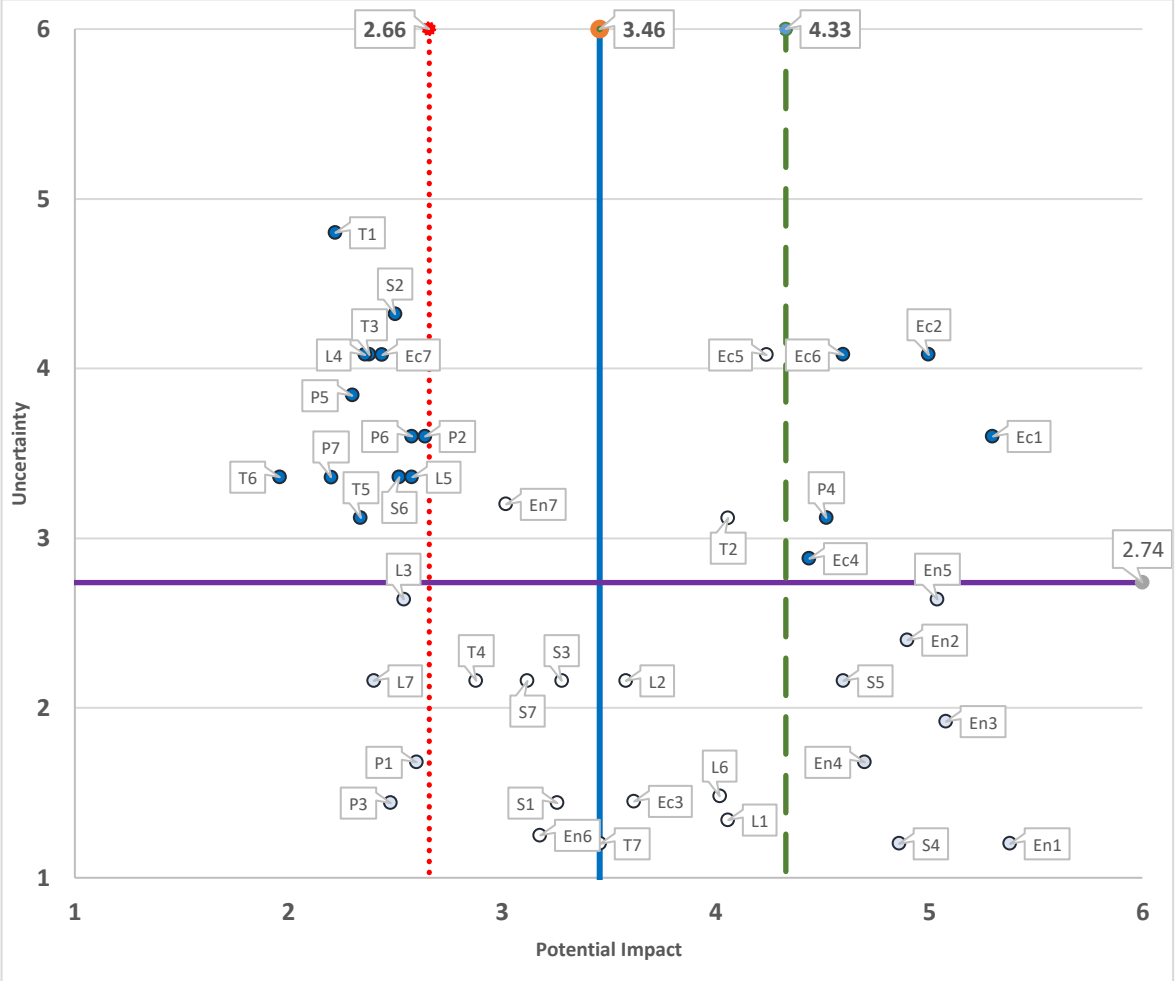


Figure 4.9: The outcomes of the expert surveys related to the uncertainty of the factors (as indicated in Table 3.4).

In this study, the Impact/Uncertainty Grid is divided into six sections:

- The lower left (between the negative point (red line) and below the global uncertainty average) and lower right (between the positive point and below the global uncertainty average) areas of the grid represent factors with significant impact (either negative or positive) but with relatively predictable outcomes. These are referred to as trends and are essential for shaping recommendations aimed at promoting the wider adoption of sustainable anaerobic digestion plants (Schwartz, 1996).

- Factors found in the upper left and upper right corners of the grid are labelled critical uncertainties. These elements have a significant impact on performance, but their future trajectory is uncertain (Van der Heijden, 2005).

- The middle section of the grid, with an impact range between 2.66 and 4.33 (both above and below the global uncertainty average), contains factors with a relatively lower impact on performance. These are referred to as secondary elements and are not considered further in the recommendations.

This section identifies the key factors from specific groups that had the most significant influence on the sustainable growth of the anaerobic digestion (AD) sector in Bangladesh. Drawing on the survey results assessing the impact and uncertainty of these key factors, a dependency structure matrix was created to map the relationship between these two parameters (impact and uncertainty) (Figure 4.9). Dark blue highlights the critical uncertainties. A total of 18 key factors of strategic importance were identified, including the following components:

Negative and uncertain

1. T6: Alternative source of highly efficient renewable energy (such as solar energy).
2. P7: National coordination among stakeholders
3. T1: Planning and installation issues for the biogas plant in Bangladesh.
4. P5: Corruption at the national and individual level.
5. T5: New technology and research.
6. L4 : The range of requirement for anaerobic digestate / bio-slurry as fertiliser or quality protocol (Fertilizer Recommendation Guide 2018, Bangladesh)
7. T3 : Biogas extraction technology available in Bangladesh.
8. Ec7: Security on investment
9. S2 : Level of information dissemination and advertising.
10. S6 : Level of social stigma (cultural and religious viewpoint).
11. P6 : Bureaucratic complication (The level of administrative obstacles)
12. L5: Feed-in Tariffs for produced biogas.
13. P2 : Taxation policies on landfilling with waste (in Bangladesh).

Positive and Uncertain

1. Ec4: New Job opportunities
2. P4 : Stability of political framework of Bangladesh government.
3. Ec6: Labour costs.
4. Ec2: Biogas plant construction cost.
5. Ec1: Availability and price of feedstock.

The remaining assessed Key factors (11 key factors) are in light blue. Those which were located at the bottom left (between the negative point (Red line) and below the uncertainty global average) and the bottom right (between the positive point (Green line) and below the uncertainty global average) section of the Impact/Uncertainty Grid also considered as significant, but relatively stable and predictable. These are

Negative and predictable (certain)

1. L7: Local government law for setup AD plant in premises (range of requirements).
2. P1 : Existing Renewable Energy and Climate Change Policy of Bangladesh
3. P3 : Government support (incentives) and bank loan policy for the AD industries in Bangladesh.
4. L3: Biogas guidelines/ legislation.

Positive and predictable (certain)

1. S4 : Improvement of household welfare among the AD plant users.
2. En1: Reduction of GHG emissions (SDG agenda).
3. En4: Climatic condition of Bangladesh.
4. En3: Reduction of indoor air pollution.
5. S5: Vermin and malodour reduction (especially in poultry firms).
6. En2: Waste management.
7. En5: Access to adequate water for the biogas plant.

On the other hand, the issues found in the middle (impact range between 2.66 and 4.33 for both above and below the global average of uncertainties) are secondary key factors, which have a minor impact on the analysis. These include

1. T4: Post-treatment technology to improve the efficiency of digestate.
2. En7: Flooding and other natural disasters.
3. S7 : Unwillingness to accept new technology (Biogas system).
4. En6: Eutrophication or groundwater contamination.
5. S1 : Knowledge and awareness about the Biogas plant.
6. S3 : Level of literacy rate among the mass population in Bangladesh.
7. T7: Availability of expert technicians for biogas plant construction and maintenance.
8. L2: Bangladesh Standards and Guideline for sludge management (2016).
9. Ec3: Level of maintenance costs for the Biogas plant.
10. L6: Environmental Law for setup and operation of biogas plant.
11. L1: National 3R Strategy for waste management (2010), Bangladesh.
12. T2: Efficiency/ Performance of existing biogas plants (AD) in Bangladesh.
13. Ec5: Revenue from biogas and digestate.

Finally, the findings from this chapter have been used in the next chapters to develop recommendations for sustainable AD growth in Bangladesh in the “conclusion and recommendations” chapter.

Chapter 05: In-Depth Analysis of the Political Pillar of PESTEL

5.1 Introduction

The progress and sustainability of the anaerobic digestion (AD) sector in Bangladesh are significantly influenced by the political pillar of the PESTEL framework. The political context directly affects the planning, execution, and scalability of AD systems since AD technology offers the potential to solve both waste management and renewable energy needs.

Political elements like government policies, legal frameworks, national coordination, and the degree of corruption highly influence the adoption and spread of AD technology in Bangladesh. All of these are vital for the expansion of the AD sector; the political environment shapes the support and incentives accessible for renewable energy projects.

Nevertheless, Bangladesh's political landscape presents both opportunities and challenges for the AD industry. Although the nation has advanced its policies on renewable energy, a certain gap in support for small-scale AD initiatives still exists. Problems, including inconsistent policies, low financial incentives, corruption, and poor regulatory execution, hamper AD systems' sustainable expansion.

Analysing the political elements affecting AD growth using the PESTEL framework reveals that tackling these issues calls for concerted government, business sector, and other stakeholders' efforts. Effective political will and reforms would help Bangladesh to create a strong AD sector that supports its sustainable development and renewable energy targets.

5.2 Insights from expert stakeholder opinion on the political pillar of PESTEL

Stakeholders considered all seven key factors essential for sustainable AD growth in Bangladesh (Figure 4). These key factors are discussed below,

Negative and uncertain

- P7: National coordination among stakeholders
- P5: Corruption at the national and individual level.
- P6: Bureaucratic complication (The level of administrative obstacles)

- P2: Taxation policies on landfilling with waste (in Bangladesh).

Positive and Uncertain

- P4: Stability of the political framework of Bangladesh government.

Negative and predictable (certain)

- P1: Existing Renewable Energy and Climate Change Policy of Bangladesh
- P3: Government support (incentives) and bank loan policy for the AD industries in Bangladesh.

5.2.1 P7: National coordination among stakeholders

One of the major Key factors, "P7: National coordination among stakeholders" within the political pillar, was ranked extremely negatively and uncertain for the sustainable expansion of anaerobic digestion (AD) in Bangladesh during the PESTEL analysis. This negative score demonstrates major concern about the poor coordination among several stakeholders, which is essential for the development and execution of AD programs. The uncertainty related to this element suggests that although stakeholders believe the present level of coordination is insufficient, there is room for development without any promise of advancement.

The successful expansion of AD sector relies on efficient national coordination among various sectors. It involves the coordination among several stakeholders, including government agencies, business organisations, non-governmental organisations (NGOs), and research institutions, which would be a good model of national coordination among all stakeholders (Hasan et al., 2020; Venus et al., 2021). In Bangladesh, the AD sectors appear to be hindered by fragmented policies and the lack of a clear, unified approach. Planning and implementation often run into delays, largely because stakeholders operate without a shared strategy and communication tends to break down (Hasan et al., 2020).

In the renewable energy field, particularly within anaerobic digestion (AD), Germany is considered a role model for national coordination, which can be effectively implemented (Venus et al., 2021). The country has managed to establish a structure that links federal and state authorities with private firms, research institutions, and NGOs in a manner that appears remarkably coherent. The Renewable Energy

Sources Act (EEG) of Germany outlines clear incentives for producing and utilising biogas, which has helped propel the AD sector forward. It is not a perfect system, but Germany's integrated model does appear to align the interests of very different stakeholders toward shared goals. That alignment may explain why the country has seen steady progress in both biogas technology and public acceptance (Weiland, 2010).

In contrast, India experiences a high level lack of coordination among stakeholders although the country has made real progress in renewable energy, yet the AD sector seems to lag behind. Poor cooperation across government departments, state agencies, and private actors slows down the progress. Conflicting mandates, outdated regulations, and a general lack of communication often get in the way of effective implementation and scaling (Bhattacharya and Jana, 2009; Kumar and Majid, 2020).

In addition, the lack of governmental coordination processes in Kenya (LMICs) affects the growth of the AD sector. Efforts to promote biogas in Kenya have been severely disrupted for lack of cooperation among government agencies, donors, and implementation companies (Wanjohi et al., 2022).

It is clear from the above discussion that national coordination among stakeholders is essential for the expansion of AD sector and its lack poses significant challenges. Stakeholders (in this study) believe that better national coordination requires the creation of a central coordinating body capable of harmonising the efforts of all stakeholders, simplifying policies, and promoting efficient communication. This would help reduce the significant, negative, and unclear influence of this element on the steady development of the AD industry.

5.2.2 P5: Corruption at the national and individual level

In this research, stakeholders have found "P5: Corruption at the national and individual level" within the political pillar as a "high negative" and "uncertain" key factor influencing the sustainable expansion of AD sector in Bangladesh. While the uncertainty reflects the interests of stakeholders about the uncertain character of this key factor and the extent of corruption that could affect the future development of the

AD sector, this high negative score suggests that stakeholders suggest "corruption" greatly hinders the development and implementation of AD projects.

Regarding small-scale anaerobic digestion (AD) systems in Bangladesh, corruption on governmental and personal levels poses major difficulties. As several studies show, corruption seriously affects the political climate, which is very important for the development of such sustainable technology. Pervasive corruption in Bangladesh influences all spheres of governance, including government. Bangladesh regularly ranks among the most corrupt nations worldwide on Transparency International's Corruption Perceptions Index (Transparency International, 2023). Reflecting the ingrained corruption problems in Bangladesh, the nation scored 24 out of 100 in 2023, placing 149th out of 180 countries (Transparency International, 2023). Stakeholders in this study believe that corruption seriously affects AD projects in Bangladesh. Corruption causes project costs to rise, resource misallocation, and lower investor trust. Particularly specific behaviours like favouritism, nepotism, and bribery compromise the effectiveness and efficiency of AD programs (Khatun, 2021; Transparency International, 2023). For instance, the demand to pay bribes to get required permissions and funds causes stakeholders to suffer major delays and rising expenses (Transparency International, 2023; UNCAC-Coalition, 2023).

When Bangladesh is compared to other LMICs, it is clear how negatively corruption can affect AD projects. In India, for instance, corruption has caused diversion of funding intended for biogas projects (among other renewable energy projects), therefore causing project delays and higher prices (Gandhi et al., 2022; Kumar and Majid, 2020). Similar challenges for the growth of the AD sector have been caused by corruption in Nigeria when money is sometimes misappropriated, therefore compromising the accomplishment of projects (Akinbami et al., 2001).

Countries like Germany, Denmark, and the UK, with relatively low corruption in grid access, feed-in tariffs, and gas pricing, seem better positioned for steady AD sector (level 2 and 3) growth. Germany’s strong anti-corruption laws and transparent energy policies make it easier to integrate biogas into the national grid (Thrän et al., 2023). Denmark’s record is similar; its reputation for integrity creates a predictable legal environment where projects can actually take root (Transparency International,

2020). Over time, such consistency and enforcement appear to build investor confidence, keeping the AD industry on a stable growth path.

Bangladesh's recent efforts to improve digital transparency may help curb corruption and strengthen governance in the AD sector (Alam et al., 2023; Rahman, 2021). Still, stakeholders believe corruption remains a major obstacle, suggesting that lasting progress will depend on stronger integrity measures and consistent enforcement.

5.2.3 P6: Bureaucratic complication (the level of administrative obstacles)

In this study, the key factor "P6: Bureaucratic Complication: (The Level of Administrative Obstacles)" within the Political pillar was rated as "negative" and "uncertain" by stakeholders (participants) concerning the growth of AD sectors in Bangladesh. This negative score captures the major obstacle bureaucratic difficulties provide to the advancement and execution of AD projects. The uncertainty rating shows stakeholders' worries about the inconsistent character and degree of these administrative barriers that can influence operational effectiveness and future investments.

Conceptually, bureaucracy is a system of administration distinguished by a clear division of labor, set norms, and ordered hierarchy. Sociologist Max Weber called bureaucracy a logical and effective kind of organisation meant to guarantee consistency, responsibility, and predictability (Weber, 1947). In practice, bureaucratic systems can, however, become unduly inflexible and ineffective, creating administrative roadblocks and delays.

Complications in bureaucracy occur due to administrative procedures and procedural guidelines becoming complicated and burdenful. This can result from things like antiquated laws, poor inter-agency cooperation, and inadequate governmental institutional capability. Particularly in industries like renewable energy (such as the AD sector), where timely permits and clear regulatory frameworks are absolutely essential for project success, these complexities can hinder innovation, lower operational efficiency, and discourage investment (Barnett and Finnemore, 2004). Bureaucratic issues refer to the degree of administrative difficulties that companies encounter when interacting with governmental and regulatory authorities. These

challenges include prolonged authorisation procedures, unreasonable documentation requirements, and uneven regulation application.

Stakeholders have pointed out that bureaucratic red tape at various government levels often slows down processes in Bangladesh (Hossain, 2017; Jannatul, 2016). The approval and implementation of projects slow down due to a lack of cooperation among multiple government departments (Hossain, 2017; Jannatul, 2016; Transparency International, 2023). Bureaucratic issues are not unique to Bangladesh, but relatively common in many LMICs. For example, bureaucratic red tape greatly hinders the growth of AD sectors and other renewable energy projects in Kenya (Wanjohi et al., 2022). Additionally, the clearance procedures for renewable energy projects in India are protracted, resulting in delays and increased project costs (Kamau et al., 2018).

The Philippines struggles with bureaucratic delays that hinder renewable projects, while Vietnam's streamlined legal processes and clear regulatory framework show how efficient governance can accelerate AD sector growth (Ricardo, 2022; Thoa, 2020; Urban et al., 2018; Venus et al., 2021).

Bureaucratic hurdles continue to slow and raise the costs of small-scale AD projects in Bangladesh. Simplifying procedures and improving coordination among agencies could help attract investment and support sector growth.

5.2.4 P2: Taxation policies on landfilling with waste

Stakeholders in this study have identified the key factor "P2: Taxation policies on landfilling with waste" within the Political pillar, which both negatively impacts and is uncertain for AD growth. Stakeholders in this study (negative rating) raise serious questions regarding the present landfilling taxation policies, and also show concerns regarding the unpredictable nature of these policies.

A landfill tax is a fee paid for the disposal of garbage at landfill sites, thus encouraging AD sector (level 1,2 and 3) growth. The United Kingdom introduced a landfill fee in 1996, which is credited with significantly reducing the amount of waste transported to landfills, thereby increasing recycling rates (HM Revenue and Customs, 2021). By making garbage disposal more costly, it is possible to reduce the amount of waste

going to landfills, thereby promoting waste reduction, recycling, and the use of other waste management techniques (such as AD system) (HM Revenue and Customs, 2021; OECD, 2017).

The present landfilling with trash taxes in Bangladesh is viewed as insufficient in encouraging environmentally friendly waste management techniques. Encouragement of waste diversion toward more sustainable alternatives like AD depends on efficient landfilling taxes. The lack of such policies in Bangladesh implies that waste creators have little incentive to move waste from landfills to AD facilities. Stakeholders see this as a major obstacle to the acceptance and spread of AD technology in the nation since the AD industry depends on organic waste feedstock that is otherwise being thrown in landfills.

Many low- and middle-income nations (LMICs) have provision of taxing laws on landfilling, so not unique to Bangladesh. For example, the absence of strong landfill levies in India has been noted as a deterrent to the use of alternative waste management techniques including AD systems. While some state Indian governments have instituted waste management rules, including landfill charges, their implementation and enforcement remain inconsistent (Kumar and Majid, 2020). In Nigeria, the lack of landfill laws has led to ongoing reliance on landfilling as the main waste disposal technique. Thus, the AD sector, as well as other sustainable waste management technologies, have suffered development due to this (Ifeoma and Yusuf, 2016; Olatunji et al., 2023). On the other hand, certain LMICs, such as South Africa, have instituted landfill charges (in 2015) to incentivise waste avoidance toward sustainable AD practices (DEFF, 2020).

Often higher and more rigorously enforced, landfill levies in developed nations offer a substantial financial incentive to cut garbage dumped in landfills. For instance, high landfill prices combined with tight rules have greatly lowered landfilling rates in Sweden and boosted the acceptance of AD systems and other sustainable waste management techniques (Clark, 2022). The waste management plan of Denmark has included the landfill charge as an absolutely vital component. The tax has worked well in encouraging AD system-based recycling and energy recovery as well as in lowering landfill waste. Denmark now has one of the lowest landfill rates in the European Union for this strategy (EEA, 2022).

Finally, the negative and uncertain ratings for this key factor "P2: Taxation policies on landfilling with waste" in Bangladesh draw attention to important issues regarding the present laws' influence on the long-term sustainability of the small-scale AD sector. Bangladesh has to create and apply sensible landfilling taxation regulations to solve this issue, as the PESTEL study brings forth. Such laws should be meant to prevent landfill waste dumping and advance alternate waste management techniques, including the AD system. Furthermore, helping the sector's expansion might be the reinvested income from landfill taxes in research and development as well as sustaining AD infrastructure. Furthermore, the experiences of other LMICs and industrialised nations show how important good landfill tax laws are in encouraging environmentally friendly waste management techniques. Still, in many LMICs (including Bangladesh) the execution and enforcement of such rules remain difficult.

5.2.5 P4: Stability of the political framework of Bangladesh government

In the PESTEL study, stakeholders regarding the sustainable development of small-scale anaerobic digestion (AD) systems in Bangladesh evaluated the key factor "P4: Stability of political framework of Bangladesh government" positively and uncertainly inside the Political pillar. The positive score shows the confidence of stakeholders in the current political stability as a necessary component for the growth and execution of AD projects. The uncertainty score, however, shows worries about possible political changes that would influence sector investments and future expansion.

A political framework is the framework and set of procedures by which a government functions including power distribution, legal rule, and policy stability and predictability. Encouragement of an environment fit for investment and economic progress depends on a strong political framework, which encourages AD sector (level 1,2 and 3) growth. It covers ethical governance, open decision-making, and consistent policy execution (North, 1990). For instance, Germany's political stability has been essential in supporting renewable energy projects by means of a consistent regulatory environment that motivates investment in sustainable technology (Thrän et al., 2023).

Stakeholders involved in this study have seen how the present political stability benefits the expansion of small-scale AD systems. Apart from excluding AD sectors, the stakeholders also thought that a stable governance structure has helped several policy measures aiming at supporting renewable energy and sustainable development. Nonetheless, stakeholders also took into account the uncertainty element resulting from worries about possible political volatility or policy changes compromising these initiatives. The cautious optimism of the stakeholders can be explained by historical political unrest occasionally upsetting economic operations and investment flows (Transparency International, 2023).

Furthermore, political stability is crucial in determining the expansion of AD systems in other low- and middle-income countries (LMICs). For example, political stability in India has made it possible to carry out various initiatives and policies aimed at renewable energy. Notwithstanding sporadic political obstacles, the general stable environment has helped the AD sector to make large investments (Kumar and Majid, 2020). On the other hand, political unrest and regular policy changes in Ethiopia have produced an unclear climate that discourages investment in AD systems among other renewable energy projects (Kamp and Bermúdez Forn, 2016). Vietnam is a good example where political stability has been crucial in the forward progress of the nation's renewable energy program. Consistent and stable policies of the government have drawn significant domestic and foreign investments in renewable energy projects, including the AD sector, so supporting sustainable development (Nguyen, 2021).

Stable political environments in developed nations often translate into more strong and well followed renewable energy regulations. Political stability has been a pillar of Germany's success in renewable energy, including AD systems, for instance. Long-term investments in renewable energy technology have been supported by a steady policy environment created by the German Renewable Energy Sources Act (EEG) (Thrän et al., 2023). Likewise, Denmark's steady political environment has allowed consistent and progressive energy policies that have greatly expanded the nation's renewable energy sector (Gregg et al., 2014; Jacobsen et al., 2013).

Finally, the favourable and negative ratings for the key factor "P4: Stability of political framework of Bangladesh government" underline the need for political stability in the

sustainable development of small-scale AD systems in Bangladesh. Although the present stability is considered encouraging, worries about possible political changes provide some degree of uncertainty. Comparisons with other LMICs and affluent nations show that an environment fit for investment and the growth of renewable energy projects depends on a strong political framework. The steady expansion of the AD sector in Bangladesh depends on political stability being maintained as well as on addressing uncertainties.

5.2.6 P1: Existing renewable energy and climate change policy of Bangladesh

Stakeholders have evaluated the key factor "P1: Existing Renewable Energy and Climate Change Policy of Bangladesh" inside the Political pillar negatively but predictably for the sustainable development of small-scale anaerobic digestion (AD) systems in Bangladesh in the framework of the PESTEL study. This negative score implies that rather than aiding in the expansion of the AD industry, current policies are seen as impediments. The certainty score implies that stakeholders see these rules as stable and unlikely to shift significantly in the near future, which challenges continuous AD expansion.

Critics of Bangladesh's present renewable energy and climate change policies note that they do not sufficiently support small-scale AD systems to expand (MoEF, 2009; Power Division, 2008). Among the main challenges observed by stakeholders in this study as insufficient incentives, ambiguous policies, and poor infrastructure development strategy are those connected to infrastructure development. These policies seem to be more focused on conventional energy sources and larger-scale renewable projects, therefore disregarding the probable benefits of small-scale AD systems (Hasan et al., 2020; Rahman, 2021).

Analogous problems persist in many low- and middle-income countries (LMICs). For instance, even if there are multiple renewable energy projects in India, large-scale solar and wind projects have often grabbed the front stage. The lack of focussed policy for small-scale AD systems has limited their expansion (Kumar and Majid, 2020). Nations like Vietnam have also made great success by putting specific rules to help biogas and small-scale AD systems into their renewable energy plan which leads to more investments and development in this sector (Thoa, 2020; Urban et al.,

2018). Nigeria provides another example when regulations supporting renewable energy sources have not been sufficiently supporting small-scale AD systems. The emphasis on oil and gas has superseded the opportunity for renewable energy solutions, including AD, therefore depriving opportunities for sustainable energy development in Nigeria (Nnaji et al., 2019).

Small-scale AD systems must be specifically addressed and detailed within the policies on renewable energy and climate change for their expansion in Bangladesh. This can entail offering clear legal frameworks, financial incentives, and infrastructural support catered to AD system demands. In addition to that, it might be helpful to include knowledge from nations such as Vietnam, which has effectively supported small-scale biogas plants (Thoa, 2020; Urban et al., 2018).

Finally, the negative and predicted results for the key factor "P1: Existing Renewable Energy and Climate Change Policy of Bangladesh" draw attention to major obstacles to the small-scale AD systems' sustainable development. The similarity with other LMICs emphasises the need for a policy on climate change and renewable energy. A favourable atmosphere for developing AD systems depends on addressing these issues inside Bangladesh's political system.

5.2.7 P3: Government support (incentives) and bank loan policy for the AD industries in Bangladesh

Stakeholders (in this study) considered small-scale AD systems must be specifically addressed within the government policies for financial support. They ranked this key factor "P3: Government support (incentives) and bank loan policy for the AD industries in Bangladesh" within the Political pillar negatively and predictably regarding the sustainable growth of small-scale anaerobic digestion (AD) sectors in Bangladesh. This negative score indicates substantial concern about the current level of government and financial support, which, in the opinion of stakeholders (in this research), is deemed inadequate to promote the growth and implementation of AD projects. Long-term strategic planning and investment in AD technologies suffer, as the predictability score indicates that stakeholders believe these policies are stable and unlikely to change considerably in the near future.

The growth of Bangladesh’s anaerobic digestion (AD) sector is held back by weak financial incentives and limited support mechanisms. Although tools like low-interest loans or subsidies could attract investors and reduce risks, current policies remain inadequate. High loan rates, scarce subsidies, and complex procedures—despite limited efforts by IDCOL, continue to discourage small-scale AD development (IDCOL, 2020).

In contrast, Bangladesh's solar energy loan program demonstrates the potential impact of effective financial support. The Solar Home Systems (SHS) program, managed by IDCOL, has been highly successful due to accessible financing, subsidies, and streamlined application processes. This program has enabled millions of rural households to adopt solar energy, showcasing the importance of strong financial support mechanisms (IDCOL, 2020).

Many low- and middle-income countries (LMICs) face similar challenges, but some have made strides in providing better support for renewable energy projects, including AD systems. For instance, in India, the government has implemented several incentive schemes such as capital subsidies, interest subsidies, and tax benefits to promote the adoption of renewable energy technologies, including biogas plants. These incentives have encouraged more investments and accelerated the growth of the AD sector (Kumar and Majid, 2020).

In contrast, Nigeria struggles with insufficient government incentives and supportive financial policies for renewable energy projects. The lack of a coherent policy framework and financial incentives has hindered the growth of AD systems, similar to the situation in Bangladesh (Oyedepo et al., 2018). However, countries like Vietnam have shown significant progress. The Vietnamese government provides substantial incentives, including low-interest loans, which have fostered a conducive environment for the growth of AD systems and other renewable energy projects (Thoa, 2020; Urban et al., 2018).

In conclusion, the negative and predictable scores for the key factor "P3: Government support (incentives) and bank loan policy for the AD industries in Bangladesh" highlight significant challenges for the sustainable growth of small-scale AD systems. The comparison with other LMICs underscores the importance of

targeted and supportive policies. Addressing these issues within Bangladesh's political framework is essential for fostering an environment conducive to the development of AD systems, thereby supporting the sustainable growth of the AD sector in Bangladesh.

5.3 Outcome of AD user survey (political point of view)

Addressing the political challenges within the PESTEL framework for anaerobic digestion (AD) technology in Bangladesh, AD users encounter several significant obstacles that impact the adoption and long-term sustainability of this technology. Key political challenges include;

5.3.1 Inconsistent government policies

Frequent policy fluctuations

Frequent and unpredictable policy changes in Bangladesh create uncertainty for anaerobic digestion (AD) users, discouraging investment and slowing adoption. Similar instability in countries like Nigeria and Kenya has had comparable effects, showing how inconsistent policies can undermine renewable energy development across low- and middle-income nations (Olatunji et al., 2023; Wanjohi et al., 2022). In this survey, we observed that potential new users were confronted with newly introduced regulations regarding AD construction and access to government support, which were not present for earlier adopters. This inconsistency creates confusion and discourages adoption.

Lack of clear AD-specific policies

All respondents in the survey of AD users (100%) reported no knowledge about a dedicated policy framework to support AD technology in Bangladesh. Bangladesh lacks a clear, dedicated policy for anaerobic digestion (AD), which creates uncertainty for users and hinders sector growth. Similar policy gaps exist in Ethiopia (Kamp and Bermúdez Forn, 2016), while India’s structured NBMMP (National Biogas and Manure Management Programme, India) (Raha et al., 2014) shows how defined support and incentives can effectively boost AD adoption.

5.3.2 Bureaucratic delays and red tape

Complexity of regulatory approvals

Roughly 86% of anaerobic digestion (AD) users in the study felt that getting regulatory approval was slow and complicated. The maze of permits and overlapping agencies often delays projects and discourages new adopters, especially in places with heavy bureaucracy. Similar problems arise in India, Kenya, and South Africa, where small-scale biogas or renewable energy initiatives often get stuck in paperwork or are abandoned midway due to poor inter-agency coordination (Kumar and Majid, 2020; Mwirigi et al., 2014; Wanjohi et al., 2022). Simpler, better-aligned approval systems are clearly needed for sustainable AD growth in developing countries.

Corruption issues

In Bangladesh, every AD user surveyed identified corruption, through bribes, informal fees, or political influence as a significant obstacle to project approvals. This not only drives up costs but also erodes trust and deters new investors. Similar patterns are observed in other developing countries, such as Nigeria and Ghana, where corruption increases expenses and delays renewable energy projects (Arthur et al., 2011; Ifeoma and Yusuf, 2016). In contrast, countries with stronger governance, such as Costa Rica (Riet et al., 2020), demonstrate how transparency and clear regulations can facilitate the smooth growth of the AD sector.

5.3.3 Political instability

Impact of political volatility

Approximately 68% of AD users in this study reported their views, a problem in long-term planning due to frequent changes in political leadership and government policies. Political instability has made it difficult for most anaerobic digestion (AD) users in Bangladesh to plan for the long term, as frequent leadership changes and shifting policies undermine confidence and continuity. This uncertainty discourages investors and slows project progress. Similar challenges are also present in other developing countries, such as Nigeria and Kenya, which have faced policy

disruptions linked to political unrest or election cycles (Olatunji et al., 2023; Wanjohi et al., 2022). In contrast, Rwanda's relative political stability appears to have supported steady growth in renewable energy, illustrating how a consistent political climate can either facilitate or hinder AD development in low- and middle-income contexts (Rupf et al., 2015a).

Shifts in government priorities

Around one-third (38%) of AD users in Bangladesh worry that if new governments form, they may sideline renewable energy projects developed by the previous government, creating uncertainty for funding and long-term planning. Similar instability affects countries like South Africa and India, where shifting political priorities have disrupted biogas and AD programs (Baker and Phillips, 2019; Meena et al., 2024). By contrast, Brazil's consistent policy framework demonstrates a stable, long-term commitment that can sustain progress (Mathias and Mathias, 2015; Santos et al., 2018). For Bangladesh, it is essential to establishing a durable national strategy that is less vulnerable to political turnover.

5.3.4 Weak enforcement of environmental regulations

Ineffective waste management policies

AD users (100%) in this survey agreed that ineffective waste management policies exists in Bangladesh. Weak enforcement of waste management policies in Bangladesh limits the supply of organic waste to AD plants, making their operation inefficient. All surveyed users noted an absence of regulatory action against poor waste practices. Similar enforcement gaps have slowed AD progress in countries such as Nigeria and Kenya, while Brazil's stricter oversight demonstrates how consistent enforcement can sustain feedstock supply and support AD growth (Mathias and Mathias, 2015; Olatunji et al., 2023; Santos et al., 2018; Wanjohi et al., 2022).

5.3.5 Limited public-private partnerships (PPP)

Challenges in government collaboration

Building effective public-private partnerships (PPPs) for anaerobic digestion (AD) in Bangladesh remains difficult due to poor coordination, unclear roles, and limited government engagement. Similar problems exist in countries like Nigeria and India, where weak frameworks and bureaucratic delays have discouraged private investment. Kenya has made some progress with formal PPP structures, though issues in implementation still persist. Overall, Bangladesh's experience reflects a broader challenge among LMICs in aligning public and private efforts to support AD development.

Minimal involvement of local authorities

None of the respondents in this survey received any motivation from the local authority regarding PPP**.** Local governments in Bangladesh play a limited role in supporting anaerobic digestion (AD) projects, primarily due to their limited capacity, resources, and interest. This lack of involvement weakens the waste collection and feedstock supply systems necessary for AD operations, a problem also observed in countries like Ghana and (Arthur et al., 2020; Lwiza et al., 2017). Rwanda's experience, where empowered local authorities have driven community-based AD initiatives, shows the value of decentralised governance (Rupf et al., 2015b). For Bangladesh, strengthening local government engagement and formalising public-private partnerships could significantly improve AD development.

5.3.6 Insufficient foreign investment and international support

Access to international climate funding is crucial for supporting large-scale renewable energy projects, such as anaerobic digestion (AD), in Bangladesh. However, 98% of AD users in this survey had never heard about international funding or the climate change trust fund. Bangladesh struggles to access international climate funds needed to expand anaerobic digestion (AD) projects (Islam, 2018). Weak institutional coordination and limited engagement with global financing mechanisms, such as the Green Climate Fund, have slowed progress. The National Climate Change Trust Fund (NCCTF) primarily supports adaptation rather than

renewable energy, leaving AD underfunded. Countries like Kenya and India have shown that proactive international engagement and clear funding frameworks can attract substantial support (Kumar and Majid, 2020; Mwirigi et al., 2014; Wanjohi et al., 2022). For Bangladesh, improving coordination and prioritising AD within climate policy may help unlock global financing opportunities.

5.3.7 Exclusion from policy-making processes

No one in this survey have been asked to contribute their knowledge or experience with authority. In Bangladesh, anaerobic digestion (AD) users are often excluded from policy-making at both national and local levels, resulting in policies that overlook the needs of small-scale and rural users. This top-down approach mirrors challenges observed in countries such as Nigeria, Kenya, and South Africa, where limited community input has hindered the adoption of these initiatives (Baker and Phillips, 2019; Nethengwe et al., 2018; Olatunji et al., 2023; Wanjohi et al., 2022). In contrast, India and Nepal demonstrate that involving local communities in policy design and implementation yields more practical and sustainable AD outcomes. For Bangladesh, adopting a more bottom-up, participatory approach could make AD policies more relevant and effective.

5.4 SWOT Analysis: Political pillar of PESTEL

SWOT analysis table focusing on the political landscape for sustainable growth in Bangladesh's anaerobic digestion (AD) sector. This analysis emphasises political strengths, weaknesses, opportunities, and threats, identifying areas where policy reform and collaboration can enhance sector growth. The table provides a concise overview, serving as a quick reference for strategic planning.

Table 5.1: SWOT Analysis for the political pillar of PESTEL

Category	Key Points
Strengths	• Political stability: Bangladesh has maintained a relatively stable political environment since 2024. If the trend

Category	Key Points
	continues, it can provide a foundation for long-term support in the AD sector. • National climate change trust Fund (BCCTF): As the Bangladesh Climate Change Trust Fund shows commitment to climate resilience, this can be leveraged to support AD initiatives.
Weaknesses	• Lack of coordination among stakeholders: The absence of cohesive policy implementation and national coordination creates inefficiencies, hindering the effective deployment of AD projects. • Corruption at various levels: Pervasive corruption adds financial burdens, delays projects, and reduces investor confidence. • Bureaucratic inefficiencies, including lengthy approval processes, administrative red tape, and inconsistent enforcement of regulations, create barriers to project implementation. • Weak environmental regulation enforcement: The poor enforcement of environmental and waste management regulations reduces the feedstock supply for AD plants and hampers sector growth.
Opportunities	• Growing international interest in renewable energy: Bangladesh could tap into international climate funds (e.g., Green Climate Fund, Clean Technology Fund) to support AD sector growth. • Public-private partnerships (PPP): Establishing formal frameworks for PPPs could attract private investment, mobilise resources, and bring expertise from the private sector.

Category	Key Points
	• Potential for policy reform: There is an opportunity to revise existing renewable energy and climate policies to include specific support for small-scale AD systems, incorporating financial incentives, regulatory frameworks, and infrastructure planning.
Threats	• Political volatility: Any future changes in political leadership or shifts in government priorities could disrupt renewable energy initiatives, creating uncertainty for the AD sector. • Inconsistent government policies: Frequent policy changes and a lack of a dedicated AD policy create an unstable regulatory environment, which may deter long-term investments. • Competition for climate funds: Limited government capacity to secure international climate funds may restrict access to the necessary financial resources, especially when competing with other countries. • Limited Involvement of local authorities: Local authorities' lack of engagement in waste management and energy distribution poses a risk to community-based AD projects, affecting the sector's scalability.

This SWOT analysis highlights the political strengths that can be leveraged to boost AD sector growth, such as political stability and an existing renewable energy framework. Addressing weaknesses, especially coordination, corruption, and bureaucratic inefficiencies, will be crucial to unlocking opportunities like international funding and PPPs. However, the threats of policy inconsistency and political volatility remain significant challenges that need proactive strategies to mitigate.

Chapter 06: In-Depth Analysis of the Economic Pillar of PESTEL

6.1 Introduction

Economic factors play a crucial role in the growth of small-scale (level 1) AD plants in Bangladesh. With limited rural energy access and rising waste challenges, AD offers a practical way to turn farm and organic waste into biogas for cooking or power. However, its long-term viability appears to hinge on cost, financial support, and market incentives that still need careful attention.

Bangladesh's steady economic growth and renewed focus on renewable energy seem to make AD a natural fit for its sustainability goals. But, its future remains uncertain, hinging on practical issues such as subsidies, feedstock costs, and government spending, which ultimately determine whether small-scale plants can remain financially viable. Government incentives, such as subsidies or tax (free) breaks, can ease investment in small-scale AD plants; however, high construction costs, especially in rural areas still pose a significant challenge. Fluctuating labour and feedstock prices further complicate profitability and day-to-day operation.

The success of AD plants often hinges on how the local market absorbs biogas and by-products, such as digestate, which is commonly used as an organic fertiliser. Financial incentives, such as renewable energy subsidies, could improve market conditions; however, their effectiveness depends on the stability of these policies. There is also an employment element, as AD plants are established in rural areas to create jobs and, in turn, support local economies. Carefully analysing these economic factors appears vital for evaluating the real potential of AD development. The success of AD plants largely depends on market demand for biogas and digestate, as well as stable financial incentives. Their role in creating rural jobs is notable, yet the sector's true potential seems to rest on how consistently these economic factors align.

Assessing these economic factors is key to judging the feasibility of small-scale AD in Bangladesh. Investment hurdles, high setup costs, labour limits, and feedstock uncertainty all shape performance, highlighting both the promise and the constraints of AD's expansion.

6.2 Insights from expert stakeholder opinion

Drawing on PESTEL analysis, the following five critical economic factors have been identified as pivotal for the sustainability of the AD sectors in Bangladesh.

Negative and uncertain

- Ec7: Security on investment

Positive and Uncertain

- Ec4: New Job opportunities
- Ec6: Labour costs.
- Ec2: Biogas plant construction cost.
- Ec1: Availability and price of feedstock.

6.2.1 Ec7: Security on investment

Within the PESTEL analysis, the economic pillar, specifically “Ec7: Security on Investment”, emerged as a significant concern. Stakeholders tended to see it in a negative and uncertain way, particularly regarding the long-term viability of small-scale AD in Bangladesh. Their view appears to reflect confusion about the economic conditions shaping the prospects for attracting and securing investment in renewable energy projects.

In Bangladesh, the economic context creates challenges for investment security. Policies shift frequently, financial markets remain unstable, and access to financing remains limited. Together, these issues seem to generate a high level of uncertainty for potential investors in the AD sector, which in turn may constrain the scale and long-term viability of renewable energy projects (Kabir and Endlicher, 2011).

This situation can be better understood when compared with the experiences of other low- and middle-income countries, as well as developed economies, where the challenges differ and the strategies to reduce investment risks vary considerably.

Similar to Bangladesh, India, a low- and middle-income country (LMIC), struggles with inconsistent policies and financial risks. India has made noticeable progress in shaping a more stable investment environment for renewables, primarily through the

implementation of government-backed guarantees and engagement with international donor support; however, it still faces some financial risks (Singh, 2019). Kenya provides another example, while it still contends with economic uncertainties, government-backed guarantees and the involvement of international donors have helped create a steadier flow of investment (Ouedraogo, 2017).

Brazil, an upper-middle-income country, use long-term contracts and supportive regulatory measures that appear to have strengthened investor confidence, creating conditions far more stable than those seen in Bangladesh (IRENA, 2016).

This comparison brings out the different economic settings and policy choices shaping investment security in the renewable sector across LMICs countries. It shows how varying strategies and regulatory frameworks can shape investor confidence. For Bangladesh, the contrast suggests there is still significant scope to strengthen its investment, particularly if it reflects some of the successes seen elsewhere.

6.2.2 Ec4: New job opportunities

In the PESTEL analysis, the factor “Ec4: New Job Opportunities” under the Economic pillar was evaluated both positively and with some uncertainty by stakeholders, concerning the sustainable growth of small-scale AD systems in Bangladesh. On one hand, there is optimism about the potential for job creation in sectors such as construction, operations and maintenance, logistics, sales, or even research and development. However, stakeholders have expressed concerns about the stability and sustainability of these jobs due to various factors, including the variability in government policies, financial incentives, and market acceptance of AD technologies.

Despite various opportunities, job security in the AD sector remains a significant concern. Shifting government support and uncertain financial incentives often render employment unstable. This is further complicated by the country’s broader unemployment problem, which was recorded at 5.3% in 2021 (World Bank, 2021). Without consistent policies and greater market acceptance, the long-term sustainability of AD-related jobs appears doubtful (Rahman, 2022).

Comparison with other LMICs such as Brazil and Nigeria clearly reflects the position of job opportunities within a successful AD sector (level 1). Brazil's AD industry has been steadily expanding, particularly within its agricultural base. Jobs have arisen in the construction and operation of AD plants; however, economic challenges and shifting policies create a level of job insecurity that parallels Bangladesh's experience (Silva, 2020). Nigeria exhibits a similar pattern. The incentives implemented by Nigeria focus on waste management and energy generation, leading to the creation of technical and operational roles. Nonetheless, uncertainty around government policies and funding gaps seem to undermine job stability, mirroring the challenges faced in Bangladesh (Adewuyi, 2019).

6.2.3 Ec6: Labour costs

In the PESTEL framework, stakeholders rated the factor "Ec6: Labour Costs" within the Economic pillar as both positive and uncertain in shaping the sustainable growth of small-scale AD systems in Bangladesh. This mixed assessment indicates that low wages can certainly help reduce operating costs and enhance competitiveness. However, doubts persist regarding wage stability and the wider economic environment, which may undermine these perceived benefits (Johnson et al., 2008). Labour costs in Bangladesh remain lower than in many other countries, giving the AD sector a cost advantage. The average monthly wage in Bangladesh is approximately $101, positioning the country firmly within a low-wage economy (World Bank, 2021). On the surface, this reduces daily project expenses and could make AD ventures more appealing to investors. However, this advantage is tempered by concerns about fluctuating wages and the unpredictability of broader economic conditions, which can raise doubts about whether these low labour costs can be sustained in the long term (Rahman, 2022).

In Brazil (LMIC), the average monthly wage is considerably higher, at around $450. While this makes labour costs more expensive than in Bangladesh, Brazil has a more developed labour market and relative economic stability appears to mitigate some of the risks typically associated with wages (Silva, 2020). Higher pay may also suggest a more skilled workforce, which can be important given the technical demands of the AD sector.

Nigeria (LMIC) sits somewhere in between. Average wages are roughly $170 per month, placing them midway between those of Bangladesh and Brazil. Nigeria face many of the same problems as Bangladesh. Unstable economic conditions and fluctuations in wage patterns make cost predictions less reliable (Adewuyi, 2019).

6.2.4 Ec2: Biogas plant construction cost

In the PESTEL analysis, stakeholders rated “Ec2: Biogas Plant Construction Cost” under the Economic pillar as both positive and uncertain regarding the sustainable growth of small-scale (level 1) AD in Bangladesh. The mixed view indicates optimism about the economic benefits and affordability of biogas plant construction, but doubts remain about fluctuating costs and financial risks that could unsettle long-term planning.

Actual expenses vary considerably based on plant size and the technology used. A small unit producing 2–5 m^3 of biogas daily could cost between $500 and $1,200. Medium-sized plants, processing 10–20 m^3, generally range from $5,000 to $15,000, while larger installations, exceeding 50 m^3, may cost above $30,000 (Rahman, 2022). These figures, of course, are not fixed; they fluctuate with local material prices, labour conditions, and the level of technological integration.

In Brazil, a lower-middle-income country, the cost of building biogas plants is influenced by its strong agricultural sector and easy access to local materials. Small units usually cost between $1,000 and $3,000, medium-scale systems range from $10,000 to $20,000, and large facilities can reach $50,000–$100,000 (Silva, 2020). These higher figures, especially when compared with Bangladesh, appear linked to the use of more advanced technology and higher-quality construction materials. Nigeria (LMIC) faces similar conditions, although it shares some economic characteristics with Bangladesh. Construction costs vary from around $800 to $2,000 for small plants, $7,000 to $18,000 for medium ones, and $25,000 to $50,000 for larger facilities (Adewuyi, 2019). However, these figures are quite flexible. They fluctuate depending on the availability of local materials, changes in labour costs, and the broader economic uncertainty that heavily influences project planning.

6.2.5 Ec1: Availability and price of feedstock

In the PESTEL analysis, stakeholders rated “Ec1: Availability and Price of Feedstock” under the Economic pillar as both positive and uncertain for the sustainable growth of small-scale AD in Bangladesh. The rating indicates optimism about the country’s abundant feedstock potential, although it also raises concerns about price fluctuations and the reliability of these material supplies.

Bangladesh’s extensive agricultural sector provides a wide range of potential feedstocks, including rice straw, cattle manure, and organic municipal waste. On paper, the volume appears substantial, and much of it could, in theory, support AD systems (Kabir and Endlicher, 2011). However, the reality is less clear-cut. Seasonal changes, competition for residues, and market pressures for alternative uses all seem to complicate both the cost and consistent availability of these materials.

Brazil (LMIC) offers significant potential for feedstock in AD systems, with a large agricultural sector, especially in sugarcane and soy. The substantial quantities of bagasse generated by the country's sugarcane industry can be utilised as feedstock. However, this apparent abundance is not without complications. Prices and supply are often influenced by global demand for sugar and bioethanol, introducing uncertainty (Silva, 2020).

Nigeria (LMIC) has an agricultural sector mainly focused on crops such as cassava and oil palm, which supply materials like cassava peels and palm oil mill effluent. At the same time, the availability of feedstock such as cassava peel appears promising. However, in practice, price volatility results from competition with food production and other industrial uses. Moreover, logistical challenges in transporting materials across rural areas and inconsistencies in the steady supply of feedstock become much less predictable (Adewuyi, 2019).

6.3 Outcome of AD user survey (economic point of view)

A carefully structured questionnaire was used to gather data on several key points, including the adequacy of the energy supply, the sources households relied on before installing a biogas plant, the difficulties they faced in obtaining reliable energy, and how biogas is now being utilised in daily life. The aim was to capture the shift in

energy use before and after installation, providing a clear picture of the impact of the AD system on both sustainability and household practices.

6.3.1 Impacts of AD plants on cooking fuel

6.3.1.1 Conversion from traditional fuels to biogas

Among the surveyed households, 94% switched their cooking fuel from firewood to biogas after the installation of AD plants. The remaining 6% did not fully trust the continuous gas supply from the AD plants. Before the AD plant was installed, 82% of respondents reported that their energy supply (e.g., firewood, LPG) for cooking was interrupted at least once a week, especially during the rainy season. In contrast, only 8% reported no significant changes in cooking fuel availability before and after the plant's installation. Following the AD plant's installation, households generally received cooking gas at regular intervals, although a notable decline in gas supply was observed during winter (Section 9.2.2).

Additionally, all respondents reported needing extra fuel during festivals and guest arrivals. At these times, LPG, despite its high cost, was used as an alternative fuel by 72% of respondents, followed by wood and other sources at 28%.

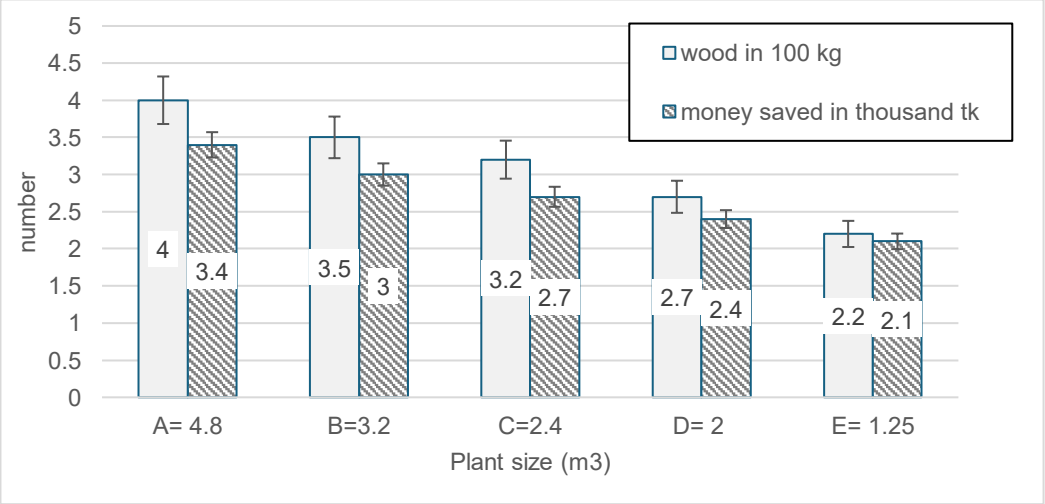


Figure 6.1: Money and wood saved after using AD plants. Error bars are standard

Based on the plant size, the monthly savings for each family ranged from 2100 TK (£21) to 3400 TK (£34) by using biogas for cooking. In other words, each family saved approximately 250 kg to 400 kg of wood every month. Figure 6.1 illustrates the ratio

of money and firewood savings per household by AD plants. A strong positive correlation was observed between plant size and money saved.

The figure above shows a clear trend indicating that as the size of the AD plant increases, both the quantity of wood saved and the amount of money saved also rise. This trend is due to the greater efficiency and increased gas production capacity of larger AD plants, which can more effectively meet the cooking fuel needs of bigger households or more intensive cooking routines.

For instance, households with the largest units, 4.8 m^3 (Group A), saved about 400 kg of wood and approximately 3,400 TK each month. On the other hand, households using the smallest plants, 1.25 m^3 (Group E), managed savings of only 220 kg of wood and 2,100 TK per month. The difference indicates a clear trend, mentioning that the larger systems provide more substantial economic and environmental benefits.

6.3.1.2 Detailed savings breakdown

- AD Plant (4.8 m^3): Households with this plant size saved approximately 400 kg of wood per month and about 3,400 TK (£34). Such figures indicate the higher efficiency and gas output of larger units, although the exact savings may vary depending on household cooking habits.
- AD Plant (2.4 m^3): This was the most common plant size among surveyed households, and the savings were still considerable—roughly 320 kg of wood and 2,700 TK (£27) each month. It appears to strike a balance: efficient enough to cut costs meaningfully, yet still manageable in scale for average households.
- AD Plant (1.25 m^3): The smallest plant sizes also provide significant savings. Households saved approximately 220 kg of wood and 2100 (£21) each month. This represents notable benefits that minimal biogas steps can provide over traditional cooking fuels.

These benefits are not only economical but also environmental, as they decrease firewood consumption, alleviating pressure on forests and resulting in reduced

carbon emissions. These contributions, although incremental at the household level, could accumulate into significant environmental improvements over time.

The shift from traditional cooking fuels to biogas affects both household economy and health significantly. In Kenya, for example, one study found that families using biogas spent considerably less on firewood and reported fewer health issues related to indoor smoke (Mwirigi et al., 2014). In India, the adoption of biogas has reduced reliance on firewood, thereby easing pressure on forests and lowering the incidence of smoke-related illnesses (Katuwal and Bohara, 2009).

In Nepal, biogas plants have served both as a source of energy and for improved waste management, while increasing crop yields through the use of bio-slurry as fertiliser (Pant, 2018). These results are similar to those in Bangladesh, where adoption has led to significant savings alongside enhanced energy security.

The link between plant size and socio-economic benefits also appears across many LMICs. In Uganda, for example, larger biogas plants were associated with greater financial savings and more reliable energy access (Walekhwa et al., 2009). This pattern seems consistent with the Bangladeshi data, where households with larger systems saved more money and used less firewood than those with smaller ones.

6.3.2 Impacts of AD on the sustainability of agriculture

The survey indicates that most respondents managed slurry by mixing it with water, while only a few chose simple disposal. Its nutrient profile appeared largely unchanged from the fresh cow dung fed into the digester. About 44% of households with AD plants, primarily those already farming or owning land, reported using it alongside farmyard manure, other bio-slurry, or even chemical fertilisers (Figure 6.2). This pattern seems to emphasise the value of bio-slurry as a nutrient-rich fertiliser, although its level of use probably varies depending on farming practices and access to land.

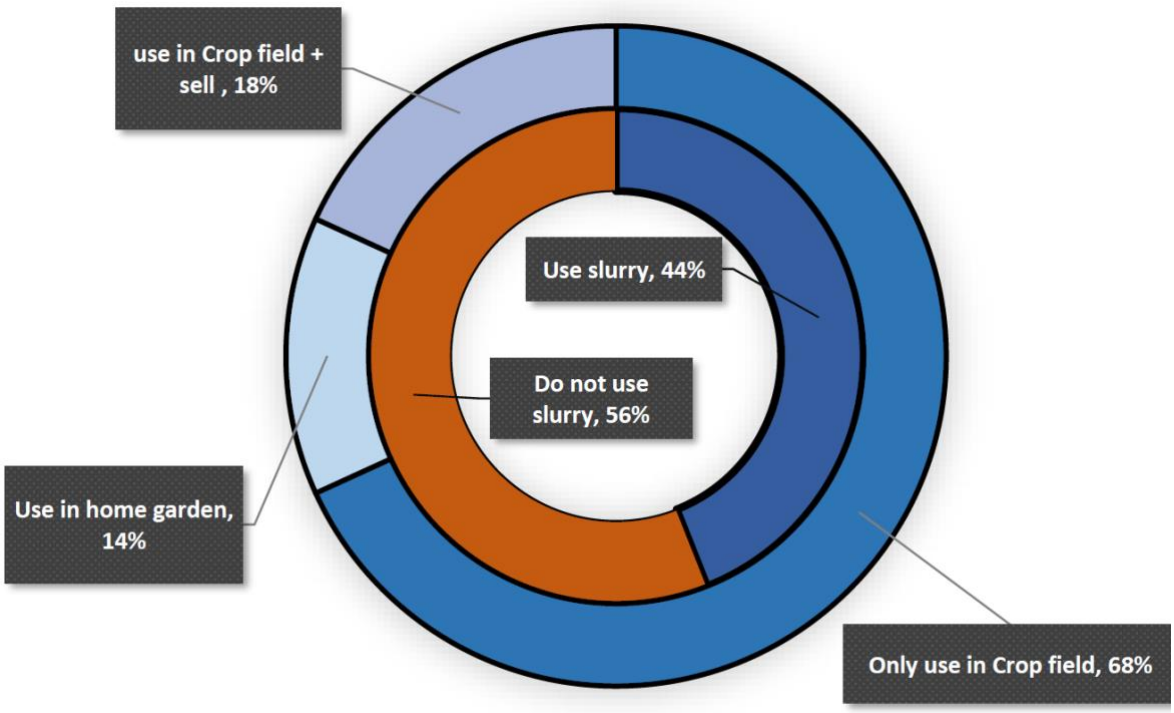


Figure 6.2: Percentages of the Use of Slurry in Agriculture (n=50)

Despite the benefits of using slurry, only 20% of farmers with sufficient land could utilise their entire slurry output. Meanwhile, the remaining 50% only used part of the slurry due to limited land. All respondents confirmed they did not sell the digestate (slurry), though two households gave it away free of charge for disposal. The study revealed that farmers (AD owners) saved between 27000 TK (£270) and 30000 TK (£300) each year by incorporating slurry into their agricultural practices.

The nutrient-rich slurry from AD processes has been highlighted in numerous studies. For instance, Möller and Müller (2012) emphasised the high nutrient content in biogas slurry, which includes nitrogen, phosphorus, and potassium, essential for plant growth. This aligns with the findings in Bangladesh, where farmers utilise these nutrients to reduce their reliance on chemical fertilisers, thereby lowering their costs.

Recent research has further supported these findings. Li et al. (2021), for instance, discussed that applying biogas slurry can enhance soil fertility and significantly increase crop yields, promoting more sustainable farming practices.

In contrast to the results in Bangladesh, where only about 20% of farmers were able to fully utilise their slurry, mainly due to land constraints. Other countries have demonstrated different adoption and utilisation patterns.

- India: Studies by Katuwal and Bohara (2009) indicate that Indian farmers often use slurry as fertiliser due to its nutrient content and the increasing cost of chemical alternatives. More recent findings by Sinha et al. (2020) show that this pattern has persisted, with greater adoption in agriculture.
- Kenya: According to Mwirigi et al. (2014), Kenyan farmers frequently use slurry to enhance soil fertility, which supports higher yields.
- Nepal: Gautam et al. (2009) reported that nearly 60% of biogas users in Nepal utilise slurry as organic fertiliser, a significantly higher usage rate than in Bangladesh.

In Bangladesh, the economic advantages of using biogas slurry are clear, with annual savings of about 27,000–30,000 TK (£270–£300) (here, £1 = 100 TK, in April 2020). For smallholder farmers in low-income settings, where agricultural inputs often make up a large part of expenses, this level of savings can be quite meaningful. In India, according to Katuwal and Bohara (2009), the use of slurry reduced fertiliser costs by up to 20% annually. A more recent study by Sharma et al. (2019) noted similar economic benefits. Farmers in Kenya reported similar advantages, with the money saved often redirected into farm reinvestment (Mwirigi et al., 2014).

6.3.3 Impacts of the production of biogas on the income of a family

This fourth section of the questionnaire specifically targeted savings. It looked at household expenditures on dung cakes, fuelwood, and liquefied petroleum gas (LPG). On average, families reported spending between £90 and £130 annually on cooking fuel. A clear majority, 88% (n=44), said they were now saving considerably, mainly because they no longer needed to buy kerosene, wood, or LPG cylinders regularly (Figure 6.3). However, a small group, 12% (n=6), mentioned they had not been able to achieve any financial savings, indicating that the benefits may not be universal.

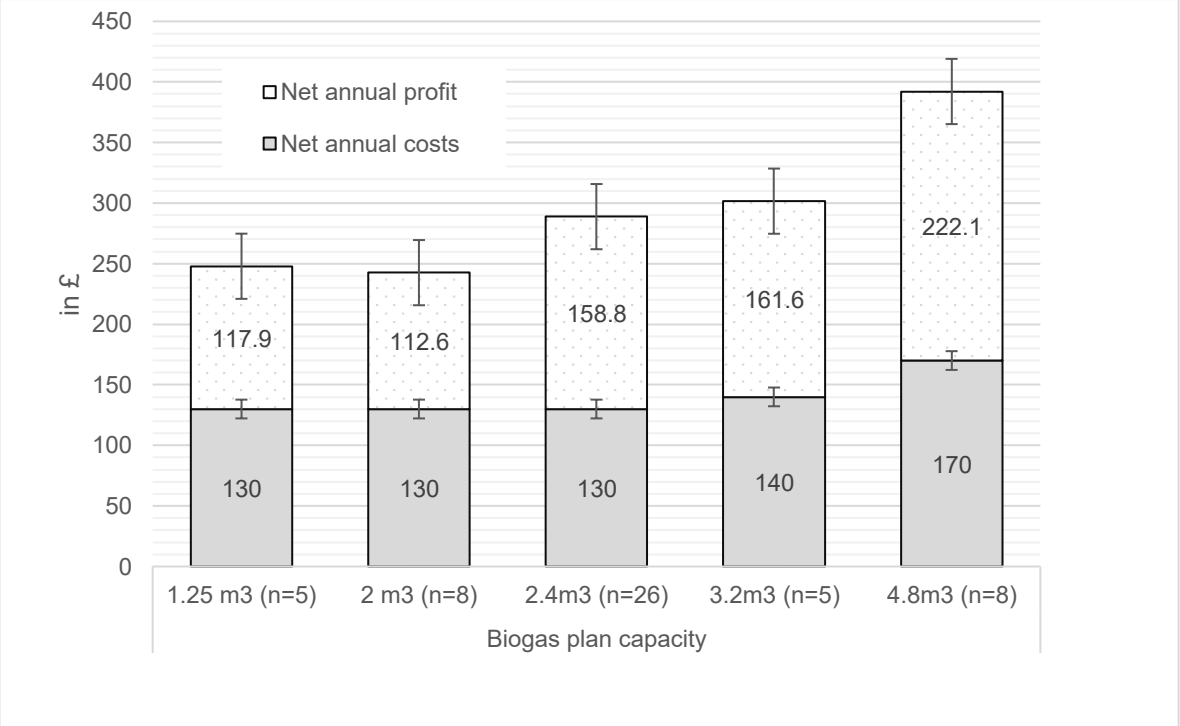


Figure 6.3: Estimating annual profit from biogas plants (£/year). Error bars are standard error bars.

The findings reveal a clear economic impact of biogas use on household fuel costs. For most families, switching to AD plants seems to have reduced daily expenses on traditional cooking fuels, indicating that these systems can ease families' financial burdens. However, a smaller group reported little or no savings, which raises questions about why the benefits are uneven. The reasons could include the efficiency of individual plants, variations in household cooking needs, or differences in local fuel prices. Investigating these factors more thoroughly could help explain the disparities and, in turn, make biogas adoption more consistently beneficial for a broader range of users.

6.3.3.1 Cooking time

A paired-samples t-test was conducted to compare cooking hours before and after AD plant installation. The following tables show Paired Samples Statistics and Paired Samples test results.

Table 6.1: A paired-samples t-test results for daily cooking time before and after AD plant installation

Paired Samples Statistics					
		Mean	N	Std. Deviation	Std. Error Mean
Pair 1	Before AD Pants : Time cooking per day (hour)	5.160	50	2.1055	.2978
	After AD Pants : time for cooking per day (hour)	3.700	50	1.5386	.2176

		Paired Differences					t	df	Sig. (2-tailed)
		Mean	Std. Deviation	Std. Error Mean	95% Confidence Interval of the Difference				
					Lower	Upper			
Pair 1	Cooking time per day (hour)	1.4600	.9082	.1284	1.2019	1.7181	11.367	49	.000

There was a significant difference in the scores of cooking hours before AD plant installation (M=5.16, SD=2.11) and after AD plant installation (M=3.7, SD=1.54); $t(49)=11.367$, $p < 0.001$. These results suggest that AD plant installation does have an impact on cooking hours. Specifically, our results indicate that after the installation of a successful AD plant, the number of cooking hours decreases.

The notable reduction in cooking time after installing the AD plant highlights the efficiency and convenience of biogas as a cooking fuel. Biogas stoves tend to burn more efficiently and provide a steady flame, helping to cut down the cooking time compared to traditional biomass stoves that often have inconsistent heat and need constant attention (Rao et al., 2020).

These findings are consistent with research conducted in various Low- and Middle-Income Countries (LMICs). For example, a study in Nepal showed that households using biogas for cooking experienced a significant reduction in cooking time, which also led to better time management for other household and economic activities (Katuwal and Bohara, 2009). Similarly, in India, the adoption of biogas technology has been found to significantly reduce cooking time, thereby giving women more time to engage in income-generating activities and childcare (Bedi et al., 2020).

A study in Kenya suggested that biogas use not only shortened cooking times but also appeared to improve indoor air quality, since biogas stoves release fewer pollutants than traditional wood-burning ones (Njenga et al., 2019). The improvement in air quality is particularly important for women and children, who often spend long hours near the cooking area. Cleaner air in such spaces can make daily life noticeably easier.

In Bangladesh, Islam et al. (2013) reported that households adopting biogas technology experienced tangible gains in efficiency, most notably faster cooking. The reduction in cooking time had positive implications. Mothers, in particular, could spend more time supporting their children's schooling—an outcome that links a kitchen technology to something as far-reaching as education.

Overall, the consistent findings across various studies highlight the multifaceted benefits of biogas technology. The decrease in cooking time is a crucial factor that not only enhances household efficiency but also contributes to improved health and economic outcomes.

6.3.3.2 Fuel cost

A paired-samples t-test was carried out to compare the fuel cost per month before and after the AD plant installation. The following tables display Paired Samples Statistics and Paired Samples test results.

Table 6.2: A paired-samples t-test results for fuel cost before and after AD plant installation

Paired Samples Statistics					
		Mean	N	Std. Deviation	Std. Error Mean
Pair 2	Before AD Pants : fuel cost per month (Tk.)	2290.00	50	1517.046	214.543
	After AD Pants : Fuel cost per-month (other than biogas)	955.00	50	1285.219	181.757

	Paired Differences				t	df	Sig. (2-tailed)
	Mean	Std. Deviation	Std. Error Mean	95% Confidence Interval of the Difference			

					Lower	Upper			
Pair 2	Fuel cost per month (Tk.)	1335.000	838.641	118.602	1096.661	1573.339	11.256	49	.000

There was a significant difference in the scores of fuel costs per month before AD plant installation (M=2290, SD=1517.05) and after AD plant installation (M=955, SD=1285.22); $t(49)=11.256$, $p < 0.001$. These results suggest that AD Plant installation significantly reduces monthly fuel costs after implementation.

The sharp reduction in monthly fuel expenses after installing the AD plant emphasises the economic potential of biogas technology. By utilising gas produced from everyday organic waste, households can reduce their dependence on fuels such as firewood, charcoal, or kerosene, which are not only costly but also often supply-inconsistent. The savings are evident and may also lead to greater financial security and a marginally better quality of life.

Evidence from other contexts indicates that this trend is supported. For example, in Nepal, one study found that families adopting biogas saved a significant portion of their household budget after they stopped purchasing traditional fuels (Katuwal and Bohara, 2009). Likewise, in India, households that switched to biogas consistently reported lower monthly energy costs, enabling families to reallocate funds to other urgent needs (Bedi et al., 2020).

In Bangladesh, Islam et al. (2013) found that installing biogas plants significantly cut household fuel expenses. The savings were often used for schooling, medical needs, or other essentials, which has improved overall well-being.

Overall, the pattern across different outcomes remains quite consistent regarding the economic advantages of biogas technology. Biogas lowers fuel costs, which is a vital factor. It boosts the economic stability of households and promotes a more efficient allocation of resources.

6.3.3.3 Fuel wood consumption

A paired-sample t-test was conducted to compare firewood consumption before and after the installation of the AD plant. The following tables display paired sample statistics and paired sample test results.

Table 6.3: A paired-samples t-test results for fuel wood consumption before and after AD plant installation

Paired Samples Statistics					
		Mean	N	Std. Deviation	Std. Error Mean
Pair 3	Before AD Pants : Fuel wood consumption kg/ month	459.17	50	394.159	56.892
	After AD Pants : Fuel wood consumption kg/ month	77.92	50	166.57	24.042

		Paired Differences					t	df	Sig. (2-tailed)
		Mean	Std. Deviation	Std. Error Mean	95% Confidence Interval of the Difference				
					Lower	Upper			
Pair 3	Fuel wood consumption kg/month	381.250	354.483	51.165	278.319	484.181	7.451	49	.000

There was a significant difference in the scores for fuel wood consumption before AD plant installation (M=459.17, SD=394.16) and after AD plant installation (M=77.92, SD=166.57); $t(49)=7.451$, $p < 0.001$. These results suggest that AD plant installation significantly reduces fuel wood consumption, with consumption decreasing following the installation.

The decline in fuelwood use after the AD plant was installed highlights the environmental benefits of biogas technology. Offering an alternative to traditional biomass, biogas helps ease pressure on forests while reducing carbon emissions. This shift also benefits households, as less smoke from wood stoves usually results in cleaner, safer indoor air.

Similar trends appear across several countries. In Kenya, for example, households using biogas have sharply reduced their fuelwood use, a shift that appears to have

eased pressure on nearby forests while also reducing indoor smoke exposure and related health risks (Njenga et al., 2019). In Nepal, the adoption of biogas has also reduced dependence on firewood, supporting both forest conservation and environmental stability (Katuwal and Bohara, 2009). India presents a comparable story: families switching to biogas use far less wood, which not only lightens the strain on forests but also frees up time for work or education, hinting at broader social and economic benefits (Bedi et al., 2020).

Findings from Bangladesh show a similar pattern. Households using biogas relied far less on firewood and other biomass fuels, a shift associated with cleaner indoor air, fewer respiratory problems, and less time spent by women and children gathering wood (Islam et al., 2013). Taken together, these studies suggest that cutting fuelwood use through biogas adoption not only supports environmental goals but also quietly improves daily life in rural communities.

6.3.3.4 Time involvement for collecting fuel wood

A paired-samples t-test was conducted to compare the hours spent on fuel collection per day before and after the installation of the AD plant. The following tables display Paired Samples Statistics and Paired Samples test results.

Table 6.4: A paired-samples t-test results for daily time spent collecting fuel wood before and after AD plant installation

Paired Samples Statistics					
		Mean	N	Std. Deviation	Std. Error Mean
Pair 5	Before AD Pants : Total time (hour) spent for fuel collection per day previously	1.090	50	1.0286	.1455
	After AD Pants : Total time (hour) spent for fuel collection per day at present	.286	50	1.0148	.1435

	Paired Differences					t	df	Sig. (2-tailed)
	Mean	Std. Deviation	Std. Error Mean	95% Confidence Interval of the Difference				
				Lower	Upper			

Pair 5	Time involvement for collecting of fuel wood (hour/day)	.63191	.59494	.08678	.45723	.80660	7.282	49	.000

There was a significant difference in the scores for the time spent collecting fuel wood before AD plant installation (M=1.09, SD=1.03) and after AD plant installation (M=0.286, SD=1.015); t(49)=7.282, p < 0.001. These results suggest that AD plant installation significantly impacts the time spent collecting fuel wood each day, with a substantial reduction in hours dedicated to this activity after the installation.

The sharp drop in time spent collecting firewood after installing AD plants shows how biogas can ease daily labour demands. In many rural households, where fuel gathering often falls to women and children, this shift seems especially meaningful. With biogas, families depend less on firewood, freeing up hours for school, income-generating work, or rest. Similar patterns have been observed elsewhere; for instance, in India, women reported spending significantly less time gathering wood after adopting biogas, a change that appears to have gradually improved both their livelihoods and household well-being (Bedi et al., 2020).

In Kenya, the introduction of biogas has noticeably reduced the time families spend collecting firewood each day. This shift appears to have made household energy use more manageable, while also improving daily life, especially for women and children, who can now utilise that time for school or much-needed rest (Njenga et al., 2019). A similar pattern appears in Nepal, where biogas adoption has eased the burden of fuel collection and opened more space for women to take part in community and economic activities (Katuwal and Bohara, 2009). Findings from Ethiopia also confirmed these results (Tucho et al., 2021).

In Bangladesh, Islam et al. (2013) found that installing biogas plants sharply reduced the time families spent collecting firewood. This change was also linked to improved health, as reduced exposure to smoke during collection and cooking appeared to lower respiratory problems. Taken together, such findings suggest that biogas brings more than just energy; it can free up time, ease household routines, and quietly improve well-being across several fronts.

6.3.4 AD construction cost and IDCOL support

In Bangladesh, the construction costs of small-scale AD plants vary depending on size and capacity. The Infrastructure Development Company Limited (IDCOL), a government-owned financial institution, actively supports the biogas sector by providing subsidies to promote the development of small-scale biogas plants, especially in rural areas. Here is an overview of the construction costs by plant size and IDCOL's subsidy structure.

6.3.4.1 Construction Costs by Plant Size

- AD Plants (1.2 m^3 - 2.5 m^3)

  Capacity: Suitable for households with 2-3 cattle, producing biogas for cooking.

  Construction cost: BDT 25,000 to BDT 40,000 (approx. $250 to $400)

  Usage: Primarily for household cooking.

- AD Plants (3 m^3 - 6 m^3)

  Capacity: Suitable for households with 4-6 cattle or small farms.

  Construction cost: BDT 45,000 to BDT 85,000 (approx. $450 to $850)

  Usage: Household cooking and small-scale electricity generation.

6.3.4.2 IDCOL subsidy structure

IDCOL offers financial incentives through subsidies and low-interest loans to promote biogas technology adoption. The subsidy scheme depends on plant size and location, with rural areas receiving greater support due to lower economic capacity.

- AD Plants (1.2 m^3 - 2.5 m^3):
  Subsidy: BDT 12,000 to BDT 15,000 (approx. $120 to $150)
  Effective cost after subsidy: BDT 13,000 to BDT 25,000 (approx. $130 to $250)
- AD Plants (3 m^3 - 6 m^3):
  Subsidy: BDT 18,000 to BDT 25,000 (approx. $180 to $250)

Effective cost after subsidy: BDT 27,000 to BDT 60,000 (approx. $270 to $600)

Alongside subsidies, IDCOL provides low-interest loans through microfinance institutions, helping farmers and rural households manage AD plant costs over time. Construction expenses vary by plant size, but these combined supports appear to make small-scale AD a more realistic and sustainable option for rural communities.

6.3.5 Cost-benefit analysis of level 1 household AD plant in Bangladesh

A meaningful economic assessment of Level 1 domestic AD requires grounding in the specific financial context of a peasant farming household in rural Bangladesh. The economic logic of the programme is that the upfront capital cost of the plant, which is beyond the immediate cash resources of most rural households, can be financed through a low-interest microfinance loan repaid over three to five years from the savings that the plant generates (IDCOL, 2020; Power Division, 2018). This savings-led repayment model, delivered through microfinance institutions with established rural networks, has been adapted into the NDBMP-IDCOL framework and remains the most appropriate financial mechanism for extending household AD to rural farming households (IDCOL, 2020; Hossain, 2020).

6.3.5.1 Capital cost and subsidy

Construction costs vary by plant size, ranging from approximately BDT 28,000 to BDT 35,000 for a standard 2 m3 plant and BDT 40,000 to BDT 55,000 for larger plants of 3 to 4.8 m3 (Rahman, 2022; Power Division, 2018). The NDBMP-IDCOL programme provides a per-plant subsidy of BDT 7,000 (approximately £65), which represents only 13 to 20 per cent of typical construction costs and has been widely criticised as insufficient (Power Division, 2018; NDBMP-IDCOL, 2013). The household finances the remainder through a low-interest microfinance loan at an interest rate of 6 to 8 per cent per year (IDCOL, 2020; Power Division, 2018).

6.3.5.1 Savings from cooking fuel

Among the 50 surveyed households, 88% reported making considerable financial savings after installation. Monthly fuel costs fell from a mean of BDT 2,290 to BDT 955, a statistically significant saving of BDT 1,335 per month ($t(49) = 11.256$, $p < 0.001$). Based on plant size, monthly savings ranged from BDT 2,100 for the smallest plants (1.25 m3) to BDT 3,400 for the largest (4.8 m3), with families also saving between 250 kg and 400 kg of firewood per month (Section 6.3.1).

6.3.5.2 Time savings

Daily firewood collection time fell from a mean of 1.09 hours to 0.29 hours per day, a statistically significant saving of 0.63 hours daily ($t(49) = 7.282$, $p < 0.001$). Daily cooking time also fell significantly from 5.16 hours to 3.70 hours per day, a saving of 1.46 hours ($t(49) = 11.367$, $p < 0.001$). In rural Bangladesh, where firewood collection falls predominantly on women and children, these time savings represent a meaningful improvement in daily life (Hossain, 2020; Quinn et al., 2018).

6.3.5.3 Bio-slurry benefit

Approximately 44% of surveyed households used bio-slurry in their agricultural practices, with farmers saving between BDT 27,000 and BDT 30,000 (£270 to £300) per year through reduced fertiliser expenditure (Section 6.3.2; Möller and Müller, 2012; Bond and Templeton, 2011). However, only 20% of farmers could utilise their entire slurry output due to limited land availability, indicating that the full potential of this benefit remains unrealised. Addressing this gap requires not only plant installation but targeted agricultural extension support to advise users on composting and bio-slurry application (Islam, 2018; Hossain, 2020).

6.3.5.4 Health cost savings

The replacement of smoky biomass fuels with biogas generates additional economic value through reduced household health expenditure. As documented in Section 9.3, statistically significant reductions in indoor air pollution, eye infections, and respiratory infections were recorded following AD adoption, translating into lower

medical costs for rural households and reduced demand on public health services (Puzzolo and Pope, 2017; Quinn et al., 2018).

6.3.5.5 Programme funding

The NDBMP-IDCOL framework operates through a blend of international development finance and domestic financial mechanisms, with the World Bank and ADB providing concessional loan finance to IDCOL, which on-lends at subsidised rates to partner organisations and ultimately to households (IDCOL, 2020; Power Division, 2018). The success of IDCOL's solar home system programme demonstrates that well-designed financial support can drive widespread rural adoption; applying similar principles to the AD sector, including expanding the role of microfinance institutions with established rural outreach and lower-cost loan products, would significantly strengthen the programme's financial reach and accessibility for the poorest farming households (IDCOL, 2020; Hossain, 2020; Power Division, 2018).

6.4 SWOT analysis: Economic pillar of PESTEL

This SWOT analysis examines the potential for sustainable growth of small-scale anaerobic digestion (AD) in Bangladesh, with a focus on the economic realities that shape its adoption and long-term prospects. AD seems promising for rural energy, turning farm and organic waste into biogas, but its success depends on navigating the country’s financial and market constraints. The analysis weighs key strengths, weaknesses, opportunities, and threats to suggest where efforts might best be directed to expand renewable energy access in rural communities.

Table 6.5: SWOT Analysis for the economic pillar of PESTEL

Catagories	Key points
Strengths	• Job creation potential: Anaerobic digestion (AD) plants open up a range of job opportunities, during construction, daily operation, maintenance, and even through supply chains and local marketing. These activities can give a real boost to rural economies, though the extent of impact often

Catagories	Key points
	depends on how well projects are managed and supported locally. • Economic valuation of the environment: AD technology appears to contribute to environmental protection by reducing deforestation and greenhouse gas emissions. It does this by offering biogas as an alternative to wood fuel, a small but meaningful shift that supports broader environmental goals. • Utilisation of agricultural waste: The agricultural sector provides a steady flow of organic residues that can be turned into biogas and nutrient-rich bio-slurry. This approach not only encourages better waste use but also seems to lessen farmers' dependence on chemical fertilisers, making the cycle a bit more sustainable.
Weaknesses	• High initial construction costs: The high upfront costs of constructing AD plants hinder adoption for rural households. • Inconsistent policy and financial support: Unstable economic policies and financial uncertainty foster an environment of insecurity, discouraging long-term investments. • Market limitations for by-products: A developing market for biogas by-products, such as digestate, hinders potential profitability, as rural communities are often unfamiliar with their application. • Wage instability: While labour costs stay relatively low, fluctuations in wages lead to financial unpredictability, affecting the economic viability of AD plant operations.
Opportunities	• Expansion of rural energy access: AD plants can deliver reliable energy in remote areas where alternative sources (LPG, natural gas) are scarce, improving the quality of life and fostering rural development.

Catagories	Key points
	• Enhanced environmental and economic resilience: AD technology offers a sustainable, decentralised energy source that supports Bangladesh's renewable energy targets and helps households save on cooking fuel costs. • Development of digestate markets: Promoting digestate as a nutrient-rich organic fertiliser can foster local agricultural markets, helping reduce dependency on chemical fertilisers and enhancing agricultural sustainability.
Threats	• Feedstock price and availability fluctuations: Seasonal changes and competing uses for agricultural residues lead to unpredictability in feedstock supply, which in turn affects AD plant productivity. • Reliance on government support: The AD sector's growth heavily depends on government policies and incentives, which can be unpredictable, affecting investor confidence and long-term viability. • Competitive market of other renewable sources: Solar and wind energy projects often attract more government and investor attention, potentially overshadowing the AD sector and limiting resources for its growth.

To maximise strengths and opportunities while addressing weaknesses and mitigating threats, Bangladesh should prioritise stable policies, workforce development, community-scale AD projects, and market development for by-products. This strategic approach would support the sustainable growth of small-scale AD plants, helping to meet renewable energy and rural development goals effectively.

Chapter 07: In-Depth Analysis of the Social Pillar of PESTEL

7.1 Introduction

The social pillar within the PESTEL framework influences the prospects of AD plants in Bangladesh. Small-scale (level 1) AD systems are not only technical installations but also community-oriented technologies; their success depends on the perception and acceptance of the engineering design (Gandhi et al., 2022; Urban et al., 2018). In Bangladesh, the adoption and long-term sustainability of AD plants are influenced by shifting social attitudes, communication strategies, and cultural sensitivities, collectively contributing to the sector's potential growth instability (NDBMP-IDCOL, 2011; Rahman et al., 2019; Zifu et al., 2013).

Some of the challenges are more about how people interact with technology than the technology itself. Limited information flow, along with ongoing social stigmas around waste management, has slowed the adoption of AD systems. Despite their environmental and economic advantages, awareness among households and local communities tends to be low. Cultural and religious views on cleanliness and waste can also, at times, act as a silent yet strong barrier to adoption (NDBMP-IDCOL, 2011; Rahman et al., 2019; Zifu et al., 2013). However, the same plants can clearly improve daily life, enhancing sanitation, reducing unpleasant odours, and providing cleaner cooking options that significantly benefit rural households. This tension, between hesitation and potential, captures much of the social challenge facing AD in Bangladesh.

This introduction to the social pillar examines both the promises and obstacles influencing the success or failure of AD plants in Bangladesh. Public perception, community involvement, and cultural norms may not always be apparent in technical reports, but they often serve as the real tipping points. By closely analysing these social dynamics, we can better understand why adoption remains inconsistent and how AD technology might be made more relevant for local communities.

7.2 Insights from expert stakeholder opinion on the social pillar of PESTEL

Stakeholders have recognised four key factors (discussed in Chapter 4) within the social pillar as essential for the sustainable growth of the AD sector in Bangladesh. The following discussion elaborates on these critical factors.

Negative and uncertain:

- S2: Information dissemination and advertising.
- S6: Social stigma (cultural and religious viewpoint).

Positive and predictable (certain):

- S4: Improvement of household welfare among the AD plant users.
- S5: Vermin and malodour reduction.

7.2.1 S2: Information dissemination and advertising

In the PESTEL review, stakeholders rated “S2: Information Dissemination and Advertising” under the social pillar as both negative and uncertain for the sustainable growth of small-scale AD in Bangladesh. That reaction appears to reflect lingering doubts about how awareness campaigns and promotional efforts are actually being carried out, often seen as inconsistent, poorly coordinated, and rarely followed through.

Generally, communication in this sector has been driven by NGOs and international development agencies (Rahman and Tasnim, 2023). These programmes aim to demonstrate to rural communities the economic and environmental benefits of AD systems, including improved waste management, reduced reliance on firewood or kerosene, and welfare improvements following the installation of the AD. However, the efforts often seem fragmented, underfunded, and lacking a clear innovative plan, which may explain why public interest and understanding remain limited.

A weak media presence aggravates the issue. Without consistent coverage on television, radio, or digital platforms, many households never receive the message. This lack of dissemination and promotion of the benefits of AD may partly explain

why the initiatives fail to progress. Despite their sincerity, they still face scepticism, as earlier studies also indicated (Kabir and Endlicher, 2011).

In Brazil, the promotion of AD systems appears more organised, with both government and private sectors playing a vital role. Awareness campaigns are often integrated into larger renewable energy initiatives, utilising television, radio, and social media to reach a broad audience. Despite this structured approach, gaps remain; achieving a consistent and widespread public understanding has been more challenging to attain (Silva, 2020).

Nigeria (LMIC) struggles with limited and fragmented efforts to share information on AD systems. Most awareness programs driven by NGOs are region-specific, which leaves large portions of the public unreachable. The absence of national coordination further weakens their reach and may explain why public knowledge remains unreliable at best (Adewuyi, 2019).

Bangladesh, however, is facing difficulties in this sector regarding sustainability. Stakeholders consider information efforts as inadequate, and the outlook for AD's future remains uncertain. The challenges are comparable to those in other LMICs, such as Brazil or Nigeria, where awareness programmes are fragmented, underfunded, and rarely integrated into a broader plan.

7.2.2 S6: Social stigma (cultural and religious viewpoint)

In the PESTEL analysis, the factor "S6: Social Stigma (Cultural and Religious Viewpoint)" under the social pillar was rated by stakeholders as both negative and uncertain for the growth of small-scale AD systems in Bangladesh. That assessment highlights significant concerns about how cultural and religious attitudes may hinder the acceptance of AD technologies.

The social stigma surrounding AD in Bangladesh is influenced by cultural and religious beliefs. Handling or processing waste, particularly human or animal excreta, is often considered impure, conflicting with longstanding cultural and religious norms. Consequently, communities tend to be cautious about adopting AD systems, even when the technology provides specific economic and environmental advantages

(Kabir and Endlicher, 2011). This persistent view of waste as shameful or unclean may help explain why uncertainty and resistance continue.

In Brazil (LMIC), social stigma around AD systems is less evident. Although there may be some cultural resistance to handling waste, the government's robust promotion of renewable energy and the economic advantages of AD systems help alleviate these concerns. Public education campaigns have successfully reduced stigma and enhanced acceptance of AD technologies (Silva, 2020).

Nigeria, by contrast, encounters challenges more similar to those in Bangladesh. Deeply ingrained cultural and religious beliefs about the impurity of waste often deter communities from adopting AD systems. Nevertheless, targeted efforts by NGOs and government bodies have been beneficial in certain areas, with education campaigns gradually reducing stigma and creating space for adoption (Adewuyi, 2019).

In Bangladesh, cultural and religious perspectives often foster a negative view of AD systems, leading to uncertainty and hindering adoption. The level of stigma resembles what is observed in other LMICs such as Brazil and Nigeria, although the extent of its impact seems to depend on the effectiveness of public education initiatives and government support.

7.2.3 S4: Improvement of household welfare among the AD plant users

In the PESTEL analysis, the factor “S4: Improvement of household welfare among AD plant users” under the social pillar was rated as positive and with a high degree of certainty. Stakeholders perceived it as a reliable contributor to the sustainable growth of small-scale AD systems in Bangladesh. This assessment likely reflects the very real ways AD can impact household welfare, especially in rural areas, from health improvements to educational gains.

In practice, AD systems make a noticeable difference in rural households. They reduce the burden of waste management, reduce reliance on firewood and other traditional fuels, and provide biogas for everyday needs such as cooking and lighting. These changes improve living conditions, support better health, and create more space for educational opportunities (Kabir and Endlicher, 2011).

Using biogas for cooking and lighting decreases indoor air pollution, a major health hazard in rural households. Clearer air inside the home seems to cause fewer respiratory problems, which can help children attend school more regularly and possibly improve their academic performance. The availability of biogas lamps also allows study hours to extend into the evening, enabling children to complete homework in an environment that genuinely promotes learning (Rahman, 2022).

AD systems, more broadly, provide a cleaner and more efficient energy source that promotes better health. Replacing smoky conventional stoves decreases instances of respiratory illnesses and eye irritation, especially among women and children, who are typically the most exposed. Simultaneously, the use of bio-slurry as fertiliser appears to enhance crop yields, which can improve household nutrition and bolster food security in rural areas (Kabir and Endlicher, 2011).

In Brazil, the use of AD systems has led to noticeable improvements in household welfare. Biogas availability reduces firewood use, which in turn slows deforestation and appears to ease indoor air pollution problems, a factor that directly impacts health. Families gain consistent educational benefits; for instance, children can study under better lighting rather than relying on dim, smoky lamps (Silva, 2020). Nigeria presents a broadly similar picture. Households benefit from cleaner air, resulting in fewer respiratory issues, and the simple fact of having biogas lighting provides children with more consistent study time. However, despite these positive outcomes, adoption of AD technology remains limited due to economic barriers and weak infrastructure, which continue to restrict wider use, suggesting that the potential benefits are still out of reach for many (Adewuyi, 2019).

Bangladesh presents a somewhat different picture. In rural communities, especially, the connection between AD systems and everyday welfare feels more immediate; indoor air quality or a simple biogas lamp can make a visible difference for both health and children’s study time. The experience generally aligns with countries such as Brazil and Nigeria, although the scale of benefits in Bangladesh seems to depend heavily on infrastructure and levels of adoption.

7.2.4 S5: Vermin and malodour reduction

In the PESTEL review, stakeholders rated the social factor “S5: Vermin and Malodour Reduction“ as both positive and fairly certain for the growth of small-scale AD systems in Bangladesh. Their judgment reflects a straightforward reality, as these systems reduce vermin problems and unpleasant smells, which in turn can ease health risks and improve daily living conditions in rural areas.

In rural Bangladesh, waste continues to be managed through open dumping or pit latrines, practices that attract pests and produce foul odours. Beyond the obvious discomfort, such conditions often promote the spread of disease. AD systems appear to offer a cleaner alternative, converting organic waste into biogas and bio-slurry while reducing vermin and odour (Kabir and Endlicher, 2011).

- Decreased disease transmission: By reducing the numbers of vermin such as rats and flies, AD systems lower the risk of illnesses they commonly spread, conditions like leptospirosis or typhoid (Rahman, 2022).
- Improved sanitation: When waste is managed through AD rather than left untreated, overall hygiene improves. This change reduces cases of diarrhoeal disease and other infections often linked to unsanitary practices (Kabir and Endlicher, 2011).
- Enhanced air quality: The reduction of malodours improves indoor and outdoor air quality, leading to better respiratory health and overall well-being for rural inhabitants (Rahman, 2022).

The positive and predictable impact of AD systems on reducing vermin and bad odours in Bangladesh highlights important health benefits for rural communities. Compared to other LMICs like Brazil and Nigeria, Bangladesh sees similar advantages, including better sanitation and lower disease spread.

7.3 Outcome of AD user survey (social point of view)

7.3.1 Status of the surrounding environment

The analysis examines the impact of time, specifically before and after AD installation, on the condition of the surrounding environment. The hypothesis tested

is H0, which claims there is no difference in the state of the environment before and after the installation of a biogas plant. The contingency table is presented as follows:

Table 7.1: McNemar-Bowker Test results for changes in surrounding environment status before and after AD Plant Installation

		Previous status of the surrounding environment				
		Good	Moderate	Bad	Unchanged	Total
Present status of the surrounding environment	Good	2	0	0	0	2
	Moderate	0	25	6	0	31
	Bad	0	3	5	0	8
	Unchanged	0	4	1	4	9
Total		2	32	12	4	50

	Value	N	df	Asymptotic Significance (2-sided)
McNemar-Bowker Test	6	50	3	0.112

Since the p-value is 0.112, which is greater than the 0.05 significance level, H_0 is not rejected. Consequently, we conclude that there is no significant difference in the status of the surrounding environment before and after the installation of a biogas plant.

The conclusion that the surrounding environment remains largely unchanged after installing a biogas plant is striking, especially when compared to experiences from other low- and middle-income countries. In Kenya, for example, some research suggests that biogas systems made a real difference within households, resulting in less smoke in kitchens and reduced dependence on firewood. However, when it came to soil health or local biodiversity, the shifts were far less noticeable (Mutune et al., 2017). India's case presents a more complex picture. Some areas reported gains, such as slowing deforestation, while others saw barely any change at all, often because waste was mismanaged or the plants were not maintained (Katuwal and Bohara, 2009).

These studies suggest that while biogas technology tends to deliver clear benefits at the household level, its wider environmental effects appear far less predictable and

often hinge on context. The scale of adoption, the surrounding ecological conditions, and even the reliability with which the systems are maintained seem to shape the outcomes in significant ways.

The statistical results support this interpretation, showing no significant environmental shifts following the installation of the plants. This finding echoes earlier mixed evidence reported in other LMICs (McNemar-Bowker Test, 2024; Mutune et al., 2017; Katuwal and Bohara, 2009).

7.3.2 Status of social environment

The analysis examines the impact of time, specifically before and after AD installation, on the status of the social environment. The hypothesis tested is H_0 , which states there is no difference in the social environment status before and after the installation of a biogas plant. The contingency table is as follows:

Table 7.2: McNemar-Bowker Test results for changes in social environment status before and after AD Plant Installation

		Previous status of social environment				
		Good	Moderate	Bad	Unchanged	Total
Present status of social environment	Good	2	0	0	0	2
	Moderate	0	25	5	0	30
	Bad	0	4	2	0	6
	Unchanged	0	6	0	6	12
Total		2	35	7	6	50

	Value	N	df	Asymptotic Significance (2-sided)
McNemar-Bowker Test	6.111	50	2	0.05

Since the p-value is equal to 0.05, H_0 is not rejected. Consequently, we conclude that there is no significant difference in the social environment status before and after the installation of a biogas plant.

This finding indicates that the installation of biogas plants did not cause any significant changes in the social environment within the study area. This contrasts

with results reported from other low- and middle-income countries. For instance, in Uganda, one study found that biogas adoption eased daily burdens by reducing the time women and children spent collecting firewood, which in turn freed up more hours for schooling and community involvement (Walekhwa et al., 2009). In Bangladesh, it is reported that biogas plants can strengthen the social system, as neighbours often cooperate in maintaining and using shared facilities (Islam et al., 2013).

More recent work points in a similar direction. In India, evidence suggests that biogas contributes to social well-being by replacing smoky fuels with cleaner alternatives, thereby reducing health risks from indoor air pollution while also giving women more time to pursue education or income-generating activities (Bedi et al., 2020). In Ethiopia, biogas has been linked to stronger community resilience, where joint projects encourage collaboration and build tighter networks of support (Tucho et al., 2021).

The lack of noticeable changes in the social environment, as shown by the current data, could be due to several factors, such as the limited scope of biogas adoption, uneven community participation, or broader socio-economic challenges that take time to change. Although biogas systems are often linked to positive social results, these effects may not be immediately visible, and in some cases, they might remain subtle for quite some time.

In this context, the findings support the idea that the social impact of biogas technology is neither consistent nor guaranteed; it seems to vary with local circumstances. The varied outcomes reported across studies imply that real benefits are likely to hinge on approaches that consider community dynamics and genuinely involve local people in the process.

From a statistical perspective, no significant changes in social conditions were observed following plant installation, a result that reflects the mixed evidence reported across other low- and middle-income countries (McNemar-Bowker Test, 2024; Walekhwa et al., 2009; Islam et al., 2013; Bedi et al., 2020; Tucho et al., 2021).

7.3.3 Time involvement for child education

A paired-sample t-test was conducted to compare time involvement for child education (hour/day). The following tables show paired samples statistics and paired samples test results.

Table 7.3: A paired samples t-test results for daily time spent on child education before and after AD plant installation

Paired Samples Statistics					
		Mean	N	Std. Deviation	Std. Error Mean
Pair 4	Previously time involved for children education (hour/day)	2.330	44	1.0283	.1550
	Currently time involved for children education	2.511	44	1.1688	.1762

		Paired Differences					t	df	Sig. (2-tailed)
		Mean	Std. Deviation	Std. Error Mean	95% Confidence Interval of the Difference				
					Lower	Upper			
Pair 4	Time involvement for child education (hour/day)	-.1818	.3902	.0588	-.3004	-.0632	-3.091	49	.003

There was a significant difference in the scores for time involvement in child education before AD plant installation (M = 2.33, SD = 1.03) and after AD plant installation (M = 2.51, SD = 1.17); t(43) = -3.091, p = 0.003. These results suggest that the installation of an AD plant significantly impacts the time spent on child education, with increased hours allocated to education after the installation.

The noticeable rise in time devoted to children's education after the installation of the AD plant may indicate wider socio-economic benefits associated with biogas use. By reducing labour-intensive tasks, such as fuelwood collection and long hours spent

over the stove, families, particularly women and children, appear to free up more time in their day for schooling and other productive activities.

Evidence from other low- and middle-income countries supports this finding. In India, for instance, a study found that biogas adoption alleviated children's household burdens, resulting in less time spent gathering fuel or handling chores, which, in turn, gave them more opportunities to focus on schoolwork, with noticeable gains in academic performance (Bedi et al., 2020).

In Kenya, biogas adoption seems to have freed up time that household chores might otherwise consume, and much of that benefit fell to girls. Since they often carry the heavier share of domestic work, the shift appears to have created space for more regular school attendance and, in some cases, improved performance in class (Njenga et al., 2019).

Nepal offers a comparable story, though with a slightly different angle. A study there noted that families using biogas spent less time on daily chores, and parents reported being able to channel some of that saved time into supporting their children's studies. The outcome was improved educational progress (Katuwal and Bohara, 2009).

Research from Ethiopia points in the same direction. Households that adopted biogas appeared to gain extra time for children to spend on schoolwork, which in turn was linked to better attendance and, in some cases, stronger academic performance (Tucho et al., 2021).

In Bangladesh, Islam et al. (2013) observed a comparable trend. Once biogas plants were in place, families spent far less time gathering firewood or managing long cooking routines. That freed-up time often ended up being redirected toward children's studies, giving them more consistent chances to focus on schoolwork and other learning activities.

Overall, these studies suggest a reasonably consistent pattern that biogas technology lightens household labour; it may also ripple outward, shaping education and, by extension, community development.

7.3.4 Time involvement for collecting fuel wood

A paired-sample t-test was conducted to compare hours spent on fuel collection per day before and after AD plant installation. The following tables show paired samples statistics and paired samples test results

Table 7.4: A paired samples t-test results for daily time spent on collecting fuel wood before and after AD plant installation

Paired Samples Statistics					
		Mean	N	Std. Deviation	Std. Error Mean
Pair 5	Before biogas plant installation Total time (hour) spent for fuel collection per day previously	1.090	50	1.0286	.1455
	After biogas plant installation Total time (hour) spent for fuel collection per day at present	.286	50	1.0148	.1435

		Paired Differences					t	df	Sig. (2-tailed)
		Mean	Std. Deviation	Std. Error Mean	95% Confidence Interval of the Difference				
					Lower	Upper			
Pair 5	Time involvement for collecting of fuel wood (hour/day)	.63191	.59494	.08678	.45723	.80660	7.282	49	.000

There was a significant difference in the scores for the time spent collecting fuel wood before AD plant installation (M=1.09, SD=1.03) and after AD plant installation (M=0.286, SD=1.015); $t(49)=7.282$, $p < 0.001$. These results suggest that AD plant installation significantly impacts the time spent collecting firewood per day, with a substantial decrease in the hours spent on this activity after the installation.

After installing the AD plant, people spent much less time collecting firewood, highlighting the labour-saving benefits of biogas. In rural villages, fuel collection is a time-consuming task, often undertaken by women and children. With biogas, the hours previously spent searching for wood can be used for schooling, earning a small

income, or simply managing household chores. This pattern is not limited to a single community. Studies in several low- and middle-income countries show similar results. In India, for instance, researchers found that biogas adoption significantly reduced the time women spent collecting fuelwood. The extra time allowed women to engage in economic activities, which in turn improved overall household welfare. (Bedi et al., 2020).

In Kenya, the shift to biogas brought similar outcomes, with households spending noticeably less time gathering firewood. That change appears to have improved the efficiency with which families manage their energy needs, and perhaps more importantly, eased the daily burden on women and children, allowing them space for schooling or even a bit of leisure (Njenga et al., 2019).

Research from Nepal points in the same direction. Biogas adoption reduced the time burden of collecting firewood. This shift proved especially meaningful for women, who could then participate more fully in community life and pursue income-earning opportunities (Katuwal and Bohara, 2009).

Research in Ethiopia points to a similar trend. Households that adopted biogas technology appeared to spend far less time gathering firewood, which in many rural areas can be a time-consuming and exhausting daily task. This shift freed up hours that were previously redirected towards schooling for children and day-to-day household work, suggesting wider social and economic benefits (Tucho et al., 2021).

In Bangladesh, Islam et al. (2013) observed that the introduction of biogas plants significantly reduced the hours families spent collecting fuelwood. The effect was not only about efficiency; it also seemed to mitigate health risks, as spending less time in smoky environments, whether while gathering wood or cooking, resulted in fewer cases of respiratory trouble.

Overall, the evidence indicates that the benefits of biogas go well beyond simple convenience. Reducing the effort involved in collecting fuelwood enhances household efficiency, promoting better health, education, and economic opportunities, although the extent of these benefits varies across different contexts.

7.3.5 Social stigma related to religious and cultural perspectives in Bangladesh and its impact on sustainable AD growth

In Bangladesh, the expansion of AD systems faces persistent setbacks due to social stigma, often rooted in cultural and religious beliefs. Much of the hesitation appears to originate from how people perceive waste, particularly when the gas derives from animal or human sources. Although the technology offers environmental, health, and economic benefits, these perceptions still hold significant influence. The opposition is especially evident in rural areas, where traditions and belief systems continue to influence daily decisions.

This research reveals key insights into how these perceptions influence potential AD users in Bangladesh, mentioning that 82% of potential AD users who own cows believe that gas for cooking from AD plants is not sacred. 78% of potential AD users believe biogas from AD plants is unhygienic and poses health risks. 68% of potential AD users believe that food cooked using biogas is not tasty. These figures underscore the powerful influence of cultural and religious norms on public perception and reveal the depth of misunderstanding surrounding AD systems. Biogas and the Concept of Sacredness (82% view it as "Not Sacred"). In a predominantly muslim country like Bangladesh, where religious values influence everyday life, the idea of sacredness plays a vital role in shaping societal attitudes. Many potential AD users, particularly those who own cows, associate the use of biogas from AD systems with impurity. The process of converting cow dung and other organic waste into fuel is perceived as conflicting with religious norms that emphasise cleanliness and purity. This perception contributes to the belief that biogas, because it is derived from waste, is not sacred and should not be used for cooking or other domestic purposes.

This belief reflects a deeper cultural hesitation to embrace technologies that involve waste management, as waste is often seen as dirty and spiritually unclean. As a result, the idea of using biogas, despite being a clean energy source, is overshadowed by the negative connotations associated with handling waste materials.

Hygiene issue: Another major obstacle is the widespread belief, shared by nearly 78% of potential users, that biogas is dirty and unhygienic. The idea seems to stem from its connection to waste, especially human and animal excreta, which many people instinctively regard as sources of disease and contamination. Many tend to assume that since biogas comes from such materials, it must carry the same dirt and disease; however, in reality, the digestion process usually breaks down waste into a much cleaner, usable form of energy.

This hesitation means many families think AD systems are not hygienic for cooking. On the contrary, they rely on those fuels for cooking, which are actually hazardous. The smoke they produce is a major driver of respiratory problems in rural Bangladesh, yet biogas, which avoids those health risks altogether, is often dismissed as unsafe.

Taste issue: Alongside concerns about hygiene and even safety, nearly 68% of potential users believe food cooked with biogas varies in taste. The assumption seems to rest on the idea that, since biogas comes from waste, it must somehow leave a trace on the flavour. In Bangladesh, cooking is not just about heat; it is bound up with identity and tradition. Fuels like wood or crop residue are used to cook that feel and taste "authentic," so the notion of burning gas made from waste understandably raises mistrust.

In reality, there is no evidence for this belief. Biogas burns with a clean, smokeless flame that leaves food unaffected. Still, deep-seated habits and a degree of mistrust toward new systems appear to reinforce the misconception, slowing down the acceptance of AD in many communities.

The social stigma related to AD systems in Bangladesh stems largely from religious and cultural attitudes, which still significantly influence public acceptance. Some people view biogas as impure, others worry it might contaminate food or dull its taste, and these perceptions make households hesitant to adopt the technology. Addressing these barriers likely depends on shifting public perception, so that the benefits of AD systems, improved health, better sanitation, and cleaner energy, are acknowledged without being overshadowed by cultural or religious reservations.

7.4 SWOT analysis for the social pillar of PESTEL

The social pillar of the PESTEL framework plays a critical role in determining the success or failure of AD systems in Bangladesh. Social factors, including public perception, cultural beliefs, and community engagement, significantly influence the adoption and sustainability of AD technology. While AD systems offer substantial benefits in terms of improved household welfare, better sanitation, and reduced reliance on traditional fuels, they face challenges related to social stigma and limited public awareness. A SWOT analysis provides a structured overview of these social dynamics, highlighting the strengths, weaknesses, opportunities, and threats that will help to shape the growth of potential AD systems in Bangladesh.

Table 7.5: SWOT Analysis: Social pillar of PESTEL

Category	Key points
Strengths	• Improvement in household welfare (S4): AD systems can bring noticeable benefits to rural households, ensuring better management of waste, less dependence on firewood or kerosene, and cleaner options for cooking. These shifts are often linked with healthier living conditions and, in some cases, improved opportunities for women and children. • Reduction of vermin and melodour (S5): AD systems tend to make waste management more manageable, which in turn reduces foul smells and the pests they usually attract. The outcome, at least in many rural settings, appears to be cleaner surroundings and healthier day-to-day living. • Potential for public health improvement: AD systems promote cleaner energy and improved waste management, which may contribute to better public health, particularly by reducing the risks associated with poor sanitation and polluted air.
Weaknesses	• Ineffective information dissemination and advertising (S2): Information campaigns around AD systems are often patchy

Category	Key points
	and inconsistent, leaving many people only vaguely aware of their benefits. The absence of clear, coordinated messaging seems to limit adoption, especially in rural areas where understanding of renewable energy options is already thin. NGOs and international agencies do attempt to bridge this gap, but their projects tend to be underfunded, and as a result, community interest rarely builds momentum. • Deep-rooted social stigma (S6): Cultural and religious attitudes toward waste remain a strong obstacle. For many, the very idea of handling animal or human waste carries a sense of impurity, which makes biogas from AD systems appear suspect. Some believe it to be unsafe, while others simply view it as unclean and unhygienic. Even food prepared with biogas has a stigma of being less tasty, which naturally slows acceptance, despite the clear environmental and health advantages.
Opportunities	• Public awareness: A respected religious leader or a long-trusted community organiser, who is a local figure, can slowly influence cultural and religious attitudes and motivate people for the benefit of biogas, resulting in the sector's growth. • Social and education campaigns: Schools, social media feeds, and radio announcements remain relevant for campaigning the benefits of AD locally. • Leveraging success stories: Word of mouth still travels faster than most policy briefs. When one village can point to an AD project that reduces foul odours, eases sanitation work, or saves money, the story itself becomes persuasive. • Social advocacy and incentive programs: Recognition has its own currency. A plaque at a community center, a small grant, or even a shout-out at a public event may encourage early adopters. Once one community receives praise for

Category	Key points
	embracing AD systems, neighbouring areas often feel an unspoken challenge to match or outdo them. That sense of pride or competition can quietly drive broader adoption. • Improvement in educational outcomes: Time is perhaps the most underrated benefit. In families where children no longer spend hours gathering fuel, those same hours often shift to schoolwork or rest. Over the long term, this extra time can translate into better academic performance and, gradually, stronger economic opportunities for those households. It's not guaranteed, of course, but the pattern shows up often enough to suggest real potential.
Threats	• Persistent cultural resistance: Deeply ingrained cultural and religious beliefs about cleanliness, purity, and waste management pose ongoing challenges. Overcoming these long-held stigmas will require consistent and culturally sensitive efforts. • Lack of social cohesion in information dissemination: The fragmented nature of information campaigns has led to inconsistent messaging about the benefits of AD systems. Without a unified strategy for public engagement and education, local communities may continue to resist adoption due to misinformation or a lack of clarity. This issue is further complicated by the absence of strong, coordinated efforts from central authorities or national initiatives to collectively address social barriers. • Influence of traditional practices: In many communities, traditional fuels such as wood, dung, and biomass are not only culturally accepted but are also perceived as more natural and reliable than biogas. These long-established practices are challenging to displace, as they are deeply rooted in the cultural identity of rural households. AD

Category	Key points
	systems, perceived as a break from tradition, face strong resistance from those who value these traditional methods of cooking and fuel usage. • Community distrust of new technologies: In rural Bangladesh, there is often a general scepticism toward new technologies, especially those introduced by outside organisations or government bodies. The lack of trust in such innovations, coupled with limited success stories from within the community, makes it difficult to convince people to adopt AD systems. This distrust is compounded when local leaders or influencers do not endorse the technology, further dampening its acceptance.

Chapter 08:Insights from the Technological Pillar of PESTEL

8.1 Introduction

The sustainability of Level 1 AD plants in Bangladesh largely hinges on technology, which determines both efficiency and scalability. While AD is often viewed as a means to address waste and energy issues simultaneously, whether it can truly achieve both goals sustainably remains uncertain (Iqbal et al., 2014; Khan and Martin, 2016; Sarker et al., 2020).

Bangladesh presents both opportunities and hurdles in the technological landscape for AD expansion. On one side, advances in biogas extraction, updated digester designs, and alternative feedstock processing methods appear likely to raise efficiency and production capacity. Such progress could strengthen AD systems' ability to generate renewable energy, curb greenhouse gas emissions, and manage organic waste more effectively (Dhar et al., 2017; Mengistu et al., 2015; Obileke et al., 2021; Zoo et al., 2008).

Still, a number of technological hurdles persist. Weak infrastructure, limited availability of modern equipment, and patchy research and development (R&D), along with continued use of older biogas extraction methods, appear to hold back the broader uptake of AD systems (Khan and Martin, 2016; Sarker et al., 2020). At the same time, the Bangladesh government has invested more attention and resources into other renewables, especially solar, which makes the future growth of AD feel somewhat uncertain (IDCOL,2020).

Dealing with these technological hurdles seems necessary if the AD sector in Bangladesh is to grow sustainably. That probably means trying out new approaches, improving access to modern technologies, and making sure the right infrastructure is in place to keep biogas systems functioning. If these gaps can be addressed, AD may well take on a stronger role in the country's renewable energy and environmental goals, which will lead to economic growth.

8.2 Insights from expert stakeholder opinion on the technological pillar of PESTEL

For the technological pillar, stakeholders consider 4 key factors to be high significance for AD growth in Bangladesh, and stakeholders consider all 4 key factors are high Negative and uncertain. Key factors are:

Negative and uncertain

- T6: Alternative source of highly efficient renewable energy (such as solar energy).
- T1: Planning and installation issues for the biogas plant in Bangladesh.
- T5: New technology and research.
- T3: Biogas extraction technology available in Bangladesh.

8.2.1 T6: Alternative source of highly efficient renewable energy (such as solar energy)

Under the PESTEL study, stakeholders in the framework for the sustainable development of small-scale anaerobic digestion (AD) systems in Bangladesh evaluated the key factor "T6: Alternative Source of Highly Efficient Renewable Energy (such as Solar Energy)" within the Technological pillar as negative and uncertainly.

This suggests that the development of the AD sector suffers from the present concentration on solar energy. Furthermore, stakeholders view this factor as uncertain because the introduction of advanced and highly efficient AD technology in Bangladesh could potentially help mitigate these negative effects. The most widely used and affordable renewable energy source accessible in Bangladesh is solar (Obaideen et al., 2023; Uddin et al., 2019). Solar technology has developed dramatically; initial solar cells from the 1800s were less than one percent effective, so they were not extensively employed (Obaideen et al., 2023; Panwar et al., 2011). Originally developed by Bell Labs in 1954, the first practical silicon solar panel had about a six per cent efficiency. Modern cell designs have lately allowed researchers to reach up to 47.1 percent efficiencies. Better efficiency and manufacturing processes have helped solar panel installations drop dramatically from $8.50 per watt

in 2009 to $2.77 per watt over the past ten years (Matasci, 2022;Obaideen et al., 2023). This fast technology transfer between countries has greatly affected the adoption of solar energy globally.

By contrast, the history of AD technology begins in 1859 with the first digestion plant constructed in Bombay, India, at a leper colony. Arriving in England in 1895, AD technology made use of biogas collected from a sewage treatment plant to run street lamps in Exeter, UK. Important developments in microbiology throughout the 1930s improved knowledge of and optimisation for anaerobic bacteria used in methane generation enhance AD system. Bangladesh Agricultural University first brought AD technologies to Bangladesh in 1972 (Khan and Martin, 2016; SREDA, 2020). Modernised AD plants have not yet been brought into local homes in Bangladesh despite their advances. Viewed as a negative and uncertain element, stakeholders believe that, with proper introduction, modern AD technology could grow in appeal.

Both solar and AD technologies are encouraged in Brazil (LMIC); but, solar energy gets greater focus because of its better efficiency and less running expenses. The Brazilian government has launched several incentive schemes to encourage the acceptance of solar energy, therefore driving notable expansion in this industry. Notwithstanding this emphasis, AD systems, especially in the agricultural sector, have value due to their waste management capacity and biogas generation capabilities (Silva, 2020). With a heavy focus on solar energy because of its efficiency and high sun irradiation, Nigeria (LMIC) has issues much like those of Bangladesh. To address power shortages, particularly in rural regions, the Nigerian government has invested heavily in solar energy systems. AD technology, by contrast, has received less support and is often considered as less efficient than solar energy system, which may explain why its development continues to lag behind (Adewuyi, 2019; Khan and Martin, 2016; SREDA, 2020).

The emphasis on solar energy as a very efficient renewable energy source in Bangladesh has generated questions regarding the evolution and encouragement for AD systems. Although solar energy has significant advantages and is fast becoming popular, it is crucial to understand how complementary anaerobic digestion technology is in energy generation and waste management. Other LMICs such as Brazil and Nigeria give solar power top priority, however, they nevertheless support

AD systems in some level (Adewuyi, 2019; Khan and Martin, 2016; Silva, 2020; SREDA, 2020).

8.2.2 T1: Planning and installation issues for the biogas plant in Bangladesh

Stakeholders in this study, aiming to address the sustainable development of small-scale anaerobic digestion (AD) systems or biogas plants in Bangladesh, assessed the key factor "T1: Planning and Installation Issues for the Biogas Plant in Bangladesh" within the Technological pillar as negative and uncertain in the PESTEL study. These negative and uncertain results indicate major challenges and unpredictability towards the planning and installation phases of biogas plants, which hinder their widespread adoption and effective implementation.

Bangladesh's biogas plant planning and installation experiences several difficulties:

- Technical expertise: A Lack of staff with technical knowledge who can design, construct, and properly maintain biogas plants appears to undermine performance, often leading to systems that break down more frequently than expected (Kabir and Endlicher, 2011; Khan and Martin, 2016).
- Infrastructure: Weak infrastructure, poor road networks and limited access to essential equipment and materials which makes the installation of plants even more challenging (Rahman, 2022; SREDA, 2020).
- Obstacles in regulation: Complex and unevenly applied regulations make the process of obtaining licenses and permits unnecessarily difficult, leaving many stakeholders uncertain and frustrated (Kabir and Endlicher, 2011; Zaman et al., 2017).

In Brazil, the rollout of biogas plants benefits from stronger infrastructure and a degree of government backing. Even so, familiar obstacles remain, high upfront costs and regulatory bottlenecks continue to pose problems. On the technical side, Brazil has made notable progress in training specialists, which seems to ease some of the difficulties around planning and installation (Silva, 2020).

Nigeria, by contrast, faces challenges that look much closer to Bangladesh’s reality. Lack of technical expertise, vulnerable infrastructure, and complicated regulations all heavily disrupt biogas development. The government has introduced policies aimed

at easing regulatory pressures and offering incentives, but progress so far appears to have been slow and uneven (Adewuyi, 2019; Aliyu et al., 2015).

By contrast, the negative and uncertain picture for Bangladesh points to real barriers that stand in the way of small-scale AD systems gaining ground. The challenges resemble those in other LMICs such as Brazil and Nigeria, yet Bangladesh seems to lack the level of support and infrastructure needed to push through them.

8.2.3 T5: New technology and research

Within a PESTEL framework, the “Technological” pillar often decides whether a system can grow or decline. In this study, stakeholders repeatedly point to “T5: New Technology and Research” as a decisive factor for sustainable AD growth in Bangladesh. But, rather than seeing it as a clear opportunity, they describe it as uncertain and, in many respects, negative in Bangladesh. That hesitation may reflect deeper anxieties about how technology actually plays out on the real world. Scepticism stems from inadequate research and development support, weak infrastructure, high costs, and maintenance challenges, which make new technology seem risky for small operators and investors (Bhuiyan et al., 2022).

By contrast, Nepal's (LMIC), biogas initiatives benefited from government incentives and outside partnerships. With that extra push, more advanced systems found their way into rural areas, improving efficiency and keeping the projects afloat in the long run (Kandel et al., 2019). Of course, whether Bangladesh could replicate that path is less certain; what works in one national context doesn’t always transfer neatly to another.

Nepal, a low- and middle-income country (LMIC), has presented a slightly more encouraging prospect through its government incentives and external cooperation in research and development. Improved biogas setups have taken root, especially in rural areas, and these appear to have boosted both efficiency and long-term sustainability (Kandel et al., 2019).

Vietnam’s story looks different again. The country has placed a noticeable emphasis on integrating renewable energy into its farming sector, and this focus appears to have translated into stronger R&D investments in AD. Public–private partnerships

have also played a role, not only pushing technical improvements forward but also shaping how ordinary people perceive them (Le et al., 2021).

On the other hand, Nigeria faces hurdles that bear an uncomfortably familiar resemblance to those in Bangladesh. Underfunded research and development, vulnerable infrastructure, and the added weight of political instability all contribute to a cautious, sometimes outright negative, stakeholder outlook. While international aid and local training programs have stopped at the barriers, progress still feels slow and uneven (Oni et al., 2020).

The new technology proposed in the Bangladesh guidelines emphasises low-cost, locally adaptable solutions designed to enhance the efficiency and sustainability of small-scale AD systems (Power Division, 2018). These technologies focus on improving feedstock preprocessing, enhancing biogas yield through microbial inoculants, and developing robust, easy-to-maintain digester designs. While these innovations have the potential to address some of the existing challenges, their successful implementation requires strong policy support, financial incentives, and continuous stakeholder engagement (Hossain, 2020).

Various upgrading technologies have been developed worldwide to improve the sustainability and efficiency of anaerobic digestion systems. These technologies have quite different operational systems, benefits and drawbacks, and future promise.

1. Advanced pre-treatment methods: Thermal hydrolysis and ultrasonic pretreatment have been extensively embraced to improve the digestibility of feedstocks, thereby boosting biogas output (Nizami et al., 2017). Although they frequently require large energy inputs and effort, these techniques can more effectively break down complex organic materials.

2. Microbial inoculants: Using certain microbial cultures may speed up the digestion process and raise biogas generation. Although this biotechnological method is suitable for several feedstocks and various environmental conditions, it relies on precise management to maintain microbial health and activity (Angelidaki et al., 2018).

3. Improved digester designs: To get more out of anaerobic digestion, engineers have been experimenting with newer setups such as plug-flow and Continuous Stirred Tank Reactor (CSTR) systems. These approaches generally help by maintaining a steady temperature and ensuring better mixing. That said, adopting them is not always straightforward, their installation and operation can turn out to be both costly and technically demanding (Ward et al., 2008).

4. Biogas upgrading technologies: Techniques like pressure swing adsorption, water scrubbing, and membrane separation are being used to strip out unwanted gases, mainly carbon dioxide and hydrogen sulfide. The result is a cleaner stream of biogas with higher methane content (Ryckebosch et al., 2011). Whether that upgraded gas is suitable for running vehicles or feeding directly into the natural gas grid largely depends on the success of these methods.

In Bangladesh, the government has signalled its interest in advancing the AD sector, supporting locally manufactured glass-fibre digesters through the IDCOL financing program. The plan, at least on paper, spans from 2016 to 2035, with a broader rollout envisioned for the 2021–2035 period (Power Division, 2016). However, despite the ambition, progress appears to have stalled in Bangladesh, with no concrete steps taken so far. Stakeholders often point to a familiar stumbling block: the lack of dedicated funding for AD research.

8.2.4 T3 : Biogas extraction technology in Bangladesh

In the PESTEL analysis, the key factor "T3: Biogas Extraction Technology Available in Bangladesh" within the Technological pillar was assessed as having a negative impact and uncertainty among stakeholders regarding the sustainable growth of small-scale anaerobic digestion (AD) systems or biogas plants in Bangladesh. This assessment reflects significant concerns about the current state of biogas extraction technology, which is perceived as inadequate and unpredictable, thus hindering the effective implementation and scalability of biogas projects.

In Bangladesh, biogas extraction technology carries a reputation for being unreliable, and several issues seem to explain why.

- Outdated technology: Much of the system still relies on older designs, which tends to drag down efficiency and limit performance (Kabir and Endlicher, 2011; Khan and Martin, 2016).
- Shortage of modern equipment: Plants often lack the machinery required for proper extraction and purification. The result is higher operating costs and gas that is not as clean or consistent as it should be (Rahman, 2022).
- Insufficient R&D support: Investment in research and development remains limited. Without stronger backing, improvements in design or technique appear unlikely to materialise any time soon (Khan and Martin, 2016).

Biogas extraction technology is more advanced in Brazil than in Bangladesh. The progress in Brazil in the adoption of modern purification methods for produced gas is supported by government incentives and a steady flow of private investment. Techniques such as membrane filtration and pressure swing adsorption (PSA) are now fairly common, improving both the purity and efficiency of the gas (Silva, 2020).

Nigeria (LMIC) presents a different scenario, similar to Bangladesh's, marked by many of the same hurdles. That said, there have been recent attempts to shift course through targeted investments and international partnerships aimed at transferring expertise. Even so, adoption of advanced purification technologies remains slower than the urgency of the problem requires (Adewuyi, 2019).

Advanced techniques for extracting and purifying biogas seem to play an important role in improving both its efficiency and quality. Among the commonly used methods are:

- Water scrubbing: Here, carbon dioxide (CO_2) and other impurities are absorbed by water, which leaves the gas richer in methane (Ryckebosch et al., 2011).
- Chemical absorption: To provide high-purity biogas, this process, which often relies on amines, selectively captures CO_2 and produces biogas of notably high purity (Petersson and Wellinger, 2009; Ryckebosch et al., 2011).

- Membrane filtration: By passing the gas through selective membranes, methane can be separated from CO_2 and other components, reaching high levels of purification (Bauer et al., 2013).
- Pressure swing adsorption (PSA): This method makes use of shifting pressure conditions to sort gases by their molecular properties, which typically ensures a high concentration of methane (Ryckebosch et al., 2011).
- Cryogenic separation: Perhaps the most technically demanding, it involves cooling biogas to very low temperatures so that methane can be separated from other gases according to their boiling points (Petersson and Wellinger, 2009).

The negative and uncertain outlook for biogas extraction technology in Bangladesh points to serious obstacles for the growth of small-scale AD systems. In countries like Brazil and Nigeria, similar struggles with problems appear, but Bangladesh seems to lag further behind, especially in terms of institutional backing and infrastructure.

8.3 Outcome of AD user survey (technological point of view)

8.3.1 Operation and maintenance of the biogas plant

The survey of 50 active level 1 AD plants in Bangladesh offered a mixed picture of how these systems are actually working on the ground. About 62% of the plants seemed to be running smoothly, at least according to user reports. Still, 38% of respondents pointed to ongoing operational issues. That number may not sound overwhelming, but it does hint at a pattern of problems that can not be brushed aside. The findings suggest that if biogas technology is going to hold its ground as a sustainable option, stronger support systems and troubleshooting mechanisms will likely be needed.

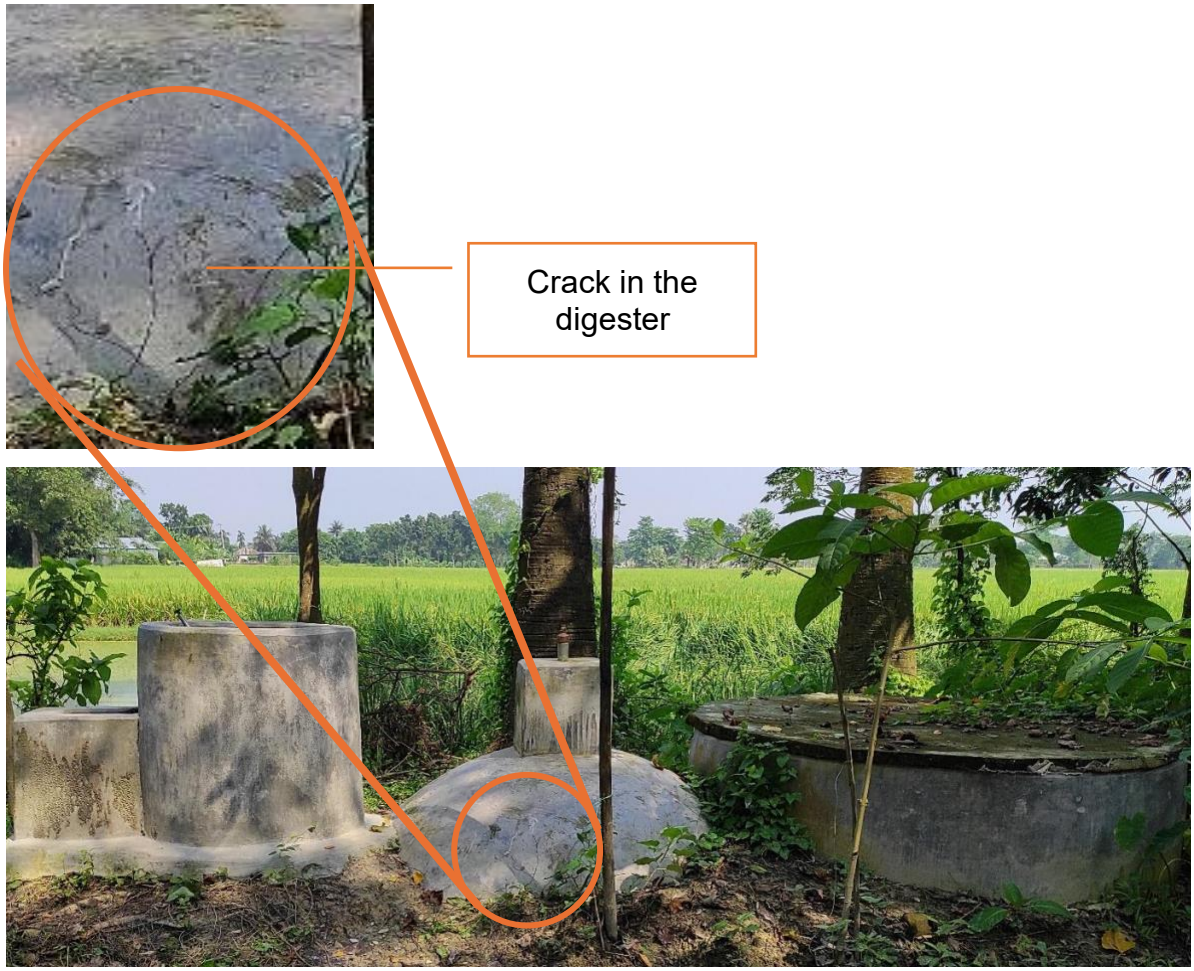


Figure 8.1: An example of a failed AD plant (due to a construction fault, after 1 month).

Key operational problems

1. Slurry entry into gas pipes

Nearly half of the respondents (46%) pointed to slurry entering the gas pipes as a recurring problem. When this occurs, the flow of biogas becomes obstructed, which can significantly reduce the overall efficiency of the system. It is the kind of issue that not only slows things down but can also throw the performance of a plant off balance. Similar situations have been reported elsewhere. Take Tanzania, for instance: Mwirigi et al. (2014) observed that slurry blockages were not only common but also one of the main reasons biogas plants there struggled with reliability and consistent output.

2. Poor maintenance services

About 26% of respondents pointed to poor after-sales support as a serious obstacle in running their biogas plants smoothly. Without proper maintenance services, minor problems can drag on, leading not only to longer downtime but also to growing frustration for users. This finding seems to align with work done in Nepal, where Gautam and colleagues (2009) pointed out that the lack of technical support and proper maintenance often held back the smooth running of biogas plants.

3. Clogged pipes

Clogged pipes often came up as a reason for plant failures. While routine cleaning and upkeep could usually prevent the problem, many users did not have the training or sometimes even the basic tools, to manage it properly. A study from India by Katuwal and Bohara (2009) made a similar point, noting that poor maintenance habits frequently caused breakdowns and underlining the importance of stronger user training and support.

4. Risk of plant failure

About 60% of respondents said they were worried their plants might fail within a year because of poor maintenance (Figure 8.1). That figure alone suggests a pressing need for more dependable support systems and easier access to spare parts. A similar pattern shows up elsewhere. In Uganda, for example, Balasubramanya et al. (2020) observed that the long-term survival of biogas plants seemed to hinge largely on whether maintenance services and spare parts were actually available.

5. Gendered operation responsibilities

In most cases, it was women (mainly housewives) who handled the daily running of the plants, from loading raw materials to mixing water. They made up roughly 76% of those directly involved in operations. This pattern highlights the central, though often underacknowledged, role women play in sustaining these systems. Comparable dynamics appear elsewhere. In Kenya, for instance, Walekhwa et al. (2009) noted that women were typically the main operators of household biogas plants. Findings like these suggest that training

programs might be more effective if they take gender roles into account and are designed with women, the primary users, in mind.

The difficulties in running and maintaining biogas plants are hardly limited to Bangladesh; they have been noted across many low- and middle-income countries. In Kenya, for example, Vögeli et al. (2014) reported frequent pipe blockages and a lack of reliable maintenance services, both of which significantly reduced the effectiveness of plant operation. These kinds of recurring problems may suggest that what is really missing is consistent technical support across similar contexts.

India shows a comparable story. Rajendran et al. (2019) stressed that without regular maintenance and steady technical backing, the sustainability of biogas plants becomes shaky at best. Their findings—that training and easy access to repair services are central to long-term performance echo what is been seen in Bangladesh, where weak maintenance structures appear to keep undermining day-to-day operations.

Balasubramanya et al. (2020), studying Uganda, noted that the long-term viability of biogas plants often depends less on grand design and more on small, everyday details, such as consistent maintenance and having spare parts nearby. Bangladesh appears to face much the same challenge. When upkeep is irregular and technical support is thin, systems tend to falter. It may not be a surprising pattern, but it does underline a stubborn barrier that has slowed the wider adoption of biogas technology and made its reliability more fragile than advocates might wish.

8.3.2 Plant size and seasonal variation impact on cooking hour

We perform two-way ANOVA (Analysis of Variance) (with replicates), a statistical method for analysing the effect of two independent variables (plant size and season) on a dependent (cooking hour) variable. It is also known as two-factor ANOVA because it involves two independent variables (factor or group variables). Descriptions of model parameters or variables are given below.

Table 8.1: Descriptions of model parameters or variables

Parameter	Description
Cooking Hour (y)	Dependent variable (should be continuous/ numerical variable)
Plant Size (x1)	First independent variable (should be categorical variable)
Season (x2)	Second independent variable (should be categorical variable)
Plant Size: Season (x1:x2)	Interaction between two independent variables

Descriptive statistics (mean and standard deviation) for each plant size and season are shown below:

Table 8.2: Descriptive Statistics for each plant size and different seasons

Season	Plant Size	No of Observations	Mean	Standard Deviation
Rainy	1.25	5	1.98	0.110
	2	5	2.86	0.114
	2.4	5	2.9	0.100
	3.2	5	3.42	0.205
	4.8	5	5.32	0.356
Summer	1.25	5	2.2	0.100
	2	5	3.1	0.122
	2.4	5	3.38	0.148
	3.2	5	3.74	0.241
	4.8	5	5.94	0.313
Winter	1.25	5	1.58	0.277
	2	5	2.04	0.055
	2.4	5	2.46	0.114
	3.2	5	2.82	0.192
	4.8	5	4.42	0.164

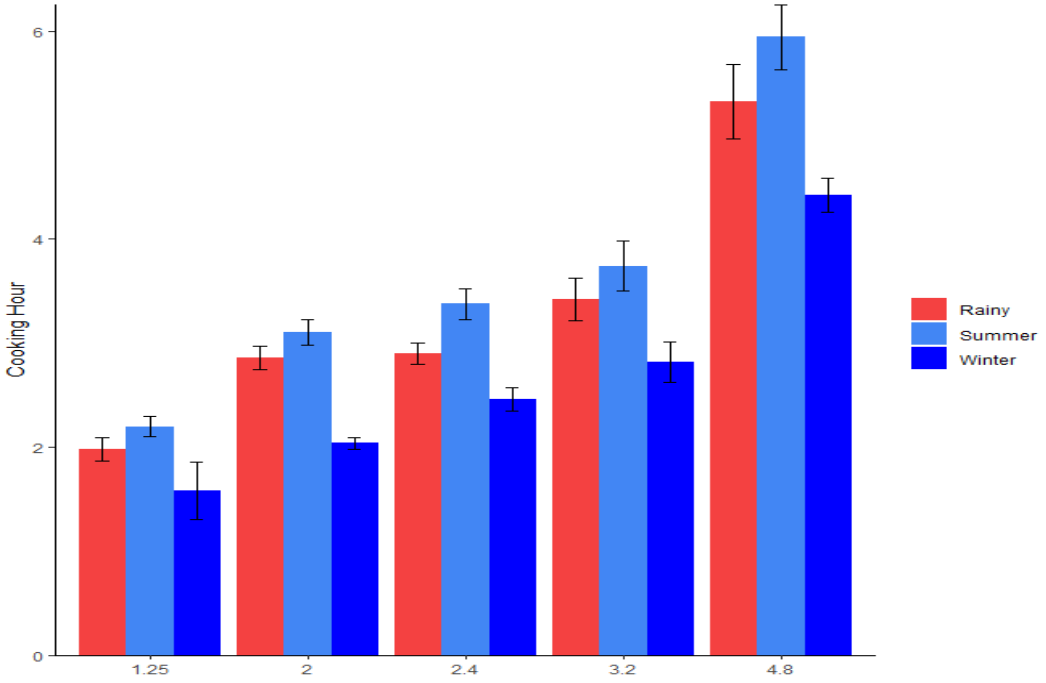


Figure 8.2: Graphical representation of mean and standard deviation for each plant size and different seasonsß

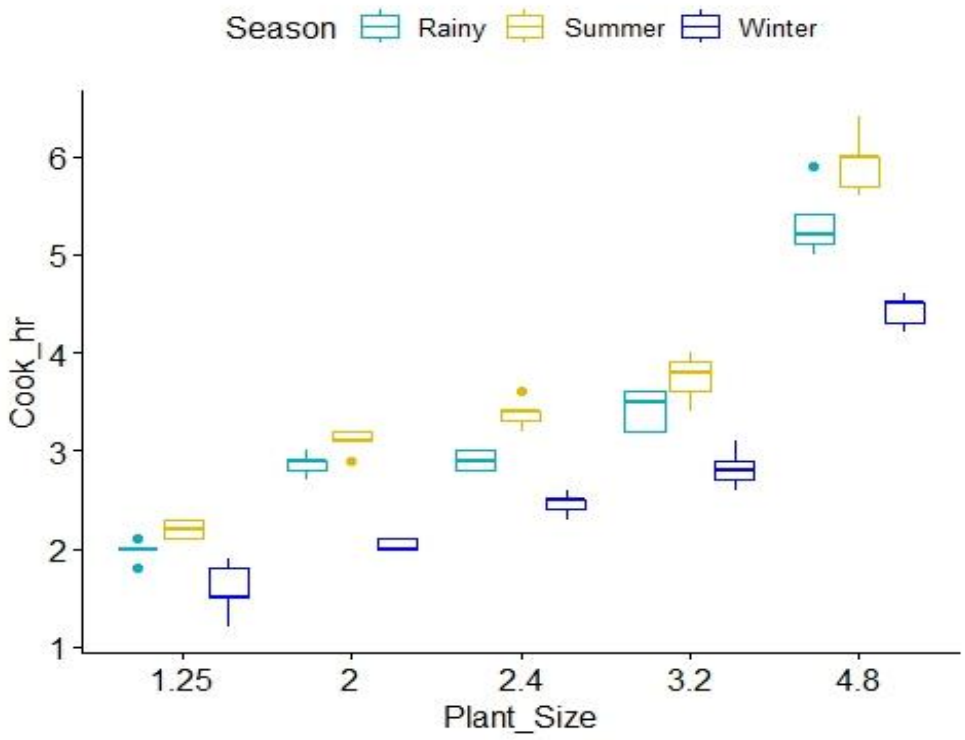


Figure 8.3: Boxplot for cooking hour in each plant size and season

The box plot and descriptive statistics show that cooking hours significantly differ by plant size and season. We performed a two-way ANOVA (several equal observations per cell) to check whether these differences in cooking hours are statistically significant and if there is a significant interaction effect between plant size and season.

For this, we want to test the following null hypotheses:

H_{01}: The cooking hour is equal among plant sizes, i.e. the mean of cooking hours for all plant sizes are equal

H_{02}: The cooking hour is equivalent at a different season, i.e. the mean of a cooking hour for every season is equal

H_{03}: There is no significant effect of plant size and season on the cooking hour of the plants, i.e. there is no significant interaction effect

Here, the alternative hypothesis is two-sided as the plant size can be lesser or greater for individual independent variables or for their interaction.

Checking The Assumption of Two-way Analysis of Variance (ANOVA)

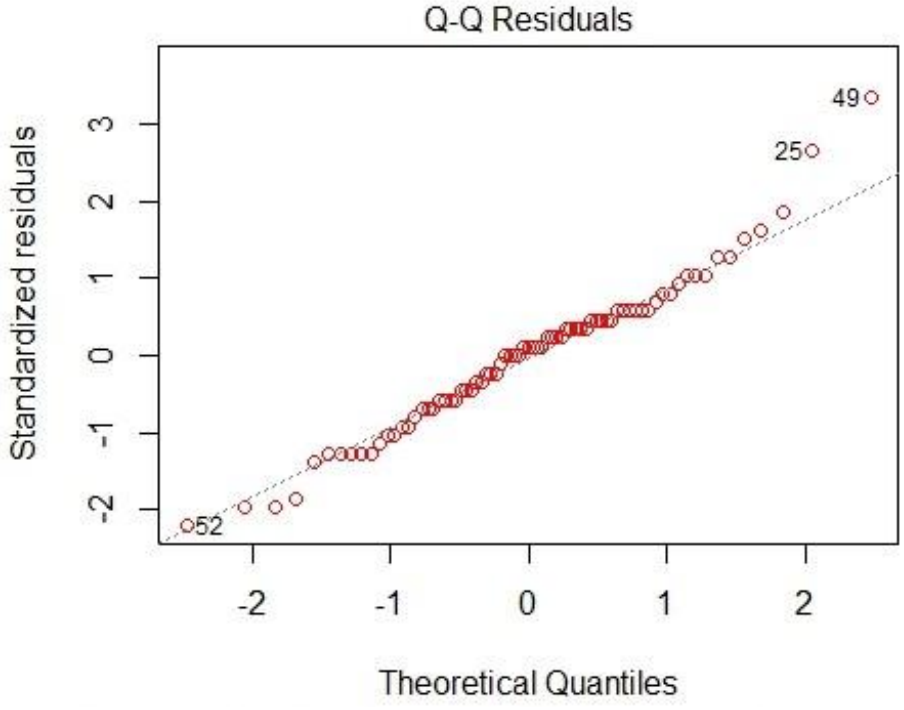


Figure 8.4: Normal Probability Plot

The idea behind a Q-Q plot is simple. If the residuals fall along a roughly straight line at a 45-degree angle, then the residuals are roughly normally distributed. The above Q-Q plot shows that the residuals lie mainly along the 45-degree straight line, with some minor deviations along each tail. Based on this plot, we could safely assume that this data set is normally distributed.

The Q-Q plot is an informal test of normality that can give us some insight into the deviation from normality. Another widely used formal test of normality is the Shapiro-wilk test. This produces a coefficient *W* with a value of 1 corresponding to perfect normality (no deviation from the theoretical distribution) and lower values representing the deviations from normality.

Shapiro Wilks Normality Test

H_0: The sample data are normally distributed.

H_1: The sample data are not normally distributed.

The test statistics

$$W = \frac{\left(\sum_{i=1}^{n} a_i x_{(i)}\right)^2}{\sum_{i=1}^{n}(x_i - \bar{x})^2}$$

By using R software, we get

W = 0.97446, p-value = 0.1335

Here p-value= 0.1335 is greater than level of significance α=0.05, so we fail to reject the null hypothesis of normality. That means the dataset are normally distributed. We can check the homogeneity of the variances by using Levene's test.

Levene's Test for Equality of Variances

H_0: $\sigma_1^2 = \sigma_2^2 = \ ... \ = \sigma_t^2$

H_1: Not all of the variances are equal.

	DF	F-value	Pr(>F)
Group	14	1.0988	0.3775
	60		

From the above table we can see that the p-value (0.3775) is greater than the level of significance (α=0.05), so we fail to reject the null hypothesis of homogeneity. That means the variances among all groups are equal.

As the assumptions are fulfilled, we can conduct the two-way ANOVA with several equal observations per cell. The outcome of ANOVA is given below:

Table 8.3 : ANOVA Table

	df	SS	MS	F-value	Pr(>F)
Plant Size	4	91.92	22.980	611.158	< 2e-16 ***
Season	2	12.97	6.487	172.525	< 2e-16 ***
Plant Size * Season	8	1.24	0.155	4.134	0.000558 ***
Error	60	2.26	4.134		
Total	74	108.391			

From the above ANOVA-Table, it is seen that the p-values are less than 0.001 (level of significance) [$F(4,60) = 611.158$, $p < 0.001$] So, we can reject the null hypothesis (H_{01}) and conclude that cooking hour among each plant size is significantly different.

Similarly, the p-value is significant [$F(2, 60) = 172.525$, $p < 0.001$] for the season. Hence, we reject the null hypothesis (H_{02}) and conclude that seasons significantly affect cooking hours. The interaction between plant size and season is also significant [$F(8, 60) = 4.134$, $p < 0.001$]. Hence, we reject the null hypothesis (H_{03}), concluding that plant size and season significantly influence cooking hours.

Multiple Comparison Tests

If the hypothesis is rejected by F-test, we need to test the significance of the hypothesis. Several tests are available to test the significance of the hypothesis, such as Student's t-test, Student-Newman-Keuls test, Duncan's multiple range test, Dunnett's test, and Tukey's test. These are called multiple comparison tests.

We can conduct the Tukey HSD test to compare the pairwise means of cooking hours for every season. The stated null hypotheses are:

H_{01}: There is no difference between the mean of cooking hours in summer and rainy seasons.

H_{02}: There is no difference between the mean cooking hours in winter and rainy seasons.

H_{03}: There is no difference between the mean of cooking hours in the winter and summer seasons.

Table 8.4: Pairwise comparison test (season)

Season	Mean Difference	Lower limit	Upper limit	p-value
Summer-Rainy	0.376	0.244195	0.507805	<0.001
Winter-Rainy	-0.632	-0.763805	-0.500195	<0.001
Winter-Summer	-1.008	-1.139805	-0.876195	<0.001

From the above table, we can say that all the p-values are less than 0.001 (level of significance), so we can reject the null hypothesis. Thus, the mean cooking hours for different seasons are significantly different.

We can conduct the Tukey HSD test to compare the pairwise means of cooking hours for each plant size. The stated null hypotheses are:

H0: There is no difference between the mean of cooking hours among each plant size.

Table 8.5: Pairwise comparison test (plant sizes)

Plant Size (m^3)	Mean Difference	Lower limit	Upper limit	P-Value
2-1.25	0.7466667	0.54753077	0.9458026	<0.001
2.4-1.25	0.9933333	0.79419744	1.1924692	<0.001
3.2-1.25	1.4066667	1.20753077	1.6058026	<0.001
4.8-1.25	3.3066667	3.10753077	3.5058026	<0.001
2.4-2	0.2466667	0.04753077	0.4458026	0.00797
3.2-2	0.6600000	0.46086410	0.8591359	<0.001
4.8-2	2.5600000	2.36086410	2.7591359	<0.001
3.2-2.4	0.4133333	0.21419744	0.6124692	<0.001
4.8-2.4	2.3133333	2.11419744	2.5124692	<0.001
4.8-3.2	1.9000000	1.70086410	2.0991359	<0.001

From the above table, we can say that all the p-values are less than 0.05(level of significance), so we can reject the null hypothesis. Thus, the mean cooking hours for all plant sizes are significantly different. We can also show the differences among cooking hour for season, plant size and the interaction among season and plant size in graphically. If the 95% confidence interval contains zero then we know that the differences in group means is not statistically significant.

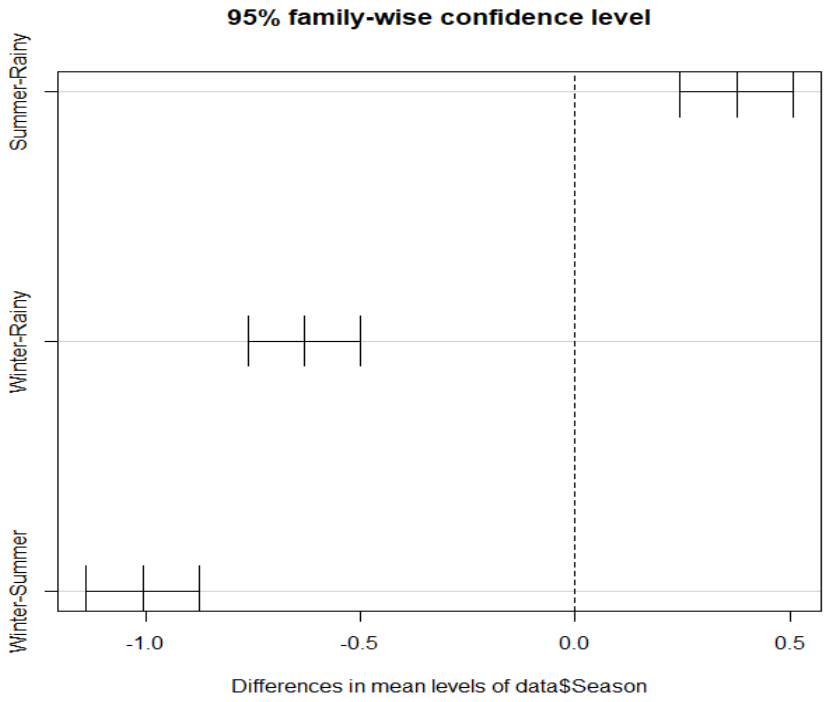


Figure 8.5: The differences of cooking hours for different seasons.

From Figure 8.5 and Figure 8.6 we can see that the 95% confidence interval does not contain zero, so we can say that the differences in the mean of cooking hour for various seasons and plant sizes are statistically significant.

From Figure 8.7 we can see that few numbers of 95% confidence interval for the interaction between seasons and plant sizes contains zero, these are not statistically significant. Most of the interaction effect between plant size and seasons have statistically significant differences for cooking hour.

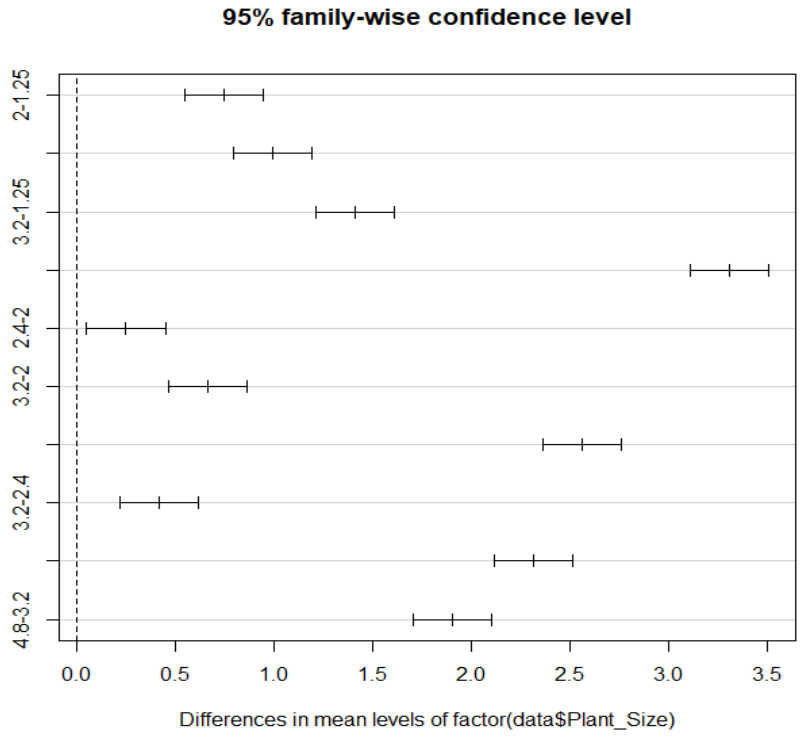


Figure 8.6: The differences among cooking hours for various size of plants

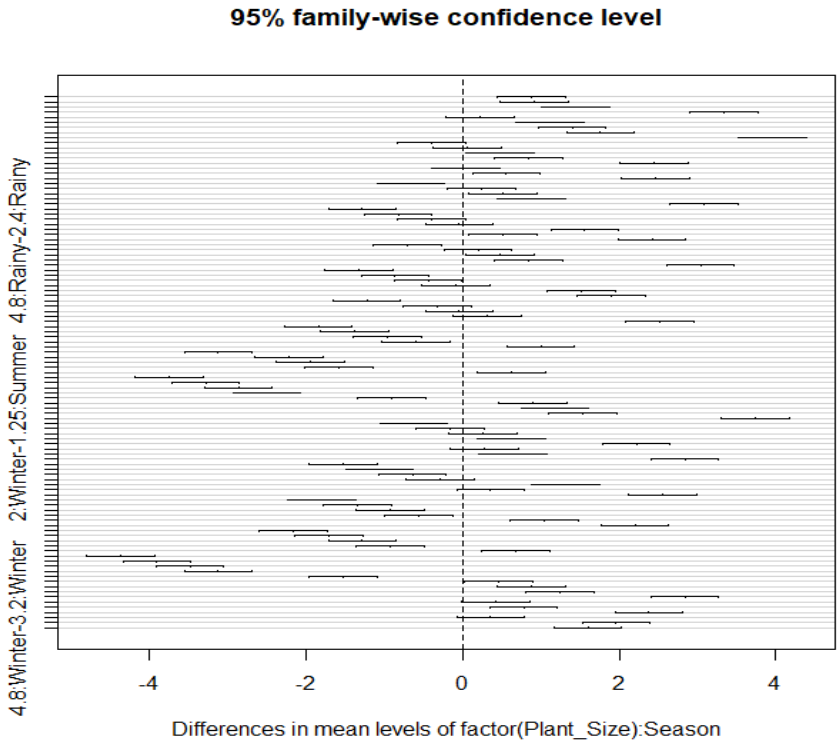


Figure 8.7: The differences among plant sizes for the interaction of various plant sizes and seasons.

Based on the results of ANOVA, we can conclude that cooking hour is significantly influenced by the size of the AD plant and the different seasons.

The seasonal variation observed here seems tied to several overlapping factors, temperature shifts, feedstock availability, and the behavior of microbes inside the digesters.

- Temperature effects: Biogas output tends to rise and fall with temperature. In winter, microbial activity slows down, which naturally reduces gas production, thus shortening cooking hours. Studies from Nepal and India indicate a similar trend: low winter temperatures can significantly reduce biogas yields (Gautam et al., 2009; Katuwal and Bohara, 2009).
- Feedstock availability: Seasonal access to raw materials also matters. During the rainy season, more organic waste, cow dung, poultry litter, and similar inputs is usually on hand, which supports higher production. In contrast, dry months often bring water shortages, making the feedstock harder to use effectively and limiting gas generation (Walekhwa et al., 2009).
- Microbial activity: The performance of an anaerobic digestion system ultimately depends on microbial performance, which also relies on both temperature and the quality of the feedstock. Microbes thrive within specific temperature ranges; once conditions drift outside this range, the digestion process along with gas yield, can suffer noticeably (Mwirigi et al., 2014).

The findings from this section of research (Bangladesh) seem to echo what has been reported in other low- and middle-income countries:

- Kenya: Studies suggest that biogas production there rises and falls with the seasons. When the weather turns cooler, output decreases, and households often have to rely on alternative energy sources (Mwirigi et al., 2014).
- India: Research points to a similar pattern. Temperature shifts and the availability of feedstock both appear to influence plant efficiency, and the winter months, in particular, tend to disrupt a steady biogas supply, thereby reducing cooking time (Katuwal and Bohara, 2009).
- Nepal: Work from Nepal also underscores these seasonal effects. Plants generally run less efficiently in colder conditions, which has pushed

researchers to explore practical ways to reduce the impact (Gautam et al., 2009).

8.4 SWOT analysis of the technological pillar of PESTEL

The technological dimension appears central to the sustainable growth of AD in Bangladesh. Although the sector shows potential in tackling both energy and waste issues, several persistent obstacles remain, aging equipment, limited research capacity, fragile infrastructure, and temperature-related inefficiencies that make operations less reliable than expected.Against this backdrop, the SWOT analysis below outlines the strengths, weaknesses, opportunities, and threats shaping the technological future of AD in Bangladesh.

Table 8.6: SWOT Analysis: Technological pillar of PESTEL

Category	Key Points
Strengths	• Potential for waste management: AD systems offer a dual solution by addressing both waste management and renewable energy needs. • Government interest: The government has shown a willingness to support AD through policies and potential local manufacturing of biogas equipment.
Weaknesses	• Outdated technology: Much of the current biogas extraction technology in Bangladesh is outdated, leading to low efficiency and high operational costs. • Insufficient R&D: Limited investments in research and development hamper innovation, affecting the introduction of modern AD technologies. • Lack of technical expertise: A shortage of trained professionals in the installation, operation, and maintenance of AD systems hinders technology adoption.

Category	Key Points
	• Poor infrastructure: Inadequate infrastructure for transporting equipment and materials complicates the setup of AD plants, particularly in rural areas.
Opportunities	• Introduction of modern technologies: Integrating advanced technologies like membrane filtration, microbial inoculants, and improved digester designs can enhance AD efficiency. • Local manufacturing and partnerships: Opportunities to establish partnerships with international technology providers and promote local manufacturing of biogas equipment to reduce costs. • Potential for integration with waste management systems: AD systems can play a major role in managing agricultural, municipal, and industrial waste. • Government support for renewable energy: The potential to secure financial incentives, subsidies, and favourable regulations to encourage the growth of AD technology. • Temperature control mechanisms: Introducing insulation, solar heating, and thermal jackets in AD systems can mitigate the impact of cold temperatures on biogas production during winter.
Threats	• Competition from solar energy: Solar energy is currently more popular and receives greater attention and investment, creating uncertainties for AD growth.

Category	Key Points
	• Uncertainty in technology adoption: Stakeholders view the introduction of new AD technologies as risky and uncertain, which can slow the pace of adoption. • Seasonal variations in biogas production: Cold temperatures during winter months reduce microbial activity, lowering biogas production efficiency, impacting system reliability.

This SWOT analysis provides a clear overview of the technological factors influencing the sustainable growth of AD systems in Bangladesh.

Chapter 09: In-Depth Analysis of the Environmental Pillar of PESTEL

9.1 Introduction

The environmental aspect of the PESTEL framework is often considered the pivotal factor in determining whether Level 1 AD can expand in Bangladesh (Hasan et al., 2020; Iqbal et al., 2014). The country is already facing numerous challenges, including greenhouse gas emissions continuing to rise, waste accumulating in an uncontrolled manner, smoky kitchens resulting from indoor cooking, and a constant struggle to maintain clean water supplies (BPDB, 2019; MoPEM, 2017; Quinn et al., 2018). To address these interconnected problems, AD represents a practically viable and environmentally beneficial solution (Elizabeth Funmi et al., 2021; Sharma et al., 2019). Turning organic residues into biogas and bio-slurry not only reduces pressure on the environment but also moves the energy and farming sectors toward cleaner practices (Panwar et al., 2011; UNEP, 2021).

Bangladesh's rural and agricultural landscape generates enormous volumes of organic material every single day (Siddiki et al., 2021; Rahman et al., 2018). If unmanaged, this material leaks methane, fouls the air, and seeps into rivers and ponds (Elizabeth Funmi et al., 2021; Paolini et al., 2018). The accumulation of vegetable waste, animal dung, and household organic material in uncontrolled settings is a common scenario that creates environmental burdens rather than solutions (Islam, 2018; Alam and Qiao, 2020). The AD system converts this equation, producing cooking fuel on one side and organic fertiliser for farming on the other (Bond and Templeton, 2011; Svensson et al., 2004). For a country striving to achieve the Sustainable Development Goals, particularly those related to clean energy (SDG 7), climate action (SDG 13), and resource management (SDG 15), AD can play a significant role in addressing these challenges (Power Division, 2016; UNEP, 2021).

Stakeholders in this study identified the environmental effects of AD technology as a positive and predictable factor for sustainable sector growth. Factors such as reduced greenhouse gas emissions, improved indoor air quality, better organic material handling, and the availability of water for plant operations were cited as the primary reasons AD is expected to grow sustainably in Bangladesh (Hasan et al., 2020; Sarker et al., 2020). The potential of capturing methane, reducing fossil fuel use, and producing organic fertiliser aligns with national objectives and SDG targets (UNEP, 2021; Power Division, 2018; Karim et al., 2019).

Bangladesh's tropical climate, with its steady warmth and humidity, is particularly well suited for anaerobic digestion, as AD plants can operate without the additional expense of artificial temperature control (Hossain, 2020; Sarker et al., 2020). The country also has water resources that, for the present, appear sufficient to sustain the microbial processes required for stable digestion (NDBMP-IDCOL, 2013). Taken together, these environmental conditions provide a favourable setting for the growth of the AD sector, as confirmed by the consistently positive seasonal performance of plants operating in rural Bangladesh outside the winter months (IDCOL, 2020).

Indoor air pollution remains a serious problem in rural Bangladesh. Traditional cooking over firewood or other biomass fuels produces smoke and fine particles that are particularly harmful to women and children, who spend the most time near the cooking fire (Puzzolo and Pope, 2017; Quinn et al., 2018). The survey findings reported in Section 9.3 of this thesis confirm that shifting to biogas from AD systems produces statistically significant reductions in indoor air pollution, eye infections due to smoke, and respiratory infections, offering households a cleaner cooking environment and the possibility of improved health outcomes (Section 9.3; Zaman et al., 2019).

By leveraging AD technology and aligning it with clear policies, steady investment, and functional infrastructure, Bangladesh can enhance its environmental sustainability while contributing to global climate efforts (UNEP, 2021; Power Division, 2018). The appeal lies in the tangible benefits: cutting emissions, producing usable by-products, and fitting well with local environmental conditions (Panwar et al., 2011; Sharma et al., 2019). With a substantial organic resource base already in place and a climate that supports the digestion process, the sector has a promising foundation (Siddiki et al., 2021; Hossain, 2020; Sarker et al., 2020). Whether AD becomes a cornerstone of Bangladesh's renewable energy strategy will depend less on these inherent advantages and more on how consistently and effectively they are acted upon through policy, finance, and institutional commitment (Hasan et al., 2020; IDCOL, 2020; Rahman et al., 2019).

9.2 Insights from expert stakeholder opinion on the environmental pillar of PESTEL

For the Environmental pillar of the PESTEL analysis, stakeholders consider five key factors that are highly significant for AD growth in Bangladesh. According to the stakeholders' estimation, the key factors are assessed as high, Positive, and predictable (certain) for the sustainable growth of the AD sector in Bangladesh. The classifications of these Key factors are as follows,

Positive and predictable (certain)

- **En1:** GHG emissions (SDG agenda).
- **En4:** Climatic conditions of Bangladesh.
- **En3:** Indoor air pollution.
- **En2:** Waste management.
- **En5:** Access to adequate water for the biogas plant.

9.2.1 En1: Reduction of GHG emissions

In the PESTEL analysis, the factor "En1: GHG Emissions" under the Environmental pillar was rated by stakeholders as both positive and certain in relation to the sustainable growth of small-scale AD systems in Bangladesh. This categorical position suggests strong evidence that AD can play a significant role in reducing greenhouse gas emissions. This goal is closely tied to the broader Sustainable Development Agenda. However, the certainty expressed here may overlook the practical challenges of implementation, which are often less predictable than the assessment suggests.

AD systems play a vital role in reducing GHG emissions by converting organic waste into biogas. Instead of disposal in open areas and releasing methane during decomposition, the AD process captures it, which may already make a significant difference. Simultaneously, using biogas as a substitute for fossil fuels seems to further decrease CO_2 emissions. In Bangladesh, the application of AD technology is likely to help lower overall emissions through several interconnected pathways as follows:

1. Methane capture and utilisation

   During the anaerobic decomposition process, organic waste naturally produces methane, a gas that is much more harmful to the climate than CO_2, with a warming potential approximately 86 times greater over a century (UNEP, 2019). AD systems capture this methane as biogas for energy, rather than allowing it to escape into the air (Kabir and Endlicher, 2011).
2. Renewable energy production

   Biogas can be used in daily life, including for cooking, heating, and powering small generators. Every time biogas replaces firewood, kerosene, or electricity generated from fossil fuels, it leads to fewer CO_2 emissions (Rahman and Melville, 2023).
3. Organic fertiliser production

   The leftover material, bio-slurry, is an organic fertiliser. Farmers can spread it on their fields to enhance soil health while reducing their dependence on chemical fertilisers. Applying the bio-slurry may also lower nitrous oxide emissions from agriculture, another highly potent greenhouse gas (Khan et al., 2016).

In Brazil, a lower-middle-income country, AD has been employing a method that genuinely appears to reduce greenhouse gas emissions. Large agricultural projects capture methane from livestock manure and convert it into biogas, an approach that not only reduces methane leaks but also supports renewable energy objectives (Santos et al., 2018; Silva et al., 2022).

Advanced AD technologies could help Bangladesh cut more greenhouse gas emissions. Hybrid systems combining AD with solar or wind, improved digester designs, and enhanced methane recovery methods show promise, but their success in local conditions may depend on steady financial and technical support (Hossain, 2020; Karmaker et al., 2020; Wasi et al., 2023)

The positive and predictable stance for reducing GHG emissions through AD systems in Bangladesh highlights the environmental promise of this approach. When set beside other lower-middle-income countries, such as Brazil, Bangladesh holds

comparable potential, though that potential hinges on whether infrastructure and institutional backing can actually be developed.

9.2.2 En4: Climatic condition of Bangladesh

In the PESTEL framework, stakeholders described the factor “En4: Climatic Condition of Bangladesh” as generally positive and predictable. That choice of words may suggest an assurance, though “predictable” might be considered, given that the local weather can change at any time.

The tropical climate of Bangladesh, characterised by consistent heat and humidity, creates a natural environment conducive to anaerobic digestion. Microbial activity in digesters tends to rise or fall with temperature, so in theory, the warmth should make the process more efficient. Basic climatic conditions that are impactful for the AD growth are described as follows:

- Optimal temperature range: Mesophilic conditions (temperatures of 30 °C and 40 °C) are ideal for growing the bacteria responsible for methane production. Mesophilic bacteria, which are commonly used in anaerobic digestion, have an optimal temperature range of 30 °C to 40 °C (Hassan et al., 2020; Singh et al., 2018). Bangladesh’s average temperature falls within this window for much of the year, which appears to promote steady biogas production (Hassan et al., 2020; Sabbir et al., 2021). That said, calling it “optimal” may be a stretch, since short-lived heat waves or local fluctuations can easily nudge microbial behaviour in less predictable directions.
- Year-round warmth: The Consistent climate of Bangladesh is another specific factor for the growth of the AD sector. In contrast to colder regions, where AD systems often depend heavily on heating, Bangladesh’s relatively warm baseline temperature allows operators to run without additional energy inputs. That can reduce costs and make daily management a bit easier (Iqbal et al., 2020; Khan et al., 2016). Still, describing the climate as “consistent” may be unpredictable during monsoon months or the dryness of peak summer, both of which can throw systems off balance.
- High availability of organic waste: Agricultural residues such as rice straw, manure, and other byproducts are readily available from agricultural practices (Rahman et al.,

2022). In warm conditions, decomposition usually speeds up, and with it, gas yields tend to rise (Hassan et al., 2020). The warm climate accelerates the decomposition of this organic matter, enhancing biogas production.

Brazil, a lower-middle-income country, has a tropical climate that generally facilitates success in AD systems. The steady warmth tends to keep microbial activity going throughout the year, which is similar to Bangladesh. Still, places with sharper seasonal fluctuations may need to take extra measures to maintain stable digester temperatures (Silva et al., 2022). Nigeria offers a similar condition with consistent warm weather. This climatic condition typically supports dependable biogas production, although local conditions can sometimes compromise that reliability (Adeleke et al., 2023).

Assessments of Bangladesh's climate for AD look far more favourable. The steady warmth seems almost tailor-made for anaerobic digestion, with biogas production holding up well across the year. In many ways, the situation resembles that of Brazil or Nigeria, where consistently warm weather also helps.

9.2.3 En3: Indoor air pollution

Within the PESTEL framework, the factor "En3: Reduction of Indoor Air Pollution" under the Environmental pillar was perceived by stakeholders as both positive and relatively certain in supporting the growth of small-scale AD systems in Bangladesh. Their assessment indicates a strong belief that biogas plants could alleviate the burden of indoor air pollution, a problem closely linked to health, particularly for women and children in rural households.

The problem itself is difficult to overlook. In many villages, cooking still relies on fuels such as firewood, crop residues, or dried dung. Used in basic stoves, these fuels emit smoke filled with fine particles, carbon monoxide, and other harmful compounds. The health risks are well established, and it is mainly women and children, who spend the most time near the hearth, that face the greatest exposure (Adeleke et al., 2023; Yasar et al., 2017). However, cleaner cooking fuel lowers certain health risks. Biogas from an AD system generally burns more cleanly than wood or crop residues and releases far fewer harmful emissions.

- Reduction of particulate matter: When burned, biogas produces almost no particulate matter compared with firewood or other biomass fuels. This significant reduction in particulate matter enhances indoor air quality and decreases the occurrence of respiratory illnesses (Cocârţă et al., 2021; Lohani et al., 2021; Rahman and Kabir, 2023).
- Lower carbon monoxide (CO) emissions: Using biogas generally reduces CO emissions, a key contributor to acute respiratory infections and health problems. Women and children, who are most exposed to indoor smoke, seem to benefit the most from this cleaner method of combustion (Iqbal et al., 2020; Khan et al., 2016).
- Reduced volatile organic compounds: Burning biogas also produces fewer volatile organic compounds. This reduction may promote a healthier indoor environment and appears likely to decrease the risk of long-term conditions such as cancer and heart disease (Rahman et al., 2022; Smith et al., 2014).

In Brazil, a lower-middle-income country, adopting AD systems in rural areas has significantly reduced indoor air pollution. Biogas used for cooking appears to improve household air quality, with women and children, who are most exposed to kitchen smoke, gaining the greatest benefits (Silva, 2020; Gomes et al., 2018). Nigeria, also classified as an LMIC, faces similar challenges due to heavy reliance on traditional biomass fuels. Small biogas projects seem to offer a cleaner alternative, and early evidence indicates improved indoor air quality and health benefits (Adeleke et al., 2023; Iqbal et al., 2020; Khan et al., 2016).

AD systems provide several advantages for lowering indoor air pollution as follows:

- Health improvements: Evidence indicates significant reductions in respiratory and cardiovascular issues, especially among women and children.
- Environmental sustainability: The cleaner combustion of biogas seems to reduce emissions and foster a healthier living environment.
- Economic benefits: Better health frequently results in reduced medical expenses and, in some instances, higher productivity.

In Bangladesh, evaluations of AD systems have consistently shown positive outcomes in lowering indoor air pollution. The technology offers a cleaner alternative

to traditional biomass fuels, which can greatly benefit rural households, particularly women and children who spend more time near cooking fires.

Compared to other LMICs such as Brazil and Nigeria, Bangladesh appears to face similar opportunities for health improvements through AD.

9.2.4 En2: Waste management

Stakeholders reviewed the key factor “En2: Waste Management” in the PESTEL analysis under the Environmental pillar, finding it both positive and fairly certain regarding the growth of small-scale AD systems in Bangladesh. That assessment of predictability suggests some certainty that AD could improve local waste management, particularly in rural areas where poor disposal practices are still prevalent.

In rural Bangladesh, poor waste management harms both health and the environment. Anaerobic digestion offers a practical alternative by turning organic waste into biogas and biofertiliser, reducing pollution and dependence on chemical fertilisers. While the environmental gains may vary, the benefits appear most noticeable where formal waste services are lacking (Iqbal et al., 2020; Katuwal and Bohara, 2009; Lackner and Besharati, 2025; Lyng et al., 2020).

In Brazil, a lower-middle-income country, AD systems are quite common in rural areas, where they are used to manage agricultural waste while also producing biogas. The results seem promising, with less waste accumulating and, in many cases, a reliable source of household energy. Government policies and subsidies appear to play a significant role in making these systems more attractive and viable (Santos et al., 2018; Silva et al., 2022). Nigeria, also classified as an LMIC, faces many greater challenges in waste management, especially outside urban centres. Nevertheless, small-scale AD systems have begun to show some potential. They not only manage organic waste but also generate biogas to meet daily needs such as cooking and lighting. In this way, the systems seem to address several issues simultaneously (Adeoti et al., 2014; Olatunji et al., 2023).

Problems associated with improper waste management as follows:

- Health hazards: Improperly managed waste often attracts flies, rodents, and other vectors that spread disease. This can increase cases of diarrhoea, cholera, or even dengue fever, issues that health agencies like WHO have repeatedly warned about (Abubakar et al., 2022; Clark, 2022; Evangelisti et al., 2014).
- Environmental pollution: Open dumping and the widespread practice of burning waste seem to worsen both air and water quality. The harm is not confined to the environment; it also affects public health (Abubakar et al., 2022; Clark, 2022; Ifeoma and Yusuf, 2016).
- Resource wastage: Much organic waste that could have been converted into biogas or biofertiliser is discarded. Consequently, valuable nutrients are lost due to short-sighted disposal practices (Islam, 2018; Muradin and Foltynowicz, 2014).

The positive and relatively predictable results of using AD systems in Bangladesh indicate that they have significant potential for enhancing rural waste management. By converting organic waste into biogas and biofertilisers, these AD systems offer a more sustainable approach to waste handling, reducing pollution and making better use of resources. Bangladesh, in many respects, faces opportunities similar to those seen in countries like Brazil and Nigeria, though the comparison is not entirely exact.

9.2.5 En5: Access to adequate water for the biogas plant

In the PESTEL analysis, the key factor "En5: Access to Adequate Water for the Biogas Plant" within the Environmental pillar was assessed positively and predictably (certain) by stakeholders regarding the sustainable growth of small-scale anaerobic digestion (AD) systems or biogas plants in Bangladesh. This positive and predictable assessment emphasises the vital role that water availability plays in the effective functioning of AD systems.

Water is a vital component in the anaerobic digestion process for several reasons, as follows:

- Facilitation of microbial activity: Water plays a key role in maintaining the proper moisture level for microbes to carry out their functions. Without it, the

bacteria that decompose organic matter into biogas may find it difficult to operate efficiently. In other words, adequate water appears to create the conditions in which microbial activity can thrive (Dean et al., 2018; Wang et al., 2019).

- Dilution of feedstock: It is also used to thin the feedstock, allowing the material to flow more smoothly into and through the digester. Achieving this balance appears to be crucial; if it is too thick, blockages may occur, while if it is too thin, the process loses efficiency (Berglund and Börjesson, 2006; Song et al., 2021).
- Temperature Regulation: Water plays a crucial role in regulating heat within the digester, distributing warmth more evenly throughout the system. Maintaining this balance seems especially vital in mesophilic and thermophilic setups, where microbes rely on a relatively narrow temperature window to remain active (Li et al., 2015; Wang et al., 2022).

Bangladesh has plentiful water resources, utilising both groundwater and surface water. In many areas, groundwater is easily accessible. Farmers depend on it for irrigation, households for drinking, and industries for daily activities. The water table generally remains shallow, which may explain why rural communities can access it with relative ease (Shamsudduha et al., 2011). Rivers, canals, and wetlands traverse the country, and the heavy monsoon rains regularly replenish these sources. This abundance of surface water provides a reliable supply for farming, household use, and even energy production such as biogas (Iqbal et al., 2014; Islam, 2018).

In Brazil, ample water resources generally support widespread biogas use, though local shortages sometimes disrupt operations (Silva, 2020). In contrast, Nigeria's persistent water scarcity poses a major barrier to AD system performance, with improvement efforts showing uneven progress (Costa et al., 2024; Silva, 2020).

The generally reliable outlook on water availability for biogas plants in Bangladesh highlights just how critical this resource is for expanding AD systems. The country's mix of groundwater and surface water appears to create a relatively supportive environment for plant operations. When compared to other low- and middle-income countries, such as Brazil or Nigeria, Bangladesh seems to have somewhat more

consistent access to water, which may be a decisive factor in how efficiently AD systems operate.

9.3 Outcome of AD user survey (Environmental point of view)

9.3.1 Air pollution (in kitchen)

The data collected aimed to evaluate the impact of biogas plant installation on air pollution levels in the kitchens of households in Bangladesh. Specifically, the study tested the hypothesis:

H_0: There is no difference between the air pollution status in the kitchen caused by smoke before and after the biogas plant installation.

The table below summarises the air pollution status in the kitchens before and after the installation of biogas plants:

Table 9.1: McNemar-Bowker Test results showing significant reduction in kitchen air pollution before and after AD plant installation

		Air pollution status in kitchen (before AD)				
		Severe	Moderate	Minimal	No pollution	Total
Air pollution status in the kitchen (After the biogas plant installation)	Severe	0	2	0	0	2
	Moderate	0	9	0	0	9
	Minimal	2	8	5	0	15
	No pollution	11	4	6	3	24
Total		13	23	11	3	50

	Value	N	df	Asymptotic Significance (2-sided)
McNemar-Bowker Test	33.000	50	6	<0.0001

Given that the p-value is less than 0.05, we reject the null hypothesis (H_0). This leads to the conclusion that there is a significant difference between the air pollution status in the kitchen caused by smoke before and after the installation of the biogas plant. This finding aligns with the results from similar studies conducted in other low- and middle-income countries (LMICs).

Reducing indoor air pollution is one of the most significant benefits of switching to biogas for cooking. Before these plants were installed, many households relied

heavily on firewood or charcoal as their primary fuel source, often facing unhealthy smoke. The move to biogas seems to have eased much of that, with noticeably cleaner air inside.

The results align with observations made elsewhere. A study in Kenya, for example, reported that adopting biogas significantly cut indoor smoke, which in turn appeared to improve household respiratory health (Carvalho et al., 2019; Wanjohi et al., 2022). In India, Singh and colleagues (2018) found that smoke in kitchens was reduced, and families faced fewer related health issues once biogas systems were in place (Mishra, 2019; Mittal et al., 2018b, 2018a).

In Uganda, it turned out that families using biogas had fewer complaints about breathing difficulties and eye irritation than those still cooking with wood or other traditional fuels (Walekhwa et al., 2009). A similar picture emerges in Bangladesh, where families with biogas plants noticed cleaner air indoors and, with it, clear health gains.

The reduction in kitchen smoke observed here suggests that biogas may be worth exploring further in rural Bangladesh. It’s not just a cleaner cooking method, it also appears to reduce people’s exposure to the type of fumes that gradually erode their health.

9.3.2 Eye infection due to smoke

The study aimed to evaluate the impact of biogas plant installation on the incidence of eye infections caused by smoke in households' kitchens in Bangladesh. The hypothesis tested was:

H_0: There is no difference between eye infection status due to smoke in the kitchen before and after biogas plant installation.

The table below presents the data on eye infection status before and after biogas plant installation:

Table 9.2: McNemar-Bowker Test results show the difference in eye infection status before and after AD plant installation

		Eye infection/ irritation before AD due to smoke				
		Severe	Moderate	Minimal	No pollution	Total
Eye infection/irritation status (After the biogas plant installation)	Severe	0	1	0	0	1
	Moderate	0	2	0	0	2
	Minimal	2	10	4	0	16
	No pollution	3	14	11	3	31
Total		5	27	15	3	50

	Value	N	df	Asymptotic Significance (2-sided)
McNemar-Bowker Test	41.000	50	6	<0.0001

Given that the p-value is less than 0.05, we reject the null hypothesis (H_0). This leads to the conclusion that there is a significant difference in eye infection status between individuals exposed to smoke before and after the installation of the biogas plant.

Eye infections linked to smoke are still a common issue in households that depend on firewood, charcoal, or other biomass fuels for daily cooking. The smoke from these fuels carries fine particles, carbon monoxide, and a mix of volatile compounds that can irritate the eyes and, over time, trigger infections. In Bangladesh, these cooking practices remain widespread, especially outside urban centres. After adopting biogas plants, the reduction in kitchen smoke creates a noticeable difference among users, with noticeably fewer eye problems. The improvement stems from the cleaner burn of biogas, which produces significantly less visible smoke compared to traditional fuels.

Studies from India, Kenya, and Uganda indicate that using biogas instead of firewood reduces smoke-related health issues such as eye irritation and respiratory problems, findings that closely mirror to our study (Carvalho et al., 2019; Mishra, 2019; Mittal et al., 2018a; Walekhwa et al., 2009; Wanjohi et al., 2022).

9.3.3 Respiratory infection status due to smoke

The study aimed to evaluate the impact of biogas plant installation on the incidence of respiratory infections caused by smoke in households' kitchens in Bangladesh. The hypothesis tested was:

H_0: There is no difference between respiratory infection status due to smoke before and after biogas plant installation.

The table below presents the data on respiratory infection status before and after biogas plant installation:

Table 9.3: McNemar-Bowker Test results show the difference in respiratory infection status before and after AD plant installation

		Previous respiratory infection status due to smoke				
		Severe	Moderate	Minimal	No pollution	Total
Present respiratory infection (After the biogas plant installation)	Severe	0	1	0	0	1
	Moderate	0	1	0	0	1
	Minimal	1	9	8	0	18
	No pollution	4	11	9	6	30
Total		5	22	17	6	50

	Value	N	df	Asymptotic Significance (2-sided)
McNemar-Bowker Test	35.000	50	6	<0.0001

Given that the p-value is less than 0.05, we reject the null hypothesis (H_0). This leads to the conclusion that there is a significant difference in respiratory infection status between individuals exposed to smoke before and after the installation of the biogas plant.

Respiratory infections caused by smoke continue to be a significant issue in households that rely on traditional biomass fuels, particularly firewood, for everyday cooking. The smoke contains fine particles, carbon monoxide, and other harmful substances that can trigger serious breathing problems. In Bangladesh, these practices remain common in rural areas; however, the introduction of biogas plants has, in many cases, begun to improve the situation. Families who made the switch reported noticeably fewer issues with coughing and breathing troubles, which may be linked to the far cleaner burn of biogas. This combustion process produces almost no smoke, which appears to be a key factor in the decline of respiratory infections observed in such households.

Rahman et al. (2023) found that introducing biogas technology in rural Bangladesh not only improved indoor air quality but also appeared to lower the rate of respiratory illnesses among local households. Our own findings point in the same direction, which suggests the health benefits of biogas may be more consistent than isolated studies imply.

Studies from India, Kenya and Uganda, indicate that households using biogas tend to experience cleaner indoor air and fewer smoke-related respiratory issues, suggesting that biogas use may contribute to better public health (Carvalho et al., 2019; Wanjohi et al., 2022)(Mishra, 2019; Mittal et al., 2018a).

9.3.4 Abundance of mosquitoes/flies

The study assessed the impact of biogas plant installation on the abundance of mosquitoes and flies in households' kitchens in Bangladesh. The hypothesis tested was:

H_0: There is no difference between the abundance of mosquitoes or flies before and after biogas plant installation.

The table below presents the data on the abundance of mosquitoes and flies before and after biogas plant installation:

Table 9.4: McNemar-Bowker Test results show the difference in abundance of mosquitoes or flies status before and after AD plant installation

		Previous Abundance of mosquitoes/flies				
		Severe	Moderate	Minimal	No pollution	Total
Abundance of mosquitoes/flies (After the biogas plant installation)	Severe	0	1	0	0	1
	Moderate	1	1	1	0	3
	Minimal	1	8	10	0	19
	No pollution	2	8	8	9	27
Total		4	18	19	9	50

	Value	N	df	Asymptotic Significance (2-sided)
McNemar-Bowker Test	24.444	50	6	<0.0001

From the table above, we see that the p-value is less than 0.05, so we reject the null hypothesis (H_0). We conclude that there is a significant difference in the abundance of mosquitoes or flies before and after the installation of a biogas plant.

The noticeable drop in mosquitoes and flies after biogas plants are installed appears to be tied to how these systems handle organic waste. By keeping manure and other scraps from sitting around and rotting, the usual breeding grounds for pests are reduced. Once the waste is converted into gas and slurry, the environment is less inviting to insects that thrive on decomposition.

In many low- and middle-income countries, similar trends have been reported. Take Kenya, for instance: researcher found that biogas plants were linked with fewer disease-carrying insects, which appears to have contributed to better public health (Carvalho et al., 2019; Wanjohi et al., 2022). A researcher from India, noted that waste management through biogas reduced pest habitats, creating healthier surroundings (Gupta et al., 2016). These international cases highlight the potential role of biogas in promoting sustainable development and improving everyday well-being in such contexts.

9.3.5 Cow shed management

H_0: There is no difference between cow shed management status before and after biogas plant installation.

The provided data presents the cow shed management status before and after the installation of biogas plants, analysed using the McNemar-Bowker Test. The table and results are as follows:

Table 9.5: McNemar-Bowker Test results show the difference in cow shed management status before and after AD plant installation

		Present cow shed management		
		Systematic	Non-Systematic	Total
Cow shed management (After the biogas plant installation)	Systematic	4	0	4
	Non-Systematic	3	41	44
Total		7	41	48

	Value	N	df	Asymptotic Significance (2-sided)
McNemar-Bowker Test	1.3333	48	1	0.2482

Given the p-value of 0.2482, which is greater than the significance level of 0.05, we fail to reject the null hypothesis (H_0). This suggests that there is no significant difference in cow shed management status before and after the installation of biogas plants.

The lack of notable changes in cow shed management practices after the installation of a biogas plant indicates that biogas technology alone may not be sufficient to improve cow shed management. The limited impact may stem from inadequate training, financial and labour constraints, and resistance to changing traditional practices—all of which make it difficult for farmers to fully benefit from biogas systems (Islam et al., 2012; Rahman and Parveen, 2014; Ahmed, 2010).

A study in India by Patel et al. (2018) observed clear improvements in cow shed management after biogas units were installed; however, much of that success appears linked to structured training programmes and consistent government support.

Another study in Kenya, by Mwangi and Mbugua (2016), reported almost no change, which aligns with the findings from Bangladesh. They attributed this stagnation not to the technology itself, but to the lack of follow-up support and the burden of financial constraints(Carvalho et al., 2019; Rotich and Musyimi, 2024; Wanjohi et al., 2022).

Nepal, meanwhile, remains somewhat in between. Shrestha et al. (2017) observed mixed outcomes; communities that collaborated experienced improvements, while those with more fragmented efforts saw little progress.

Taken together, these cases suggest that while biogas plants can indeed offer environmental and economic benefits, their impact on cowshed management in Bangladesh remains quite limited without additional support. Sustainable growth in the AD sector likely depends on more than just installing plants; it requires training, financial incentives, and possibly gradual cultural changes in farming practices.

9.3.6 Fodder management status

The analysis of the impact of time, specifically before and after AD installation, on various variables, including fodder management status, reveals significant changes.

The hypothesis tested is H_0, which states there is no difference in fodder management status before and after the installation of a biogas plant. The contingency table data is as follows:

Table 9.6: McNemar-Bowker Test results show the difference in fodder management status before and after AD plant installation

		Previous fodder management status				
		Good	Moderate	Bad	Unchanged	Total
Present fodder management status (After the biogas plant installation)	Good	9	9	0	0	18
	Moderate	0	14	1	0	15
	Bad	0	0	1	0	1
	Unchanged	1	3	0	9	13
Total		10	26	2	9	47

	Value	N	df	Asymptotic Significance (2-sided)
McNemar-Bowker Test	14	47	4	0.007

Given that the p-value is 0.007, which is less than the 0.05 significance level, H_0 is rejected. Therefore, it is concluded that there is a significant difference in fodder management status before and after the installation of the biogas plant.

The notable improvement in fodder management following the installation of biogas plants reflects patterns observed in several other low- and middle-income countries. Studies from India and Kenya, for example, suggest that biogas technology does more than provide cleaner energy or manage waste; it also influences daily farming practices, including how fodder is managed (Meena et al., 2024; Mishra, 2019; Patil, 2020). The uptake of biogas technology in these areas increased organic fertiliser availability and, in some cases, enhanced overall farm productivity. These changes may appear minor at first glance, but in lower-middle-income countries where food security and livelihoods heavily depend on agriculture, such advances are crucial to agricultural practices (Meena et al., 2024).

The comparison indicates that introducing biogas plants is likely to enhance fodder management, a trend reflected in reports from other LMICs. It is reasonable to view biogas technology as more than a narrow intervention; it could serve as a practical pathway towards greater sustainability and efficiency in farming systems that face very different social and ecological pressures.

The statistical evidence aligns on the same point. Fodder management improves notably after biogas plant installation, consistent with findings from other LMICs.

9.3.7 Environment friendly fuel

The analysis examines the impact, specifically before and after the installation of AD, on the use of environmentally friendly fuels.

The tested hypothesis is H_0, which states that there is no difference in the environmental friendliness of the fuel prior to and following the installation of a biogas plant.

The contingency table is presented as follows:

Table 9.7: McNemar-Bowker Test results show the difference in environmental friendliness of fuels before and after AD plant installation

		Is this fuel environment friendly?		
		Yes	No	Total
Was this fuel environment-friendly (Before AD)	Yes	8	0	8
	No	41	1	42
Total		49	1	50

	Value	N	df	Asymptotic Significance (2-sided)
McNemar-Bowker Test	39.024	50	1	<0.0001

Since the p-value is less than 0.05, H_0 is rejected. Consequently, we conclude that there is a significant difference in the environmental friendliness of fuels before and after the installation of a biogas plant.

Biogas adoption tends to reduce reliance on wood and charcoal, improving indoor air quality and lowering household carbon footprints, as seen in Nepal and Tanzania (Katuwal and Bohara, 2009; Sanches-pereira et al., 2017)

Data in this research also suggest that installing biogas plants encourages households to adopt cleaner fuels, reflecting similar patterns seen in other LMICs and pointing to biogas as a practical path toward sustainable energy use (Gautam et al., 2009; Mwakaje, 2008).

9.3.8 Self-assessed household environment

The analysis investigates the effect of time, specifically before and after the installation of AD, on the self-assessed condition of the household environment.

The tested hypothesis is H_0, which states that there is no difference in self-assessed household environment status before and after the installation of a biogas plant. The contingency table is as follows:

Table 9.8: McNemar-Bowker Test results show the difference in self-assessed household environment status before and after AD plant installation

		Before AD plant installation, the self-assessed household Environment				
		Good	Moderate	Bad	Unchanged	Total
After the AD plant installation, the self-assessed household Environment	Good	10	14	0	0	24
	Moderate	0	18	1	0	19
	Bad	0	1	0	0	1
	Unchanged	2	3	0	1	6
Total		12	36	1	1	50

	Value	N	df	Asymptotic Significance (2-sided)
McNemar-Bowker Test	19.000	50	4	0.001

Since the p-value is 0.001, which is less than the 0.05 significance level, the null hypothesis (H0) is rejected. Consequently, we conclude that there is a significant difference in self-assessed household environment status before and after the installation of a biogas plant.

Biogas adoption appears to improve household environments by reducing indoor smoke and enhancing sanitation, as seen in India and Vietnam, where cleaner living conditions and better waste management were reported (Islam et al., 2013; Vu et al., 2014). The resulting improvements in the household environment, and consequently in health, may not be uniform everywhere, but the overall trend is clear and hard to ignore.

The improvements in household environmental conditions reported after installing biogas plants appear to reflect patterns often observed in other low- and middle-income countries (Carvalho et al., 2019; Rotich and Musyimi, 2024; Wanjohi et al.,

2022). These points indicate the potential of such systems to foster cleaner, healthier living environments.

The statistical results also indicate a significant increase in self-assessed household conditions after installation, a finding consistent with earlier evidence from similar contexts.

9.3.9 Self-assessed kitchen environment

The analysis examines the effect of time, specifically before and after the installation of AD, on self-assessed kitchen environment conditions.

The hypothesis tested is H_0, which states that there is no difference in self-assessed kitchen environment conditions before and after installing a biogas plant.

The contingency table is provided below:

Table 9.9: McNemar-Bowker Test results show the difference in self-assessed kitchen environment status before and after AD plant installation

		Before biogas plant installation Self-assessed kitchen environment				
		Good	Moderate	Bad	Unchanged	Total
After the biogas plant installation Self assessed kitchen environment	Good	3	17	9	0	29
	Moderate	0	15	2	0	17
	Bad	0	1	0	0	1
	Unchanged	0	2	0	1	3
Total		3	35	11	1	50

	Value	N	df	Asymptotic Significance (2-sided)
McNemar-Bowker Test	28.333	50	4	<0.0001

Since the p-value is less than 0.05, the null hypothesis (H_0) is rejected. Consequently, we conclude that there is a significant difference in self-assessed kitchen environment status before and after the installation of a biogas plant.

Improvements in kitchen conditions following biogas installation are evident in the data, and similar trends have been observed in other low- and middle-income countries. In Nepal, for instance, households using biogas reported less smoke and an overall improvement in air quality and cleanliness (Katuwal, 2022). Evidence from

India indicates similar outcomes, where decreasing firewood use resulted in kitchens that appeared cleaner and less soot-covered (Meena et al., 2024).

Overall, these studies indicate that switching to biogas can solve one of the most persistent household issues: smoke-filled kitchens. By replacing traditional biomass fuels with a cleaner-burning alternative, families seem to enjoy healthier indoor air and lower the risks linked to extended smoke exposure.

The data showing improvements in how people rate their own kitchen environments appears to align with broader patterns observed in many LMICs. It indicates that biogas plants may not only reduce smoke and soot but also contribute to creating spaces that feel noticeably cleaner and healthier.

Statistical analysis shows notable improvements in self-rated kitchen conditions after installing a biogas plant, consistent with findings from other LMICs.

9.4 SWOT analysis of the environmental pillar of PESTEL

Within the PESTEL framework, the environmental pillar is vital when considering anaerobic digestion (AD) in Bangladesh. The country generates large quantities of agricultural waste but continues to face ongoing challenges such as greenhouse gas emissions, inadequate waste management systems, and health risks associated with indoor air pollution. AD technology could offer a partial solution by transforming waste into biogas for energy and bio-slurry that can be reused in farming. Climate and water resources arguably facilitate adoption, though this benefit should not be exaggerated. Nonetheless, to promote sector growth, infrastructure gaps and some cultural resistance must be addressed.

Table 9.10: SWOT analysis: Environmental pillar of PESTEL

Catagories	Key points
Strengths	• Significant decrease in GHG emissions, aligning with broader SDG targets. • A generally warm and humid climate that mostly supports anaerobic digestion without requiring costly temperature regulation. • Lower levels of indoor smoke and pollution, which are likely to improve health—especially for women and children who spend more time around cooking fires. • A clearer role in waste management, as organic waste can be transformed into biogas and nutrient-rich slurry instead of piling up unmanaged. • Access to water resources that, at least for now, simplifies operating AD plants.
Weaknesses	• Dependence on water supply in drought-prone seasons or water-scarce areas.
Opportunities	• Ability to make a significant contribution to Bangladesh's renewable energy strategy by integrating AD systems with other renewable sources.. • Potential to reduce reliance on chemical fertilisers by promoting bio-slurry as a nutrient-rich, eco-friendly alternative.
Threats	• In regions where water is already limited, the efficiency of AD systems could decrease significantly. • Changes in climate patterns could disturb the conditions these systems depend on to function optimally.

Bangladesh’s warm, humid climate generally favours anaerobic digestion (AD), reducing energy costs and supporting efficient waste-to-biogas conversion. This

contributes to lower greenhouse gas emissions and improved indoor air quality, particularly benefiting rural households. However, limited rural infrastructure and dependence on water remain major constraints. Despite these challenges, AD holds strong potential to advance Bangladesh's renewable energy and sustainability goals, especially through the use of bio-slurry as an eco-friendly fertiliser. However, changing rainfall patterns and growing water scarcity could pose future risks to system reliability.

Chapter 10: In-Depth Analysis of the Legal Pillar of PESTEL

10.1 Introduction

The legal dimension of the PESTEL framework centres on the regulatory setting that shapes how businesses operate and pursue sustainability, extending to the uptake of technologies such as anaerobic digestion (AD) (Achinas et al., 2019; Aoidh et al., 2017). In Bangladesh, the legal environment holds particular significance, as it influences the management of environmental protection, waste management, energy production, and public health(Busari, 2025; Hasan et al., 2022; Shovon et al., 2022).

In this section of the study, an exploration is conducted on specific legal factors, ranging from national and local environmental laws to renewable energy rules and international agreements, such as the Sustainable Development Goals (SDGs), that affect the development of AD in Bangladesh. The discussion also addresses the weak enforcement, the administrative burden of compliance, and legislation that often appears outdated compared to modern technologies. At the same time, this section also analyses the legal factors for broader adoption of AD, aligns with climate targets, and supports a more sustainable waste-to-energy pathway.

10.2 Insights from expert stakeholder opinion on the legal pillar of PESTEL

For the legal pillar, stakeholders consider four key factors to be highly significant for AD growth in Bangladesh, and they consider two key factors to be highly negative and uncertain and two key factors to be negative and certain. Key factors are :

Negative and uncertain

- L4: The range of requirements for anaerobic digestate / bio-slurry as fertiliser or quality protocol (Fertilizer Recommendation Guide 2018, Bangladesh)
- L5: Feed-in Tariffs for produced biogas.

Negative and predictable (certain)

- L7: Local government law for setting up an AD plant in premises (range of requirements).
- L3: Biogas guidelines/ legislation.

10.2.1 L4: The range of requirements for anaerobic digestate / bio-slurry as fertiliser or quality protocol (Fertiliser Recommendation Guide 2018, Bangladesh)

Stakeholders assessed and expressed concern about one specific rule, the "Fertilizer Recommendation Guide, 2018" (L4), regarding bio-slurry quality. It appears that the guidelines may be creating more hurdles regarding bio-slurry as a fertilise than they solve for small-scale biogas projects.

The "*Fertilizer Recommendation Guide 2018"* in Bangladesh outlines different fertilisers, including bio-slurry, that should be applied to promote sustainable farming (BARC, 2018). Some stakeholders point out that the guidance on using anaerobic digestate as fertiliser feels incomplete and, at times, a little ambiguous. Though policy exists on paper, its lack of clarity and inconsistent enforcement is likely holding the entire sector back.

Regulatory challenges

The guidelines present some practical challenges for users, as follows:

- Lack of clear standards: The guide does not provide clear, specific standards for using bio-slurry, resulting in confusion among farmers and AD operators regarding its application. This lack of clarity creates frustration and stifles adoption, as people tend to avoid what they can not clearly understand (BARC, 2018; Chy, 2015)
- Quality assurance: The major issue is the lack of practical quality control. With insufficient protocols to verify the safety and consistency of bio-slurry, farmers have no way of assuring whether the batch they are using is safe or could potentially introduce risks to their crop production (Rahman et al., 2022).

Nutrient management

In farming practices, the challenges shift from regulatory confusion to agricultural unpredictability in the nutrient composition and application rates.

- Nutrient composition: Unlike standardised chemical fertilisers, the nutrient makeup of bio-slurry varies significantly. It depends entirely on feedstook. This

heterogeneous variation makes it nearly impossible to create reliable, consistent recommendations that work for different crops and diverse soil conditions of Bangladesh (Khan and Martin, 2016).

- Application rates: The guide does not provide any information about the applications of bio-slurry. Without detailed guidance on the quantity of use, farmers are essentially struggling. It is no surprise that this leads to over- or underapplication, deteriorating soil health in the long run, and directly impacting seasonal crop yields (Akter et al., 2021). It is not possible to achieve widespread adoption when instructions are missing, as this may harm soil health or even affect yields, leaving users to wonder if it is even worth it.

Bio-slurry fertiliser has a wider range of guidelines across the globe. The Government of India has established guidelines and recognised its value for soil health and crop production (Singh et al., 2018). They have even launched initiatives to push, but receive a poor response. The research highlights several major issues, including a frustrating inconsistency in the bio-slurry quality itself, and in some cases, hidden cultural hesitancy, a trust gap that keeps farmers from fully embracing it (Devarenjan et al., 2019).

In the case of Brazil, its system for handling bioslurry feels more mature and structured. Studies describe a fairly comprehensive framework with clearer, more practical rules for safe application (Silva et al., 2022). And crucially, it is not just a guideline but also backed by financial incentives. This combination of clear policy and subsidies probably explains the reason for higher adoption rates (Sanches-pereira et al., 2017; Silva et al., 2022).

The success rate of Denmark depends on the approach, which is not about gentle promotion; it is about non-negotiable quality standards enforced through regular monitoring and evaluation. This rigour has effectively made bio-slurry a safe, reliable, and utterly mainstream component of their agriculture (Jacobsen et al., 2013; Krog et al., 2017).

In Bangladesh, the regulatory landscape appears uncertain regarding the application of bioslurry in agricultural fields (BARC, 2018; Chy, 2015). This ambiguity appears to be a significant obstacle to the sustainable growth of the AD sector. For farmers and

operators, the main source of confusion often stems from the official guidelines "Fertilizer Recommendation Guide, 2018"; while it mentions bio-slurry, it does not offer the clear, practical standards needed for safe and effective use. This leaves everyone in a difficult position, unsure about application rates or safety protocols.

It is a common challenge in many lower-middle-income countries, including India (Singh et al., 2018) and Brazil (Sanches-pereira et al., 2017; Silva et al., 2022), which are grappling with similar issues. Denmark is an approach, for example, that might offer a helpful model, having moved past these initial hurdles to establish a more coherent system (Jacobsen et al., 2013; Krog et al., 2017). Learning from such examples could be a crucial first step.

10.2.2 L5: Feed-in Tariffs for produced biogas

Stakeholders examined the policy and legal landscape for small-scale biogas in Bangladesh; one legal factor stood out as a particular point of concern: feed-in tariffs (FiTs) for the produced biogas. This aspect of the legal parameter in the PESTEL analysis has considerable scepticism and concern. The general perception in this study appears to be that the current FiT framework is both problematic and unpredictable, which hinders scaling up the AD sectors.

In theory, feed-in tariffs are a brilliant tool, designed to boost renewable energy by ensuring a fixed price for the electricity (Fusi et al., 2016; Lyng et al., 2020). This certainty is intended to provide investors with the financial stability they need to make informed investment decisions. For a capital-intensive technology like AD, such policy support could be a real game-changer. The challenge in Bangladesh, however, appears to be translating that great idea into a clear and reliable policy that people can actually work on.

- Making biogas production more attractive: A well-designed Feed-in Tariff (FiT) can be a powerful tool for ensuring **r**evenue assurance**,** which appears to lower the financial risk for producers (Fusi et al., 2016; Lyng et al., 2020). Knowing there is a guaranteed buyer for their energy can make investors more comfortable backing anaerobic digestion projects. By creating a stable

and predictable market, FiTs can help ease biogas into the national energy grid (Rouf, 2015; Yousuf et al., 2016).

- Technological advancements**:** The accurate financial incentives can also foster technological innovation**.** The logic is that by making advanced biogas technology more profitable, FiTs encourage producers to adopt more efficient systems (Sanches-pereira et al., 2017; Silva et al., 2022). However, this depends heavily on how the tariff is structured; it must reward genuine efficiency gains, not just output, and can achieve economies of scale**.** This is likely a key factor in reducing the overall production costs, which is essential for biogas to compete on its own merits with traditional fossil fuels (Fusi et al., 2016; Lyng et al., 2020).

A few persistent issues have confined the journey with biogas Feed-in Tariffs (FiTs) in Bangladesh. To begin with, the regulatory landscape is surprisingly unclear (IDCOL, 2020; SREDA, 2016). Despite some government interest, there is still no comprehensive FiT policy that investors can actually bank on (Rahman et al., 2022). This ambiguity, noted by SREDA as far back as 2016, understandably makes everyone anxious.

And even when support exists, it is wildly inconsistent. As researchers such as Rahman et al., (2022) have noted, this stop-and-start approach (support for AD) introduces financial unpredictability. A local farmer or small business will not invest in a biogas digester with an uncertain FiT. The tariffs on offer tend to fall short of covering the actual costs and technical risks associated with setting up a biogas plant. It is not just about being insufficient on paper; delayed payments compound the problem.

A lower-middle-income country like India has turned to Feed-in Tariffs (FiTs) for biogas to boost its renewable energy capacity. The strategy of offering a fixed tariff appears to have been successful, as it has encouraged a noticeable increase in investment for anaerobic digestion projects (Sawale et al., 2021; Singh et al., 2018). Reports suggest that securing timely payments can be a significant hurdle, which, of course, undermines the financial viability that the FiTsa are intended to guarantee.

In Brazil, another LMIC, the story is somewhat similar but perhaps a bit more successful. Their approach with FiTs has often been cited as a key driver for the biogas sector's growth(Sanches-pereira et al., 2017; Silva et al., 2022). By putting competitive tariffs on the table, they have managed to attract significant investment and spur some genuine technological advancements. This kind of policy backing appears to have been absolutely crucial for weaving biogas into the nation's broader energy strategy.

Germany offers a classic case study from the developed world. They were true pioneers, utilising a famously robust FiT system to build a sustainable biogas industry (Thrän et al., 2020). The main focus was not just the money, but the long-term stability those guaranteed tariffs provided. This financial security gave producers the confidence not only to enter the market but also to innovate, leading to widespread adoption and cutting-edge technology.

When stakeholders examine the regulatory framework for feed-in tariffs (FiTs) in Bangladesh, the assessment tends to be quite negative and clearly uncertain. It could stall the sustainable growth of anaerobic digestion (AD) systems. Now, comparing this situation to other lower-middle-income countries, such as India and Brazil, the gap becomes clearer. They have managed to establish FiT regimes that, while not perfect, offer a degree of financial stability and market access that investors need to feel confident.

10.2.3 L7: Local government law for setting up an AD plant in premises (range of requirements)

The legal factors in the PESTEL analysis highlighted one issue that stood out for its particularly negative and certain rating from stakeholders, which was the complex web of local government laws governing the establishment of anaerobic digestion (AD) plants in Bangladesh. It appears that this regulatory complexity is widely seen as (by stakeholders) a significant obstacle to the sustainable growth of small-scale biogas systems.

The problem is that it is not a single law, but rather the layers of compliance required. For potential users, this compromises the motivation for AD adoption.

- Land use and zoning: The permit process alone is a significant burden, entangled in various local regulations that can dramatically increase both the timeline and budget for a new AD facility (Hasan et al., 2022). Furthermore, the site approval requirements often necessitate comprehensive environmental impact studies and community consultations. While these steps have their merits in theory, in practice, they appear to create a costly and time-consuming barrier that may ultimately discourage the actual investment Bangladesh needs (Rahman et al., 2022; Yousuf et al., 2016)
- Environmental regulations: For controlling emissions and managing digestate, the rules and regulations are stringent, resulting in few disputing their necessity (DoE, 2023). In practice, the path to compliance is rarely straightforward. The constant monitoring and exhaustive reporting add up to a massive administrative burden for plant users.

The Environmental Conservation Rules (ECR) 2023 provide a comprehensive regulatory framework for environmental management in Bangladesh (DoE, 2023). These rules include provisions specific to the establishment and operation of AD plants, which further complicate the regulatory landscape.

- Stringent environmental assessments: ECR 2023 mandates detailed Environmental Impact Assessments (EIAs) for all new AD plants, adding to the time and cost of project development (DoE, 2023)
- Compliance monitoring: The rules require continuous monitoring and reporting of environmental parameters, increasing the operational burden on AD plant operators (DoE, 2023).

Regulatory approaches play a significant role in the progress of the AD sector in the country. India made a conscious effort to cut through the red tape, creating clearer guidelines that seem to have genuinely simplified the approval process for renewable energy projects. This reason plays a central part in the thriving of their biogas sector (Sawale et al., 2021; Singh et al., 2018). Brazil appears to have followed a similar playbook, establishing supportive regulations with specific, practical rules for environmental compliance that have attracted investment (Costa et al., 2024; Santos et al., 2018). The framework of Germany is less about simply removing barriers and more about creating a sophisticated system (Thrän et al., 2020). The country has

well-defined laws that ensure environmental protection and safety. From all these examples, it is clear that Bangladesh needs to learn from lessons that can help to develop or grow the AD sector. From the outside, the regulatory environment appears particularly challenging to navigate. The laws are often described as complex and unclear, which discourages operators and potential innovation. Every country's context is indeed unique; the contrasting models of India, Brazil, and Germany may suggest that a move toward greater clarity and support could be a powerful model.

10.2.4 L3: Biogas guidelines/legislation

Stakeholders in Bangladesh regarding the legal landscape for small-scale biogas have a reasonably clear consensus that the current guidelines and legislation are a real problem. In fact, this specific issue from our PESTEL analysis was not just viewed negatively; it was identified as a significant barrier to sustainable growth for AD systems.

- Lack of comprehensive guidance: Upon closer examination, the regulatory framework appears to be a complex of well-intentioned but ultimately ineffective rules. One agency might have one set of requirements, while another contradicts it, making compliance a frustrating guessing game (IDCOL, 2020; SREDA, 2016).
- The existing policies are primitive, which discourages new operators or owners from following, resulting in the growth of the AD sector in Bangladesh. The rules on the books often fail to account for fresher, more efficient technologies or the operational best practices that have emerged over the last decade (Hasan et al., 2022; Yousuf et al., 2016).
- Complex approval processes and bureaucratic hurdles: Obtaining all the necessary approvals and permissions for an AD plant can be a surprisingly slow and frustrating process. It often feels complicated, with different regulatory bodies each requesting their own forms, standards, and timelines (Islam and Hossain, 2021). From the field interviews with operators, it has been identified that even minor errors in paperwork can slow a project for weeks or sometimes months.

- Limited incentives: Another hurdle appears to be the scarcity of supportive policies. Financial incentives, subsidies, or technical assistance programs for small operators are threatened. Without this kind of backing, sustaining a biogas project can feel like pushing a boulder uphill, especially for those trying to do it independently (SREDA, 2016).
- Application of guideline: The Draft "Biogas Policy/Guideline" of 2018 was meant to tackle some of the long-standing hurdles in the AD sector in Bangladesh. On paper, it appears to be a step toward a more transparent and supportive framework. However, the implementation of the guidelines has not yet reached the practical stage (Power Division, 2018).
- Policy provisions: The draft promises financial incentives, subsidies, and some technical support for biogas projects. It also claims to simplify the approval process, thereby reducing red tape (SREDA, 2021). Smaller operators often say the reality feels unchanged, as navigating paperwork still drags on, and approvals can take a considerable amount of time.
- Quality standards: The guidelines highlight quality requirements for production and use, aiming to ensure safer and more efficient operations (SREDA, 2021). Some operators note that meeting these standards is not easy without additional training or guidance. It appears that the policy may have underestimated the steepness of the learning curve for new producers.

Even so, the final "Biogas Policy/Guideline 2018" draft issued by the Energy Power Division, Ministry of Power, Energy and Mineral Resources (Power Division, 2018), has not escaped criticism:

- Implementation delays: Despite the good intentions, rollout has been slow. Many of the hurdles the draft aimed to address remain (Power Division, 2018)
- Lack of clarity: Stakeholders also complain about vague sections that can easily cause confusion and, in practice, make compliance harder than it should be (Hossain, 2020; Mang et al., 2017; Rahman et al., 2019).

The usefulness of the Final Draft Guidelines on Biogas Technology for the Energy and Power Division, Ministry of Power, Energy and Mineral Resources, really depends on following (Hossain, 2020; Mang et al., 2017; Rahman et al., 2019).

- Comprehensive coverage: It is not enough to list standards or procedures; the guidelines must clearly define terms, outline practical steps, and remain consistent throughout. Without that, operators may interpret things differently, resulting in a system more complex than transparent.
- Streamlined processes: Currently, obtaining approvals and permits can be a painfully slow process. A single-window clearance system can facilitate the establishment of AD plants, making the procedure easier and quicker, thereby streamlining the process
- Financial and technical support: Financial incentives, grants, subsidies, and even low-interest loans play a significant role in encouraging investment. Additional technical assistance is also required for the AD growth. Well-funded projects also face risks without the guidance of trained and expert professionals (Sanches-pereira et al., 2017; Silva et al., 2022).
- Stakeholder engagement: Guidelines require occasional updates as technology evolves and new practices emerge. Bringing in stakeholders, industry specialists who know the details and local communities who deal with the impact, appears essential if the rules are to stay practical rather than merely symbolic (Rahman et al., 2022).

India, as a lower-middle-income country, has made significant progress in establishing a supportive framework for biogas. Their approach is not just theoretical; the government has implemented policies that clearly outline how to establish a plant, backed by financial incentives and technical support. This practical support appears to have been crucial, making it easier for the sector to grow and attracting investment into anaerobic digestion systems (Singh et al., 2018). That said, the real-world application of these policies can sometimes be tangled in local bureaucracy, a common hurdle in a country as vast and diverse as India.

Brazil, another LMIC, tells a similar but distinct story. They have also established a fairly robust regulatory framework for biogas, complete with clear rules, financial incentives, and efforts to streamline the often tedious approval processes (Sanches-pereira et al., 2017; Silva et al., 2022).

Germany has established another example of a smart field for AD sector. They have crafted one of the world's most advanced frameworks for biogas. The transparent

regulatory pathways and innovative technical expertise of Germany have unconditionally covered its position as a global leader (Thrän et al., 2020).

It seems clear that the rules and regulations governing biogas in Bangladesh are posing some real problems, particularly for smaller operations. While the 2018 Draft Biogas Policy was intended to address these issues, it has remained mainly on the shelf since then.

10.3 Outcome of AD user survey (legal point of view)

The survey highlights some legal obstacles that are holding back the wider adoption of AD systems in Bangladesh. Many obstacles, including a lack of awareness of existing regulations, complicated and delayed legal frameworks, bureaucratic processes, and a lack of financial incentives, among others, hinder the growth of the AD sector in Bangladesh.

10.3.1 Regulatory awareness and compliance

10.3.1.1 Awareness of policies

In this research, a striking 86% of respondents reported being unaware of government policies or regulations regarding AD systems. People are justifiably uncertain about investing in something as complex and costly as an AD system if they do not have clear knowledge of the legal or institutional support that actually exists.

Different LMICs have developed and implemented various awareness policies, which have transformed their AD sector into a successful growth. In India, the government has deliberately promoted public awareness through programs such as the National Biogas and Manure Management Program (NBMMP) (Mishra, 2019). Reports suggest this has boosted people's understanding of AD systems and their willingness to adopt them (Meena et al., 2024; Mittal et al., 2018). Brazil has integrated awareness campaigns into broader environmental and energy strategies, framing biogas as part of the country's sustainable energy future (Costa et al., 2024; Santos et al., 2018). Kenya's approach has placed a serious emphasis on partnerships with international organisations, which can sometimes be more effective in rural contexts

where trust in local government may be limited (Carvalho et al., 2019; Chanyisa, 2021).

10.3.1.2 Clarity of legal requirements and compliance

In this study, only about 10% of respondents reported finding the legal requirements for setting up and operating AD systems clear. That meagre number mentions the actual reason for being disorganised, or even discouraging, for people who might otherwise consider adopting the technology (Hasan et al., 2022).

Compared to some LMICs, Bangladesh is struggling to disseminate the legal requirements and compliance to every stage of society, which is a significant reason hindering the growth of the AD sector. Brazil, for example, has built regulations that are not only well-structured but also easier to follow. That clarity seems to have lowered the entry barrier, making adoption more common (IREA, 2015). The Philippines has taken a similar approach by rolling out government initiatives aimed at simplifying rules and promoting the use of biogas in both rural households and urban settings.

Germany has held up AD as the model case, implementing its regulations that are not just accessible but organised into step-by-step guidance, which gives producers a precise roadmap (Thrän et al., 2020).

10.3.1.3 Official acceptance process for obtaining permission

In this research, nearly 90% of respondents stated that it typically takes between one and three months to obtain the permits for setting up AD systems. Dealing with small operators in rural areas, extra weeks or extended time can translate into higher costs and frustrating delays. Ultimately, it becomes a bigger barrier than the technology itself.

In India, for example, the government has streamlined the bureaucratic process for renewable energy projects, including biogas, which appears to have made the process less cumbersome (Mittal et al., 2018). Brazil took a step further, rolling out simplified approval systems for small-scale plants, which appears to have significantly accelerated adoption (IREA, 2015). China's rural biogas programs also

demonstrate how strong government backing can reduce waiting times, something that likely contributes to the widespread adoption of the technology there (Chen and Liu, 2017). In Germany, the Renewable Energy Act is cited as a model; its permitting framework is not just theoretical, but actually enables the faster deployment of AD systems (Thrän et al., 2023; Venus et al., 2021).

10.3.1.4 Compliance with environmental laws

During the field investigation, most respondents stated that once their AD systems were operational, environmental regulations were not a significant issue. Several mentioned that just trying to understand the rules and figuring out how to meet them actually feels like an obstacle in itself. For smaller operators, especially those without technical support, this first step may be discouraging enough to deter them from even starting.

In Brazil, environmental laws are tied directly to incentives for biogas producers. That link appears to shift the focus from “compliance as a burden” to “compliance as an opportunity” (Mathias and Mathias, 2015). Denmark, meanwhile, folds its environmental requirements into a broader renewable energy framework. In practice, this means that AD producers are not only ticking regulatory boxes; they are also able to access financial and policy incentives simultaneously (Abdmouleh et al., 2015).

10.3.2 Legal framework for bio-slurry and fertiliser use

10.3.2.1 Awareness of fertiliser guidelines

In Bangladesh, nearly all respondents (approximately 96%) stated that they were unfamiliar with the Fertilis*er Recommendation Guide 2018*. It may suggest not just a lack of awareness but also that information on bio-slurry use has simply not been reaching farmers in any meaningful way. As a result, one of the most valuable by-products, like bio-slurry of anaerobic digestion systems, is still not being used to its full potential in agriculture (Ahmmed et al., 2018).

Many countries have achieved progress in the AD sector by utilising the fertiliser guidelines properly. In India, for instance, the government has actively circulated bio-

slurry guidelines through agricultural extension services. Farmers there appear to have clearer access to both the benefits and the practical know-how of using it (Mishra, 2019; Gurung, 1997). Indonesia has taken a similar path, pairing guidelines with hands-on training sessions to encourage adoption, especially in rural communities (Dewi and Setiawan, 2022). Germany has taken it even further, maintaining that strict quality regulations are not only in place but also well communicated, making bio-slurry a fairly standard feature of organic farming practices (Bonten et al., 2016).

10.3.2.2 Legal restrictions on bio-slurry use

Approximately half of the respondents in Bangladesh reported facing legal restrictions when using bio-slurry, and nearly all—98%—admitted that meeting the quality regulations is challenging. It appears that the rules, although intended to ensure safety, can be overly strict to follow in practice.

Looking abroad, the situation differs significantly. In Brazil, for example, regulations on bio-slurry are flexible yet thorough, aiming to protect safety without overburdening farmers (Martins et al., 2024). China takes a somewhat different approach, encouraging the use of bio-slurry as part of its circular economy policies, with rules that appear to support agricultural applications rather than hinder them (Chen and Liu, 2017). Denmark, on the other hand, combines strict rules with strong government support, allowing farmers to comply without feeling discouraged (Pelkonen et al., 2014).

10.3.3 Feed-In tariffs and financial incentives

10.3.3.1 Awareness of FiTs

Not a single respondent in this research reported having ever heard of feed-in tariffs (FiTs) or other financial incentives associated with biogas production. A complete 100% of respondents do not have an idea about the existence of the policy. In a way, the absence of awareness becomes a barrier in itself, shutting down possibilities before they even take off.

India, for example, rolled out FiTs for biogas, and reports suggest that those incentives nudged adoption of AD systems in the right direction (Gandhi et al., 2022). In Brazil, FiTs not only smoothed the deal but also arguably shifted the calculation for investors who might otherwise have sat on the fence (Costa et al., 2024; Santos et al., 2018). South Africa took a similar route, offering FiTs across renewables, including biogas, and the sector appears to have expanded at a steady pace (Baker and Phillips, 2019). In Germany, the FiT model is often cited as one of the key reasons renewables, including biogas, scaled so rapidly (Thrän et al., 2023; Venus et al., 2021).

Many other countries have utilised FiTs to propel the sector forward, while Bangladesh is still struggling with the most fundamental aspect of awareness. That missing link between knowing and not knowing may turn out to be just as crucial as the policy design itself.

10.3.3.2 Sufficiency of financial incentives

According to the survey report, it is evident that the financial incentives are insufficient. Although about 64% reported having applied for government subsidies, the process appears to be hindered by inefficiencies, leaving many discouraged or stuck in limbo.

Looking abroad, the picture is a bit different. In India, for example, the government has made financial incentives more accessible by offering subsidies and low-interest loans to small-scale biogas producers (Gurung, 1997; Mishra, 2019). Brazil takes a stronger route, offering grants and tax breaks that have given its biogas sector a noticeable push (Costa et al., 2024; Santos et al., 2018). The approach of Thailand combines financial support with technical expertise, promoting AD systems not only in rural villages but also in cities (Tantiwatthanaphanich and Zou, 2016). In Germany, where long-term commitment has paid off, the country has relied on subsidies, grants, and a well-established feed-in tariff system, which many argue has been at the heart of its biogas expansion (Thrän et al., 2023; Venus et al., 2021).

10.3.4 Local Government Regulations

10.3.4.1. Challenges with Local Regulations

In this study, about 22% of respondents reported difficulties with local government laws. The issues they mentioned most often were zoning restrictions, site approvals, and the sometimes lengthy process of environmental impact assessments. While this is not the majority, it does highlight real obstacles that can hinder progress in certain areas.

For comparison, India has taken steps to simplify local regulations, especially to encourage biogas projects in rural communities (Meena et al., 2024; Raha et al., 2014). Kenya appears to be moving in a similar direction by reducing bureaucratic red tape for renewable energy projects (Chanyisa, 2021). Germany, on the other hand, offers a different picture: local regulations there are closely aligned with national policies, which means biogas producers rarely encounter the same kinds of bureaucratic delays (Thrän et al., 2020).

10.4 SWOT analysis: Legal pillar of PESTEL

It’s quite clear that the legal dimension of the PESTEL framework strongly shapes how anaerobic digestion (AD) systems evolve in Bangladesh. This pillar covers regulations on renewable energy, environmental protection, waste management, and public health. Yet, the existing legal framework still feels incomplete. Ambiguities around bio-slurry use, the absence of clear feed-in tariffs or financial incentives, and overlapping permit requirements all suggest a system that, perhaps unintentionally, slows rather than supports progress. These regulatory gaps continue to hinder the scaling of AD initiatives needed to meet national sustainability goals.

The SWOT analysis that follows assesses the strengths, weaknesses, opportunities, and threats associated with this legal landscape, providing a clearer understanding of where the framework supports sustainable AD growth and where it appears to hinder it.

Table 10.1: SWOT Analysis of Legal pillar of PESTEL

Category	Key Points
Strengths	• Commitment to environmental protection: Bangladesh has established formal regulations, "*Environmental Conservation Rules" (ECR 2023),* that aim to manage waste, guide energy production, and protect the environment. • Draft biogas policy: A draft biogas policy now in progress offers some hope, outlining potential incentives, subsidies, and simpler approval procedures to strengthen institutional support.
Weaknesses	• Unclear rules on bio-slurry use: The rules and regulations governing the application of bio-slurry in agricultural fields remain uncertain. AD operators often feel insecure about acceptable, which hinders the adoption of new technologies. • No feed-in tariffs (FiTs): Bangladesh lacks a well-defined framework for FiTs in the AD sector. This lack of FiTs influences investors to view the AD sector as not viable for long-term investment, which hinders the AD project. • Bureaucratic hurdles in local approvals: Setting up an AD plant typically requires lengthy and complex dealings at the local government level. These prolonged administrations appear to discourage investors and slow down wider adoption. • Outdated legislation on biogas: Existing legal compliances are outdated and do not reflect current technologies or international best practices. This mismatch seems to act as a barrier rather than a bridge for the sector's growth.

Category	Key Points
Opportunities	• Legislative reform: Bangladesh could strengthen its approach to AD sector by developing more transparent and supportive policies. Practical lessons from the experiences of some countries (Germany, Denmark, India, Brazil) that are benefiting from the AD sector and have well-established growth in the industry can be an opportunity for Bangladesh. Following their practices regarding the AD sector can help grow this platform. • International collaboration can help modernise the legal framework and shape workable biogas guidelines, assuring potential investors that the sector is backed by credible, long-term planning. • Strengthening incentives: Implementing precise and up-to-date feed-in tariffs and subsidies in Bangladesh can help expand the AD sector.
Threats	• Regulatory uncertainty: Unclear and unpredictable regulatory requirements for the use of bio-slurry and FiTs can hinder the expansion of the AD sector in Bangladesh. • Bureaucratic delays: Bureaucratic delays, including lengthy approval processes and complex compliance requirements for AD plant setup, deter investors from adopting the AD system. • Enforcement challenges: Weak enforcement of environmental regulations and inconsistent policy support may hinder the growth of the AD sector.

This SWOT analysis highlights the legal challenges of Bangladesh in promoting sustainable anaerobic digestion (AD) growth, particularly unclear regulations, weak financial incentives, and bureaucratic barriers. It also identifies opportunities for reform and international collaboration.

Chapter 11: Systemic Interrelationships Among Critical Key Factors: A Causal Loop Diagram (CLD)–Based Systems Thinking Approach

11.1 Systemic interrelationships among critical key factors: a causal loop diagram (CLD)–based systems thinking approach

A high level of systemic complexity arises in Bangladesh when adopting AD for sustainable energy production and organic waste management. This complexity arises from a tangled web of interdependencies that span the country's political governance, economic viability, technological readiness, social acceptance, environmental responsibility, and legal regulation—factors often grouped under the PESTEL framework.

Using Causal Loop Diagrams (CLDs) can be a valuable tool for understanding this complexity (Brereton and Jagals, 2021; Tobin et al., 2022; Veldhuis et al., 2025). They can reveal how different variables interact and how delayed or indirect effects accumulate, sometimes producing unexpected patterns in the behaviour of the AD system (Meadow, 2008). Trying to untangle this problem often leads researchers to Causal Loop Diagrams (CLDs). These diagrams do not just connect boxes with lines; however, they suggest how small interactions might resonate through the system, bouncing back in loops that either build momentum or quietly dissipate it (Brereton and Jagals, 2021; Newberry and Carhart, 2024; Veldhuis et al., 2025). A well-meaning subsidy, for instance, could set off a reinforcing chain of adoption or, just as plausibly, spark resistance that cools the whole effort. CLDs can be useful not because they predict the future (they do not), but because they surface hidden feedback patterns and show how indirect or delayed effects can quietly accumulate into major shifts. It's the sort of thing Donella Meadows wrote about years ago: "complex systems rarely behave the way we expect them to, and by the time they do, it is often too late to steer them neatly".

In this study, a comprehensive CLD was developed to map the interconnections among critical factors influencing the growth of the anaerobic digestion sector in Bangladesh (discussed in the results chapters 4 to 10). The CLD (Figure 11.1 and Table 11.1) identifies 21 key feedback loops, comprising 10 reinforcing loops (R1–R10) and 11 balancing loops (B1–B11). Reinforcing loops represent self-amplifying mechanisms that accelerate growth, such as the expansion of government subsidies, technological innovation, social awareness, and community acceptance. Balancing loops, on the other hand, capture self-regulating or limiting forces, such as

institutional corruption, public resistance, environmental risks, and bureaucratic delays, which can counteract growth or slow the momentum of AD sectors' expansion.

And these forces sometimes collide, sometimes cancel each other out, and at other times send the whole system careening in directions no one planned for. For example, a push of government incentives and improvements in waste collection might trigger a surge of new AD projects (R1, R2); yet, a shortage of trained technicians or a labyrinth of red tape (B5, B11) can smother that surge almost overnight. This constant tug-of-war between reinforcing and balancing forces may explain why certain policies seem to suddenly gain momentum, while others, despite promising starts, fail to have a significant impact.

11.2 Reinforcing feedback loops (R1–R10)

Reinforcing loops (Table 11.1) describe the self-feeding dynamics that can push anaerobic digestion (AD) into a faster growth trajectory. They do not guarantee smooth progress, but once they catch on, momentum has a way of compounding, sometimes in ways no one reasonably anticipates.

11.2.1 R1: Policy–economy loop

Political stability forms the invisible scaffolding for large-scale renewable projects. In Bangladesh, those rare instances of steady leadership have, at times, given long-term policy frameworks a chance actually to take hold (GOV.UK, 2022). That is no small thing for a sector as infrastructure-heavy and capital-intensive as AD. A stable government with a constant agenda, it can implement incentives such as subsidies, low-interest loans, and feed-in tariffs, and, just as importantly, keep them in place long enough to have an impact (Hasan et al., 2022; Hossain, 2020).

In practice, however, these are the quiet, behind-the-scenes levers that can transform a risky spreadsheet proposal into something tangible and actionable. Covering part of the cost of hauling organic waste or offering capital support for building digesters can make projects feel less like a tangible (Roy and Kabir, 2020). With cheaper and more reliable feedstock, AD plants can run closer to full capacity,

which tends to boost yields. More output means better revenue, and once operators start showing consistent profit, investors get less skittish. That shaky but crucial sense of financial safety often cracks open the door for broader private-sector involvement (Miah et al., 2021).

From there, the whole thing can start looping back on itself: more plants get built, politicians rally behind a “success story,” and the sector reinforces its own momentum. The fragile bit, of course, is that this entire feedback loop hangs on political stability, never a given in a region where sudden policy shifts are practically routine.

11.2.2 R2: Technology–efficiency loop

Technological advancements serve as the primary driver of process efficiency and cost savings in anaerobic digestion. In Bangladesh, both universities and private R&D groups have played a growing role in shaping technologies tailored to local needs, such as high-solid digesters or modular units that can actually fit the scale of rural households (Islam and Khan, 2017; Patil, 2020). These designs seem to push yields higher while cutting down the digestion time, which, at least in practice, makes the whole system run more smoothly.

Improved AD technologies appear to offer a clearer path toward more effective waste management, encompassing everything from municipal waste to livestock manure and crop residues (Adeleke et al., 2023). By expanding what can be processed, these systems cut methane and other greenhouse gases, which, at least on paper, brings Bangladesh closer to its Paris Agreement and NDC commitments (Busari, 2025; DoE, 2023). That said, while the environmental case is strong, the actual translation into consistent policy support is often less straightforward (Kabir et al., 2019).

When policymakers recognise the dual benefits of reduced emissions and improved waste management, support for AD through incentives is likely to grow. This can create a reinforcing cycle where wider adoption encourages more research, though progress may still lag behind the urgency of the problems it aims to solve.

11.2.3 R3: Jobs and welfare Loop

The growth of the anaerobic digestion (AD) sector could open up a large number of jobs, especially in rural and semi-urban areas where steady work is often hard to come by. Employments are generated throughout the entire chain, not just in operating the plants, but also in constructing them, transporting feedstock, repairing equipment, and managing the leftover digestate (Hossain et al., 2021; Iqbal et al., 2014). For families living on the financial edge, that kind of steady income can make a significant difference, nudging households toward greater stability.

As earnings rise, families often end up spending more on basic needs, better food, healthcare when they actually need it, and school fees that were once out of reach. These small but visible changes tend to ripple through communities. People start to see AD not as some abstract “green” project, but as something that genuinely improves everyday life. That shift in perception can soften local resistance to new plants. And once the scepticism fades, projects tend to get off the ground more quickly. Over time, as adoption spreads, the cycle seems to feed itself, jobs and welfare rise together, reinforcing each other in a way that’s hard to ignore.

11.2.4 R4: Revenue–investment loop

Revenue generation often ends up being the make-or-break factor for whether anaerobic digestion (AD) systems can stand on their own financially. When plants manage to sell their biogas or feed electricity back into the grid, and when they can actually find buyers for the digestate as fertiliser, they start to see steady cash coming in (Hoo et al., 2018; Meena et al., 2024). That kind of consistency appears to lower the perceived risk for investors, which in turn makes the whole sector look like a safer investment.

Table 11.1: Reinforcing Feedback Loops (R1–R10) and Balancing Feedback Loops (B1–B11)

Reinforcing Feedback Loops (R1–R10)	Balancing Feedback Loops (B1–B11)
R1: Policy-Economy Loop Political Stability (P4) → (+) Government incentives & Loans (P3) → (+) Feedstock Availability & Price (Ec1) → (+) Revenue from AD (Ec5) → (+) Investment Security (Ec7) → (+) AD Growth Political Stability (P4) → (+) Government incentives & Loans (P3) → (-) Personal AD construction cost → (+) Revenue from AD (Ec5) → (+) Investment Security (Ec7) → (+) AD Growth	**B1: Social Resistance Loop** Social Stigma (S6) → (–) AD Growth → (+) increase Social Stigma (S6) → (-) AD Growth
R2: Technology-Efficiency Loop New Tech & Research (T5) → (+) Biogas Extraction Tech (T3) → (+) AD Growth → (+) Waste Management (En2) → GHG Emission Reduction (En1) → (+) Policy Support (P1) → (+) Government incentives & Loans (P3) → (+) AD Growth	**B2: Corruption-Planning Loop** Corruption (P5) → (-) Planning Quality (T1) → (–) Biogas Extraction Tech (T3) → (–) Waste Management (En2) → (–) AD Growth Corruption (P5) → (+) Plant Construction Cost (Ec2) → (–) AD Growth
R3: Jobs & Welfare Loop AD Growth → (+) Job Opportunities (Ec4) → (+) Household Welfare (S4) → (+) Community Support & Social Acceptance → (+) AD Growth	**B3: Renewable Energy Competition Loop** Feed-in Tariff (L5) → (+) Alternative Energy (T6) → (–) AD Tech Acceptance (S7) → (–) Revenue from AD (Ec5) → (–) Investment Security (Ec7) → (–) AD Growth
R4: Revenue-Investment Loop Revenue from AD (Ec5) → (+) Investment Security (Ec7) → (+) Job Opportunities (Ec4) → (+) AD Growth → (+) Revenue from AD (Ec5)	**B4: Labour Cost Loop** Labour Costs (Ec6) → (+) Plant Construction Cost (Ec2) → (–) AD Growth
R5: Awareness & Social Adoption Loop Information Dissemination (S2) → (+) Household Welfare (S4) → (–) Social Stigma (S6) → (+) AD Growth → (+) Community Awareness (S1) → (+) Information Dissemination (S2)	**B5: Technical Expertise Gap Loop** AD Growth → (+) Demand for Technicians (T7) → (–) Availability of Skilled Experts → (–) Operational Quality & Growth → (–) AD Growth
R6: Legal Incentives Loop Government incentives & Loans (P3) → (+) Feed-in Tariff (L5) → (+) Revenue from AD (Ec5) → (+) Investment Security (Ec7) → (+) AD Growth → (+) Landfilling Tax (P2) → (+) Government incentives & Loans (P3)	**B6: Environmental Compliance Loop** AD Growth → (+) Environmental Law Enforcement (L6) → (–) Flexibility for New Projects → (–) AD Growth
R7: Environmental Public Support Loop AD Growth → (+) Waste Management (En2) → (+) GHG Emission Reduction (En1) → (+) Policy Support (P1) → (+) Government incentives & Loans (P3) → (+) AD Growth	**B7: Environmental Risk Loop** AD Growth → (+) Post-treatment Demand (T4) → (+) Risk of Water Pollution (En6) → (–) Public Support → (–) AD Tech Acceptance (S7) → (–) AD Growth
R8: Education & Literacy Loop Information Dissemination (S2) → (+) Community Awareness (S1) → (+) Literacy Rate (S3) → (+) AD Tech Acceptance (S7) → (+) AD Growth → (+) Interest in AD → (+) Information Dissemination (S2)	**B8: National Coordination Gap Loop** Lack of National Coordination (P7) → (–) Policy Alignment & Program Synergy → (–) Implementation Efficiency → (–) Investment Security (Ec7) → (–) AD Tech Acceptance (S7) → (–) AD Growth
R9: Regulatory Quality Loop Biogas Guidelines (L3) → (+) Planning Quality (T1) → (+) Biogas Extraction Tech (T3) → (+) Biogas Output → (+) Revenue from AD (Ec5) → (+) AD Growth → (+) Regulatory Confidence	**B9: Technology Obsolescence Loop** Biogas Extraction Tech (T3) → (–) Operational Efficiency (T2) → (+) System Failures & Maintenance Needs → (–) AD Tech Acceptance (S7) → (–) User Satisfaction & Social Acceptance → (–) Community Awareness (S1) → (–) User Adoption → (–) AD Growth
R10: Digestate Utilization Loop AD Growth → (+) Digestate Production → (+) Fertilizer Protocol (L4) → (+) Farmer Adoption → (+) Agricultural Benefits → (+) Household Welfare (S4) → (+) AD Growth	**B10: Feed-in Tariff Absence Loop** Feed-in Tariff (L5) → (–) Biogas-to-Grid Revenue Potential → (–) Revenue from AD (Ec5) → (–) Investment Security (Ec7) → (–) Financial Attractiveness → (+) Alternative Energy (T6) → (–) AD Growth
	B11: Bureaucratic Barrier Loop Bureaucratic Complications (P6) → (–) Permit & License Approval Speed → (–) Planning Quality (T1) → (+) Project Delays & Transaction Costs → (+) Plant Construction Cost (Ec2) → → (–) AD Growth

Still, “safe” can be a slippery word here. The flow of investment doesn’t always follow logic alone; it often hinges on shifting policies or even the mood of the market. But when investors do feel confident, money tends to move in. Those financial inflows can fund new plants, expand infrastructure, and create jobs, each piece feeding into the next.

As more people get involved and plants scale up operations, revenue usually grows, especially when projects are set up to pull income from several streams at once. At that point, the cycle starts to reinforce itself: higher profits encourage more trust, which draws in even more capital. If all goes well, that momentum can push the whole AD sector into its next phase of growth.

11.2.5 R5: Awareness and social adoption loop

The dissemination of positive information can subtly reshape how people think, and it often sets the pace for social change. Campaigns that highlight the health, economic, and environmental upsides of AD may shift public attitudes (Ghafoor et al., 2016; Karim et al., 2019). When households start to see the appeal of cleaner cooking fuels or notice fewer smoky stoves making them cough, they are more inclined to support or at least not resist the idea of AD systems installation.

As some families experience the benefits, the long-standing stigma around waste-to-energy technologies begins to decline. These AD systems, once considered dirty or unhealthy, start to seem less threatening. As that perception softens, communities grow more willing to install and use biogas units. Each new system makes the technology more visible, sparking curiosity, building local awareness, and nudging the cycle forward. Step by step, AD will become popular and a regular part of everyday life.

11.2.6 R6: Legal Incentives loop

Legal processes, such as feed-in tariffs and landfill taxes, often set the background for how energy markets evolve. Feed-in tariffs, for instance, assure AD operators/ owners a fixed price for their produced electricity, which appears to offer a sense of long-term profit stability (Chowdhury et al., 2025; Karmaker et al., 2020; Patil, 2020).

That kind of confidence can make AD systems seem less risky and more appealing to careful stockholders (investors).

Rising revenues can boost investor confidence, leading to more AD projects that reduce landfill waste and generate environmental and economic gains. Seeing this, policymakers may raise landfill taxes to promote resource recovery and redirect the revenue toward AD incentives, reinforcing the positive cycle.

11.2.7 R7: Environmental public support loop

AD systems can bring clear environmental gains, primarily by minimising organic waste and curbing greenhouse gas emissions. By handling waste in a more controlled way, they may help reduce the open dumping and unregulated landfilling that often contaminate soil, pollute waterways, and release methane (Mudassar, 2021).

As local conditions start to improve, public attitudes toward AD tend to soften. Communities and sometimes NGOs begin pushing for broader use, seeing it as a step toward cleaner surroundings. Policymakers, picking up on both public sentiment and environmental data, often respond with grants, policy support, or awareness drives. Each new installation then adds to the visible benefits, which strengthens public support and nudges the cycle forward.

11.2.8 R8: Education and literacy loop

Education often lays the groundwork for a society's readiness to embrace new technologies. Campaigns that explain how AD systems work can raise community awareness and, step by step, build broader literacy around sustainable energy. As people start to understand the basics, they seem more likely to accept and even invest in AD systems (Karim et al., 2019; Kraij, 2009).

As acceptance grows, deployment picks up pace, and AD becomes more visible in everyday life. That visibility tends to spark curiosity among students, local entrepreneurs, and even government officials. Their interest often leads to more research, discussion, and knowledge-sharing, which feeds back into more

transparent communication and stronger energy literacy, tightening the cycle of education and adoption.

11.2.9 R9: Regulatory quality loop

Clear and consistent regulation is often what gives investors the confidence to commit and helps projects run smoothly. The introduction of national biogas guidelines appears to have improved how AD projects are planned, designed, and rolled out (Power Division, 2018; Singh et al., 2018). When the rules are straightforward, administrative slowdowns are less common, and quality control in procurement and installation is easier to maintain.

Better planning usually leads to more reliable biogas extraction and stronger system performance. Higher gas output boosts economic returns, which in turn fuels further growth of AD projects. As these successes add up, regulatory bodies gain confidence in the sector and are more likely to refine and expand their guidelines, tightening the feedback loop.

11.2.10 R10: Digestate utilisation loop

Digestate (the by-product of anaerobic digestion) is rich in nutrients and can be used as an organic fertiliser in sustainable agriculture. When proper fertiliser protocols are in place, farmers are more willing to adopt digestate instead of chemical fertilisers (Khan and Martin, 2016; Salam et al., 2020). This adoption results in improved soil health, increased crop yields, and cost savings for farmers.

In rural farming communities, these agricultural benefits directly improve household welfare and enhance the public perception of AD, encouraging broader support and adoption. Thus, an increase in AD adoption leads to higher digestate production, ensuring the loop continues.

11.3 Balancing feedback loops (B1–B11)

The balancing loops (as illustrated in Table 11.1) represent self-regulating dynamics that constrain or stabilise the growth of anaerobic digestion (AD), mainly when key limiting factors interact. These include:

11.3.1 B1: Social resistance loop

One of the most stubborn obstacles to adopting AD technologies in Bangladesh seems to be the social stigma tied to waste-based energy systems. This stigma, related to cleanliness, caste, and the perceived “unclean” nature of handling organic waste, often discourages public (pushback against AD projects) towards AD adaptation, particularly in rural and peri-urban communities (Mittal et al., 2018; Nevzorova and Kutcherov, 2019). Even when a system is technically sound or backed by funding, this resistance slows the AD sector expansion.

Once a few AD systems prove successful, scepticism begins to fade. Visible benefits, cleaner fuel, reduced smoke, and extra income, encourage community support and awareness, creating a feedback loop where early success helps overcome initial resistance.

11.3.2. B2: Corruption–planning loop

Corruption in administrative processes often acts as a quiet but powerful brake on the spread of decentralised renewable energy systems in places like Bangladesh. Within the AD sector, it tends to warp strategic planning, skewing priorities, inflating budgets, and allowing projects to go ahead with shaky execution. Biased procurement, for example, can push contracts toward poorly qualified firms, lead to badly chosen sites, or bypass critical steps like environmental impact assessments (Khatun, 2021; Transparency International, 2023).

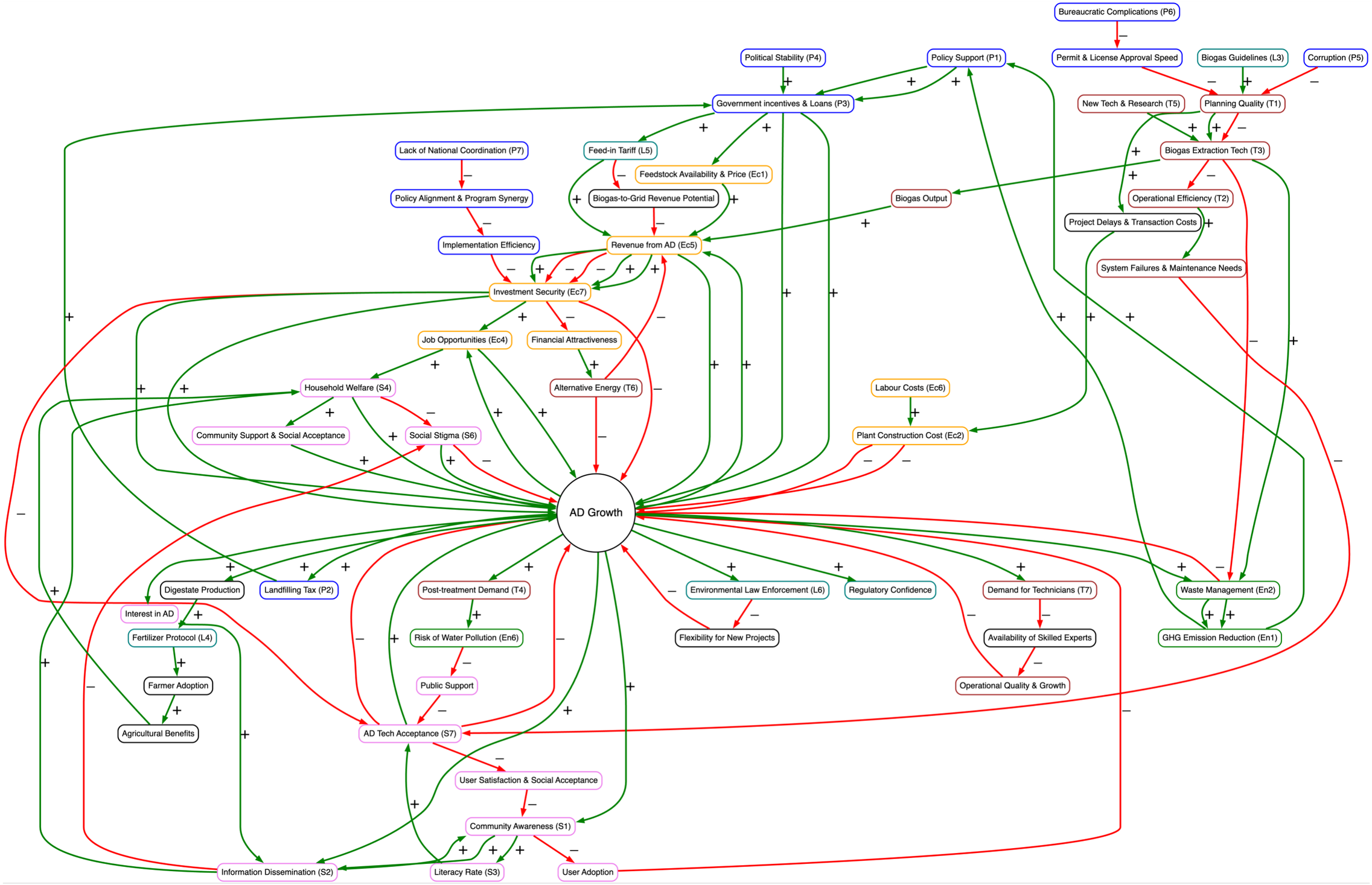


Figure 11.1: **Causal Loop Diagrams (CLDs)**—offers a powerful lens through which to analyse the dynamic behaviour of the AD system in Bangladesh.

These cracks in planning usually echo down the line. Subpar technology ends up installed on the ground, plants produce less biogas than expected, and some fail altogether. When that happens, the promised gains in waste management barely materialise. The sector's credibility takes a hit, returns drop, and investors grow cautious. It becomes a self-reinforcing loop: institutional dysfunction seeps into technical performance, and that underperformance, in turn, slows the broader push for AD development.

11.3.3. B3: Renewable energy competition loop

In Bangladesh, the rapid growth of solar photovoltaics, solar home systems, and mini-grids has started to crowd the field, often pulling both funding and policy attention away from AD. Solar, with its steady international backing and relatively straightforward setup, has become the go-to option for many public and private actors (Mushtaq et al., 2016; Tucho et al., 2016).

As these alternatives gain ground, the revenue prospects for AD systems seem to shrink, especially when biogas-based electricity has no real grid integration or feed-in tariff to rely on (Nasrin et al., 2018). Lower returns chip away at investor confidence and cast doubt on the long-term stability of AD projects. In this way, competition from other renewables quietly works as a balancing force, slowing, and at times even reversing, the growth of niche technologies like AD when policy support does not line up (Roy and Kabir, 2020).

11.3.4. B4: Labour cost loop

Labour market pressures often quietly limit how far AD can expand. As construction ramps up, the demand for skilled and semi-skilled workers rises, and in places where the labour pool is already stretched or competing sectors like garments, road building, or housing are hiring aggressively, wages tend to climb (Mushtaq et al., 2016; Tucho et al., 2016). Those rising wages push up the upfront costs of building new AD plants.

For smaller or mid-sized investors, especially without targeted subsidies, those higher costs can be enough to make projects look risky or outright unviable. When that happens, new installations slow down, and the sector's momentum fades. It

becomes a balancing loop, where rising labour costs quietly drag on growth—mirroring how broader economic pressures like inflation or regional wage gaps can undercut the staying power of green infrastructure projects.

11.3.5. B5: Technical expertise gap loop

Running an anaerobic digestion system isn’t exactly plug-and-play, it depends on steady operation and careful maintenance from trained staff. As more plants come online, the demand for biogas technicians and process engineers continues to rise. Yet vocational and technical institutes in Bangladesh do not seem fully prepared to supply a consistent trained personnel with proper skills (Angelidaki et al., 2018; Ryckebosch et al., 2011).

That gap leaves many systems poorly maintained or operated through trial and error, which can drag down efficiency and reduce biogas output (Rahman et al., 2020). When plants underperform, users get frustrated, word spreads, and public confidence starts to wobble. As the sector's reputation weakens, adoption slows. It's a familiar pattern, growth stalls not because of technology itself, but because the human resource system around it can’t quite keep pace.

11.3.6. B6: Environmental compliance loop

As the AD sector expands, regulatory bodies will tighten the rules by setting rules for environmental impact assessments, digestate handling, and emissions control. That kind of scrutiny is meant to prevent new ecological harm; however, it can also make project approvals take longer and be less flexible (DoE, 2019; Hossain, 2024).

More rigid rules often result in drawn-out timelines, increased administrative costs, and sometimes outright rejection of projects in sensitive areas. It is a bit of a double-edged sword: it protects ecosystems, but it can also stall growth when no supportive pathways exist. This loop shows the uneasy push-and-pull between safeguarding the environment and trying to scale green technologies quickly.

11.3.7. B7: Environmental risk loop

As more AD systems come into operation, dealing with their by-products, especially liquid digestate and effluent, needs more attention for treatment. When post-treatment infrastructure is lacking, or waste is handled carelessly, the result can be leaching, surface water contamination, and public health problems (Iqbal et al., 2014, 2014).

Such events rapidly sour public opinion. Once trust is shaken, communities become far less willing to host new projects. With acceptance dropping and a slow adoption rate the AD sector growth tapers off. This loop makes it clear how critical proper safeguards and infrastructure are for protecting both the environment and the reputation of renewable technologies.

11.3.8 B8: National coordination gap loop

In Bangladesh, the push for renewable energy often becomes entangled in policy fragmentation among ministries, including energy, environment, agriculture, and local government. This lack of coordination tends to create mismatched funding schemes, duplicate pilot projects, and sometimes even contradictory rules (Hasan et al., 2020; Jannatul, 2016; Sarker et al., 2020). As agencies pull in different directions, progress slows, investors lose patience, and confidence slips away. Over time, this kind of institutional disconnection quietly undermines both technology uptake and public trust, making it harder for decentralised AD systems to take root.

11.3.9 B9: Technology obsolescence loop

Poor planning, limited budgets, and at times corruption lead to the use of outdated or poorly matched AD technologies, reducing efficiency and reliability (Jannatul, 2016; Sarker et al., 2020). As plants underperform, users grow frustrated, trust declines, and adoption slows, creating a cycle that weakens overall sector growth. This pattern may also discourage future investments, as potential users become wary of system failure. Over time, such repeated disappointments can quietly erode public confidence in renewable energy initiatives more broadly.

11.3.10 B10: Feed-in tariff absence loop

The lack of a clear feed-in tariff (FiT) system for produced electricity/gas makes it difficult for AD operators/owners in Bangladesh to gain reasonable revenue. Without a foreseeable revenue stream, biogas-to-electricity projects often appear risky and unattractive to investors (Carlini et al., 2017; Kumaran et al., 2016).

With a decline in interest, the AD owner loosens capital, and thus confidence slips. Investors and financiers of the renewable energy sector are gradually shifting their attention to safer projects, such as solar or mini-grids, because of uncertain FiT. That shift pulls policy focus away from AD even further, creating a loop where regulatory gaps quietly undercut the technology's chance to gain traction.

11.3.11 B11: Bureaucratic barrier loop

Bureaucratic obstacles (complex permit processes, land disputes, and overlapping regulatory authorities) often delay the planning and implementation of AD projects (Hossain, 2017). These delays increase transaction costs and create uncertainty, and make investments vulnerable by increasing transaction costs.

As costs increase and returns grow unpredictable, momentum stalls. This loop illustrates how administrative complexity can quietly hinder AD sector progress unless governance begins to loosen its grip.

11.4. Strategic recommendations for sustainable anaerobic digestion development in Bangladesh

In Bangladesh, expanding AD plant installations alone does not guarantee sectoral progress, as outcomes depend on institutional, social, and environmental factors. Drawing on CLD insights, this section proposes time-bound policy directions grounded in systems thinking and adaptive governance, acknowledging that sustainability transitions rarely unfold in a linear manner.

11.4.1 Short-term recommendations

Short-term interventions focus on relatively accessible points, such as policy parameters, administrative procedures, and information flows. These initiatives can produce immediate system responses by accelerating and enabling feedback loops and mitigating low-level resistance.

*11.4.1.**1 Reforming the feed-in tariff (FiT) mechanism***

The revision of biogas-specific feed-in tariff policies represents a critical yet technically straightforward intervention. Although changes to FiT levels can significantly influence investor confidence and improve project viability in the short term (Sterman, 2000). A differentiated FiT structure that accounts for the unique production characteristics of biogas and guarantees long-term grid access could catalyse financial flows into the AD sector. However, this must be complemented by compliance mechanisms that ensure environmental safeguards, such as mandatory digestate treatment (R6, B10).

11.4.1.2 Streamlining permitting and licensing procedures

Administrative bottlenecks and slow-moving bureaucracy remain widely cited hurdles in Bangladesh's infrastructure projects (B11). Setting up a digital one-stop portal for AD project approvals, encompassing everything from land-use permits to environmental clearances and grid connection requests, could significantly reduce much of the red tape. It would not solve the deeper structural problems lurking underneath, but it might speed things up enough to make a noticeable difference, easing transaction costs and shortening development timelines. That kind of efficiency could, in turn, strengthen the planning-related feedback loops (R2, R9) that often stall out before they gain momentum.

11.4.1.3 Launching public awareness and education campaigns

Public perception can quietly make or break new technologies, and AD is no exception. Information flow shapes how people respond, often more than the technology itself (R5, R8). Well-aimed awareness campaigns, especially

those that speak directly to local misconceptions or cultural stigma around waste-based systems, might not convert everyone overnight, but they can chip away at resistance (B1) and gradually build community interest and trust (R3).These initiatives should prioritise culturally relevant narratives delivered through trusted institutions such as local NGOs, religious leaders, and community educators. In systems terms, these campaigns represent medium-strength, medium-feasibility interventions with the potential to unlock latent reinforcing loops in public perception.

11.4.1.4 Supporting small-scale AD deployment in rural communities

Subsidising household- or community-level digesters in rural agricultural zones provides an opportunity to link AD with rural energy access, sanitation, and agriculture. This recommendation is closely tied to reinforcing loops related to welfare (R3) and digestate utilisation (R10), and may be effectively implemented through existing government microcredit and energy access schemes.

11.4.2. Medium-Term Recommendations

Medium-term strategies target structural points, such as regulatory frameworks and institutional coordination. These actions are more politically and administratively demanding but offer significant systemic returns.

11.4.2.1 Enhancing environmental enforcement and monitoring

Ensuring compliance with environmental standards is critical for sustaining public trust and mitigating unintended ecological consequences (B6, B7). Investment in institutional capacity-building, including staffing, laboratory infrastructure, and mobile monitoring units, is essential for enforcing digestate handling, emissions control, and land use norms. Though more challenging than parameter changes, legal reinforcement improves both legitimacy and accountability in AD expansion.

11.4.2.2 Strengthening inter-ministerial coordination

Anaerobic digestion in Bangladesh sits at the crossroads of several ministries, Power, Energy and Mineral Resources (MoPEMR); Environment, Forest and Climate Change (MoEFCC); Local Government; and Agriculture. The problem is, they rarely move in step. Weak horizontal coordination (B8) tends to produce patchy policies and frustrating delays. Creating a National Biogas Task Force or some equivalent high-level body, could help these institutions pull in the same direction. It would not be a cure-all, but it might at least bring some coherence to energy, waste, and agriculture policies, allowing key reinforcing loops (R1, R6, R9) to work together instead of at cross purposes.

11.4.2.3 Developing technical training and certification programs

Right now, the growth of AD projects seems to be outpacing the pool of people who actually know how to build, run, and maintain them (B5). Supporting vocational schools and polytechnic institutes in offering AD-focused training, ideally in partnership with industry, could help begin to close that gap. Standardised certification for digester construction, daily operations, and post-treatment practices may not sound glamorous, but it would likely improve reliability and create new job opportunities, especially in rural areas. Strengthening this technical backbone could also feed into loop R2, which depends on dependable day-to-day operations.

11.4.2.4 Promoting digestate valorisation and agricultural Integration

Digestate often ends up as an afterthought, yet it could be a real bridge between the energy and agricultural sectors. Treating it as a co-product rather than waste would require clear quality standards, practical farmer training, and local marketing channels that actually move the material. If done well, formalising digestate use could boost both the profitability and public perception of AD systems, helping loops R10 and R3 gain traction.

11.4.3. Long-term recommendations

Long-term interventions concern deep systems control points, such as mental models, value systems, and overarching policy goals. These changes are slow and politically sensitive, but they represent the most powerful levers for sustained transformation.

11.4.3.1 Embedding AD within the national energy and climate strategy

To achieve long-term viability and integration, AD must be recognised as a waste management technology and a strategic pillar of Bangladesh's energy, agricultural, and environmental future. This requires embedding AD targets and metrics into the country's Nationally Determined Contributions (NDCs), Sustainable Development Goals (SDGs), and the Renewable Energy Policy 2023. Such a shift redefines the system's goals and enables the reorganisation of financial and institutional priorities around circular bioeconomy principles.

11.4.3.2 Transforming social norms through public education

The social stigma associated with waste, sanitation, and biogas remains prevalent in society (B1), subtly influencing people's attitudes toward new technologies. To break the mindset of the general public may take more than a few awareness campaigns; however, it requires steady, long-term shifts in education. Implementing ideas of sustainability and the circular economy into national school curricula, madrasa syllabi, and public university programs could gradually familiarise/ popularise them. On a more local level, community-based learning hubs and small recognition programs for early adopters of AD might also be helpful. When people see their peers being celebrated, it can start to shift the story they tell themselves about what's acceptable or even admirable. If done well, these changes can create self-reinforcing momentum in public behaviour and demand for better policies.

11.4.3.3 Establishing a national AD roadmap (2025–2040)

It also seems crucial for the government to map out the future of the AD sector. A clear and phased roadmap could provide the direction that includes setting targets for capacity growth, workforce training, policy milestones, and monitoring systems. Planning tools that use scenario modelling, grounded in CLD logic and system dynamics, may help decision-makers stay flexible when things do not unfold as expected.

11.5 Sector Analysis of the Bangladesh AD Extension Programme

The PESTEL framework and the Causal Loop Diagram developed in this research provide a systemic map of the macro-environmental factors and feedback structures influencing AD sector growth. A complementary analytical perspective is offered by a sector analysis: an examination of the specific institutional sectors whose active and coordinated engagement is a necessary condition for a sustainable national extension programme. This approach is embodied in Nepal's Biogas Sector Partnership (BSP-Nepal), originally established by SNV in 1992 and subsequently managed by the Alternative Energy Promotion Centre (AEPC), which explicitly structures coordination between government, finance, agriculture, health, and civil society actors (Surendra et al., 2014; IDCOL, 2020). The comparative success of the Nepal programme, which has achieved substantially higher household penetration than Bangladesh despite comparable economic conditions (Section 2.4.2; MoFE, 2021; World Bank, 2020), suggests that this multi-sectoral coordination is not incidental to programme performance but central to it. The following analysis applies this sectoral lens to Bangladesh, identifying the current state and potential contribution of each relevant sector to the sustainable development of the Level 1 AD programme.

11.5.1 The Political Sector

As discussed in Chapter 5, the political sector was identified by stakeholders in this research as exerting a predominantly negative influence on AD sector growth, with the absence of dedicated policy provision for household biogas systems emerging as a recurrent concern (Section 5.2.6; Power Division, 2008; MoEF, 2009). The

Renewable Energy Policy of 2008 makes only brief reference to biogas, and the Power System Master Plan 2016 addresses the sector primarily through the proposed adoption of glass-fibre digesters rather than through a coherent extension framework (Power Division, 2016; Power Division, 2018). This stands in contrast to Nepal, which published a detailed plan for the small-scale AD sector in its Rural Energy Policy of 2006, and Vietnam, which articulated a national AD strategy in 2011 (Dao et al., 2020; SNV-Vietnam, 2020).

The political transition of 2024 has, however, altered the context in a potentially significant way. The interim administration was advised by Professor Muhammad Yunus, founder of the Grameen Bank and, through it, of Grameen Shakti, an organisation with more than two decades of practical experience in rural renewable energy extension in Bangladesh (IDCOL, 2020; Hossain, 2020). This creates an opportunity to anchor household biogas policy within a national framework informed by field-level operational experience rather than by projections drawn from larger-scale renewable technologies. A reformed policy that explicitly recognises the savings-led financial model of household AD, provides an adequate per-plant subsidy, and integrates bio-slurry promotion into agricultural extension would address several of the structural weaknesses identified in this research (Section 5.3; Hasan et al., 2020).

11.5.2 The Financial Sector

At Level 1 household scale, the appropriate financing mechanism is a low-interest agricultural loan structured around the cost savings that the technology generates, rather than investment finance of the kind appropriate to Level 2 commercial systems (Section 6.3.5). The findings of this research confirm that the savings generated by a functioning household plant, a statistically significant mean reduction of BDT 1,335 per month in fuel expenditure (Section 6.3.3.2), are sufficient to service loan repayments over a three-to-five-year term, provided that loan terms are appropriately structured.

The current NDBMP-IDCOL framework provides subsidised loans through partner organisations, but stakeholders in this research rated government support and bank loan policy negatively, citing high loan rates, scarce subsidies, and complex

application procedures as persistent deterrents (Section 5.2.7; IDCOL, 2020). The per-plant subsidy of BDT 7,000 represents only 13 to 20 % of typical construction costs and has been widely criticised as inadequate (Power Division, 2018; NDBMP-IDCOL, 2013). By contrast, IDCOL's Solar Home Systems programme demonstrates what accessible financing, adequate subsidy, and streamlined procedures can achieve, having enabled millions of rural households to adopt solar energy (IDCOL, 2020). International comparison reinforces this point: India's capital subsidies, interest subsidies, and tax benefits have accelerated biogas adoption, while Vietnam's provision of low-interest loans has fostered a conducive environment for AD growth (Kumar and Majid, 2020; Thoa, 2020; Urban et al., 2018).

Expanding the role of microfinance institutions with established rural outreach, lower lending costs, and proven loan recovery systems within the biogas financing chain represents the most direct route to extending programme reach to the poorest farming households (Hossain, 2020; Mwirigi et al., 2014).

11.6.3 The Agricultural Sector

The agricultural sector is, on the evidence of this research, the sector whose engagement is most urgently required and most substantially neglected within the current programme architecture. The economic value of bio-slurry as a fertiliser substitute is considerable: surveyed households using bio-slurry in agriculture reported annual savings of between BDT 27,000 and BDT 30,000 (£270 to £300) through reduced chemical fertiliser expenditure (Section 6.3.2). Bio-slurry contains nitrogen, phosphorus, and potassium in plant-available forms, and its consistent application improves soil structure, water retention, and long-term fertility (Möller and Müller, 2012; Bond and Templeton, 2011; Svensson et al., 2004).

Yet this value remains substantially unrealised. Only 44% of surveyed households used bio-slurry in agriculture at all, and only 20% were able to utilise their full slurry output, with land availability the principal constraint (Section 6.3.2). Comparison with Nepal is instructive: Gautam et al. (2009) report that approximately 60 per cent of Nepali biogas users apply slurry as organic fertiliser, a markedly higher rate than that observed in Bangladesh. In India, rising chemical fertiliser costs have driven

comparable uptake, with documented reductions in fertiliser expenditure of up to 20% annually (Katuwal and Bohara, 2009; Sinha et al., 2020).

Realising this benefit in Bangladesh requires agricultural extension services that understand the nutritional composition of bio-slurry, the value of composting and vermiculture prior to application, and the difference in agronomic effect between raw dung and processed slurry. At present, the institutional link between the energy sector, which administers the NDBMP, and the national agricultural extension system remains weak. Joint training programmes, integrated extension services, and demonstration plots would unlock substantial value from infrastructure investment already made.

11.5.4 The Health Sector

The survey findings reported in Chapter 9 provide direct evidence of the health benefits of household biogas adoption. Statistically significant improvements were recorded in kitchen air pollution ($p < 0.0001$), eye infections attributable to smoke, and smoke-related respiratory infections following the transition from biomass fuels to biogas (Section 9.3). These findings are consistent with international evidence on the health burden of household solid fuel combustion, which falls disproportionately on women and children who spend the greatest time near the cooking fire (Puzzolo and Pope, 2017; Quinn et al., 2018).

The economic significance of these health improvements is systematically underrepresented in programme financial analyses. Reduced incidence of respiratory and ocular illness translates into lower household medical expenditure and reduced demand on public health services, benefits documented in comparable settings in Kenya, India, and Bangladesh (Mwirigi et al., 2014; Katuwal and Bohara, 2009; Islam et al., 2013). Engaging the health sector in documenting, quantifying, and communicating these benefits would strengthen both the public health case for programme expansion and the economic case presented to individual households considering investment.

11.5.5 The Publicity and Communications Sector

Social acceptance emerged in this research as a significant constraint on adoption. Stakeholders identified limited public knowledge and awareness of biogas technology as a persistent barrier, noting that dissemination of information about AD is negligible compared with that for solar energy (Section 7.2; Power Division, 2018). More specifically, cultural resistance to using gas derived from animal dung and organic residues for cooking was identified as a factor in some rural communities, alongside a general reluctance to adopt unfamiliar technologies in place of traditional practices (Section 7.2; Hossain, 2020; Zaman et al., 2019).

Experience from Nepal indicates that sustained, accessible public communication can materially influence uptake. In the contemporary communications environment, social media content creators with authentic reach into rural communities may be able to perform a comparable function to that historically played by print journalism. The cultural and religious dimensions of resistance to biogas adoption are likely to be addressed more effectively through trusted local voices than through formal government messaging. This sector has not been strategically engaged within the NDBMP outreach framework, and its potential remains largely untapped.

11.5.6 The Education and Research Sector

Universities and research institutions have contributed to the Bangladesh AD sector through technical surveys, performance assessment, and analytical work, including the research reported in this thesis (Khan and Martin, 2016; NDBMP-IDCOL, 2013; Mang et al., 2017). Educational institutions were also represented among the expert stakeholders consulted through the Delphi process in this research (Section 3.3.6).

There is, however, a risk that the education sector, by orienting toward advanced technologies or comparators drawn from more developed economies, may advocate approaches poorly matched to Level 1 operational realities. The evidence of this research indicates that the most acute technical constraints at household level are elementary rather than advanced: only 50 % of biogas plant operators surveyed nationally in 2012 had received training in operation and maintenance (NDBMP-IDCOL, 2013); construction defects arising from inadequate mason training are a recurrent cause of failure (Khan and Martin, 2016; Ghafoor et al., 2016); and stove

clogging persists partly because of a shortage of trained local repair technicians (Khan and Martin, 2016; Salam et al., 2020).

The most valuable contribution of the education sector at Level 1 is therefore the training of masons, field officers, and programme managers in directly applicable skills, together with applied research addressing practical failure modes: better-performing stove burners, more reliable pipe fittings, and improved construction quality standards. This orientation aligns with the capacity development principle on which the programme's institutional architecture was originally founded (Section 2.3.1; Ubels, Acquaye-Baddoo and Fowler, 2010).

11.5.7 The Environmental Sector

The environmental benefits of household AD adoption in Bangladesh are substantial but are not consistently articulated in terms that connect to the mandates of environmental sector organisations. The survey findings demonstrate a statistically significant reduction in household firewood consumption following plant installation, with households saving between 220 kg and 400 kg of firewood monthly depending on plant size (Section 6.3.1; Section 6.3.3). Aggregated across the approximately 107,353 household plants installed nationally, this represents a materially significant reduction in pressure on forest resources (IDCOL, 2020; SREDA, 2020).

Comparable effects have been documented internationally. In Kenya, biogas adoption has sharply reduced household fuelwood consumption with consequent reduction in pressure on local forests (Njenga et al., 2019); similar findings are reported from Nepal, India, and Ethiopia (Katuwal and Bohara, 2009; Bedi et al., 2020; Tucho et al., 2021). In the coastal districts of Bangladesh, reduced firewood demand carries particular significance given the role of mangrove ecosystems in coastal protection, carbon sequestration, and habitat provision.

Engaging environmental sector actors, including conservation organisations, the Department of Forests, and international climate funders, as advocates for and potential co-funders of the AD extension programme would provide both additional resources and a broadened constituency for programme expansion. The opportunity to access international climate finance mechanisms, identified in the political pillar

SWOT analysis as an underexploited opportunity (Table 5.1), is most likely to be realised through such partnerships.

Finally,The sector analysis presented above indicates that the constraints on Level 1 AD sector growth in Bangladesh are not confined to any single institutional domain, and that the programme's current architecture engages only a subset of the sectors whose contribution is required. The financial and political sectors are engaged but inadequately resourced; the agricultural, health, communications, and environmental sectors remain substantially disengaged despite each holding capacity to address a specific constraint identified in this research. The Nepal BSP model demonstrates that structured multi-sectoral coordination is achievable within a comparable economic context. Bangladesh needs a similar coordinating body to bring these sectors together under one shared framework.

11.6 Summary

This well-developed Causal Loop Diagram (CLD) in this research serves as both a diagnostic map and a strategic guide. This CLD will help to understand the progress of the anaerobic digestion (AD) sector in Bangladesh. It does not claim to predict outcomes with certainty. Still, it does make visible the web of political, economic, technological, social, environmental, and legal (PESTEL) factors that keep pulling the system in different directions. Some loops push progress forward, others quietly hold it back.

In the short term, interventions such as a feed-in tariff or a well-timed awareness campaign can certainly spark momentum. Without better coordination across institutions, tighter enforcement of rules, or a genuine shift in public attitudes toward waste, the system tends to fall back into its old patterns. In fact, progress can be cancelled out altogether by competing forces already built into the system.

From that angle, the CLD does not provide policymakers with a tidy checklist, but rather a way to see the bigger picture. It reminds them that problems do not occur in isolation; they are reinforced, delayed, or undermined by feedback. Knowing where those loops accelerate or stall change makes it easier to identify leverage points—places where even modest action could shift the longer-term direction.

Of course, this approach does not erase uncertainty. However, it does encourage a style of governance that adapts more easily, avoids one-off fixes, and aligns decisions with Bangladesh's complex realities in energy and the environment. The diagram is not a "solution," but a lens. It suggests how the AD sector might evolve if policies or institutions shift, and it offers a starting point for designing interventions that are not only technically sound but also politically workable and socially acceptable. Done right, that could edge the country closer to its development goals while still keeping sustainability in view.

Chapter 12: Conclusion

12 Conclusion

This thesis, “An exploration of the key factors influencing the success and failure of small-scale anaerobic digestion (AD) programmes in Bangladesh,” set out to make sense of the tangled forces shaping the country’s AD sector. Anaerobic digestion may offer a way to tackle two persistent challenges: waste management and energy shortages. In this research, our findings suggest that its success hinges on a delicate balance of social, technical, and other systemic factors; however, failure to ensure the balance of these pieces can cause the entire system to fail.

12.1 Challenges

A few patterns kept showing up. Politically, the institutional landscape is fragmented. Due to overlapping policies, different government bodies often lead to jurisdictional conflicts, paperwork drags on for months, and occasional corruption quietly derails the progress that is made. Policies do exist, but they often stall halfway between drafting and doing.

The economics are not exactly reassuring either. High startup costs deter potential investors, and the market for by-products like biogas and digestate remains unstable (more of an idea than a functioning marketplace). Without steady buyers or predictable pricing, it is hard to argue that small-scale AD is financially sound, and most people can sense that risk.

Public attitudes add another quiet layer of resistance. In many rural communities, working with organic waste is still viewed as something shameful or even “unclean.” Public awareness campaigns have tried to chip away at that, but they often come across as abstract or out of touch with local realities. People can not embrace a technology they instinctively distrust.

Technology itself has not kept pace either. There are not enough trained technicians to install or maintain systems, and local R&D efforts are scattered and underfunded. Many existing digesters run far below capacity, which only deepens the perception that they’re not worth the trouble.

Environmental conditions do not make things easier. Feedstock availability fluctuates with the seasons, while the challenges of securing water are becoming harder to overcome, and reliable waste collection systems are still missing in many regions. These issues may seem secondary, but they silently weaken the base that AD projects need to survive.

And then there is the legal framework, which is technically present, but often dense, confusing, and clearly written with large operators in mind. From a distance, it looks like support exists, but up close, it is more like a maze. For small-scale AD projects, it offers little real protection or guidance.

12.2 Key opportunities

Despite the challenges, the study finds many opportunities to scale up small-scale AD programmes. Bangladesh's warm tropical climate is conducive to AD operations. Community engagement, if done sensitively, can be a pathway to building grassroots support and adoption. Integrating AD into national waste management strategies can create synergy between renewable energy generation and waste disposal. With the growing focus on climate action and access to international funding mechanisms, there is an opportunity to secure funding for AD initiatives.

12.3 Knowledge contribution

This research makes distinct contributions to knowledge across three dimensions: theoretical, methodological, and practical. Each contribution is articulated below with explicit reference to the sections of this thesis in which the underlying analysis is presented.

12.3.1 Theoretical Contributions

12.3.1.1 Extension of the PESTEL framework to small-scale renewable energy transitions in a low-income country context

The PESTEL framework has been widely applied to corporate strategy and to large-scale infrastructure assessment, but its application to household-level

renewable energy technology in a low-income agricultural economy has been limited. This research extends PESTEL theory by demonstrating that the six macro-environmental pillars operate with markedly different weight and character at the household scale than at the commercial or industrial scale. Specifically, the analysis presented in Chapters 5 to 10 establishes that in the Level 1 domestic AD context, the Social and Technological pillars exert influence primarily through user knowledge, training, and cultural acceptance rather than through market structures or technological sophistication, while the Political and Legal pillars operate through the absence of dedicated policy rather than through the constraints of existing regulation. This finding challenges the implicit assumption in much of the PESTEL literature that macro-environmental factors act uniformly across scales of technology deployment.

12.3.1.2 Integration of macro-environmental analysis with micro-level user experience

A persistent limitation in the sustainability transitions literature is the separation between macro-level policy analysis and micro-level user studies, which are typically conducted independently and rarely reconciled. This research contributes theoretically by demonstrating, through the parallel analysis presented in Chapters 5 to 10, that expert stakeholder assessment at the macro level and household user experience at the micro level frequently diverge in identifiable and analytically meaningful ways. For example, stakeholders identified financial incentive structures and government support as dominant barriers (Section 5.2.7 and Section 6.2.1), whereas surveyed users identified after-sales maintenance support and technical training as their most immediate operational constraints (Section 8.3). This divergence is itself a theoretical finding: it indicates that policy diagnosis derived exclusively from expert consultation risks misidentifying the barriers that are actually operative at the point of technology use.

12.3.1.3 Systems-theoretic understanding of AD sector stagnation

The Causal Loop Diagram developed in Chapter 11 contributes theoretically by reconceptualising AD sector underperformance in Bangladesh not as the consequence of discrete individual barriers, but as an emergent property of interacting feedback structures. The identification of ten reinforcing (Section 11.2) and eleven balancing loops (Section 11.3) demonstrates that several interventions which appear beneficial when considered in isolation are neutralised by balancing loops operating elsewhere within the system. This finding advances systems thinking theory in the renewable energy domain by providing an empirically grounded illustration of why single-intervention policy approaches in this sector have repeatedly failed to produce durable change.

12.3.2 Methodological contributions

12.3.2.1 A novel integrated mixed-methods research design

The principal methodological contribution of this research is the design and application of an integrated framework combining a modified Delphi process, PESTEL analysis, pillar-specific SWOT analysis, a structured household user survey, and Causal Loop Diagram construction within a single study. This combination, described in full in Chapter 3, has not to the researcher's knowledge been applied previously to renewable energy sector analysis in a low-income country context. The design allows macro-level expert judgement and micro-level empirical user data to be brought into direct analytical relation with one another and then synthesised systemically. The methodological sequence is documented in Section 3.2, and the logic governing the integration of the two data strands is set out in Section 3.5.

12.3.2.2 Development of a weighted scoring method for Delphi-derived PESTEL factors

This research contributes a replicable quantification procedure for converting Delphi expert judgements into comparable composite scores, presented in Section 3.3.5. The method combines a six-point forced-choice Likert scale

with a weighted scoring calculation (Table 3.1) and a mathematically derived range classification system (Table 3.2), in which the classification boundaries are anchored to the structure of the scale itself rather than to researcher-defined cut-off points. This procedure addresses a recognised weakness in Delphi-based studies, namely the subjectivity involved in interpreting consensus, and provides a transparent and reproducible basis for ranking factors both within and across the six PESTEL pillars.

12.3.2.3 Application of paired statistical testing to before-and-after household technology adoption

The user survey component contributes methodologically by demonstrating the appropriate application of paired statistical techniques to the retrospective before-and-after assessment of household technology adoption, as set out in Section 3.4.8 and reported in Chapters 6, 7, 8 and 9. The use of the McNemar-Bowker test for paired categorical outcomes and the paired samples t-test for paired continuous outcomes, with assumption verification through the Shapiro-Wilk and Levene's tests, provides a methodological template for future household-level renewable energy impact assessment in comparable low-income settings. The reporting and interpretation of a null result for cow shed management (Section 9.3.5) further demonstrates the analytical value of retaining non-significant findings rather than reporting only confirmatory results.

12.3.2.4 Empirical construction of a Causal Loop Diagram from primary mixed-methods data

While Causal Loop Diagrams are widely used in systems research, they are frequently constructed conceptually from the literature rather than empirically from primary data. This research contributes methodologically by deriving its CLD directly from the triangulated findings of the Delphi process and the household user survey, with each causal link traceable to a specific empirical source, as documented in Section 11.2. This approach strengthens the evidentiary basis of the resulting systems model and offers a replicable

procedure for empirically grounded CLD construction in sustainability transitions research.

12.3.3 Practical contributions

12.3.3.1 Identification of the operative barriers to Level 1 AD sector growth in Bangladesh

This research provides the first systematic, empirically grounded identification of the macro- and micro-level factors constraining small-scale AD adoption in Bangladesh since the national biogas survey of 2012. The PESTEL analysis presented in Chapters 5 to 10 identifies, scores, and ranks the specific political, economic, social, technological, environmental, and legal factors influencing sector growth, providing policymakers with a prioritised evidence base rather than a general description of sector conditions.

12.3.3.2 Quantified evidence of household-level benefits

The household user survey provides quantified, statistically validated evidence of the benefits of Level 1 AD adoption for rural farming households, which was previously absent from the Bangladesh evidence base. The findings reported in Chapters 6, 7 and 9 establish statistically significant reductions in monthly fuel expenditure, daily cooking time, monthly firewood consumption, and daily firewood collection time, together with significant improvements in kitchen air quality, smoke-related eye infections, and respiratory infections, and a significant increase in the time devoted to child education. This body of evidence provides programme administrators and funders with defensible figures for cost-benefit assessment and for the economic justification of subsidy reform.

12.3.3.3 A revised financial case for household AD

The cost-benefit analysis presented in Section 6.3.5 contributes practically by demonstrating that conventional programme financial assessments, which account only for cooking fuel savings, materially understate the economic

value of household AD. By incorporating the quantified bio-slurry fertiliser benefit and the health cost reduction alongside fuel savings, the analysis produces a substantially stronger economic case for the technology and identifies the current per-plant subsidy level as inadequate relative to actual construction costs.

12.3.3.4 Strategic recommendations structured by time horizon and system leverage

Chapter 11 contributes a set of strategic recommendations organised into short-, medium-, and long-term horizons (Section 11.4), each linked explicitly to the specific feedback loops it is intended to influence. This structure enables programme administrators to distinguish between interventions that address symptoms and those that act upon system leverage points, and provides an implementation sequence rather than an undifferentiated list of desirable actions.

12.3.3.5 A multi-sector implementation framework

The sector analysis presented in Section 11.5 contributes practically by identifying the seven institutional sectors whose coordinated engagement is required for sustainable programme growth, and by specifying the distinct contribution required from each. In particular, the analysis identifies the agricultural extension sector as the most significant currently underutilised actor, given its capacity to unlock the substantial but largely unrealised bio-slurry benefit documented in Section 6.3.2.

12.3.3.6 Transferability to comparable programme contexts

Finally, because the analytical framework developed in this research is not specific to Bangladesh, the methodology is transferable to other national Level 1 biogas extension programmes, particularly those operating within the SNV and ABPP institutional lineage discussed in Section 2.3.1. The framework offers such programmes a structured means of diagnosing whether their own constraints are principally macro-environmental, technical, financial, or systemic in nature.

Summary of Contributions

Table 12.1: Summary of the theoretical, methodological, and practical contributions of this research

Dimension	Contribution	Section(s)
Theoretical	Extension of PESTEL to household-scale renewable energy in a low-income country context	Chapters 5–10
Theoretical	Demonstration of macro–micro divergence in barrier identification	5.2.7, 6.2, 8.3
Theoretical	Systems-theoretic reconceptualisation of sector stagnation	11.3
Methodological	Integrated Delphi–PESTEL–SWOT–survey–CLD research design	3.2, 3.5
Methodological	Weighted scoring procedure for Delphi-derived PESTEL factors	3.3.5, Tables 3.1–3.2
Methodological	Paired statistical testing template for household adoption studies	3.4.8, Chapters 6–9
Methodological	Empirically derived Causal Loop Diagram construction procedure	11.2 and 11.3
Practical	Prioritised identification of operative sector barriers	Chapters 5–10
Practical	Quantified household benefit evidence	Chapters 6, 7, 9
Practical	Revised financial case incorporating bio-slurry and health value	6.3.5
Practical	Time-horizoned, leverage-based strategic recommendations	11.4
Practical	Seven-sector implementation framework	11.5
Practical	Transferable framework for comparable national programmes	2.3.1

12.4 Final Thoughts

This study shows that small-scale anaerobic digestion (AD) can be a game-changer for Bangladesh, addressing waste management, renewable energy and environmental sustainability. But it needs to address the complex interplay of political, economic, social, technological, environmental and legal factors. A multi-stakeholder approach is the key to overcoming these challenges and unlocking the full potential of AD in the country.

Anaerobic digestion aligns with the global sustainability agenda, particularly the United Nations Sustainable Development Goals (SDGs), by promoting clean energy (SDG 7), sustainable cities and communities (SDG 11), responsible consumption and production (SDG 12), and climate action (SDG 13). With its growing population, urbanisation and waste management challenges, small-scale AD systems are a

localised, scalable solution that contributes to these goals while addressing the country's unique socio-economic and environmental context.

Small-scale AD systems can improve the lives of millions, especially in rural and peri-urban areas. They can provide a reliable source of clean, renewable energy for cooking and lighting, reducing dependence on traditional biomass fuels that cause indoor air pollution and respiratory diseases, especially among women and children. Biogas reduces household energy costs and provides a sustainable alternative to non-renewable energy sources. AD programmes also create employment opportunities in system construction, maintenance and operation and contribute to rural economic development and poverty alleviation.

Bringing anaerobic digestion (AD) into Bangladesh's renewable energy plans may be one of the more realistic ways to boost energy security (especially in rural areas), where power lines sometimes feel more like a promise than a presence. Instead of waiting for grid extensions that may or may not ever arrive, villages could start producing their own energy from available feedstock (rice stalks after harvest, manure piling up behind cattle sheds, and even the scraps that usually rot behind kitchen doors) as a raw material for AD.

Bangladesh has the opportunity to emerge as a global leader in the small-scale AD sector. If Bangladesh can manage to strike a workable balance between affordability, scalability, and long-term sustainability, it may offer a model that other developing nations can learn from, especially those facing similar waste and energy challenges. Additionally, integrating advanced technologies and fostering partnerships with international organisations and technology providers can make Bangladesh a hub for AD research and development.

In conclusion, small-scale AD systems are considered a solution to immediate waste management and energy demand, forwarding the pathway toward a more sustainable, equitable, and resilient future for Bangladesh. Despite its high potential, the systemic barriers highlighted in this study hinder the sector's growth. Bangladesh can serve as a global example of sustainable development for LMICs by adopting the recommendations outlined in this research. Immediate actions are required in the small-scale (level 1)AD sector of Bangladesh to ensure a sustainable future.

References

References

Abdallah, M., Shanableh, A., Adghim, M., Ghenai, C., Saad, S., 2018. Biogas production from different types of cow manure. 2018 Adv. Sci. Eng. Technol. Int. Conf. ASET 2018 1–4. https://doi.org/10.1109/ICASET.2018.8376791

Abdmouleh, Z., Alammari, R.A.M., Gastli, A., 2015. Review of policies encouraging renewable energy integration & best practices. Renew. Sustain. Energy Rev. 45, 249–262. https://doi.org/10.1016/j.rser.2015.01.035

Abubakar, I.R., Maniruzzaman, K.M., Dano, U.L., AlShihri, F.S., AlShammari, M.S., Ahmed, S.M.S., Al-Gehlani, W.A.G., Alrawaf, T.I., 2022. Environmental sustainability impacts of solid waste management practices in the global south. Int. J. Environ. Res. Public Health 19. https://doi.org/10.3390/ijerph191912717

Achinas, S., Horjus, J., Achinas, V., Euverink, G.J.W., 2019a. A PESTLE analysis of biofuels energy industry in Europe. Sustain. 11, 1–24. https://doi.org/10.3390/su11215981

Achinas, S., Li, Y., Achinas, V., Euverink, G.J.W., 2019b. Biogas potential from the anaerobic digestion of potato peels: Process performance and kinetics evaluation. Energies 12. https://doi.org/10.3390/en12122311

Adeleke, A.J., Ajunwa, O.M., Golden, J.A., Antia, U.E., Adesulu-Dahunsi, A.T., Adewara, O.A., Popoola, O.D., Oni, E.O., Thomas, B.T., Luka, Y., 2023. Anaerobic digestion technology for biogas production: Current situation in Nigeria (A Review). UMYU J. Microbiol. Res. 8, 153–164. https://doi.org/10.47430/ujmr.2382.018

Adeoti, O., Ayelegun, T.A., Osho, S.O., 2014. Nigeria biogas potential from livestock manure and its estimated climate value. Renew. Sustain. Energy Rev. 37, 243–248. https://doi.org/10.1016/j.rser.2014.05.005

Ahsan, A., Alamgir, M., El-Sergany, M.M., Shams, S., Rowshon, M.K., Daud, N.N.N., 2014. Assessment of municipal solid waste management system in a developing country. Chinese J. Eng. 2014, 1–11. https://doi.org/10.1155/2014/561935

Akinbami, J.F.K., Ilori, M.O., Oyebisi, T.O., Akinwumi, I.O., Adeoti, O., 2001. Biogas energy use in Nigeria: current status, future prospects and policy implications. Renew. Sustain. energy Rev. 5, 97–112. https://doi.org/10.1016/S1364-

0321(00)00005-8

Aksyutin, O.E., Ishkov, A.G., Romanov, K. V., Grachev, V.A., 2019. The influence of methane on climate change. Int. J. GEOMATE 16, 153–159. https://doi.org/10.21660/2019.55.55974

Akter, M., Islam, M., Hossain, M., Sultana, N., Khanam, J., Basunia, A., 2021. Performance of bio-slurry and inorganic fertilizer on growth, yield and quality of Indian Spinach (Basella alba L.). J. Bangladesh Agric. Univ. 19, 287. https://doi.org/10.5455/jbau.55243

Alam, O., Qiao, X., 2020. An in-depth review on municipal solid waste management, treatment and disposal in Bangladesh. Sustain. Cities Soc. 52, 101775. https://doi.org/10.1016/j.scs.2019.101775

Alam, T., Aftab, M., Abbas, Z., Ugli, K.M.M., Bokhari, S.A.A., 2023. Impact of E-government initiatives to combat corruption mediating by behavioral intention: A quantitative analysis from emerging economies. Sustain. 15. https://doi.org/10.3390/su15032694

Ammenberg, J., Anderberg, S., Lönnqvist, T., Grönkvist, S., Sandberg, T., 2018. Biogas in the transport sector—actor and policy analysis focusing on the demand side in the Stockholm region. Resour. Conserv. Recycl. 129, 70–80. https://doi.org/10.1016/j.resconrec.2017.10.010

Amuzu-Sefordzi, B., Martinus, K., Tschakert, P., Wills, R., 2018. Disruptive innovations and decentralized renewable energy systems in Africa: A socio-technical review. Energy Res. Soc. Sci. 46, 140–154. https://doi.org/10.1016/j.erss.2018.06.014

Angelidaki, I., Treu, L., Tsapekos, P., Luo, G., Campanaro, S., Wenzel, H., Kougias, P.G., 2018. Biogas upgrading and utilization: Current status and perspectives. Biotechnol. Adv. 36, 452–466. https://doi.org/10.1016/j.biotechadv.2018.01.011

Angouria-Tsorochidou, E., Seghetta, M., Trémier, A., Thomsen, M., 2022. Life cycle assessment of digestate post-treatment and utilization. Sci. Total Environ. 815. https://doi.org/10.1016/j.scitotenv.2021.152764

Aoidh, A.N., Hülsken, C., Good, C., Neachtain, E.Ó., Elfgren, E., HOgáin, F.Ó., 2017. PESTLE analysis of Barriers to Community Energy Development.

Arthur, R., Baidoo, M.F., Antwi, E., 2011. Biogas as a potential renewable energy source: A Ghanaian case study. Renew. Energy 36, 1510–1516.

https://doi.org/10.1016/j.renene.2010.11.012

Arthur, R., Baidoo, M.F., Osei, G., Boamah, L., Kwofie, S., 2020. Evaluation of potential feedstocks for sustainable biogas production in Ghana: Quantification, energy generation, and CO2 abatement. Cogent Environ. Sci. 6. https://doi.org/10.1080/23311843.2020.1868162

Asif, M., Barua, D., 2011. Salient features of the Grameen Shakti renewable energy program. Renew. Sustain. Energy Rev. 15, 5063–5067. https://doi.org/10.1016/j.rser.2011.07.050

Baker, L., Phillips, J., 2019. Tensions in the political economy of South Africa's renewable energy transition. Environ. Plan. C Polit. Sp. 37, 177–198.

Barbrook-Johnson, P., Penn, A.S., 2022. System Mapping : How to build and use causal models of systems, Systems Mapping. Palgrave Macmillan.

BARC, 2018. Fertilizer Recomendation Guide- 2018. Bangladesh Agric. Res. Counc. (BARC), Farmgate, Dhaka 1215.

Barnett, M., Finnemore, M., 2004. Rules for the World: International Organizations in Global Politics. Cornell University Press.

Bauer, F., Persson, T., Huteberg, C., Tamm, D., 2013. Biogas upgrading - technology overview, comparison and prospectives for the future. Biofpr 499–511.

BCU, 2010. Birmingham City University's research ethical framework.

Berglund, M., Börjesson, P., 2006. Assessment of energy performance in the life-cycle of biogas production. Biomass and Bioenergy 30, 254–266. https://doi.org/10.1016/j.biombioe.2005.11.011

Bernstein, S.L., Weiss, J., Curry, L., 2020. Visualizing implementation: contextual and organizational support mapping of stakeholders (COSMOS). Implement. Sci. Commun. 1, 1–11. https://doi.org/10.1186/s43058-020-00030-8

Bhattacharya, S.C., Jana, C., 2009. Renewable energy in India: Historical developments and prospects. Energy 34, 981–991.

Bond, T., Templeton, M.R., 2011. History and future of domestic biogas plants in the developing world. Energy Sustain. Dev. 15, 347–354. https://doi.org/https:/doi.org/10.1016/j.esd.2011.09.003

Börjesson, P., Berglund, M., 2006. Environmental systems analysis of biogas systems-Part I: Fuel-cycle emissions. Biomass and Bioenergy 30, 469–485.

https://doi.org/10.1016/j.biombioe.2005.11.014

BP, 2020. Statistical Review of World Energy. London, UK.

BPDB, 2019. Bangladesh Power Development Board Annual Report 2018-2019, Bangladesh Power Development Board.

Brereton, C.F., Jagals, P., 2021. Applications of systems science to understand and manage multiple influences within children's environmental health in least developed countries: A causal loop diagram approach. Int. J. Environ. Res. Public Health 18, 1–26. https://doi.org/10.3390/ijerph18063010

Bubela, T., Mykyychuk, M., Hunkalo, A., Boyko, O., Basalkevych, O., 2016. A study of uncertainty of expert measurement results in the quality management system. Eastern-European J. Enterp. Technol. 3, 4–11. https://doi.org/10.15587/1729-4061.2016.71607

Bull, J.W., Jobstvogt, N., Böhnke-Henrichs, A., Mascarenhas, A., Sitas, N., Baulcomb, C., Lambini, C.K., Rawlins, M., Baral, H., Zähringer, J., Carter-Silk, E., Balzan, M. V., Kenter, J.O., Häyhä, T., Petz, K., Koss, R., 2016. Strengths, Weaknesses, Opportunities and Threats: A SWOT analysis of the ecosystem services framework. Ecosyst. Serv. 17, 99–111. https://doi.org/10.1016/j.ecoser.2015.11.012

Busari, M., 2025. Government and institutional response overview of existing environmental laws and policies in Bangladesh.

Buysman, E., Mol, A.P.J., 2013. Market-based biogas sector development in least developed countries -The case of Cambodia. Energy Policy 63, 44–51. https://doi.org/10.1016/j.enpol.2013.05.071

Carlini, M., Mosconi, E.M., Castellucci, S., Villarini, M., Colantoni, A., 2017. An economical evaluation of anaerobic digestion plants fed with organic agro-industrial waste. Energies 10, 1–15. https://doi.org/10.3390/en10081165

Carvalho, R.L., Lindgren, R., García-López, N., Nyambane, A., Nyberg, G., Diaz-Chavez, R., Boman, C., 2019. Household air pollution mitigation with integrated biomass/cookstove strategies in Western Kenya. Energy Policy 131, 168–186. https://doi.org/10.1016/j.enpol.2019.04.026

Chakrabarty, S., Boksh, F.I.M.M., Chakraborty, A., 2013. Economic viability of biogas and green self-employment opportunities. Renew. Sustain. Energy Rev. 28, 757–766. https://doi.org/10.1016/j.rser.2013.08.002

Chanyisa, K.S., 2021. Access to Green Energy Financing in Kenya: Case Study of Private Energy Projects.

Chen, Q., Liu, T., 2017. Biogas system in rural China: Upgrading from decentralized to centralized? Renew. Sustain. Energy Rev. 78, 933–944. https://doi.org/10.1016/j.rser.2017.04.113

Chen, Y., Hu, W., Chen, P., Ruan, R., 2017. Household biogas CDM project development in rural China. Renew. Sustain. Energy Rev. 67, 184–191. https://doi.org/10.1016/j.rser.2016.09.052

Cheng, S., Zhao, M., Mang, H.P., Zhou, X., Li, Z., 2017. Development and application of biogas project for domestic sewage treatment in rural China: Opportunities and challenges. J. Water Sanit. Hyg. Dev. 7, 576–588. https://doi.org/10.2166/washdev.2017.011

Chien Bong, C.P., Ho, W.S., Hashim, H., Lim, J.S., Ho, C.S., Peng Tan, W.S., Lee, C.T., 2017. Review on the renewable energy and solid waste management policies towards biogas development in Malaysia. Renew. Sustain. Energy Rev. 70, 988–998. https://doi.org/10.1016/j.rser.2016.12.004

Chowdhury, P., Mahi, N.A., Yeassin, R., Chowdhury, N.U.R., Farrok, O., 2025. Biomass to biofuel: Impacts and mitigation of environmental, health, and socioeconomic challenges. Energy Convers. Manag. X 25, 100889. https://doi.org/10.1016/j.ecmx.2025.100889

Christensen, D., Bach, L.T., 2015. A Danish-Vietnamese partnership for business and technology development in solid waste management. Resour. Conserv. Recycl. 105, 123–133. https://doi.org/10.1016/j.resconrec.2015.10.019

Chy, S.M.N., 2015. Study and Review of Biogas Experience in Bangladesh and other Countries A thesis is submitted in partial fulfillment of the requirements for the degree of Master of Science in Renewable Energy Technology Institute of Energy University of Dhaka.

Clark, T., 2022. Swedish Waste Management 2022, Avfall Sverige.

Cocârţă, D.M., Prodana, M., Demetrescu, I., Lungu, P.E.M., Didilescu, A.C., 2021. Review indoor air pollution with fine particles and implications for workers' health in dental offices: A brief review. Sustain. 13, 1–17. https://doi.org/10.3390/su13020599

Costa, J.M., Aguiar, A.B.S., Montanari, A.F.P., Damasceno, B.G., Duran, K.A.,

Jerônimo, K.A., Silva, M.M., Silva, T.C.T., Rodriguez, R.P., 2024. Environmental aspects and perspectives of the Brazilian market for biogas and biomethane from anaerobic digestion: a review. Bioenergy Res. 17, 59–72. https://doi.org/10.1007/s12155-023-10657-9

CQC UK, 2015. NHS Patient Survey Programme Survey scoring method.

Dahlin, J., Herbes, C., Nelles, M., 2015. Biogas digestate marketing: Qualitative insights into the supply side. Resour. Conserv. Recycl. 104, 152–161. https://doi.org/10.1016/j.resconrec.2015.08.013

Dao, K.M., Yabar, H., Mizunoya, T., 2020. Unlocking the energy recovery potential from sustainable management of bio-resources based on GIS analysis: Case study in Hanoi, Vietnam. Resources 9, 1–24. https://doi.org/10.3390/resources9110133

Davis, W., 2017. The Relationship between Atmospheric Carbon Dioxide Concentration and Global Temperature for the Last 425 Million Years. Climate 5, 76. https://doi.org/10.3390/cli5040076

Dean, J.F., Middelburg, J.J., Röckmann, T., Aerts, R., Blauw, L.G., Egger, M., Jetten, M.S.M., de Jong, A.E.E., Meisel, O.H., Rasigraf, O., Slomp, C.P., in't Zandt, M.H., Dolman, A.J., 2018. Methane Feedbacks to the Global Climate System in a Warmer World. Rev. Geophys. 56, 207–250. https://doi.org/10.1002/2017RG000559

DEFF, 2020. National Waste Management Strategy 2020, Department of Environment Foretry and Fisheries - Republic of South African.

Department of Environment, 2015. Bangladesh Standards and Guidelines for Sludge Management.
URL:https://doe.gov.bd/pages/publications/6922dafe81fc96cef9eb85f1

Devarenjan, J., Herbert, G.M.J., Amutha, D., 2019. Utilization of Bioslurry from Biogas Plant as Fertilizer. Int. J. Recent Technol. Eng. 8, 12210–12213. https://doi.org/10.35940/ijrte.d8144.118419

Dhar, H., Kumar, S., Kumar, R., 2017. A review on organic waste to energy systems in India. Bioresour. Technol. 245, 1229–1237. https://doi.org/10.1016/j.biortech.2017.08.159

DLS, 2020. Livestock Economy at a Glance 2019-2022 [WWW Document]. Livest. Econ. Sect. Dep. Livest. Serv. (DLS), People's Repub. Bangladesh. URL

http://www.dls.gov.bd/site/page/22b1143b-9323-44f8-bfd8-647087828c9b/Livestock-Economy (accessed 5.22.21).

DoE, 2023. Environment Conservation Rules, 2023. https://doi.org/10.2139/ssrn.4674890

DoE, 2019. Environmental Law Collection, Department of Environment, Government of People's Republic of Bangladesh.

Drosg, B., 2013. Process monitoring in biogas plants. IEA Bioenergy 1–38.

EEA, 2022. Early warning assessment related to the 2025 targets for municipal waste and packaging waste — Denmark 2022.

Ejdys, J., Gudanowska, A., Halicka, K., Kononiuk, A., Magruk, A., Nazarko, J., Nazarko, Ł., Szpilko, D., Widelska, U., 2019. Foresight in higher education institutions: Evidence from poland. Foresight STI Gov. 13, 77–89. https://doi.org/10.17323/2500-2597.2019.1.77.89

Ekwurzel, B., Boneham, J., Dalton, M.W., Heede, R., Mera, R.J., Allen, M.R., Frumhoff, P.C., 2017. The rise in global atmospheric CO2, surface temperature, and sea level from emissions traced to major carbon producers. Clim. Change 144, 579–590. https://doi.org/10.1007/s10584-017-1978-0

Elizabeth Funmi, A., Abiodun Suleiman, M., Inioluwa Deborah, O., Tofunmi Dorcas, A., 2021. Biogas production as energy source and strategy for managing waste and climate change. SN Appl. Sci. 3, 1–11. https://doi.org/10.1007/s42452-020-03973-8

Environment Agency, 2003. Guidance on Monitoring of Landfill Leachate, Groundwater and Surface Water, Environment Agency Guidance. Bristol.

Esposito, G., Frunzo, L., Panico, A., Pirozzi, F., 2012. Enhanced bio-methane production from co-digestion of different organic wastes. Environ. Technol. (United Kingdom) 33, 2733–2740. https://doi.org/10.1080/09593330.2012.676077

Evangelisti, S., Lettieri, P., Borello, D., Clift, R., 2014. Life cycle assessment of energy from waste via anaerobic digestion: A UK case study. Waste Manag. 34, 226–237. https://doi.org/10.1016/j.wasman.2013.09.013

Fen, C., Gao, Y., Wei, L., Fenwu, L., Wuping, Z., Yushan, B., Xiaomei, L., 2017. Maximal methane potential of different animal manures collected in northwest region of China. Int. J. Agric. Biol. Eng. 10, 202–208.

https://doi.org/10.3965/j.ijabe.20171001.2469

Fulford D.J., 2015. Small-scale rural biogas programmes: A handbook. Rugby: Practical Action.

Fusi, A., Bacenetti, J., Fiala, M., Azapagic, A., 2016. Life cycle environmental impacts of electricity from biogas produced by anaerobic digestion. Front. Bioeng. Biotechnol. 4. https://doi.org/10.3389/fbioe.2016.00026

Gandhi, H.H., Hoex, B., Hallam, B.J., 2022. Strategic investment risks threatening India's renewable energy ambition. Energy Strateg. Rev. 43, 100921. https://doi.org/10.1016/j.esr.2022.100921

Gebreegziabher, Z., Naik, L., Melamu, R., Balana, B.B., 2014. Prospects and challenges for urban application of biogas installations in Sub-Saharan Africa. Biomass and Bioenergy 70, 130–140. https://doi.org/10.1016/j.biombioe.2014.02.036

Ghafoor, A., Rehman, T.U., Munir, A., Ahmad, M., Iqbal, M., 2016. Current status and overview of renewable energy potential in Pakistan for continuous energy sustainability. Renew. Sustain. Energy Rev. 60, 1332–1342. https://doi.org/10.1016/j.rser.2016.03.020

Ghimire, P.C., 2005. Final Report on Technical Study of Biogas Plants Installed in National Program on Domestic Biogas in Bangladesh. Dhaka.

Ginige, K., Amaratunga, D., Haigh, R., 2018. Mapping stakeholders associated with societal challenges: A Methodological Framework. Procedia Eng. 212, 1195–1202. https://doi.org/10.1016/j.proeng.2018.01.154

Godin, B., Mayer, F., Agneessens, R., Gerin, P., Dardenne, P., Delfosse, P., Delcarte, J., 2015. Biochemical methane potential prediction of plant biomasses: Comparing chemical composition versus near infrared methods and linear versus non-linear models. Bioresour. Technol. 175, 382–390. https://doi.org/10.1016/j.biortech.2014.10.115

GOV.UK, 2022. Guidance Overseas Business Risk: Bangladesh (Updated 12 July 2021) URL https://www.gov.uk/government/publications/overseas-business-risk-bangladesh/overseas-business-risk-bangladesh (accessed 5.24.22).

GOV.UK, 2016. Policy paper Landfill Tax: increase in rates [WWW Document]. URL https://www.gov.uk/government/publications/landfill-tax-increase-in-rates/landfill-tax-increase-in-rates (accessed 5.24.22).

Gregg, J.S., Bolwig, S., Ola, S., Vejlgaard, L., Gundersen, S.H., Grohnheit, P.E., 2014. Experiences with biomass in Denmark Systems Analysis Division Department of Management Experiences with biomass in Denmark 34.

Gupta, K.K., Aneja, K.R., Rana, D., 2016. Current status of cow dung as a bioresource for sustainable development. Bioresour. Bioprocess. 3. https://doi.org/10.1186/s40643-016-0105-9

Gurung, J.B., 1997. Review of Literature on Effects of Slurry Use on Crop production. Biogas Support Progr. 109.

Habib, M.A., Ahmed, M.M., Aziz, M., Beg, M.R.A., Hoque, M.E., 2021. Municipal solid waste management and waste-to-energy potential from rajshahi city corporation in bangladesh. Appl. Sci. 11. https://doi.org/10.3390/app11093744

Hanafi, B.M., Bhattacharjee, L., Rahman, S.M.R., Basit, M.A., 2016. Application of kitchen waste in biogas system : a solution for solid waste management in Chittagong, in: Proceedings of 3rd International Conference on Advances in Civil Engineering. CUET, Chittagong, pp. 118–121.

Hanusz, Z., Tarasińska, J., 2011. Tables for Shapiro–Wilk w statistic according to Royston approximation. Colloq. Biometricum 41 2, 211–219.

Hao, Q., Peng, W., Wang, J., Tu, Y., Li, H., Zhu, T., 2022. The correlation between internet addiction and interpersonal relationship among teenagers and college students based on Pearson ' s correlation coefficient : A systematic review and Meta-Analysis. Front. Psychiatry 13. https://doi.org/10.3389/fpsyt.2022.818494

Hasan, A.S.M.M., Kabir, M.A., Hoq, M.T., Johansson, M.T., Thollander, P., 2022. Drivers and barriers to the implementation of biogas technologies in Bangladesh. Biofuels 13, 643–655. https://doi.org/10.1080/17597269.2020.1841362

Hassan, M., Liu, Y., Naidu, R., Parikh, S.J., Du, J., Qi, F., Willett, I.R., 2020. Influences of feedstock sources and pyrolysis temperature on the properties of biochar and functionality as adsorbents: A meta-analysis. Sci. Total Environ. 744, 140714. https://doi.org/10.1016/j.scitotenv.2020.140714

HM Revenue and Customs, 2021. Landfill Tax rates - GOV.UK [WWW Document]. HM Revenue Cust. URL https://www.gov.uk/government/publications/rates-and-allowances-landfill-tax/landfill-tax-rates-from-1-april-2013 (accessed 7.10.24).

Holm-Nielsen, J.B., Al Seadi, T., Oleskowicz-Popiel, P., 2009. The future of anaerobic digestion and biogas utilization. Bioresour. Technol. 100, 5478–5484. https://doi.org/10.1016/j.biortech.2008.12.046

Hoo, P.Y., Hashim, H., Ho, W.S., 2018. Opportunities and challenges: Landfill gas to biomethane injection into natural gas distribution grid through pipeline. J. Clean. Prod. 175, 409–419. https://doi.org/10.1016/j.jclepro.2017.11.193

Hoppe, T., Sanders, P.T.M., 2014. Agricultural green gas demonstration projects in the Netherlands. A stakeholder analysis. Environ. Eng. Manag. J. 13, 3083–3096. https://doi.org/10.30638/eemj.2014.347

Hossain, I., 2024. Analysis of Environmental Laws and Policies.

Hossain, M.A., 2017. Bureaucratic System in Bangladesh. Rev. Public Adm. Manag. 05, 3–6. https://doi.org/10.4172/2315-7844.1000214

Hossain, M.R., 2020. Can small-scale biogas projects mitigate the energy crisis of rural Bangladesh? A study with economic analysis. Int. J. Sustain. Energy 0, 1–17. https://doi.org/10.1080/14786451.2020.1749056

Hossain, S., Rahman, M.A., Chowdhury, M.A., Mohonta, S.K., 2021. Plastic pollution in Bangladesh: A review on current status emphasizing the impacts on environment and public health. Environ. Eng. Res. 26, 0–2. https://doi.org/10.4491/eer.2020.535

Iacovidou, E., Busch, J., Hahladakis, J.N., Baxter, H., Ng, K.S., Herbert, B.M.J., 2017. A parameter selection framework for sustainability assessment. Sustain. 9, 1–18. https://doi.org/10.3390/su9091497

IDCOL, 2020. Infrastructure Development Company Limited (IDCOL) [WWW Document]. Infrastruct. Dev. Co. Ltd. URL http://idcol.org/home/dbiogas (accessed 4.30.19).

IER, 2018. A Snapshot of BP's World Energy Outlook 2018 [WWW Document]. Inst. Energy Res. URL https://www.instituteforenergyresearch.org/uncategorized/snapshot-bp-world-energy-outlook-2018/ (accessed 5.21.21).

Ifeoma, A.R., Yusuf, A.E., 2016. Waste management and sustainable development in Nigeria: A study of anambra state waste management agency. Eur. J. Bus. Manag. 8, 2222–2839.

Igliński, B., Buczkowski, R., Cichosz, M., 2015. Biogas production in Poland - Current

state, potential and perspectives. Renew. Sustain. Energy Rev. 50, 686–695. https://doi.org/10.1016/j.rser.2015.05.013

Ikhwan, M.F., Mansor, W., Khan, Z.I., Khairil, M., Mahmood, A., Bujang, A., Haddadi, K., Mara, U.T., 2024. Pearson Correlation and Multiple Correlation Analyses of the Animal Fat S-Parameter. TEM J. 13, 155–160. https://doi.org/10.18421/TEM131

ILO, 2022. Minimum wage chart: Bangladesh, Cambodia & Viet Nam [WWW Document]. URL https://www.ilo.org/asia/WCMS_223988/lang--en/index.htm (accessed 5.28.22).

IPE Triple Line., 2018. Demonstrating the potential of biogas to contribute to the SDGs. https://tripleline.com/downloads/Demonstrating_Biogas_Contribution_SDGs_Final.pdf)

Iqbal, M.M., Abid, I., Hussain, S., Shahzad, N., Waqas, M.S., Iqbal, M.J., 2020. The effects of regional climatic condition on the spread of COVID-19 at global scale. Sci. Total Environ. 739, 140101. https://doi.org/10.1016/j.scitotenv.2020.140101

Iqbal, S.A., Rahaman, S., Yousuf, A., 2014. Present scenario of biogas technology in Bangladesh-prospects, potentials and barriers. Proc. 15th Annu. Pap. meet 7, 8.

IREA, 2015. Renewable Energy Policy Brief : Brazil. Abu Dhabi.

IRENA, 2017. Biogas for domestic cooking: Technology brief, IInternational Renewable Energy Agency. Abu Dhabi.

Islam, F.R., Mamun, K.A., 2017. Possibilities and challenges of implementing renewable energy in the light of PESTLE & SWOT analyses for island countries, in: Islam, F., Mamun, K., Amanullah, M. (Eds.), Smart Energy Grid Design for Island Countries, Green Energy and Technology. https://doi.org/10.1007/978-3-319-50197-0_1

Islam, K.M.N., 2018. Municipal solid waste to energy generation: An approach for enhancing climate co-benefits in the urban areas of Bangladesh. Renew. Sustain. Energy Rev. 81, 2472–2486. https://doi.org/10.1016/j.rser.2017.06.053

Islam, S., Hossain, M.S., 2021. Strategic framework for enhancing stakeholder coordination in Bangladesh's renewable energy sector. J. Sustain. Energy 45, 275–289.

Islam, S., Khan, M.Z.R., 2017. A review of energy sector of Bangladesh. Energy Procedia 110, 611–618. https://doi.org/10.1016/j.egypro.2017.03.193

Jacobsen, B.H., Laugesen, F.M., Dubgaard, A., 2013. The economics of biogas in Denmark: a farm and socioeconomic perspective. Int. J. Agric. Manag. 3, 135–144. https://doi.org/10.5836/ijam/2014-03-02

Jäger, J., Rothman, D., Anastasi, C., Kartha, S., van Notten, P., 2008. Scenario Development and Analysis, in: GEO Resource Book: A Training Manual on Integrated Environmental Assessment and Reporting. United Nations Environment Programme (UNEP), Nairobi, p. 29 pp.

Jannatul, F., 2016. Bureaucracy in Bangladesh : past , present experiences and future Expectations. Public Policy Adm. Res. 6, 1–10.

Jared, N., Erastus, G., Christopher, N., Steve, A., 2016. Evaluation of Biogas Slurry as An Alternative Organic Fertilizer : A Case Study in Kenya. Int. J. Extensive Res. 9, 10–14.

Johnson, M., Brown, T., Wilson, D., 2008. PESTEL analysis of the renewable energy sector. J. Environ. Plan. 30, 123–136.

Kabir, H., Endlicher, W., 2011. AD Technologies in Developing Countries. Renew. Energy J. 45, 235–244.

Kamp, L.M., Bermúdez Forn, E., 2016. Ethiopia's emerging domestic biogas sector: Current status, bottlenecks and drivers. Renew. Sustain. Energy Rev. 60, 475–488. https://doi.org/10.1016/j.rser.2016.01.068

Karim, M.E., Karim, R., Islam, M.T., Muhammad-Sukki, F., Bani, N.A., Muhtazaruddin, M.N., 2019. Renewable energy for sustainable growth and development: An evaluation of law and policy of Bangladesh. Sustain. 11. https://doi.org/10.3390/su11205774

Karmaker, A.K., Hossain, M.A., Kumar, N.M., Jagadeesan, V., Jayakumar, A., Ray, B., 2020. Analysis of using biogas resources for electric vehicle charging in Bangladesh: A techno-economic-environmental perspective, Sustainability (Switzerland). https://doi.org/10.3390/su12072579

Katuwal, H., 2022. Biogas adoption in Nepal: empirical evidence from a nationwide survey. Heliyon 8, e10106. https://doi.org/10.1016/j.heliyon.2022.e10106

Katuwal, H., Bohara, A.K., 2009. Biogas: A promising renewable technology and its impact on rural households in Nepal. Renew. Sustain. Energy Rev. 13, 2668–

2674. https://doi.org/10.1016/j.rser.2009.05.002

Kaushik, V., Walsh, C.A., 2019. Pragmatism as a Research Paradigm and Its Implications for Social Work Research. Soc. Sci. 8, 1–17.

Kelebe, H.E., 2018. Returns, setbacks, and future prospects of bio-energy promotion in northern Ethiopia: The case of family-sized biogas energy. Energy. Sustain. Soc. 8. https://doi.org/10.1186/s13705-018-0171-2

Khan, E.U., Martin, A.R., 2016. Review of biogas digester technology in rural Bangladesh. Renew. Sustain. Energy Rev. 62, 247–259. https://doi.org/10.1016/j.rser.2016.04.044

Khan, M.A., Ngo, H.H., Guo, W.S., Liu, Y., Nghiem, L.D., Hai, F.I., Deng, L.J., Wang, J., Wu, Y., 2016. Optimization of process parameters for production of volatile fatty acid, biohydrogen and methane from anaerobic digestion. Bioresour. Technol. 219, 738–748. https://doi.org/10.1016/j.biortech.2016.08.073

Khatri, K.K., 2020. Research paradigm: A philosophy of educational research. Int. J. English Lit. Soc. Sci. 5, 1435–1440. https://doi.org/10.22161/ijels.55.15

Khatun, F., 2021. The journey towards fighting corruption. Dly. Star.

Kivunja, C., Kuyini, A.B., 2017. Understanding and Applying Research Paradigms in Educational Contexts. Int. J. High. Educ. 6, 26. https://doi.org/10.5430/ijhe.v6n5p26

Kordana, S., Słyś, D., 2020. An analysis of important issues impacting the development of stormwater management systems in Poland. Sci. Total Environ. 727. https://doi.org/10.1016/j.scitotenv.2020.138711

Kraij, D., 2009. Sustainable green business. Adv. Mark. Manag. Financ. Proc. 3rd Internatio nal Conf. Manag. Mark. Financ. 142–147.

Krog, J.S., Forslund, A., Larsen, L.E., Dalsgaard, A., Kjaer, J., Olsen, P., Schultz, A.C., 2017. Infiltration des virus et autres micro-organismes naturellement présents dans le lisier de porc via un réseau de drains dans un terrain limoneux bien structuré au Danemark. Hydrogeol. J. 25, 1045–1062. https://doi.org/10.1007/s10040-016-1530-8

Kumar Ghosh, S., Mandal, S., 2018. Evaluation of biogas as an alternative driving force of electrically operated vehicles: A case study. Int. J. Eng. Trans. B Appl. 31, 834–840. https://doi.org/10.5829/ije.2018.31.05b.20

Kumar, J.C.R., Majid, M.A., 2020. Renewable energy for sustainable development

in India: current status, future prospects, challenges, employment, and investment opportunities. Energy, Sustainability and Society, 10(1) | 10.1186/s13705-019-0232-1. Energy. Sustain. Soc. 10, 1–36.

Kumaran, P., Hephzibah, D., Sivasankari, R., Saifuddin, N., Shamsuddin, A.H., 2016. A review on industrial scale anaerobic digestion systems deployment in Malaysia: Opportunities and challenges. Renew. Sustain. Energy Rev. 56, 929–940. https://doi.org/10.1016/j.rser.2015.11.069

Kurchania, A.K., Panwar, N.L., Pagar, S.D., 2010. Design and performance evaluation of biogas stove for community cooking application. Int. J. Sustain. Energy 29, 116–123. https://doi.org/10.1080/14786460903497391

Lackner, M., Besharati, M., 2025. Agricultural Waste: Challenges and Solutions, a Review. Waste 3, 18. https://doi.org/10.3390/waste3020018

Larsen, M., 2016. Comprehensive public health benefits of AD systems in Denmark. Energy Syst. Res. 41, 33–49.

Le, T.T., Himmelstein, D.S., Hippen, A.A., Gazzara, M.R., Greene, C.S., 2021. Analysis of scientific society honors reveals disparities. Cell Syst. 12, 900-906.e5. https://doi.org/10.1016/j.cels.2021.07.007

Li, C., Liao, Y., Wen, X., Wang, Y., Yang, F., 2015. The development and countermeasures of household biogas in northwest grain for green project areas of China. Renew. Sustain. Energy Rev. 44, 835–846. https://doi.org/10.1016/j.rser.2015.01.027

Lohani, S.P., Dhungana, B., Horn, H., Khatiwada, D., 2021. Small-scale biogas technology and clean cooking fuel: Assessing the potential and links with SDGs in low-income countries – A case study of Nepal. Sustain. Energy Technol. Assessments 46, 101301. https://doi.org/10.1016/j.seta.2021.101301

Lönnqvist, T., Sandberg, T., Birbuet, J.C., Olsson, J., Espinosa, C., Thorin, E., Grönkvist, S., Gómez, M.F., 2018. Large-scale biogas generation in Bolivia – A stepwise reconfiguration. J. Clean. Prod. 180, 494–504. https://doi.org/10.1016/j.jclepro.2018.01.174

Lwiza, F., Mugisha, J., Walekhwa, P.N., Smith, J., Balana, B., 2017. Dis-adoption of Household Biogas technologies in Central Uganda. Energy Sustain. Dev. 37, 124–132. https://doi.org/10.1016/j.esd.2017.01.006

Lyng, K.A., Skovsgaard, L., Jacobsen, H.K., Hanssen, O.J., 2020. The implications

of economic instruments on biogas value chains: a case study comparison between Norway and Denmark. Environ. Dev. Sustain. 22, 7125–7152. https://doi.org/10.1007/s10668-019-00463-9

Maarouf, H., 2019. Pragmatism as a supportive paradigm for the mixed research approach: conceptualizing the ontological, epistemological, and axiological stances of pragmatism. Int. Bus. Res. 12, 1. https://doi.org/10.5539/ibr.v12n9p1

Mahachi, D., Mokgalo, L.L., Pansiri, J., 2015. Exploitation of renewable energy in the hospitality sector: case studies of gaborone sun and the Cumberland hotel in Botswana. Int. J. Hosp. Tour. Adm. 16, 331–354. https://doi.org/10.1080/15256480.2015.1090253

Malahayati, M., Masui, T., 2018. Challenges in implementing emission mitigation technologies in Indonesia agricultural sector: Criticizing the available mitigation technologies. Open Agric. 3, 46–56. https://doi.org/10.1515/opag-2018-0006

Mang, H.-P., Haque, S., Chowdhury, M.B., Haque, M.N., Khan, S.I., Aragundy, J., Kabir, H., Huba, E., Ryndin, R., Köttner, M., 2017. Situation analysis of agro-industrial biogas plants in Bangladesh. DHAKA.

Mann, P.S., 2011. Introductory Statistics, 7th Ed. John Wiley Sons, Inc. 8, 736.

Martin, M., 2015. Potential of biogas expansion in Sweden: Identifying the gap between potential studies and producer perspectives. Biofuels 6, 233–240. https://doi.org/10.1080/17597269.2015.1090769

Martínez-Gutiérrez, E., 2018. Biogas production from different lignocellulosic biomass sources: advances and perspectives. 3 Biotech 8, 1–18. https://doi.org/10.1007/s13205-018-1257-4

Masud, M.H., Nuruzzaman, M., Ahamed, R., Ananno, A.A., Tomal, A.N.M.A., 2020. Renewable energy in Bangladesh: current situation and future prospect. Int. J. Sustain. Energy 39, 132–175. https://doi.org/10.1080/14786451.2019.1659270

Mathias, M.C.P.P., Mathias, J.F.C.M., 2015. Biogas in Brazil: A Governmental Agenda. J. Energy Power Eng. 9, 1–15. https://doi.org/10.17265/1934-8975/2015.01.001

McCrone, A., Ajadi, T., Boyle, R., Strahan, D., Kimmel, M., Collins, B., Cheung, A., Becker, L., 2019. Global trends in renewable energy investment 2019. Bloom. New Energy Financ. 76.

McDermott, F., 2012. UK jobs in the bioenergy sectors by 2020. NNFCC Bioeconomy

Consult. Rep. 1–43.

Meadow, Do.H., 2008. Thinking in Systems. Chelsea Green Publishing, Vermot, USA.

Meena, P.K., Pal, A., Gautam, S., 2024. Zone-wise biogas potential in India: fundamentals, challenges, and policy considerations. Environ. Sci. Pollut. Res. Int. 31, 1841–1862. https://doi.org/10.1007/s11356-023-31328-4

Melnikovas, A., 2018. Towards an explicit research methodology: Adapting research onion model for futures studies. J. Futur. Stud. 23, 29–44. https://doi.org/10.6531/JFS.201812_23(2).0003

Melville, L., Weger, A., Wiesgickl, S., Franke, M., 2014. Anaerobic Digestion, in: Evans, A., Strezov, V., Evans, T.J. (Eds.), Transformation of Biomass Theory to Practice. John Wiley & Sons, Ltd, pp. 31–54. https://doi.org/10.1002/9781118693643.ch2

Mengistu, M.G., Simane, B., Eshete, G., Workneh, T.S., 2015. A review on biogas technology and its contributions to sustainable rural livelihood in Ethiopia. Renew. Sustain. Energy Rev. 48, 306–316. https://doi.org/10.1016/j.rser.2015.04.026

Mezzullo, W.G., McManus, M.C., Hammond, G.P., 2013. Life cycle assessment of a small-scale anaerobic digestion plant from cattle waste. Appl. Energy 102, 657–664. https://doi.org/10.1016/j.apenergy.2012.08.008

Mishra, S., 2019. the Upliftment of Rural India Biogas Technology. NEW INDIA PUBLISHING AGENCY, New Delhi – 110 034.

Mittal, S., Ahlgren, E.O., Shukla, P.R., 2018. Barriers to biogas dissemination in India: A review. Energy Policy 112, 361–370. https://doi.org/10.1016/j.enpol.2017.10.027

MoDMR, 2017. National plan for disaster management 2016-2020, Ministry of Disaster Management and Relief. Dhaka, Bangladesh.

MoEF, 2018. National environmental policy 2018, Ministry of Environment, Forest and Climate Change , Government of People's Republic of Bangladesh.

MoEF, 2009. Bangladesh climate change and action plan 2009, Ministry of Environment and Forests Ministry of Environment and Forests, Government of the People's Republic of Bangladesh, Dhaka, Bangladesh. https://doi.org/984-8574-25-5

MoFE, 2021. Assessment of electric cooking targets for Nepal's 2020 Nationally Determined Contributions (NDC).

MoFL, 2015. Draft national integrated livestock manure management (ILMM) Policy, Ministry of Fisheries and Livestock, Government of the People's Republic of Bangladesh.

MoPEM, 2017. Generation Plan, Power Division, Ministry of Power, Energy and Mineral Resources, Government of the Republic of Bangladesh. [WWW Document]. URL http://www.powerdivision.gov.bd/user/brec/41/58%0A

Msibi, S.S., Kornelius, G., 2017. Potential for domestic biogas as household energy supply in South Africa. J. Energy South. Africa 28, 1–13. https://doi.org/10.17159/2413-3051/2017/v28i2a1754

Mudassar, M., 2021. Economic and Environmental benefits of Biogas Plant and its Impact on Female Health in Punjab. Int. J. Altern. Fuels Energy 21–33.

Mukherjee, N., Hugé, J., Sutherland, W.J., Mcneill, J., Van Opstal, M., Dahdouh-Guebas, F., Koedam, N., 2015. The Delphi technique in ecology and biological conservation: Applications and guidelines. Methods Ecol. Evol. 6, 1097–1109. https://doi.org/10.1111/2041-210X.12387

Muradin, M., Foltynowicz, Z., 2014. Potential for producing biogas from agricultural waste in rural plants in Poland. Sustain. 6, 5065–5074. https://doi.org/10.3390/su6085065

Mushtaq, K., Zaidi, A.A., Askari, S.J., 2016. Design and performance analysis of floating dome type portable biogas plant for domestic use in Pakistan. Sustain. Energy Technol. Assessments 14, 21–25. https://doi.org/10.1016/j.seta.2016.01.001

Mwirigi, J., Balana, B.B., Mugisha, J., Walekhwa, P., Melamu, R., Nakami, S., Makenzi, P., 2014. Socio-economic hurdles to widespread adoption of small-scale biogas digesters in Sub-Saharan Africa: A review. Biomass and Bioenergy 70, 17–25. https://doi.org/10.1016/j.biombioe.2014.02.018

Naveen, B.P., Sumalatha, J., Malik, R.K., 2018. A study on contamination of ground and surface water bodies by leachate leakage from a landfill in Bangalore, India. Int. J. Geo-Engineering 9. https://doi.org/10.1186/s40703-018-0095-x

NDBMP-IDCOL, 2013. BIOGAS AUDIT BANGLADESH 2011 - 2013 (Summary of Findings and Recommendations). Dhaka.

Nelms, K.R., Porter, A.L., 1985. EFTE: An interactive Delphi method. Technol. Forecast. Soc. Change 28, 43–61. https://doi.org/10.1016/0040-1625(85)90072-1

Nethengwe, N.S., Uhunamure, S.E., Tinarwo, D., 2018. Potentials of biogas as a source of renewable energy: A case study of South Africa. Int. J. Renew. Energy Res. 8, 1112–1123.

Nevzorova, T., Kutcherov, V., 2019. Barriers to the wider implementation of biogas as a source of energy: A state-of-the-art review. Energy Strateg. Rev. 26, 100414. https://doi.org/10.1016/j.esr.2019.100414

Newberry, P., Carhart, N., 2024. Constructing causal loop diagrams from large interview data sets. Syst. Dyn. Rev. 40, 1–40. https://doi.org/10.1002/sdr.1745

Nnaji, E.C., Adgidzi, D., Dioha, M.O., Ewim, D.R.E., Huan, Z., 2019. Modelling and management of smart microgrid for rural electrification in sub-saharan Africa: The case of Nigeria. Electr. J. 32. https://doi.org/10.1016/j.tej.2019.106672

Obileke, K.C., Nwokolo, N., Makaka, G., Mukumba, P., Onyeaka, H., 2021. Anaerobic digestion: Technology for biogas production as a source of renewable energy—A review. Energy Environ. 32, 191–225. https://doi.org/10.1177/0958305X20923117

OECD, 2020. Overview of Methodologies [WWW Document]. Organ. Econ. Co-operation Dev. URL https://www.oecd.org/site/schoolingfortomorrowknowledgebase/futuresthinking/overviewofmethodologies.htm (accessed 11.26.20).

OECD, 2017. Waste management and the circular economy in selected OECD countries, OECD Environment Working Papaers.

Okesina, M., 2020. A Critical Review of the Relationship between Paradigm, Methodology, Design and Method in Research. IOSR J. Res. Method Educ. 10, 57–68. https://doi.org/10.9790/7388-1003015768

Olatunji, O.P., Itohan, I., Abdulakeem, A.S., 2023. Waste Management administration and environmental sustainability in Nigeria. Int. J. Nov. Res. Eng. Pharm. Sci. 10, 28–41.

Paglini, R., Gandiglio, M., Lanzini, A., 2022. Technologies for deep biogas purification and use in zero-emission fuel cells systems. Energies 15. https://doi.org/10.3390/en15103551

Panwar, N.L., Kaushik, S.C., Kothari, S., 2011. Role of renewable energy sources in environmental protection: A review. Renew. Sustain. Energy Rev. 15, 1513–1524. https://doi.org/10.1016/j.rser.2010.11.037

Paolini, V., Petracchini, F., Segreto, M., Tomassetti, L., Naja, N., Cecinato, A., 2018. Environmental impact of biogas: A short review of current knowledge. J. Environ. Sci. Heal. - Part A Toxic/Hazardous Subst. Environ. Eng. 53, 899–906. https://doi.org/10.1080/10934529.2018.1459076

Park, Y.S., Konge, L., Artino, A.R., 2020. The positivism paradigm of research. Acad. Med. 95, 690–694. https://doi.org/10.1097/ACM.0000000000003093

Patil, D.A., 2020. Main treaming biofuels in India: Analysing s weaknesses and opportunities for the sustainability of biofuel and its future policy making. Indian J. Ecol. 47, 543–548.

Pazera, A., Slezak, R., Krzystek, L., Ledakowicz, S., Bochmann, G., Gabauer, W., Helm, S., Reitmeier, S., Marley, L., Gorga, F., Farrant, L., Suchan, V., Kara, J., 2015. Biogas in Europe: Food and beverage (FAB) waste potential for biogas production. Energy and Fuels 29, 4011–4021. https://doi.org/10.1021/ef502812s

Pelkonen, P., Mustonen, M., Asikainen, A., Egnell, G., Kant, P., Sylvain, L., Pettenella, D., 2014. Forest bioenergy for Europe. What science can tell us 4, European Forest Institute.

Petersson, A., Wellinger, A., 2009. Biogas upgrading technologies–developments and innovations. IEA Bioenergy 20.

Pham, H., 2023. Basic Statistics. Springer Handbooks 3–41. https://doi.org/10.1007/978-1-4471-7503-2_1

Pluye, P., Gagnon, M.P., Griffiths, F., Johnson-Lafleur, J., 2009. A scoring system for appraising mixed methods research, and concomitantly appraising qualitative, quantitative and mixed methods primary studies in Mixed Studies Reviews. Int. J. Nurs. Stud. 46, 529–546. https://doi.org/10.1016/j.ijnurstu.2009.01.009

Power Division, 2018. Final draft guidelines on biogas technology for energy power division Ministry of Power , Energy and Mineral Resources Government of the People ' s Republic of Bangladesh. Dhaka.

Power Division, 2016. Power system master plan 2016., Ministry of Power, Energy

and Mineral Resources Government of the People's Republic of Bangladesh.

Power Division, 2008. Renewable energy policy of Bangladesh, Power Division, Ministry of Power, Energy and Mineral Resources, Government of the peoples Republic Bangladesh.

Puzzolo, E., Pope, D., 2017. Clean fuels for cooking in developing countries. Encycl. Sustain. Technol. 289–297. https://doi.org/10.1016/B978-0-12-409548-9.10153-8

Quinn, A.K., Bruce, N., Puzzolo, E., Dickinson, K., Sturke, R., Jack, D.W., Mehta, S., Shankar, A., Sherr, K., Rosenthal, J.P., 2018. An analysis of efforts to scale up clean household energy for cooking around the world. Energy Sustain. Dev. 46, 1–10. https://doi.org/10.1016/j.esd.2018.06.011

Raha, D., Mahanta, P., Clarke, M.L., 2014. The implementation of decentralised biogas plants in Assam , NE India : The impact and effectiveness of the National Biogas and Manure Management Programme 68, 80–91. https://doi.org/10.1016/j.enpol.2013.12.048

Rahman, A., Farrok, O., Haque, M.M., 2022. Environmental impact of renewable energy source based electrical power plants: Solar, wind, hydroelectric, biomass, geothermal, tidal, ocean, and osmotic. Renew. Sustain. Energy Rev. 161, 112279. https://doi.org/10.1016/j.rser.2022.112279

Rahman, K.M., Edwards, D.J., Melville, L., El-Gohary, H., 2019. Implementation of bioenergy systems towards achieving United Nations' sustainable development goals in rural Bangladesh. Sustain. 11. https://doi.org/10.3390/su11143814

Rahman, K.M., Harder, M.K., Woodard, R., 2018. Energy yield potentials from the anaerobic digestion of common animal manure in Bangladesh. Energy Environ. 29, 1338–1353. https://doi.org/10.1177/0958305X18776614

Rahman, K.M., Melville, L., 2023. An investigation into the conversion of non-hazardous medical wastes into biogas— A case study from the health and family planning sector in Bangladesh. Processes 11. https://doi.org/10.3390/pr11051494

Rahman, K.M., Woodard, R., Manzanares, E., Harder, M.K., 2014. An assessment of anaerobic digestion capacity in Bangladesh. Renew. Sustain. Energy Rev. 32, 762–769. https://doi.org/10.1016/j.rser.2014.01.026

Rahman, M.A., Møller, H.B., Alam, M.M., 2018. Assessing the energy potential of

agricultural residues and an approach to meet the rural energy demand: the Bangladesh perspective. Biomass Convers. Biorefinery 8, 925–934. https://doi.org/10.1007/s13399-018-0343-5

Rahman, M.A., Saha, C.K., Feng, L., Møller, H.B., Alam, M.M., 2019. Anaerobic digestion of agro-industrial wastes of Bangladesh: Influence of total solids content. Eng. Agric. Environ. Food 12, 484–493. https://doi.org/10.1016/j.eaef.2019.10.002

Rahman, M.M., 2021. Achieving sustainable development goals of agenda 2030 in Bangladesh: the crossroad of the governance and performance. Public Adm. Policy 24, 195–211. https://doi.org/10.1108/PAP-12-2020-0056

Rahman, M.M., Ahmed, R., Mashud, A.H.M., Malik, A.I., Miah, S., Abedin, M.Z., 2022. Consumption-based CO_2 emissions on sustainable development goals of SAARC region. Sustain. 14. https://doi.org/10.3390/su14031467

Rahman, R.R., Kabir, A., 2023. Spatiotemporal analysis and forecasting of air quality in the greater Dhaka region and assessment of a novel particulate matter filtration unit. Environ. Monit. Assess. 195. https://doi.org/10.1007/s10661-023-11370-y

REN21, 2020. Renewables 2020 Global Status Report. Paris: REN21 Secretariat.

Ricardo, M., 2022. Drivers roadblocks and status of renewable energy development in the Philippines: A Literature Review. J Fundam Renew. Energy Appl 12, 1000294. https://doi.org/10.35248/2090-4541-22.12.294.Citation

Riet, R. van, Skowron, A., Teske, S., 2020. SCENARIO: 100% RENEWABLE ENERGY IN COSTA RICA. Hamburg, Germany.

Riggs, W.E., 1983. The Delphi technique. An experimental evaluation. Technol. Forecast. Soc. Change 23, 89–94. https://doi.org/10.1016/0040-1625(83)90073-2

Rikkonen, P., Tapio, P., 2009. Future prospects of alternative agro-based bioenergy use in Finland-Constructing scenarios with quantitative and qualitative Delphi data. Technol. Forecast. Soc. Change 76, 978–990. https://doi.org/10.1016/j.techfore.2008.12.001

Roopnarain, A., Adeleke, R., 2017. Current status, hurdles and future prospects of biogas digestion technology in Africa. Renew. Sustain. Energy Rev. 67, 1162–1179. https://doi.org/10.1016/j.rser.2016.09.087

Rotich, I.K., Musyimi, P.K., 2024. Indoor air pollution in Kenya. Aerosol Sci. Eng. 8, 54–65. https://doi.org/10.1007/s41810-023-00205-5

Rouf, K.A., 2015. Renewable energy context, scope, application and green business in Bangladesh. Glob. J. Human-Social Sci. 15.

Rungson Chomeya, 2010. Quality of psychology test between Likert scale 5 and 6 Points. J. Soc. Sci. 6, 399–403. https://doi.org/10.3844/jssp.2010.399.403

Rupf, G. V., Bahri, P.A., De Boer, K., McHenry, M.P., 2015. Barriers and opportunities of biogas dissemination in Sub-Saharan Africa and lessons learned from Rwanda, Tanzania, China, India, and Nepal. Renew. Sustain. Energy Rev. 52, 468–476. https://doi.org/10.1016/j.rser.2015.07.107

Ryckebosch, E., Drouillon, M., Vervaeren, H., 2011. Techniques for transformation of biogas to biomethane. Biomass and Bioenergy 35, 1633–1645. https://doi.org/10.1016/j.biombioe.2011.02.033

Sabbir, A.S.M.Y.B., Saha, C.K., Nandi, R., Zaman, M.F.U., Alam, M.M., Sarker, S., 2021. Effects of seasonal temperature variation on slurry temperature and biogas composition of a commercial fixed-dome anaerobic digester used in bangladesh. Sustain. 13. https://doi.org/10.3390/su131911096

Salam, S., Parvin, R., Salam, M.A., Nasim Azad, S.M., 2020. Feasibility study for biogas generation from household digesters in bangladesh: Evidence from a household level survey. Int. J. Energy Econ. Policy 10, 23–30. https://doi.org/10.32479/ijeep.9206

Sanches-pereira, A., Onguglo, B., Pacine, H., Teixeira, S., 2017. Fostering local sustainable development in Tanzania by enhancing linkages between tourism and small-scale agriculture. J. Clean. Prod. https://doi.org/10.1016/j.jclepro.2017.06.164

Santos, I.F.S. dos, Vieira, N.D.B., Nóbrega, L.G.B. de, Barros, R.M., Tiago Filho, G.L., 2018. Assessment of potential biogas production from multiple organic wastes in Brazil: Impact on energy generation, use, and emissions abatement. Resour. Conserv. Recycl. 131, 54–63. https://doi.org/10.1016/j.resconrec.2017.12.012

Sarker, S.A., Wang, S., Adnan, K.M.M., Sattar, M.N., 2020. Economic feasibility and determinants of biogas technology adoption: Evidence from Bangladesh. Renew. Sustain. Energy Rev. 123, 109766.

https://doi.org/10.1016/j.rser.2020.109766

Sárvári Horváth, I., Tabatabaei, M., Karimi, K., Kumar, R., 2016. Recent updates on biogas production - a review. Biofuel Res. J. 3, 394–402. https://doi.org/10.18331/brj2016.3.2.4

Sasse, L., 1988. Biogas Plants, Deutsches Zentrum für Entwicklungstechnologien. Eschborn.

Saunders, M.N.K., Lewis, P., Thornhill, A., 2019. "Research methods for business students" Chapter 4: Understanding research philosophy and approaches to theory development, Researchgate.Net.

Sawale, S., Patil, D., Joshi, C., Rachappanavar, B., Mishra, D., Kulkarni, A., 2021. Biogas commercialization: Commercial players, key business drivers, potential market, and fostering investment, Biogas Production: From Anaerobic Digestion to a Sustainable Bioenergy Industry. https://doi.org/10.1007/978-3-030-58827-4_16

Seadi, T. Al, Rutz, D., Prassl, H., Kottner, M., Finsterwalder, T., Volk, S., Janssen, R., 2008. Biogas (HAND BOOK). University of Southern Denmark Esbjerg, Esbjerg, Denmark.

Shamsudduha, M., Taylor, R.G., Ahmed, K.M., Zahid, A., 2011. The impact of intensive groundwater abstraction on recharge to a shallow regional aquifer system: Evidence from Bangladesh. Hydrogeol. J. 19, 901–916. https://doi.org/10.1007/s10040-011-0723-4

Shapiro, S.S., Wilk, M.B., 1965. Biometrika trust an analysis of variance test for normality. Biometrika 52, 591–611.

Sharma, A., Laudari, R., Rijal, K., Adhikari, L., 2019. Role of biogas in climate change mitigation and adaptation. J. For. Nat. Resour. Manag. 1, 25–31. https://doi.org/10.3126/jfnrm.v1i1.22649

Shen, Y., Linville, J.L., Urgun-Demirtas, M., Mintz, M.M., Snyder, S.W., 2015. An overview of biogas production and utilization at full-scale wastewater treatment plants (WWTPs) in the United States: Challenges and opportunities towards energy-neutral WWTPs. Renew. Sustain. Energy Rev. 50, 346–362. https://doi.org/10.1016/j.rser.2015.04.129

Shostak, I., Danova, M., Kuznetsova, Y., 2017. Foresight-Research for Green IT Engineering Development, in: Kharchenko, V., Kondratenko, Y., Kacprzyk, J.

(Ed.), Green IT engineering: Concepts, models, complex systems Architectures. Studies in Systems, Decision and Control. Springer, Cham. https://doi.org /10.1007/978-3-319-44162-7_2

Shovon, K.A., Hannan, M.A., Rahman, R., 2022. Assessment of the legal framework regulating waste management in Bangladesh. Asian J. Soc. Sci. Leg. Stud. 4, 94–105. https://doi.org/10.34104/ajssls.022.0940105

Shuvo, M., 2022. The waste keeps piling up. Dly. Star.

Siddiki, S.Y.A., Uddin, M.N., Mofijur, M., Fattah, I.M.R., Ong, H.C., Lam, S.S., Kumar, P.S., Ahmed, S.F., 2021. Theoretical calculation of biogas production and greenhouse gas emission reduction potential of livestock, poultry and slaughterhouse waste in Bangladesh. J. Environ. Chem. Eng. 9, 105204. https://doi.org/10.1016/j.jece.2021.105204

Silva, P., 2020. Health and environmental benefits of AD systems in Brazil. J. Sustain. Agric. 12, 67–82.

Silva, S., Jalal, A., Eliane, R., Kawakami, K.C., Abreu-junior, C.H., Oliveira, F.C., Jani, A.D., He, Z., Zhao, F., Carvalho, M., Teixeira, M., Rossetto, R., Capra, G.F., Assis, T., Nogueira, R., 2022. Composted sewage sludge application reduces mineral fertilization requirements and improves soil fertility in sugarcane seedling nurseries. Sustain. 14. https://doi.org/10.3390/su14084684

Simms, L.J., Zelazny, K., Williams, T.F., Bernstein, L., 2019. Does the number of response options matter? Psychometric perspectives using personality questionnaire data. Psychol. Assess. 31, 557–566. https://doi.org/10.1037/pas0000648

Singh, J., Sharma, M.K., Mahawar, A.K., Singh, S.P., Bano, R., 2018. Effect of organic and inorganic sources of NPK and bio-fertilizer on enhancement of growth attributes and chlorophyll content of sweet potato. Int. J. Curr. Microbiol. Appl. Sci. 7, 3659–3667. https://doi.org/10.20546/ijcmas.2018.709.455

Singpurwalla, D., 2015. A Handbook of statistics, concurrent enterprising (ICE), 2011 17th International Conference on.

Smith, J., Abegaz, A., Matthews, R.B., Subedi, M., Orskov, E.R., Tumwesige, V., Smith, P., 2014. What is the potential for biogas digesters to improve soil fertility and crop production in Sub-Saharan Africa? Biomass and Bioenergy 70, 58–72. https://doi.org/10.1016/j.biombioe.2014.02.030

SNV-Vietnam, 2020. Household biodigesters in Viet Nam building a sector for 20 years.

Somanathan, E., Bluffstone, R., 2015. Biogas: Clean energy access with low-cost mitigation of climate change, policy research working paper 7349. https://doi.org/10.1007/s10640-015-9961-6

Song, S., Lim, J.W., Lee, J.T.E., Cheong, J.C., Hoy, S.H., Hu, Q., Tan, J.K.N., Chiam, Z., Arora, S., Lum, T.Q.H., Lim, E.Y., Wang, C.-H., Tan, H.T.W., Tong, Y.W., 2021. Food-waste anaerobic digestate as a fertilizer: The agronomic properties of untreated digestate and biochar-filtered digestate residue. Waste Manag. 136, 143–152. https://doi.org/10.1016/j.wasman.2021.10.011

Sovacool, B.K., Kryman, M., Smith, T., 2015. Scaling and commercializing mobile biogas systems in Kenya: A qualitative pilot study. Renew. Energy 76, 115–125. https://doi.org/10.1016/j.renene.2014.10.070

Speziale, L., Geneletti, D., 2014. Applying an ecosystem services approach to support land-use planning: a case study in Koboko district, Uganda. Ecol. Process. 3, 1–13. https://doi.org/10.1186/2192-1709-3-10

Srdjevic, Z., Bajcetic, R., Srdjevic, B., 2012. Identifying the criteria set for multicriteria decision making based on SWOT/PESTLE analysis: A case study of reconstructing a water intake structure. Water Resour. Manag. 26, 3379–3393. https://doi.org/10.1007/s11269-012-0077-2

SREDA, 2021. Promoting energy efficiency and renewable energy SREDA action plan 2021-25.

SREDA, 2020. Biogas [WWW Document]. Sustain. Renew. Energy Dev. Div. Power Div. Minist. Power, Energy Miner. Resour. Gov. Peoples Repub. Bangladesh. URL http://www.sreda.gov.bd/index.sphp/site/page/7670-0153-6622-d052-258b-c7c2-9e5b-ee09-ed7f-c4f0 (accessed 11.24.20).

SREDA, 2016. Energy Efficiency and Conservation Master Plan up to 2030 1–126.

Surendra, K.C., Takara, D., Hashimoto, A.G., Khanal, S.K., 2014. Biogas as a sustainable energy source for developing countries: Opportunities and challenges. Renew. Sustain. Energy Rev. 31, 846–859. https://doi.org/10.1016/j.rser.2013.12.015

Svensson, K., Odlare, M., Pell, M., 2004. The fertilizing effect of compost and biogas residues from source separated household waste. J. Agric. Sci. 142, 461–467.

https://doi.org/10.1017/S0021859604004514

Taherdoost, H., 2019. What is the best response scale for survey and questionnaire design; Review of dfferent lengths of rating scale / Attitude scale / Likert scale. Int. J. Acad. Res. Manag. 8, 2296–1747.

Thiruselvi, D., Kumar, P.S., Kumar, M.A., Lay, C.H., Aathika, S., Mani, Y., Jagadiswary, D., Dhanasekaran, A., Shanmugam, P., Sivanesan, S., Show, P.L., 2020. A critical review on global trends in biogas scenario with its up-gradation techniques for fuel cell and future perspectives. Int. J. Hydrogen Energy 46, 16734–16750. https://doi.org/10.1016/j.ijhydene.2020.10.023

Thoa, L.T., 2020. Vietnam : Lack of overall strategy on the expansion of biogas production. BIOGAS J. 37–39.

Thrän, D., Deprie, K., Dotzauer, M., Kornatz, P., Nelles, M., Radtke, K.S., Schindler, H., 2023. The potential contribution of biogas to the security of gas supply in Germany. Energy. Sustain. Soc. 13, 1–15. https://doi.org/10.1186/s13705-023-00389-1

Thrän, D., Schaubach, K., Majer, S., Horschig, T., 2020. Governance of sustainability in the German biogas sector - Adaptive management of the Renewable Energy Act between agriculture and the energy sector. Energy. Sustain. Soc. 10. https://doi.org/10.1186/s13705-019-0227-y

Tiwary, A., Williams, I.D., Pant, D.C., Kishore, V.V.N., 2015. Emerging perspectives on environmental burden minimisation initiatives from anaerobic digestion technologies for community scale biomass valorisation. Renew. Sustain. Energy Rev. 42, 883–901. https://doi.org/10.1016/j.rser.2014.10.052

Tobin, R., Crawford, G., Hallett, J., Maycock, B., Lobo, R., 2022. Utilizing causal loop diagramming to explore a research and evaluation capacity building partnership. Front. Public Heal. 10, 1–16. https://doi.org/10.3389/fpubh.2022.857918

Transparency International, 2023. Corruption perceptions index : Bangladesh [WWW Document]. URL https://www.transparency.org/en/countries/bangladesh (accessed 7.16.24).

Transparency International, 2020. Corruption Perceptions Index 2020.

Tsangas, M., Jeguirim, M., Limousy, L., Zorpas, A., 2019. The application of analytical hierarchy process in combination with PESTEL-SWOT analysis to assess the hydrocarbons sector in Cyprus. Energies 12, 1–17.

https://doi.org/10.3390/en12050791

Tucho, G.T., Moll, H.C., Schoot Uiterkamp, A.J.M., Nonhebel, S., 2016. Problems with biogas implementation in developing countries from the perspective of labor requirements. Energies 9. https://doi.org/10.3390/en9090750

Ugwu, C.I., Ekere, J.N., Onoh, C., 2021. Research paradigms and methodological choices in the research process. J. Appl. Inf. Sci. Technol. 14, 2021.

UN, 2015. The Paris agreement. Paris. https://doi.org/10.4324/9789276082569-2

UNCAC-Coalition, 2023. New civil society report on Bangladesh: Legal framework in place, but poor implementation of UNCAC provisions exacerbates corruption | UNCAC Coalition [WWW Document]. URL https://uncaccoalition.org/uncacparallelreportbangladesh/ (accessed 7.16.24).

UNEP, 2024. Emission Gap Report 2024: No more hot air … please ! With a massive gap between rhetoric and reality, countries draft new climate commitments. Nirobi. https://doi.org/10.59117/20.500.11822/46404

UNEP, 2021. Global methane assessment : Benefits and costs of mitigating methane emissions. United Nations Environment Programme and Climate and Clean Air Coalition, United Nations Environment Programme, Nairobi.

UNEP, 2019a. The emissions gap report 2019 (full report). Nairobi.

UNEP, 2019b. Frontiers 2018/19 - Emerging issues of environmental concern, UN Environment. Nirobi.

UNEP, 2019c. In Bangladesh, women's right to clean air starts in the kitchen [WWW Document]. United Nations Environ. Program. URL https://www.unep.org/news-and-stories/story/bangladesh-womens-right-clean-air-starts-kitchen (accessed 5.24.21).

UNICEF, 2015. SWOT and PESTEL, UNICEF KE Toolbox.

Urban, F., Siciliano, G., Wallbott, L., Lederer, M., Dang Nguyen, A., 2018. Green transformations in Vietnam's energy sector. Asia Pacific Policy Stud. 5, 558–582. https://doi.org/10.1002/app5.251

Veldhuis, G.A., Smits-Clijsen, E.M., van Waas, R.P.M., Hof, T., Maccatrozzo, V., Rouwette, E.A.J.A., Kerstholt, J.H., 2025. The influence of causal loop diagrams on systems thinking and information utilization in complex problem-solving. Comput. Hum. Behav. Reports 17, 100613. https://doi.org/10.1016/j.chbr.2025.100613

Venus, T.E., Strauss, F., Venus, T.J., Sauer, J., 2021. Understanding stakeholder preferences for future biogas development in Germany. Land use policy 109, 105704. https://doi.org/10.1016/j.landusepol.2021.105704

Vu, T.K.V., Vu, D.Q., Jensen, L.S., Sommer, S.G., Bruun, S., 2015. Life cycle assessment of biogas production in small-scale household digesters in Vietnam. Asian-Australasian J. Anim. Sci. 28, 716–729. https://doi.org/10.5713/ajas.14.0683

Wagaw, K., 2016. Characterization and utilization of bioslury from anaerobic digester for fertilizer in crop production. J. Fertil. Pestic. 7. https://doi.org/10.4172/2471-2728.1000169

Walekhwa, P.N., Mugisha, J., Drake, L., 2009. Biogas energy from family-sized digesters in Uganda: Critical factors and policy implications. Energy Policy 37, 2754–2762. https://doi.org/10.1016/j.enpol.2009.03.018

Wang, P., Wang, J., Jin, R., Li, G., Zhou, M., Xia, Q., 2022. Integrating biogas in regional energy systems to achieve near-zero carbon emissions. Appl. Energy 322, 119515. https://doi.org/10.1016/j.apenergy.2022.119515

Wang, S., Ma, F., Ma, W., Wang, P., Zhao, G., Lu, X., 2019. Influence of temperature on biogas production efficiency and microbial community in a two-phase anaerobic digestion system. Water (Switzerland) 11. https://doi.org/10.3390/w11010133

Wanjohi, A.M., Irungu, E.K., Gicheru, H.C., 2022. Biogas program in Kenya: History, challenges and milestones. Int. J. Environ. Heal. Sci. 2, 3.

Wasi, A.T., Anik, M.A., Hasan, Z., Meraz, S., 2023. Biogas technology in Bangladesh: A comprehensive study on history, present situation, technologies and electricity generation potential. https://doi.org/10.13140/RG.2.2.31759.36002/1

WBA, 2022. Delivering the global methane pledge, decarbonisation technology. London.

Weber, M., 1947. The Theory of Social and Economic Organization., California Law Review.

Weiland, P., 2010. Biogas production: Current state and perspectives. Appl. Microbiol. Biotechnol. 85, 849–860. https://doi.org/10.1007/s00253-009-2246-7

WHO, 2020. Sustainable Development Goals: Guidelines for the use of the SDG

logo. United Nations Dep. Glob. Commun. 1–68.

Willis, J.W., 2007. Foundations of qualitative research: Interpretive and critical approaches. Sage Publications. https://doi.org/10.4135/9781452230108

World Bank, 2020. GDP per capita (current US$) [WWW Document]. URL https://data.worldbank.org/indicator/NY.GDP.PCAP.CD?end=2020&locations=BD&start=1960&view=chart

World Bank, 2021. Overview : The World Bank In Bangladesh [WWW Document]. URL https://www.worldbank.org/en/country/bangladesh (accessed 5.28.21).

Wulf, T., Meissner, P., Stubner, S., 2010. A scenario-based approach to strategic planning – Integrating planning and process perspective of strategy. Management 32.

Yasar, A., Nazir, S., Tabinda, A.B., Nazar, M., Rasheed, R., Afzaal, M., 2017. Socio-economic, health and agriculture benefits of rural household biogas plants in energy scarce developing countries: A case study from Pakistan. Renew. Energy 108, 19–25. https://doi.org/10.1016/j.renene.2017.02.044

Yousuf, A., Khan, M.R., Pirozzi, D., Ab Wahid, Z., 2016. Financial sustainability of biogas technology: Barriers, opportunities, and solutions. Energy Sources, Part B Econ. Plan. Policy 11, 841–848. https://doi.org/10.1080/15567249.2016.1148084

Zaman, M.A.U., Kamal, M.R., Mohonta, S.C., 2019. Feasibility study of electrical energy generation from poultry waste in Bangladesh. 5th Int. Conf. Comput. Commun. Chem. Mater. Electron. Eng. IC4ME2 2019 11–12. https://doi.org/10.1109/IC4ME247184.2019.9036672

Zhou, Y., Zhu, Y., Wong, W.K., 2023. Statistical tests for homogeneity of variance for clinical trials and recommendations. Contemp. Clin. Trials Commun. 33, 101119. https://doi.org/10.1016/j.conctc.2023.101119

Zifu, L., Mang, H.-P., Neupane, K., Huba, E.-M., Wauthelet, M., 2013. Biogas Audit Bangladesh 2011-2013, Volume II. Dhaka.

Zorpas, A.A., 2020. Strategy development in the framework of waste management. Sci. Total Environ. 716, 137088. https://doi.org/10.1016/j.scitotenv.2020.137088

Zou, C., Zhao, Q., Zhang, G., Xiong, B., 2016. Energy revolution: From a fossil energy era to a new energy era. Nat. Gas Ind. B 36, 1–11. https://doi.org/10.3787/j.issn.1000-0976.2016.01.001

Appendices

Appendix 01: Ethical approval letter from BCU



Faculty of Computing, Engineering & the Built Environment Research Office
Millennium Point, Curzon Street
Birmingham
B4 7XG

BCU_ethics@bcu.ac.uk

05/Dec/2019

Mrs Tania Islam

tania.islam@mail.bcu.ac.uk

Dear Tania ,

Re: Islam /3546 /R(A) /2019 /Dec /CEBE FAEC - An exploration of the key factors influencing the success and failure of biogas programmes in Bangladesh through techno-economic assessment

Thank you for your application and documentation regarding the above activity. I am pleased to take Chair's Action and approve this activity.

Provided that you are granted Permission of Access by relevant parties (meeting requirements as laid out by them), you may begin your activity.

I can also confirm that any person participating in the project is covered under the University's insurance arrangements.

Please note that ethics approval only covers your activity as it has been detailed in your ethics application. If you wish to make any changes to the activity, then you must submit an Amendment application for approval of the proposed changes.

Examples of changes include (but are not limited to) adding a new study site, a new method of participant recruitment, adding a new method of data collection and/or change of Project Lead.

Please also note that the Computing, Engineering and the Built Environment should be notified of any serious adverse effects arising as a result of this activity.

If for any reason the Committee feels that the activity is no longer ethically sound, it reserves the right to withdraw its approval. In the unlikely event of issues arising which would lead to this, you will be consulted.

Keep a copy of this letter along with the corresponding application for your records as evidence of approval.

If you have any queries, please contact BCU_ethics@bcu.ac.uk

I wish you every success with your activity.

Yours Sincerely,

Professor Peter Larkham

On behalf of the Computing, Engineering and the Built Environment

Appendix 02: Consent form for interviews

CONSENT FORM FOR INTERVIEWS

CONSENT FORM FOR QUESTIONNAIRE:

(An exploration of the key factors influencing the success and failure of small-scale Anaerobic digestion programmes in Bangladesh)

Please tick the appropriate boxes	**Yes**	**No**
Taking Part		
I have read and understood the project information sheet dated __/__/____		
I have been given the opportunity to ask questions about the project.		
I agree to take part in the project. Taking part in the project will include being interviewed and recorded (on encrypted and password protected devices)		
I understand that my taking part is voluntary; I can withdraw from the study at any time and I do not have to give any reasons for why I no longer want to take part. If I withdraw consent any information I have provided will be destroyed.		
Use of the information I provide for this project only		
I understand my personal details such as phone number and address will not be collected as part of this study.		
I understand that my words may be anonymously quoted in publications, reports, web pages, and other research outputs. My name will not be used in any publication, report or website.		
Use of the information I provide beyond this project		
I understand that the data I provide will be retained for research purposes at Birmingham City University.		
I understand that other genuine researchers may use my words in publications, reports, web pages, and other research outputs, only if they agree to preserve the confidentiality of the information as requested in this form.		
So we can use the information you provide legally		

Name of participant..... Signature .....Date .....

Researcher ..... Signature ..... Date

Project contact details for further information:

Tania Islam
PhD student
Birmingham City University
Tania.islam@mail.bcu.ac.uk

Supervisor
Professor Lynsey Melville
Birmingham City University
Lynsey.melville@bcu.ac.uk
(+44) 121 331 5457

Appendix 03: Project overview (participant information leaflet)

THESIS TITLE:

"An exploration of the key factors influencing the success and failure of small-scale Anaerobic digestion programmes in Bangladesh."

Participant Information Leaflet



BIRMINGHAM CITY University

About the project:

The aim of this project is to identify and explore the challenges and opportunities for biogas production in tropical countries, focusing on the example of Bangladesh.

Both the government of Bangladesh and private sectors are encouraging the installation of new biogas plants by providing incentives and low interest loans across the country. In Bangladesh there are almost 73,150 biogas plants have been installed. Although the government is taking initiatives for setup more new biogas plant but on the other hand existing biogas plants are facing various problems (IDCOL, 2019).

You have a unique understanding of your community and your biogas plant. This knowledge, together with your thoughts and opinions is very important when making decisions about the future.

The project is for 2 years (Don't need to be involved for 2 years) and we would like to work closely with you to understand the current challenges and future opportunities for the biogas plant.

How will we do this?

I will visit different part of Bangladesh in December 2019. I will collect basic information about the area and locate the biogas plants.

I would also like to talk with you personally about biogas plant, energy use and waste management within the house and the community so we can understand any issues as well as any hopes you have for the future.

I would like to give you the opportunity to share your thoughts with us in a one to one meeting. This can be arranged at a convenient time or location for you during our visit.

What to expect:

I will develop a short questionnaire about how you manage (use) your biogas plant. This will take no longer than 15-20 minutes. You will also have the opportunity to provide further information about your concerns, expectations and hopes surrounding the future management of these resources in Bangladesh.

How we will use the information you have provided:

All of the information you will provide to us will be anonymous. We will not use your name or personal details in any of our reports.

The information will be used to develop some general, key principles and considerations to ensure that the voice of the community is represented in future decision making.

The findings will be documented in my thesis and presented to all of the community and stakeholders and as a participant you will have the opportunity to review this document prior to its final publications.

In some cases, the information I/we gather may be helpful to other researchers working in similar areas and with similar communities. It is therefore possible that some data and information will be presented in scientific journals or at conferences, this will remain anonymous .

Important:

Participation in this research is entirely voluntary. If you choose to participate you will be asked to sign a consent form. This can be provided in English or Bangla. I/We can arrange support and guidance with this document (or the consent form if necessary). Consent can be withdrawn at any stage of the research and any information you have provided will be withdrawn from the study and destroyed (see page 7). This will not adversely affect any future contribution you may wish to make to this project or access to services in the future.

All information collected from participants during the interviews will be anonymised. No personal data will be collected or stored during this research study and any information provided to us will be stored on BCU encrypted and password protected devices.

Notes and Questions:

Further information:
I am currently studying in Birmingham City University (BCU), UK and this research is funded by Bangabandhu Science and Technology Fellowship Trust.
The project is led by Birmingham City University (BCU) https://www.bcu.ac.uk/ and funded by Bangabandhu Science and Technology Fellowship Trust www.bstft.gov.bd.
If you have any further questions or require guidance on this document or the consent form, please contact:

Tania Islam
Tania.islam@mail.bcu.ac.uk
+447403733307 (UK number)
+8801712539901 (Bangladesh number)

Project supervisor
Professor Lynsey Melville
Lynsey.melville@bcu.ac.uk
+44 121 331 5457

Project co-supervisor
Dr. Khondokar Mizanur Rahman
Khondokar.Rahman@bcu.ac.uk
+44 (0)121 202 8545

For complaints or further information on BCU ethics processes and procedures for this project please contact ethics@bcu.ac.uk .

Regarding procedure of a respondent wishes to withdraw from this research:
Please contact:

Tania Islam (Ph.D. Researcher)
Tania.islam@mail.bcu.ac.uk
+447403733307 (UK number); +8801712539901 (Bangladesh number)
Birmingham City University
University House;15 Bartholomew Row
Birmingham; B5 5JU
United Kingdom

Appendix 04: Field Locations

Date : (17-10-2021)
01. Shafiqul Islam
Location: geo:23.09348,89.36212?z=21
https://osmand.net/go?lat=23.09348&lon=89.36212&z=21
23.09348,89.36212

02 . Aminul islam
Location: geo:23.09355,89.36181?z=21
https://osmand.net/go?lat=23.09355&lon=89.36181&z=21
23.09355,89.36181

03. Akbar Ali
Location: geo:23.09244,89.36014?z=21
https://osmand.net/go?lat=23.09244&lon=89.36014&z=21
23.09244,89.36014

04. Idris Ali
Location: geo:23.09196,89.36130?z=21
https://osmand.net/go?lat=23.09196&lon=89.36130&z=21
23.09196,89.36130

05. Akbar beg
Location: geo:23.10315,89.35457?z=21
https://osmand.net/go?lat=23.10315&lon=89.35457&z=21
23.10315,89.35457

Date : 19-10-2021

6. Shahida Khaton
Location: geo:23.54988,89.19629?z=21
https://osmand.net/go?lat=23.54988&lon=89.19629&z=21
23.54988,89.19629

07. Late A Razzak
Location: geo:23.55027,89.19687?z=21
https://osmand.net/go?lat=23.55027&lon=89.19687&z=21
23.55027,89.19687

08. parvin
Location: geo:23.53904,89.23004?z=21
https://osmand.net/go?lat=23.53904&lon=89.23004&z=21
23.53904,89.23004

09. waheduzzaman
Location: geo:23.53896,89.22951?z=21

https://osmand.net/go?lat=23.53896&lon=89.22951&z=21
23.53896,89.22951

10. NurunNahar Khatun
Location: geo:23.53849,89.17424?z=21
https://osmand.net/go?lat=23.53849&lon=89.17424&z=21
23.53849,89.17424

Date: 20-10-21
11. Golam Rabbani
Location: geo:24.37746,88.50077?z=21
https://osmand.net/go?lat=24.37746&lon=88.50077&z=21
24.37746,88.50077

12. Golam Nabi
Location: geo:24.37747,88.50168?z=17
https://osmand.net/go?lat=24.37747&lon=88.50168&z=17
24.37747,88.50168

13. Akkas Ali
Location: geo:24.37747,88.50168?z=21
https://osmand.net/go?lat=24.37747&lon=88.50168&z=21
24.37747,88.50168

14. Mansur Rahman
Location: geo:24.42820,88.60841?z=21
https://osmand.net/go?lat=24.42820&lon=88.60841&z=21
24.42820,88.60841

15. Anisur Rahman
Location: geo:24.51274,88.67409?z=16
https://osmand.net/go?lat=24.51274&lon=88.67409&z=16
24.51274,88.67409

16. Mahmudul Islam
Location: geo:25.09104,89.01197?z=16
https://osmand.net/go?lat=25.09104&lon=89.01197&z=16
25.09104,89.01197

17.Mafu Ara
Location: geo:25.09104,89.01196?z=12
https://osmand.net/go?lat=25.09104&lon=89.01196&z=12
25.09104,89.01196

18. Hyder Islam

Location: geo:25.09671,89.01100?z=16
https://osmand.net/go?lat=25.09671&lon=89.01100&z=16
25.09671,89.01100

19. Ranu Begum
Location: geo:25.09266,89.01478?z=15
https://osmand.net/go?lat=25.09266&lon=89.01478&z=15
25.09266,89.01478

20. Md Sazzad Hosen
Location: geo:25.09347,89.01417?z=16
https://osmand.net/go?lat=25.09347&lon=89.01417&z=16
25.09347,89.01417

21. Nur Alam
Location: geo:24.18550,89.15674?z=17
https://osmand.net/go?lat=24.18550&lon=89.15674&z=17
24.18550,89.15674

22. Firoz Khan
Location: geo:24.18099,89.14604?z=19
https://osmand.net/go?lat=24.18099&lon=89.14604&z=19
24.18099,89.14604
23. Rahela Khatun
Location: geo:24.18100,89.14587?z=19
https://osmand.net/go?lat=24.18100&lon=89.14587&z=19
24.18100,89.14587

24. Mustafizur Rahman Biplob
Location: geo:24.18381,89.14338?z=19
https://osmand.net/go?lat=24.18381&lon=89.14338&z=19
24.18381,89.14338

25. Asaduzzaman Khan
Location: geo:24.18394,89.14233?z=19
https://osmand.net/go?lat=24.18394&lon=89.14233&z=19
24.18394,89.14233

26. Sazzad Hossain
Location: geo:24.15027,89.15115?z=21
https://osmand.net/go?lat=24.15027&lon=89.15115&z=21
24.15027,89.15115

27. A Razzak
Location: geo:24.13597,89.13081?z=21
https://osmand.net/go?lat=24.13597&lon=89.13081&z=21
24.13597,89.13081

28. Azizul
Location: geo:24.13348,89.13000?z=21
https://osmand.net/go?lat=24.13348&lon=89.13000&z=21
24.13348,89.13000

29. Shaherul Alam
Location: geo:24.12379,89.13178?z=21
https://osmand.net/go?lat=24.12379&lon=89.13178&z=21
24.12379,89.13178

30. Sharif Ahmed
Location: geo:24.18314,89.27511?z=21
https://osmand.net/go?lat=24.18314&lon=89.27511&z=21
24.18314,89.27511
plant 31
Location: geo:22.30966,91.85346?z=19
https://osmand.net/go?lat=22.30966&lon=91.85346&z=19
22.30966,91.85346

plant 32
Solayman
Location: geo:22.29934,91.87229?z=19
https://osmand.net/go?lat=22.29934&lon=91.87229&z=19
22.29934,91.87229

plant 33
Naymul Alam
Location: geo:22.30015,91.87198?z=19
https://osmand.net/go?lat=22.30015&lon=91.87198&z=19
22.30015,91.87198

plant 34
A Hakim
Location: geo:22.30027,91.87089?z=21
https://osmand.net/go?lat=22.30027&lon=91.87089&z=21
22.30027,91.87089

plant 35
Shamsul Alam
Location: geo:22.30026,91.87034?z=21
https://osmand.net/go?lat=22.30026&lon=91.87034&z=21
22.30026,91.87034
plant 36,
Mr. Gazi
Location: geo:23.98779,90.46361?z=20
https://osmand.net/go?lat=23.98779&lon=90.46361&z=20

23.98779,90.46361

plant 37
Mr. Zahirul
Location: geo:23.98623,90.46499?z=21
https://osmand.net/go?lat=23.98623&lon=90.46499&z=21
23.98623,90.46499

plant 38,
Mr. Mukshed
Location: geo:23.98571,90.46271?z=21
https://osmand.net/go?lat=23.98571&lon=90.46271&z=21
23.98571,90.46271

plant 39,
Mr. Wahidul
Location: geo:23.98581,90.46272?z=21
https://osmand.net/go?lat=23.98581&lon=90.46272&z=21
23.98581,90.46272

plant 40
Mrs Honufa
Location: geo:23.98586,90.46255?z=21
https://osmand.net/go?lat=23.98586&lon=90.46255&z=21
23.98586,90.46255

plant 41
Mr Mannan
Location: geo:23.50877,90.93373?z=21
https://osmand.net/go?lat=23.50877&lon=90.93373&z=2
23.50877,90.93373

plant 42
Mr. Shahidullah
Location: geo:23.50753,90.93791?z=21
https://osmand.net/go?lat=23.50753&lon=90.93791&z=21
23.50753,90.93791

plant 43
Mr. Maruf
Location: geo:23.54143,90.94880?z=21
https://osmand.net/go?lat=23.54143&lon=90.94880&z=21
23.54143,90.94880

plant 44
Mr. Rafiqul
Location: geo:23.54562,90.94965?z=21

https://osmand.net/go?lat=23.54562&lon=90.94965&z=21
23.54562,90.94965

plant 45
Mr. Nabi Hosen
Location: geo:23.53445,90.93628?z=21
https://osmand.net/go?lat=23.53445&lon=90.93628&z=21
23.53445,90.93628

plant 46
Vertex (office)
Location: geo:24.29100,91.54976?z=15
https://osmand.net/go?lat=24.29100&lon=91.54976&z=15
24.29100,91.54976

plant 47
Vertex 1
Location: geo:24.29123,91.54856?z=17
https://osmand.net/go?lat=24.29123&lon=91.54856&z=17
24.29123,91.54856

plant 48
Mr. Shahbaz Ali
Location: geo:24.29008,91.51583?z=17
https://osmand.net/go?lat=24.29008&lon=91.51583&z=17
24.29008,91.51583

plant 49
Shakhawat Hosain
Location: geo:24.28989,91.51645?z=17
https://osmand.net/go?
lat=24.28989&lon=91.51645&z=17

plant 49
Mr. Shakhawat Hosain
Location: geo:24.28989,91.51645?z=17
https://osmand.net/go?lat=24.28989&lon=91.51645&z=17
24.28989,91.51645

plant 50 Hadis
Location: geo:24.29631,91.52011?z=17
https://osmand.net/go?lat=24.29631&lon=91.52011&z=17
24.29631,91.52011

Appendix 05: Questionnaire & Google Form

Category 01: Questionnaire for Biogas Plant User Survey

Plant ID Number :
Plant Size (m^3) :
Feed Material :

1. Personal information of Biogas Plant (BP) owner

1.1 Upazilla : .....**1.2 Zilla:** .....

1.3 Division : .....

1.4 Occupation (Code*): [ ] 1.13 Education (Code**): [ ]

*code: 1 - Service; 2 - Business (specify); 3 - Farmer; 4 - Day laborer; 5 - Fisherman; 6 - House wife; 7- Others (Goldsmith, Potters, Carpenter, Tailor, Village Doctor, Mason, Barber, Vender, Van puller, Rickshaw puller, Boatman etc. ..... specify in any)

**code: 1- Illiterate; 2- Literate but no institutional education; 3- Primary or equivalent; 4- Secondary or equivalent; 5- SSC passed or equivalent; 6- HSC passed or equivalent; 7- Graduation or equivalent; 8- Post Graduation or equivalent

1.5 Male member: [ ] 1.15 Female member: [ ]

2. Basic Information on biogas plant and related matters

2.1 Plant construction period	St. Date	Month	Year	Duration (days)

2.2 Is this biogas plant in operation? [1] Yes=1, [2] No=2

If Yes (Answer 2.3)

2.3 How often it requires maintenance (not cleaning)

[1] None=1 [2] Once a year=2 [3] Twice a year =3 [4] More than twice per year=4

2.4 Major repair or renovation (when and why)

If No (Answer 2.5)

2.5 Total length of plant operation time	Month	Year	TO	Month	Year

3. Information of raw materials for biogas plant

3.1 What are the raw materials used in biogas plant

1	Cattle litter =1,	2	Poultry litter =2	3	Kitchen waste =3	4	Agricultural waste =4	5	Mixed =5

3.2 Daily available raw materials(kg) ☐

3.3 Daily loading raw materials (kg) ☐

3.4 Loading frequency to plant per day

1	Not every day =1	2	Once a day=2	3	Twice a day =3	4	More than twice per day=4

3.5 Ratio of **raw materials**: **water**

Raw materials	:	Water
	:	

4. Installation and Functioning of Biogas Plant

4.1 What is the motivating reason(s) behind installing a biogas plant? (Answers can be more than one)

1	Subsidy	2	Non-availability of other fuel sources	3	Social benefits/Prestige
4	Health benefits	5	Environmental benefits	6	Economic benefits
7	Motivation from service provider	8	Motivation from existing plant owners	9	Compulsion from neighbors (in the case of poultry)
10	Saves time and energy	11	Other (specify): …….		

4.2 Who constructed your biogas plant?

_____

_____

4 .2.1 Mention the name of the PO, Mason etc.

_____

_____

4.3 Were any standards set by the service provider as regards the quality of construction materials and mason to construct biogas plants?

1	No	2	Yes	3	Do not know

4.4 If yes, what types of quality standards were set (answers can be more than one)?

4.5 Are you satisfied with the functioning of the plant?

1	No	2	Yes, partly	3	Yes, fully

4.5.1 If **partly satisfied**, what are the reasons for not fully satisfying?

4.5.2 If **fully satisfied,** what are the reasons for fully satisfying?

4.5.3 If **not satisfied,** what are the reasons for not satisfying?

4.6 If plant has failed, how long is the plant defunct?

1	Less than a month =1	2	1 to 4 months =2	3	4 to 12 months =3	4	More than a year _____=4

4.7 If plant has failed, what are the reasons for such failure? (Answers can be more than one)

4.8 Has anyone in your family received training on operation and maintenance of biogas plants?

4.9 Have you received any follow up services from the service provider?

1	No, not even when requested =1	2	No, not at all =2	3	Yes, on call =3	4	Yes, regularly =4

4.10 Is there any service centre nearby?

1	No =1	2	Yes, very near (within 5 km reach)=2	3	Yes, quite far (5-10 km reach); =3	4	Yes, very far (more than 10 km reach) =4

4.11 How much money you need per year for operation and maintenance of your plant? (Code: 1=Less than Tk.100; 2=Tk.100 – 300; 3=Tk.400 – 600; 4=Tk. 700 – 1000; 5=More than Tk. 1000)

1	Less than Tk.100=1	2	Tk.100 – 300=2	3	Tk.400 – 600=3	4	Tk. 700 – 1000=4	5	More than Tk. 1000)

5. Impacts on socio-economic condition.

Before biogas plant installation		After biogas plant installation	
5.1 Used time for cooking per day (hour)		5.2 Use time for cooking per day (hour)	
5.3 Fuel cost per month (Tk.)		5.4 Fuel cost per-month (other than biogas)	
5.5 How much fuel (kg) wood used from collection (bush and tree)		5.6 How much fuel (kg) wood use from collection (bush and tree)	
5.7 Total time (hour) spent for fuel collection per day previously		5.8 Total time (hour) spent for fuel collection per day at present	
5.9 Self assessed poverty status**		5.10 Educational facilities of HH Member*	
		5.11 Self assessed poverty status**	

*Code: 1= Improving; 2= Decreasing; 3= No change **code: 1= Surplus; 2= Breakeven 3= Deficit

5.12 Do you sell the gas to other HHs (If yes, answer question under item – 7)	

6. Bio-slurry management, marketing and potentiality

6.1 How do you use bio-slurry? (1=Liquid; 2=Semi-liquid; 3=Dried; 4=Compost)	
6.2 How many days you store bio- slurry in pit?	
6.3 Do you dry bio-slurry? (1=Yes; 2=No)	
6.4 How do you dry bio-slurry? (1= Open sun shine; 2=Under shade)	
6.5 How much (kg.) bio-slurry you collect from plant in a week?	
6.6 Do you sale bio-slurry locally? (1=Yes; 2=No)	
6.7 If yes, price of bio-slurry (kg)	
6.8 How many potential customers visited your BP for slurry?	
6.9 Do you add any other organic materials with bio slurry? (1=Yes; 2=No)	
6.10 What type of materials you add? (1= Chemical fertilizer; 2=Green compost manure; 3= Kitchen wastage; 4=others.(specify..)	
6.11 Did you pile up cow dung regularly? (1=Yes; 2=No)	
6.12 Do you compost cow dung regularly? (1=Yes; 2=No)	
6.13 Do you regularly turn the decomposing materials for aeration? (1=Yes; 2=No)	

7. Information on biogas consumers on payment

7.1 Rate: Tk. per month: .....

7.2 Condition (if any) :

7.3 Benefits any :

7.4 Problems any:

7.5 Suggestion any :

Category 02: Questionnaire for development stakeholder (NGOs / Funding agencies/ GOs) Survey

About the Project:

The aim of this project is to identify and explore the challenges and opportunities for biogas production in tropical countries, focusing on the example of Bangladesh.

Both the government of Bangladesh and private sectors are encouraging the installation of new biogas plants by providing incentives and low interest loans across the country. In Bangladesh there are almost 73,150 biogas plants have been installed. Although the government is taking initiatives for setup more new biogas plants but on the other hand existing biogas plants are facing various problems (IDCOL, 2019).

You have a unique understanding of your community and your biogas plant. This knowledge, together with your thoughts and opinions is very important when making decisions about the future.

The project is for 2 years (Don't need to be involved for 2 years) and we would like to work closely with you to understand the current challenges and future opportunities for the biogas plant.

How we will use the information you have provided:

All of the information you will provide to us will be anonymous. We will not use your name or personal details in any of our reports.

The information will be used to develop some general, key principles and considerations to ensure that the voice of the community is represented in future decision making.

The findings will be documented in my thesis and presented to all of the community and stakeholders and as a participant you will have the opportunity to review this document prior to its final publications.

In some cases, the information I/we gather may be helpful to other researchers working in similar areas and with similar communities. It is therefore possible that some data and information will be presented in scientific journals or at conferences, this will remain anonymous.

Name of the organization

Name of the respondents with designation

1. What are the criteria for funding to the new AD owner? (one or more answer)

- ☐ Low income
- ☐ Particular geographic area
- ☐ Based on raw material availability
- ☐ Other:

2. Do you appoint any engineer for AD construction?

- ○ Yes
- ○ No
- ○ Other:

3. Do you provide or nominate any AD contractor to the new AD owner?

- ○ Yes
- ○ No
- ○ Other:

4. If yes, do you train the AD contractor?

- ○ Yes
- ○ No
- ○ Other:

5. Do you inspect the AD after construction?

- ○ Yes
- ○ No
- ○ Other:

6. After construction how often do you visit the AD?

- ◉ monthly
- ○ quarterly
- ○ twice in a year
- ○ once in a year

- never
- Other:

7. Do you provide any training to the AD owner for maintenance?

- Yes
- No
- Other:

8. Do you follow any design for AD construction?

- Fixed dome
- Floating dome
- Balloon plants
- Other:

9. What are the awareness activities to promote AD?

- None
- Other:

10. Till date how many AD have been funded or constructed by this organization?

11. How many of them are still running?

12. What are the main reasons behind the failure of AD according to you / organization? (one or more answer)

- lack of training (Plant owner)
- construction fault
- Alternative fuel source (cheap and available)
- lack of maintenance
- Lack of raw materials
- Other:

13. Does renewable Energy and climate change policy support AD growth in Bangladesh?

- Yes
- No
- Maybe
- Other:

14. Do you think taxation policies for AD construction and appliances are suitable in Bangladesh ?

- Yes

- ○ No
- ○ Maybe
- ○ Other:

15. Do you think adequate financial supports are available for AD construction?

- ○ Strongly disagree
- ○ Disagree
- ○ Neutral
- ○ Agree
- ○ Strongly agree
- ○ Other:

Category 03: Questionnaire for Development stakeholder (Engineering Farm / AD Construction farm) survey

About the Project:

The aim of this project is to identify and explore the challenges and opportunities for biogas production in tropical countries, focusing on the example of Bangladesh.

Both the government of Bangladesh and private sectors are encouraging the installation of new biogas plants by providing incentives and low interest loans across the country. In Bangladesh there are almost 73,150 biogas plants have been installed. Although the government is taking initiatives for setup more new biogas plants but on the other hand existing biogas plants are facing various problems (IDCOL, 2019).

You have a unique understanding of your community and your biogas plant. This knowledge, together with your thoughts and opinions is very important when making decisions about the future.

The project is for 2 years (Don't need to be involved for 2 years) and we would like to work closely with you to understand the current challenges and future opportunities for the biogas plant

How we will use the information you have provided:

All of the information you will provide to us will be anonymous. We will not use your

name or personal details in any of our reports.

The information will be used to develop some general, key principles and considerations to ensure that the voice of the community is represented in future decision making.

The findings will be documented in my thesis and presented to all of the community and stakeholders and as a participant you will have the opportunity to review this document prior to its final publications.

In some cases, the information I/we gather may be helpful to other researchers working in similar areas and with similar communities. It is therefore possible that some data and information will be presented in scientific journals or at conferences, this will remain anonymous.

Name of the organization

Name of the respondents with designation

1. Which design do you follow for AD construction?

- ☐ Fixed dome
- ☐ Floating Drum Plant
- ☐ Balloon Plants
- ☐ Other:

2. What are the cost for AD plant construction?

	Below 20,000 TK	20,000 TK to 30,000 TK	30,000 TK to 40,000TK	40,000 TK to 50,000Tk	50,000TK to 60,000TK	60,000 TK to 80,000 Tk	1,00,000 TK to 2,00,000 TK	2,00,000 TK to 5,00,000 TK	5,00,000 TK to 10,00,000 TK
Up to 2 m3	☐	☐	☐	☐	☐	☐	☐	☐	☐
2 to 6 m3	☐	☐	☐	☐	☐	☐	☐	☐	☐
Above 6 m3	☐	☐	☐	☐	☐	☐	☐	☐	☐

3. Do you inspect the AD after construction?

- ○ Yes
- ○ No

- ○ Other:

4. After construction how often do you visit the AD?

- ○ monthly
- ○ quarterly
- ○ twice in a year
- ○ once in a year
- ○ never
- ○ Other:

5. Do you provide any training to the AD owner for maintenance?

- ○ Yes
- ○ No
- ○ Other:

6. What are the awareness activities to promote AD?

- ○ None
- ○ Other:

7. Till date how many AD have been funded or constructed by this organisation?

8. How many of them are still running?

9. What are the main reasons behind the failure of AD according to you / organisation? (one or more answer)

- ○ lack of training (Plant owner)
- ○ construction fault
- ○ Alternative fuel source (cheap and available)
- ○ lack of maintenance
- ○ Lack of raw materials
- ○ Other:

PESTEL Analysis (online feedback form for Experts)

LINK:

https://docs.google.com/forms/d/e/1FAIpQLSf03GTZt0mmk-kzIgRlb8uMSzCpTUqyyjEpcsfV7d9vET1MLA/viewform?usp=sf_link

PAGE 01

PESTEL Analysis

Political Parameters

The key drivers of political parameters are given below,
i. Renewable Energy and Climate Policy
ii. Environmental Permitting Regulation (EPR) (AD planning)
iii. Job Creation
iv. Taxation policies
v. Government support for AD industry
vi. Stability of political framework

1. Renewable energy policy and climate change policy of Bangladesh

6 = High significance and have potential and sustainability of AD industries in Bangladesh ; 5 = Moderate significance and have potential and sustainability of AD industries in Bangladesh; 4 = Low positive and have low potential and sustainability of AD industries in Bangladesh. 3= low negative significance and have potential to hinder the growth of AD industries in Bangladesh; 2= Moderate negative significance and have potential to hinder the growth of AD industries in Bangladesh; 1= High negative significance and have potential to hinder the growth of AD industries in Bangladesh;

Mark only one oval.

	1	2	3	4	5	6	
H-	◯	◯	◯	◯	◯	◯	H+

2. Environmental Permitting Regulation (AD planning)

6 = High significance and have potential and sustainability of AD industries in Bangladesh ; 5 = Moderate significance and have potential and sustainability of AD industries in Bangladesh; 4 = Low positive and have low potential and sustainability of AD industries in Bangladesh. 3= low negative significance and have potential to hinder the growth of AD industries in Bangladesh; 2= Moderate negative significance and have potential to hinder the growth of AD industries in Bangladesh; 1= High negative significance and have potential to hinder the growth of AD industries in Bangladesh;

Mark only one oval.

	1	2	3	4	5	6	
H-	◯	◯	◯	◯	◯	◯	H+

PAGE 2

3. Job Creation

6 = High significance and have potential and sustainability of AD industries in Bangladesh ; 5 = Moderate significance and have potential and sustainability of AD industries in Bangladesh; 4 = Low positive and have low potential and sustainability of AD industries in Bangladesh. 3= low negative significance and have potential to hinder the growth of AD industries in Bangladesh; 2= Moderate negative significance and have potential to hinder the growth of AD industries in Bangladesh; 1= High negative significance and have potential to hinder the growth of AD industries in Bangladesh;

Mark only one oval.

	1	2	3	4	5	6	
H-	◯	◯	◯	◯	◯	◯	H+

4. Taxation policies for AD industries

6 = High significance and have potential and sustainability of AD industries in Bangladesh ; 5 = Moderate significance and have potential and sustainability of AD industries in Bangladesh; 4 = Low positive and have low potential and sustainability of AD industries in Bangladesh. 3= low negative significance and have potential to hinder the growth of AD industries in Bangladesh; 2= Moderate negative significance and have potential to hinder the growth of AD industries in Bangladesh; 1= High negative significance and have potential to hinder the growth of AD industries in Bangladesh;

Mark only one oval.

	1	2	3	4	5	6	
H-	◯	◯	◯	◯	◯	◯	H+

5. Government support for AD industry

6 = High significance and have potential and sustainability of AD industries in Bangladesh ; 5 = Moderate significance and have potential and sustainability of AD industries in Bangladesh; 4 = Low positive and have low potential and sustainability of AD industries in Bangladesh. 3= low negative significance and have potential to hinder the growth of AD industries in Bangladesh; 2= Moderate negative significance and have potential to hinder the growth of AD industries in Bangladesh; 1= High negative significance and have potential to hinder the growth of AD industries in Bangladesh;

Mark only one oval.

	1	2	3	4	5	6	
H-	◯	◯	◯	◯	◯	◯	H+

PAGE 3

6. Stability of political framework (The new trade relationship between China and Bangladesh in 2020)

6 = High significance and have potential and sustainability of AD industries in Bangladesh ; 5 = Moderate significance and have potential and sustainability of AD industries in Bangladesh; 4 = Low positive and have low potential and sustainability of AD industries in Bangladesh. 3= low negative significance and have potential to hinder the growth of AD industries in Bangladesh; 2= Moderate negative significance and have potential to hinder the growth of AD industries in Bangladesh; 1= High negative significance and have potential to hinder the growth of AD industries in Bangladesh;

Mark only one oval.

	1	2	3	4	5	6	
H-	◯	◯	◯	◯	◯	◯	H+

Economic Parameters

The key drivers of economic parameters are given below,
i. AD costs
ii. Maintenance costs
iii. Revenue and Offset costs from digestate
iv. Revenue from biogas/ Offset cost from biogas
v. Labor costs
vi. Cost savings from waste reduction and storage efficiency

7. Cost of New Biogas plant (AD cost)

6 = High significance and have potential and sustainability of AD industries in Bangladesh ; 5 = Moderate significance and have potential and sustainability of AD industries in Bangladesh; 4 = Low positive and have low potential and sustainability of AD industries in Bangladesh. 3= low negative significance and have potential to hinder the growth of AD industries in Bangladesh; 2= Moderate negative significance and have potential to hinder the growth of AD industries in Bangladesh; 1= High negative significance and have potential to hinder the growth of AD industries in Bangladesh;

Mark only one oval.

	1	2	3	4	5	6	
H-	◯	◯	◯	◯	◯	◯	H+

PAGE 4

8. Maintenance costs

6 = High significance and have potential and sustainability of AD industries in Bangladesh ; 5 = Moderate significance and have potential and sustainability of AD industries in Bangladesh; 4 = Low positive and have low potential and sustainability of AD industries in Bangladesh. 3= low negative significance and have potential to hinder the growth of AD industries in Bangladesh; 2= Moderate negative significance and have potential to hinder the growth of AD industries in Bangladesh; 1= High negative significance and have potential to hinder the growth of AD industries in Bangladesh;

Mark only one oval.

	1	2	3	4	5	6	
H-	◯	◯	◯	◯	◯	◯	H+

9. Revenue and Offset costs from digestate

6 = High significance and have potential and sustainability of AD industries in Bangladesh ; 5 = Moderate significance and have potential and sustainability of AD industries in Bangladesh; 4 = Low positive and have low potential and sustainability of AD industries in Bangladesh. 3= low negative significance and have potential to hinder the growth of AD industries in Bangladesh; 2= Moderate negative significance and have potential to hinder the growth of AD industries in Bangladesh; 1= High negative significance and have potential to hinder the growth of AD industries in Bangladesh;

Mark only one oval.

	1	2	3	4	5	6	
H-	◯	◯	◯	◯	◯	◯	H+

10. Revenue from biogas / Offset cost from biogas

6 = High significance and have potential and sustainability of AD industries in Bangladesh ; 5 = Moderate significance and have potential and sustainability of AD industries in Bangladesh; 4 = Low positive and have low potential and sustainability of AD industries in Bangladesh. 3= low negative significance and have potential to hinder the growth of AD industries in Bangladesh; 2= Moderate negative significance and have potential to hinder the growth of AD industries in Bangladesh; 1= High negative significance and have potential to hinder the growth of AD industries in Bangladesh;

Mark only one oval.

	1	2	3	4	5	6	
H-	◯	◯	◯	◯	◯	◯	H+

PAGE 5

11. Labor costs

6 = High significance and have potential and sustainability of AD industries in Bangladesh ; 5 = Moderate significance and have potential and sustainability of AD industries in Bangladesh; 4 = Low positive and have low potential and sustainability of AD industries in Bangladesh. 3= low negative significance and have potential to hinder the growth of AD industries in Bangladesh; 2= Moderate negative significance and have potential to hinder the growth of AD industries in Bangladesh; 1= High negative significance and have potential to hinder the growth of AD industries in Bangladesh;

Mark only one oval.

	1	2	3	4	5	6	
H-	⬭	⬭	⬭	⬭	⬭	⬭	H+

12. Cost savings from waste reduction and storage efficiency

6 = High significance and have potential and sustainability of AD industries in Bangladesh ; 5 = Moderate significance and have potential and sustainability of AD industries in Bangladesh; 4 = Low positive and have low potential and sustainability of AD industries in Bangladesh. 3= low negative significance and have potential to hinder the growth of AD industries in Bangladesh; 2= Moderate negative significance and have potential to hinder the growth of AD industries in Bangladesh; 1= High negative significance and have potential to hinder the growth of AD industries in Bangladesh;

Mark only one oval.

	1	2	3	4	5	6	
H-	⬭	⬭	⬭	⬭	⬭	⬭	H+

Social Parameters

The key drivers of social parameters are given below,
i. Household welfare improvement from behaviour change
ii. Distribution to poor households
iii. Vermin and malodour reduction
iv. Job opportunities
v. Social taboo

PAGE 6

13. Household welfare improvement from behaviour change

6 = High significance and have potential and sustainability of AD industries in Bangladesh ; 5 = Moderate significance and have potential and sustainability of AD industries in Bangladesh; 4 = Low positive and have low potential and sustainability of AD industries in Bangladesh. 3= low negative significance and have potential to hinder the growth of AD industries in Bangladesh; 2= Moderate negative significance and have potential to hinder the growth of AD industries in Bangladesh; 1= High negative significance and have potential to hinder the growth of AD industries in Bangladesh;

Mark only one oval.

	1	2	3	4	5	6	
H-	⬭	⬭	⬭	⬭	⬭	⬭	H+

14. Distribution to poor households

6 = High significance and have potential and sustainability of AD industries in Bangladesh ; 5 = Moderate significance and have potential and sustainability of AD industries in Bangladesh; 4 = Low positive and have low potential and sustainability of AD industries in Bangladesh. 3= low negative significance and have potential to hinder the growth of AD industries in Bangladesh; 2= Moderate negative significance and have potential to hinder the growth of AD industries in Bangladesh; 1= High negative significance and have potential to hinder the growth of AD industries in Bangladesh;

Mark only one oval.

	1	2	3	4	5	6	
H-	⬭	⬭	⬭	⬭	⬭	⬭	H+

15. Vermin and malodour reduction

6 = High significance and have potential and sustainability of AD industries in Bangladesh ; 5 = Moderate significance and have potential and sustainability of AD industries in Bangladesh; 4 = Low positive and have low potential and sustainability of AD industries in Bangladesh. 3= low negative significance and have potential to hinder the growth of AD industries in Bangladesh; 2= Moderate negative significance and have potential to hinder the growth of AD industries in Bangladesh; 1= High negative significance and have potential to hinder the growth of AD industries in Bangladesh;

Mark only one oval.

	1	2	3	4	5	6	
H-	⬭	⬭	⬭	⬭	⬭	⬭	H+

PAGE 7

16. Job opportunities

6 = High significance and have potential and sustainability of AD industries in Bangladesh ; 5 = Moderate significance and have potential and sustainability of AD industries in Bangladesh; 4 = Low positive and have low potential and sustainability of AD industries in Bangladesh. 3= low negative significance and have potential to hinder the growth of AD industries in Bangladesh; 2= Moderate negative significance and have potential to hinder the growth of AD industries in Bangladesh; 1= High negative significance and have potential to hinder the growth of AD industries in Bangladesh;

Mark only one oval.

	1	2	3	4	5	6	
H-	⬭	⬭	⬭	⬭	⬭	⬭	H+

17. Social taboo

6 = High significance and have potential and sustainability of AD industries in Bangladesh ; 5 = Moderate significance and have potential and sustainability of AD industries in Bangladesh; 4 = Low positive and have low potential and sustainability of AD industries in Bangladesh. 3= low negative significance and have potential to hinder the growth of AD industries in Bangladesh; 2= Moderate negative significance and have potential to hinder the growth of AD industries in Bangladesh; 1= High negative significance and have potential to hinder the growth of AD industries in Bangladesh;

Mark only one oval.

	1	2	3	4	5	6	
H-	⬭	⬭	⬭	⬭	⬭	⬭	H+

Technological Parameters

The key drivers of technological parameters are given below,
i. AD Technology Efficiency
ii. Biogas Extraction Technology
iii. Post-Treatment Technology Efficiency of Digestate
iv. Biogas Scrubbing Technology Efficiency
v. New technology and research

PAGE 8

18. AD Technology Efficiency

6 = High significance and have potential and sustainability of AD industries in Bangladesh ; 5 = Moderate significance and have potential and sustainability of AD industries in Bangladesh; 4 = Low positive and have low potential and sustainability of AD industries in Bangladesh. 3= low negative significance and have potential to hinder the growth of AD industries in Bangladesh; 2= Moderate negative significance and have potential to hinder the growth of AD industries in Bangladesh; 1= High negative significance and have potential to hinder the growth of AD industries in Bangladesh;

Mark only one oval.

	1	2	3	4	5	6	
H-	⬭	⬭	⬭	⬭	⬭	⬭	H+

19. Biogas Extraction Technology

6 = High significance and have potential and sustainability of AD industries in Bangladesh ; 5 = Moderate significance and have potential and sustainability of AD industries in Bangladesh; 4 = Low positive and have low potential and sustainability of AD industries in Bangladesh. 3= low negative significance and have potential to hinder the growth of AD industries in Bangladesh; 2= Moderate negative significance and have potential to hinder the growth of AD industries in Bangladesh; 1= High negative significance and have potential to hinder the growth of AD industries in Bangladesh;

Mark only one oval.

	1	2	3	4	5	6	
H-	⬭	⬭	⬭	⬭	⬭	⬭	H+

20. Post-Treatment Technology Efficiency of Digestate

6 = High significance and have potential and sustainability of AD industries in Bangladesh ; 5 = Moderate significance and have potential and sustainability of AD industries in Bangladesh; 4 = Low positive and have low potential and sustainability of AD industries in Bangladesh. 3= low negative significance and have potential to hinder the growth of AD industries in Bangladesh; 2= Moderate negative significance and have potential to hinder the growth of AD industries in Bangladesh; 1= High negative significance and have potential to hinder the growth of AD industries in Bangladesh;

Mark only one oval.

	1	2	3	4	5	6	
H-	⬭	⬭	⬭	⬭	⬭	⬭	H+

PAGE 9

21. Biogas Scrubbing Technology Efficiency

6 = High significance and have potential and sustainability of AD industries in Bangladesh ; 5 = Moderate significance and have potential and sustainability of AD industries in Bangladesh; 4 = Low positive and have low potential and sustainability of AD industries in Bangladesh. 3= low negative significance and have potential to hinder the growth of AD industries in Bangladesh; 2= Moderate negative significance and have potential to hinder the growth of AD industries in Bangladesh; 1= High negative significance and have potential to hinder the growth of AD industries in Bangladesh;

Mark only one oval.

	1	2	3	4	5	6	
H-	◯	◯	◯	◯	◯	◯	H+

22. New technology and research

6 = High significance and have potential and sustainability of AD industries in Bangladesh ; 5 = Moderate significance and have potential and sustainability of AD industries in Bangladesh; 4 = Low positive and have low potential and sustainability of AD industries in Bangladesh. 3= low negative significance and have potential to hinder the growth of AD industries in Bangladesh; 2= Moderate negative significance and have potential to hinder the growth of AD industries in Bangladesh; 1= High negative significance and have potential to hinder the growth of AD industries in Bangladesh;

Mark only one oval.

	1	2	3	4	5	6	
H-	◯	◯	◯	◯	◯	◯	H+

Environmental Parameters

The key drivers of environmental parameters are given below,
i. Global warming potential
ii. Eutrophication potential
iii. Human toxicity potential
iv. Aquatic ecotoxicity

PAGE 10

23. Global warming potential

6 = High significance and have potential and sustainability of AD industries in Bangladesh ; 5 = Moderate significance and have potential and sustainability of AD industries in Bangladesh; 4 = Low positive and have low potential and sustainability of AD industries in Bangladesh. 3= low negative significance and have potential to hinder the growth of AD industries in Bangladesh; 2= Moderate negative significance and have potential to hinder the growth of AD industries in Bangladesh; 1= High negative significance and have potential to hinder the growth of AD industries in Bangladesh;

Mark only one oval.

	1	2	3	4	5	6	
H-	◯	◯	◯	◯	◯	◯	H+

24. Eutrophication potential

6 = High significance and have potential and sustainability of AD industries in Bangladesh ; 5 = Moderate significance and have potential and sustainability of AD industries in Bangladesh; 4 = Low positive and have low potential and sustainability of AD industries in Bangladesh. 3= low negative significance and have potential to hinder the growth of AD industries in Bangladesh; 2= Moderate negative significance and have potential to hinder the growth of AD industries in Bangladesh; 1= High negative significance and have potential to hinder the growth of AD industries in Bangladesh;

Mark only one oval.

	1	2	3	4	5	6	
H-	◯	◯	◯	◯	◯	◯	H+

25. Human toxicity potential

6 = High significance and have potential and sustainability of AD industries in Bangladesh ; 5 = Moderate significance and have potential and sustainability of AD industries in Bangladesh; 4 = Low positive and have low potential and sustainability of AD industries in Bangladesh. 3= low negative significance and have potential to hinder the growth of AD industries in Bangladesh; 2= Moderate negative significance and have potential to hinder the growth of AD industries in Bangladesh; 1= High negative significance and have potential to hinder the growth of AD industries in Bangladesh;

Mark only one oval.

	1	2	3	4	5	6	
H-	◯	◯	◯	◯	◯	◯	H+

PAGE 11

26. Aquatic Ecotoxicity

6 = High significance and have potential and sustainability of AD industries in Bangladesh ; 5 = Moderate significance and have potential and sustainability of AD industries in Bangladesh; 4 = Low positive and have low potential and sustainability of AD industries in Bangladesh. 3= low negative significance and have potential to hinder the growth of AD industries in Bangladesh; 2= Moderate negative significance and have potential to hinder the growth of AD industries in Bangladesh; 1= High negative significance and have potential to hinder the growth of AD industries in Bangladesh;

Mark only one oval.

	1	2	3	4	5	6	
H-	◯	◯	◯	◯	◯	◯	H+

Legal Parameters

The key drivers of legal parameters are given below,
i. Waste management legislations
ii. Sludge management legislations
iii. Feed-in Tariffs
iv. Environmental Permitting Regulation

27. Waste management legislations

6 = High significance and have potential and sustainability of AD industries in Bangladesh ; 5 = Moderate significance and have potential and sustainability of AD industries in Bangladesh; 4 = Low positive and have low potential and sustainability of AD industries in Bangladesh. 3= low negative significance and have potential to hinder the growth of AD industries in Bangladesh; 2= Moderate negative significance and have potential to hinder the growth of AD industries in Bangladesh; 1= High negative significance and have potential to hinder the growth of AD industries in Bangladesh;

Mark only one oval.

	1	2	3	4	5	6	
H-	◯	◯	◯	◯	◯	◯	H+

PAGE 12

28. Sludge management legislations

6 = High significance and have potential and sustainability of AD industries in Bangladesh ; 5 = Moderate significance and have potential and sustainability of AD industries in Bangladesh; 4 = Low positive and have low potential and sustainability of AD industries in Bangladesh. 3= low negative significance and have potential to hinder the growth of AD industries in Bangladesh; 2= Moderate negative significance and have potential to hinder the growth of AD industries in Bangladesh; 1= High negative significance and have potential to hinder the growth of AD industries in Bangladesh;

Mark only one oval.

	1	2	3	4	5	6	
H-	◯	◯	◯	◯	◯	◯	H+

29. Feed-in Tariffs

6 = High significance and have potential and sustainability of AD industries in Bangladesh ; 5 = Moderate significance and have potential and sustainability of AD industries in Bangladesh; 4 = Low positive and have low potential and sustainability of AD industries in Bangladesh. 3= low negative significance and have potential to hinder the growth of AD industries in Bangladesh; 2= Moderate negative significance and have potential to hinder the growth of AD industries in Bangladesh; 1= High negative significance and have potential to hinder the growth of AD industries in Bangladesh;

Mark only one oval.

	1	2	3	4	5	6	
H-	◯	◯	◯	◯	◯	◯	H+

30. Environmental Permitting Regulation

6 = High significance and have potential and sustainability of AD industries in Bangladesh ; 5 = Moderate significance and have potential and sustainability of AD industries in Bangladesh; 4 = Low positive and have low potential and sustainability of AD industries in Bangladesh. 3= low negative significance and have potential to hinder the growth of AD industries in Bangladesh; 2= Moderate negative significance and have potential to hinder the growth of AD industries in Bangladesh; 1= High negative significance and have potential to hinder the growth of AD industries in Bangladesh;

Mark only one oval.

	1	2	3	4	5	6	
H-	◯	◯	◯	◯	◯	◯	H+

Appendix 06: Statistical analysis

6.1 Introduction

The research methodology serves as the roadmap guiding the researcher toward the objectives outlined in the study. It encompasses the strategies employed to carry out the investigation. Research can be viewed as a systematic exploration of the techniques applied in scientific inquiry, including the overall research design, sampling methods, data collection procedures, and analytical techniques. The subsequent section details the research approach adopted in this study to accomplish its objectives.

6.2 Data processing

When data is acquired and transformed into usable information, it undergoes processing. This involves editing, coding, and tabulating the survey data. For this study, data was collected from 50 respondents through direct interviews. Following the creation of a preliminary data analysis plan, the data processing steps include:

- Checking questionnaires
- Editing data
- Coding data
- Transcribing data
- Cleaning data
- Statistically adjusting the data
- Selecting a data analysis strategy

Each step ensures the accuracy and reliability of the data, paving the way for meaningful analysis

6.3 Categorical data analysis

Categorical data analysis involves examining the statistical relationships between explanatory variables and categorical response variables. This type of analysis primarily employs two main approaches:

- It conducts hypothesis tests to determine the associations between these factors, performs statistical analysis using tables defined by categorical variables, and assumes a randomised process.
- It models the relationship by analysing a categorical response variable, regardless of whether the explanatory variables are continuous or categorical; this process is known as categorical response modelling.

6.4 Bivariate analysis:

One of the most fundamental forms of quantitative (statistical) analysis is bivariate analysis. This method examines the empirical relationship between two variables, typically referred to as X and Y, to determine their association. Bivariate analysis is useful for evaluating simple association hypotheses and can also assess how well knowledge of one variable (potentially a dependent variable) facilitates the prediction of the value of another variable (possibly an independent variable) (Mann, 2011; Pham, 2023; Singpurwalla, 2015). Unlike univariate analysis, which focuses on a single variable, bivariate analysis explores the relationship between two variables, offering both descriptive and inferential insights. Essentially, bivariate analysis represents a specific (two-variable) case of multivariate analysis (Mann, 2011; Pham, 2023; Singpurwalla, 2015).

6.5 Cross tabulation

Cross tabulation, often referred to as a crosstab, is a type of matrix table used to display the multivariate frequency distribution of variables in statistics. This method is extensively applied in polling, business intelligence, engineering, and scientific research. Crosstabs offer a basic description of the relationship between two variables, helping to identify and understand interactions between them (Mann, 2011; Pham, 2023; Singpurwalla, 2015).

6.6 McNemar-Bowker test

The McNemar test is a non-parametric method often applied to paired nominal data. Results from these experiments are usually arranged in a k×k contingency table of counts or proportions, which can, when needed, be extended through the McNemar–Bowker test. This procedure is particularly useful when estimating power or determining the sample size for tests of symmetry in paired designs. In studies with *N* subjects, where outcomes may fall into k possible categories, the findings are typically summarised within a k×k contingency table (Mann, 2011; Pham, 2023; Singpurwalla, 2015).

Treatment 1/Treatment 2	1	2	. . .	k	Total
1	n_{11}	n_{12}	. . .	n_{1k}	$n_{1.}$
2	n_{21}	n_{22}	. . .	n_{2k}	$n_{2.}$
. . .	. . .	. . .	. . . .	. . .	. . .
k	n_{k1}	n_{k2}	. . .	n_{kk}	$n_{k.}$
Total	$n_{.1}$	$n_{.2}$	. . .	$n_{.k}$	$n_{..}= N$

Test Statistic

The hypotheses tested by the McNemar-Bowker test are

$$H_0: p_{ij} = p_{ji} \quad \text{for all i} \neq \text{j}$$
$$H_1: p_{ij} \neq p_{ji} \text{ for some i} \neq \text{j}$$

The McNemar-Bowker test statistic used to test these hypotheses is

$$T_{MB} = \sum_{i<j} \frac{\left(n_{ij} - n_{ji}\right)^2}{n_{ij} + n_{ji}}$$

For a significance level α, the test rejects the null hypothesis if $T_{MB} > \chi^2_{(1-\alpha),k(k-1)/2}$ where $\chi^2_{(1-\alpha),k(k-1)/2}$ is the upper $(1-\alpha)$ percentile of the standard chi-square distribution with $k(k-1)/2$ degrees of freedom.

6.7 Two-way analysis of variance with several equal observations per cell

The two-way analysis of variance (ANOVA) extends the one-way ANOVA by examining the effects of two different categorical independent variables on a single continuous dependent variable. The main goal of the two-way ANOVA is to assess the individual impact of each independent variable and to identify any interaction effects between them (Hao et al., 2022; Ikhwan et al., 2024).

In our study, we consider a two-way classification with rrr observations corresponding to i^{th} level of factor A and j^{th} level of factor B. Y_{ijk} be the kth observation (k=1,2,...,r) corresponding to i^{th} level of factor A (i=1,2,...,p) and j^{th} level of factor B (j=1,2,...,q). More precisely, the average value of the response variable is represented as a mathematical expression that combines the explanatory variables in a linear manner.

$$Y_{ijk} = \mu + \alpha_i + \beta_j + (\alpha\beta)_{ij} + e_{ijk}$$

Where, the symbol μ represents the grand mean. The symbols α_i and β_j represent the fixed effects of the levels i and j from the factors A and B respectively. The symbol $(\alpha\beta)_{ij}$ represents the non-additive interaction effect of the ith level of factor A and j^{th} level of factor B. The symbol e_{ijk} represents the random error term. These random errors are considered as deviations from the means and are supposed to be independent and follow a normal distribution.

Assumption:

1. The random error term is normally independently identically distributed with mean zero and constant variance., $e_{ijk} \sim$ NID $(0, \sigma^2)$.
2. All observations are independent.
3. All the effects are additive in nature.

Restriction for the model: $\sum\alpha_i = \sum\beta_j = \sum_i(\alpha\beta)_{ij} = \sum_j(\alpha\beta)_{ij} = 0$.

Partitioning the Total Sum of Square

$$TSS = \sum_{i=1}^{p}\sum_{j=1}^{q}\sum_{k=1}^{r}\left(Y_{ijk} - \bar{Y}_{...}\right)^2$$

$$= qr\sum_{i=1}^{p}(\bar{Y}_{i..} - \bar{Y}_{...})^2 + pr\sum_{j=1}^{q}\left(\bar{Y}_{.j.} - \bar{Y}_{...}\right)^2 + r\sum_{i=1}^{p}\sum_{j=1}^{q}\left(\bar{Y}_{ij.} - \bar{Y}_{i..} - \bar{Y}_{.j.} + \bar{Y}_{...}\right)^2$$
$$+ \sum_{i=1}^{p}\sum_{j=1}^{q}\sum_{k=1}^{r}\left(Y_{ijk} - \bar{Y}_{ij.}\right)^2$$

$$TSS = SS_A + SS_B + SS_{AB} + SS_E$$

Here,

$$SS_A = \frac{\sum_{i=1}^{p}\bar{Y}_{i..}^{\,2}}{qr} - \frac{\bar{Y}_{...}^{\,2}}{pqr}$$

$$SS_B = \frac{\sum_{j=1}^{q}\bar{Y}_{.j.}^{\,2}}{pr} - \frac{\bar{Y}_{...}^{\,2}}{pqr}$$

$$SS_{AB} = \frac{\sum_{i=1}^{p}\sum_{j=1}^{q}\bar{Y}_{ij.}^{\,2}}{r} - \frac{\bar{Y}_{...}^{\,2}}{pqr} - SSA - SS_B$$

$$SS_E = TSS - SS_A - SS_B - SS_{AB}$$

Here we need to test

$H_{01} : \alpha_i = 0$ against $H_{11} : \alpha_i \neq 0$; i =1,2,...,p

$H_{02} : \beta_j = 0$ against $H_{12} : \beta_j \neq 0$; j =1,2,...,q

$H_{03} : (\alpha\beta)_{ij} = 0$ against $H_{13} : (\alpha\beta)_{ij} \neq 0$; k =1,2,...,r

H_A : At least one of them are not equal to zero.

ANOVA TABLE

Sources of Variation (SV)	Degrees of Freedom (df)	Sum of Square (SS)	Mean Sum of Square (MSS)	F-Value	P-Value
A	$(p-1)$	SS_A	$S_1^{\,2} = \frac{SS_A}{p-1}$	$F_1 = \frac{S_1^{\,2}}{S_e^{\,2}}$	$Pr(F>F_1)$
B	$(q-1)$	SS_B	$S_2^{\,2} = \frac{SS_B}{q-1}$	$F_2 = \frac{S_2^{\,2}}{S_e^{\,2}}$	$Pr(F>F_2)$
AB	$(p-1)(q-1)$	SS_{AB}	$S_3^{\,2} = \frac{SS_{AB}}{(p-1)(q-1)}$	$F_3 = \frac{S_3^{\,2}}{S_e^{\,2}}$	$Pr(F>F_3)$
Error	$pq(r-1)$	SS_E	$S_e^{\,2} = \frac{SS_E}{pq(r-1)}$		
Total	$pqr-1$	TSS			

If $F_{cal} \geq F_{0.05}$ (P-value < 0.05) with appropriate df, then H_0 is rejected. The rejection of null hypothesis leads us to conduct multiple comparison test.

6.8 Multiple comparison Test/ Post hoc test

A significant result from an analysis of variance (ANOVA) indicates that at least one group differs from the others. However, the omnibus test does not reveal the specific pattern of mean differences. The most common method for analysing these differences

using ANOVA is through pairwise comparisons, where two means are compared directly (Hao et al., 2022; Ikhwan et al., 2024).

One widely used method for pairwise comparisons is Tukey's Honestly Significant Difference (HSD) test. This test aims to calculate the HSD between two means using the q distribution. The q distribution provides the exact sampling distribution of the mean with the largest difference from a set of means originating from the same population. The HSD test evaluates all pairwise differences using this same sampling distribution, making the approach conservative (Hao et al., 2022; Ikhwan et al., 2024).

Tukey's HSD Test

$H_{01} : \alpha_i = \alpha_{i'}$ against $H_{11} : \alpha_i \neq \alpha_{i'}$

$H_{02} : \beta_j = \beta_{j'}$ against $H_{12} : \beta_j \neq \beta_{j'}$

$H_{03} : (\alpha\beta)_{ij} = (\alpha\beta)_{ij'}$ against $H_{13} : (\alpha\beta)_{ij} \neq (\alpha\beta)_{ij'}$

Test statistic

$$HSD = \frac{\bar{Y}_{max} - \bar{Y}_{min}}{\sqrt{\frac{MSE}{n}}}$$

Where, n is the total number of observations. MSE is the error of within mean square from the ANOVA table.

All possible differences between pairs of means are computed, and any difference that yields and absolute value that exceeds HSD is declared to be significant, that means if $HSD \geq q_{(0.05, k, n-k)}$ we reject the null hypothesis H_0. Where, k is the number of means in the experiments.

6.9 Coefficient of correlation

A coefficient of correlation is commonly utilized in statistics to quantify the relationship between two variables. This correlation indicates the degree of a linear relationship between variables X and Y. Among various types of correlation coefficients, Pearson's correlation coefficient (often referred to as Pearson's R) is the most frequently used.

Pearson's coefficient of correlation

Karl Pearson's coefficient of correlation is a widely employed mathematical technique that quantifies the relationship between linearly related variables through numerical representation, denoted by "r". The correlation coefficient values range between -1 and 1. An r value of 0 indicates no linear relationship, meaning that changes in one variable do not predict changes in the other. Notably, if two variables are independent, the

correlation coefficient (r) will be zero, but the converse is not necessarily true (Hao et al., 2022; Ikhwan et al., 2024).

A negative correlation suggests that the two variables move in opposite directions, meaning that an increase in one variable corresponds to a decrease in the other, and vice versa. Conversely, a positive correlation indicates that the two variables move in the same direction, so if one variable increases, the other also increases, and if one decreases, the other similarly decreases (Hao et al., 2022; Ikhwan et al., 2024).

Karl Pearson correlation coefficient formula

$$r = \frac{\sum(X-\bar{X})(Y-\bar{Y})}{\sqrt{\sum(X-\bar{X})^2}\sqrt{\sum(Y-\bar{Y})^2}} = \frac{S_{XY}}{\sqrt{S_{XX}S_{YY}}}$$

Where, $\bar{X}$ = mean of X variable

$\bar{Y}$ = mean of Y variable

6.10 Paired sample T-test:

A paired-sample t-test evaluates the mean differences between two matched groups of individuals or cases or the mean of a single cohort assessed at two distinct time points. When the same cohort undergoes repeated testing on the same measure, this test is referred to as a repeated measures t-test. This statistical technique is employed to compare the means of two related populations, wherein a correlation exists between the samples (Hao et al., 2022; Ikhwan et al., 2024)

Assumptions:

For the results of a paired samples t-test to be deemed valid, the following conditions must be satisfied:

- Participants must be randomly selected from the population.
- The differences between the paired observations should conform to a normal distribution.
- There should be no significant outliers in the differences.
- A paired samples t-test typically tests the null hypothesis that the mean difference between the paired observations is zero.

H_0: $\mu_1 = \mu_2$ (two population means are equal)

H_1: $\mu_1 \neq \mu_2$ (two population means are not equal)

Test Statistic,

$$\mathbf{t} = \frac{\bar{X}_{diff}}{\frac{S_{diff}}{\sqrt{n}}}$$

$\bar{X}_{diff} = \bar{X}_1 - \bar{X}_2 = \mathbf{d}$

$S^2_{diff} = \frac{\sum(d-\bar{d})^2}{n}$

Where,

$\bar{X}_1$ = mean of first sample

$\bar{X}_2$ = mean of second sample

n_1 = number of observations in first sample

n_2 = number of observations in second sample

${s_1}^2$ = variance of first sample = $\frac{\sum(x_1-\bar{x}_1)^2}{n_1}$

${s_2}^2$ = variance of second sample = $\frac{\sum(x_2-\bar{x}_2)^2}{n_2}$

If the p-value associated with the t-test statistic, calculated with (n-1) degrees of freedom, is smaller than the selected significance threshold (often 0.10, 0.05, or 0.01), then the null hypothesis can be rejected.

6.11 The Shapiro-Wilk and tests for normality

The Shapiro-Wilk test, developed by Samuel Sanford Shapiro and Martin Wilk and published in 1965, is a statistical test used to assess the normality of a dataset. Specifically, it determines whether a random sample originates from a normally distributed population (Hanusz and Tarasińska, 2011; Shapiro and Wilk, 1965). The test produces a W value, where smaller values suggest that the sample is not normally distributed. If the W value falls below a specific threshold, the null hypothesis—that the population is normally distributed—can be rejected (Hanusz and Tarasińska, 2011; Shapiro and Wilk, 1965) The formula for the W value is as follows:

$$W = \frac{\left(\sum_{i=1}^{n} a_i x_{(i)}\right)^2}{\sum_{i=1}^{n}(x_i-\bar{x})^2}$$

where:

- x_i are the ordered random sample values
- a_i are constants that are generated from the covariances, variances, and means of the sample (size n) from a normally distributed sample.

The exact values of the coefficient a_i are expressed as follows:

$$[a_1, a_2, \ldots a_n]' = m'V^{-1}\left[m'V^{-1}V^{-1}m\right]^{-\frac{1}{2}}$$

Where, $m = E\left[x_{(1)}, x_{(2)}, \ldots, x_{(n)}\right]'$ and $V = \left[cov(x_{(i)}, x_{(j)})\right]$ are the expected value and covariance matrix of ordered statistics, respectively. The coefficients a_i are normalized, i.e., a´a=1and have the property a_{n-i+1} = - a_i and for odd n, $a_{\frac{n}{2}+1} = 0$.

The exact elements of the matrix V are not known for large samples and algorithms for their evaluations are very memory and time consuming.

Levene's Test for Homogeneity of Variances

Levene's test, introduced by American statistician and geneticist Howard Levene in 1960, is an inferential statistic used to assess the equality of variances across two or more groups. This homogeneity-of-variance test is less reliant on the assumption of

normality compared to many other tests. It calculates the absolute difference between each case value and its respective group mean, then conducts a one-way analysis of variance on these differences (Zhou et al., 2023).

Assumptions:

- The samples drawn from the populations under study are independent.
- The populations under study are approximately normally distributed.

Checking the Assumptions:

- Assumption 1: Ensure that the samples are taken independently of each other.
- Assumption 2: Construct side-by-side boxplots or Q-Q plots by treatment groups to assess normality.

Levene's Test Procedure

Step 1: Check the assumptions.

Step 2: State the null and alternative hypotheses

Null H_0: $\sigma_1^2 = \sigma_2^2 = \ ... \ = \sigma_t^2$

Alternative H_1: Not all of the variances are equal.

Step 3: Decide the level of significance (α).

Step 4: Determine the critical value and the rejection region.

Critical Value: $F_{\alpha,(df_1=t-1,df_2=N-t)}$

Rejection Region: $F_{Levene} \geq F_{\alpha,(df_1=t-1,df_2=N-t)}$

Step 5: Compute Levene's Statistic

$$F_{Levene} = \frac{\frac{\sum_{i=1}^{t} n_i(\bar{D}_i - \bar{D})^2}{t-1}}{\frac{\sum_{i=1}^{t}\sum_{j=1}^{n_i}\left(D_{ij}-\bar{D}_i\right)^2}{N-t}}$$

Step 6: Make your decision

If the value of the test statistic F_{Levene} falls in the rejection region or if the p-value $\leq \alpha$, then reject null hypothesis H_0; otherwise we fail to reject H_0.

Levene's test may also be used as a main test to answer a stand-alone question of whether two sub-samples in a given population have equal or different variances.

Appendix 07: Anonymised raw data

“Read Me “

Appendix: Household Biogas Plant User Survey — Anonymised Raw Datas

An exploration of the key factors influencing the success and failure of small-scale Anaerobic Digestion progrc
Tania Islam (ID: 17152028)

1. Purpose of this appendix

This file provides the complete raw dataset collected from the household-level user survey of 50 small-scale anaerobic digestion (AD) plants, referred to throughout the thesis as Study 2 / the AD user survey (Section 3.4). It is provided so that the statistical analyses reported in Chapters 6, 7, 8 and 9 can be

2. Anonymisation statement

In accordance with the ethical approval granted for this research and with data protection requirements, all directly identifying information has been removed prior to inclusion in this appendix. This includes respondent names, father's names, and village/neighbourhood-level address details. Respondents are identified only by an anonymous code (R01–R50). Broad administrative Division is retained, as this refers to a region of several million people and does not identify any individual. Partner organisation codes

3. Structure of this workbook

- 'Read Me' — this sheet
- 'Codebook' — a variable dictionary explaining every column and how response categories are coded
- 'Anonymised Dataset' — the full dataset (50 respondents, anonymised), colour-coded by thematic group a

4. Important note for the reader

The descriptions given in the Codebook sheet have been reconstructed from the variable names and observed response patterns in the dataset. The author should verify each description against the original survey questionnaire (Appendix 2/3) and correct any discrepancy before final submission.

5. Referencing this appendix in the thesis

Suggested in-text reference: 'The complete anonymised dataset for the household AD user survey (n = 50) is provided in Appendix X, together with a full variable codebook.'

Code Book

Variable Name		Suggested Description (verify against questionnaire)	Data Type
Respondent_ID	ID	Anonymous respondent code (R01–R50)	Text
B_P_Size	ID	Biogas plant size (m3)	Categorical (coded)
Feed_Material	ID	Primary feedstock material used in the digester	Text
SP_name	ID	Supporting/partner organisation (PO) that installed the plant	Text
BPO_AGE	Demographics	Age of biogas plant owner/operator (years)	Numeric (continuous)
Division	Demographics	Administrative Division (region) of Bangladesh	Text
Occupation	Demographics	Primary occupation of the household head	Categorical (coded)
Business	Demographics	Secondary business/occupation, if any	Text
Education	Demographics	Educational attainment of respondent	Numeric (continuous)
Male_m	Demographics	Number of male household members	Numeric (continuous)
Female_m	Demographics	Number of female household members	Numeric (continuous)
BPC_period	Other	Period since plant construction (years)	Numeric (continuous)
BP_operation	Other	Current operational status of the plant	Categorical (coded)
Y_Maintenance	Technical	Whether the plant receives regular maintenance (Y/N)	Categorical (coded)
Y_Renovation	Other	Whether the plant has been renovated/repaired (Y/N)	Text
Y_UseofGas	Environmental	Whether biogas is currently in use (Y/N)	Categorical (coded)
Y_S_n_burner	Other	Number of stove burners in use	Categorical (coded)
Y_SB_time	Other	Time gas is available for stove use (hours/day)	Numeric (continuous)
Raw_materials	Environmental	Type of raw material fed to the digester	Categorical (coded)
N_Cattle	Technical	Number of cattle owned	Numeric (continuous)
N_birds	Technical	Number of poultry/birds owned	Numeric (continuous)
Organic_HH_waste	Other	Whether household organic waste is added as feedstock	Numeric (continuous)
D_Avail_RM	Other	Daily availability of raw material (feedstock)	Categorical (coded)
D_Load_RM	Other	Daily loading quantity of raw material	Numeric (continuous)
L_F_BP	Other	Location/site factors of the biogas plant	Categorical (coded)
Raw_materisls	Other	Other raw materials	Categorical (coded)
Water	Environmental	Water availability/source for plant operation	Categorical (coded)
Slurry_pits	Construction	Presence of slurry storage pit(s)	Categorical (coded)
length	Construction	Digester length (m)	Numeric (continuous)
width	Construction	Digester width (m)	Numeric (continuous)
Depth	Construction	Digester depth (m)	Numeric (continuous)
Length2	Construction	Outlet/compost pit length (m)	Categorical (coded)
width2	Construction	Outlet/compost pit width (m)	Categorical (coded)
depth2	Construction	Outlet/compost pit depth (m)	Categorical (coded)
P_bound_e	Construction	Plant boundary/enclosure existing (Y/N)	Categorical (coded)
P_shade_e	Construction	Plant shade/cover existing (Y/N)	Categorical (coded)

Variable Name		Suggested Description (verify against questionnaire)	Data Type
Gas_dis_pipe	Construction	Gas distribution pipe condition	Categorical (coded)
Gas_Trans_m	Environmental	Gas transmission pipe material	Categorical (coded)
Component	Construction	Which plant components are present/complete	Categorical (coded)
Princ_follow	Other	Whether construction principles/standards were followed	Categorical (coded)
Dis_WS	Other	Distance to nearest water source (m)	Numeric (continuous)
Toilet_a_BP	Social/Health	Whether a toilet is attached to the biogas plant	Categorical (coded)
Encourage_person	Other	Person/institution that encouraged plant adoption	Categorical (coded)
Social_taboos	Other	Presence of social taboos/stigma regarding biogas use	Categorical (coded)
Subsidy	Economic	Whether a government subsidy was received	Categorical (coded)
N_A_OFS	Other	Number of alternative fuel sources used	Categorical (coded)
SB_P	Other	Perceived overall satisfaction with the biogas plant	Categorical (coded)
HealthB	Social/Health	Perceived health benefit from biogas use	Categorical (coded)
ENVB	Environmental	Perceived environmental benefit	Categorical (coded)
EconomicB	Other	Perceived economic benefit	Categorical (coded)
MfSP	Other	Maintenance provided for by supporting partner (PO)	Categorical (coded)
MfEBPO	Other	Maintenance done by plant owner	Categorical (coded)
CfN	Other	Cost for necessary repairs	Categorical (coded)
STE	Other	Satisfaction with technical extension/support	Categorical (coded)
Others_mribp	Other	*[Author to confirm exact question wording]*	Categorical (coded)
BP_constructor	Construction	Who constructed the plant (mason/PO/self)	Categorical (coded)
StandardsetbySP	Construction	Whether construction standards were set by partner organisation	Categorical (coded)
Trained_masons	Construction	Whether trained masons were used for construction	Categorical (coded)
Standard_CM	Construction	Standard construction materials used (Y/N)	Categorical (coded)
St_pipe_app	Construction	Standard pipe/appliance used (Y/N)	Categorical (coded)
st_PlantDesign	Construction	Standard plant design followed (Y/N)	Categorical (coded)
DoNotKnow	Economic	Respondent indicated 'do not know'	Categorical (coded)
Statisfied_fp	Other	Satisfaction with functioning plant	Categorical (coded)
IDCOL	Other	Whether plant was financed under the IDCOL/NDBMP programme	Categorical (coded)
Know_bp	Other	Knowledge of biogas plant technology prior to installation	Numeric (continuous)
Cash_IDCOL	Economic	Cash subsidy received from IDCOL (BDT)	Categorical (coded)
Tk_IDCOL	Economic	Total IDCOL-related financial support (BDT)	Numeric (continuous)
ExpenditureBP	Economic	Total expenditure on plant construction (BDT)	Numeric (continuous)

Variable Name		Suggested Description (verify against questionnaire)	Data Type
source_fuelwood	Environmental	Source of supplementary firewood	Categorical (coded)
TSFCPD_before	Other	Time spent collecting fuel per day before AD (hours) — used in Section 6.3.3 (Table 6.3)	Categorical (coded)
TSFCPD_after	Other	Time spent collecting fuel per day after AD (hours) — used in Section 6.3.3 (Table 6.3)	Categorical (coded)
EduFacility_after	Social/Health	Change in access to education facility after AD	Categorical (coded)
SAPS_before	Other	Self-assessed poverty status before AD	Categorical (coded)
SAPS_after	Other	Self-assessed poverty status after AD	Categorical (coded)
Gas_sell	Environmental	Whether surplus gas is sold (Y/N)	Categorical (coded)
toiletHH_before	Social/Health	Household toilet facility before AD	Categorical (coded)
toiletHH_after	Social/Health	Household toilet facility after AD	Categorical (coded)
attatch_toilet	Social/Health	Toilet attached to biogas plant (Y/N)	Categorical (coded)
airpollution_before	Social/Health	Kitchen air pollution status before AD (categorical: Severe/Moderate/Minimal/None) — used in Section 9.3.1	Categorical (coded)
airpollution_after	Social/Health	Kitchen air pollution status after AD (categorical) — used in Section 9.3.1	Categorical (coded)
EyeInfec_before	Social/Health	Eye infection frequency before AD (categorical) — used in Section 9.3	Categorical (coded)
EyeInf_after	Other	Eye infection frequency after AD (categorical) — used in Section 9.3	Categorical (coded)
respiratory_bef	Social/Health	Respiratory infection frequency before AD (categorical) — used in Section 9.3	Categorical (coded)
respiratory_after	Social/Health	Respiratory infection frequency after AD (categorical) — used in Section 9.3	Categorical (coded)
Typhoid_bef	Social/Health	Typhoid incidence before AD (categorical)	Categorical (coded)
Typhoid_after	Social/Health	Typhoid incidence after AD (categorical)	Categorical (coded)
Diarrhoea_bef	Social/Health	Diarrhoea incidence before AD (categorical)	Categorical (coded)
Diarrhoea_after	Social/Health	Diarrhoea incidence after AD (categorical)	Categorical (coded)
Abun_mosq_bef	Social/Health	Abundance of mosquitoes/flies before AD (categorical) — used in Section 9.3	Categorical (coded)
Abun_mosq_after	Social/Health	Abundance of mosquitoes/flies after AD (categorical) — used in Section 9.3	Categorical (coded)
NKFI_bef	Other	Number of known family illnesses before AD	Categorical (coded)
NKFI_after	Other	Number of known family illnesses after AD	Categorical (coded)
InitiativeTaken	Other	Who took the initiative to install the plant	Categorical (coded)
DecisionTaken	Other	Who made the decision to install the plant	Categorical (coded)
Responsible	Other	Person responsible for day-to-day plant operation	Categorical (coded)
monitoring	Other	Whether the plant is monitored by the PO after installation	Categorical (coded)
Maintenance	Technical	Frequency of maintenance performed	Categorical (coded)

Variable Name		Suggested Description (verify against questionnaire)	Data Type
Contact_CPO	Other	Contact maintained with partner organisation (Y/N)	Categorical (coded)
Technical_know n	Other	Technical knowledge of plant operation (self-rated)	Categorical (coded)
Benifited	Other	Overall perceived benefit from AD (Y/N)	Categorical (coded)
BenefitsDWG	Other	Description of benefits derived from gas use	Categorical (coded)
CookTime_bf	Other	Daily cooking time before AD (duplicate/alternate variable — verify against CookTimeBefore)	Numeric (continuous)
CookTime_after	Other	Daily cooking time after AD (duplicate/alternate variable — verify against cooktimeafter)	Numeric (continuous)
ChildEduTime_b f	Social/Health	Children's daily education time before AD (hours) — used in Section 7.3.3 (Table 7.3)	Categorical (coded)
ChildEduTime_a f	Social/Health	Children's daily education time after AD (hours) — used in Section 7.3.3 (Table 7.3)	Numeric (continuous)
TCollectwood_b f	Environmental	Time spent collecting firewood before AD (duplicate/alternate variable — verify against TSFCPD before)	Numeric (continuous)
TCollectwood_a f	Environmental	Time spent collecting firewood after AD (duplicate/alternate variable — verify against TSFCPD after)	Numeric (continuous)
UseofBioSlurry	Agricultural	Whether bio-slurry is used (Y/N) — used in Section 6.3.2	Categorical (coded)
timeForStoreBS	Other	Storage time for bio-slurry before use	Numeric (continuous)
Hw_Dry_BS	Agricultural	Method of drying bio-slurry	Categorical (coded)
sale_BS_L	Agricultural	Whether bio-slurry is sold (Y/N)	Categorical (coded)
Price_BS	Economic	Sale price of bio-slurry (BDT)	Categorical (coded)
PCvisited_forBS	Other	Whether purchasers visit to collect bio-slurry	Categorical (coded)
OrganicM_BS	Agricultural	Bio-slurry treated as organic material/fertiliser (Y/N)	Categorical (coded)
TypesofOM	Other	Types of organic material combined with bio-slurry	Categorical (coded)
PileCowDungBS	Agricultural	Bio-slurry piled with cow dung before application	Categorical (coded)
CompostCowDu ng	Agricultural	Whether bio-slurry is composted with cow dung	Categorical (coded)
DMAeration	Other	Aeration method used during composting	Categorical (coded)
Farmer	Agricultural	Whether respondent is a farmer (Y/N)	Categorical (coded)
AmuontLand	Agricultural	Total land owned (decimal/bigha)	Numeric (continuous)
OwnLand	Agricultural	Land under own ownership	Numeric (continuous)
MortgageLand	Agricultural	Land under mortgage	Categorical (coded)
CultivateLand	Agricultural	Land under cultivation	Numeric (continuous)
LivestkPop_bf	Economic	Livestock population before AD	Numeric (continuous)
livestkpop_af	Economic	Livestock population after AD	Numeric (continuous)
feedingmethod _bf	Other	Animal feeding method before AD	Categorical (coded)

Variable Name		Suggested Description (verify against questionnaire)	Data Type
feedingmethod_af	Other	Animal feeding method after AD	Categorical (coded)
CSM_bf	Other	Cow shed management practice before AD — used in Section 9.3.5	Categorical (coded)
CSM_af	Other	Cow shed management practice after AD — used in Section 9.3.5 (McNemar-Bowker, p=0.2482)	Categorical (coded)
useofBS	Other	Use of bio-slurry (fertiliser/sale/other)	Categorical (coded)
place_BS_use	Agricultural	Location where bio-slurry is applied	Categorical (coded)
AnimalHealth_bf	Social/Health	Self-rated animal health before AD	Categorical (coded)
AnimalHealth_af	Social/Health	Self-rated animal health after AD	Categorical (coded)
FMS_before	Other	Farm management score before AD	Categorical (coded)
FMS_after	Other	Farm management score after AD	Categorical (coded)
EffectivenessBS	Other	Perceived effectiveness of bio-slurry as fertiliser	Categorical (coded)
BSH_ICP	Other	Bio-slurry handling in accordance with recommended practice	Categorical (coded)
MoneySaveFertilizer	Economic	Annual money saved on chemical fertiliser (BDT) — used in Section 6.3.2	Numeric (continuous)
Income_Inc_af_BP	Economic	Income increase after AD installation	Categorical (coded)
FuelCook_beforeBP1	Environmental	Primary cooking fuel before AD (rank 1)	Categorical (coded)
FuelCook_beforeBP2	Environmental	Secondary cooking fuel before AD (rank 2)	Categorical (coded)
FuelCook_beforeBP3	Environmental	Tertiary cooking fuel before AD (rank 3)	Categorical (coded)
FuelCook_afterBP1	Environmental	Primary cooking fuel after AD (rank 1)	Categorical (coded)
FuelCook_afterBP2	Environmental	Secondary cooking fuel after AD (rank 2)	Categorical (coded)
FuelCook_afterBP3	Environmental	Tertiary cooking fuel after AD (rank 3)	Categorical (coded)
FuelENVfriendly_bf	Environmental	Perceived fuel environmental friendliness before AD	Categorical (coded)
FuelENVfriendly_af	Environmental	Perceived fuel environmental friendliness after AD	Categorical (coded)
SAHE_bf	Other	Self-assessed household expenditure before AD	Categorical (coded)
SAHE_af	Other	Self-assessed household expenditure after AD	Categorical (coded)
SAKE_bf	Other	Self-assessed kitchen expenditure before AD	Categorical (coded)
SAKE_af	Other	Self-assessed kitchen expenditure after AD	Categorical (coded)
SACSE_bf	Other	Self-assessed cooking/stove expenditure before AD	Categorical (coded)
SACSE_af	Other	Self-assessed cooking/stove expenditure after AD	Categorical (coded)
SoSE_bf	Other	Source of supplementary energy before AD	Categorical (coded)
SoSE_af	Other	Source of supplementary energy after AD	Categorical (coded)

Variable Name		Suggested Description (verify against questionnaire)	Data Type
Exp_HH_owner	Other	Household owner's own expenditure contribution (BDT)	Numeric (continuous)
Loan	Economic	Whether a loan was taken for plant construction (Y/N)	Categorical (coded)
Loan_from	Economic	Source of loan (bank/PO/microfinance/other)	Categorical (coded)
Installment	Economic	Loan repayment via instalments (Y/N)	Numeric (continuous)
num_installm	Economic	Number of instalments	Numeric (continuous)
Amount_loan	Economic	Total loan amount (BDT)	Numeric (continuous)
Training_o_m	Other	Training received on operation and maintenance (Y/N)	Categorical (coded)
ASS_BP_PO	Other	After-sales service provided by partner organisation	Categorical (coded)
Relation_PO	Other	Nature of relationship with partner organisation	Categorical (coded)
comfort_PO_cons	Other	Comfort level with partner organisation consultation	Categorical (coded)
comf_po_loan	Economic	Comfort level with partner organisation loan process	Categorical (coded)
CookTimeBefore	Other	Daily cooking time before AD installation (hours) — used in Section 6.3.3	Numeric (continuous)
fuelcostBefore	Economic	Monthly cooking fuel cost before AD installation (BDT) — used in Section 6.3.3	Numeric (continuous)
lightcosbefore	Other	Monthly lighting fuel cost before AD installation (BDT)	Numeric (continuous)
cooktimeafter	Other	Daily cooking time after AD installation (hours) — used in Section 6.3.3	Numeric (continuous)
fuelcostafter	Economic	Monthly cooking fuel cost after AD installation (BDT) — used in Section 6.3.3	Numeric (continuous)
lightcostafter	Economic	Monthly lighting fuel cost after AD installation (BDT)	Numeric (continuous)
Savetime	Other	Time saved per day due to biogas use (hours)	Categorical (coded)
Incomegensec	Economic	Time reallocated to income-generating activity (hours)	Numeric (continuous)
recreationsec	Social/Health	Time reallocated to recreation (hours)	Categorical (coded)
Edusector	Social/Health	Time reallocated to household members' education (hours)	Categorical (coded)
RestTime	Other	Time reallocated to rest (hours)	Numeric (continuous)
No_use	Other	Reason for non-use, if applicable	Categorical (coded)
fuelwood_before	Environmental	Monthly firewood consumption before AD (kg) — used in Section 6.3	Numeric (continuous)
fuelwood_after	Environmental	Monthly firewood consumption after AD (kg) — used in Section 6.3	Numeric (continuous)
save_fuel	Environmental	Monthly firewood saved (kg)	Categorical (coded)
Firewood	Environmental	Firewood still used as supplementary fuel (Y/N)	Numeric (continuous)
FWTk_kg	Economic	Price of firewood (BDT/kg)	Numeric (continuous)
Electricity	Environmental	Household has electricity connection (Y/N)	Categorical (coded)
Elec_tk_kg	Economic	Electricity cost equivalent	Categorical (coded)

Variable Name		Suggested Description (verify against questionnaire)	Data Type
SSE_bf	Other	Supplementary source of energy before AD	Categorical (coded)
SSE_af	Other	Supplementary source of energy after AD	Categorical (coded)
SoDWater	Environmental	Source of drinking water	Categorical (coded)
Distance_BP_DWS	Other	Distance between biogas plant and drinking water source (m)	Numeric (continuous)
BGconsumerPayment	Economic	Whether biogas consumer makes any payment for gas use	Categorical (coded)

Anonymised Raw Data Set

Respondent_ID	RAFSFSP	ServiceCN	MNPYFOMBP	IDCOL	Know_bp	Cash_IDCOL
R01	3	2	1	2	4	1
R02	3	2	1	2	4	1
R03	3	3	1	2	7	1
R04	3	3	1	2	2	2
R05	3	3	1	2	2	1
R06	3	2	1	2	4	1
R07	3	2	1	2	4	1
R08	3	2	1	2	4	1
R09	3	2	1	2	4	1
R10	3	2	1	2	7	1
R11	2	1	1	2	2	1
R12	1	1	1	2	4	2
R13	1	1	1	2	4	2
R14	1	1	1	2	8	1
R15	1	1	1	2	2	1
R16	3	2	1	2	4	1
R17	3	2	1	2	4	1
R18	1	1	1	1	2	1
R19	3	2	1	2	4	1
R20	1	2	1	2	2	1
R21	4	2	1	2	6	1
R22	4	2	1	2	2	1
R23	4	2	1	2	2	1
R24	4	2	1	2	4	1
R25	4	2	1	2	2	1
R26	4	4	1	1	2	1
R27	4	4	1	2	2	1
R28	4	4	1	2	2	1
R29	4	4	1	2	2	1
R30	3	3	1	2	2	1
R31	2	4	1	2	3	2
R32	3	3	1	2	3	1
R33	3	3	1	1	3	1
R34	3	2	1	2	3	1
R35	3	4	1	2	3	2
R36	1	1	1	1	4	1
R37	1	1	1	2	4	1
R38	1	1	1	2	4	1
R39	1	1	1	2	2	2
R40	1	1	1	1	2	1
R41	3	2	1	2	7	1
R42	4	1	1	1	7	1
R43	4	1	1	1	7	1
R44	4	1	1	2	1	1
R45	3	4	1	1	7	1
R46	3	4	1	1	1	1
R47	2	1	1	2	2	1
R48	3	4	1	2	3	1
R49	3	3	1	2	4	1
R50	3	4	1	2	4	1

Respondent_ID	B_P_Size	Feed_Material	SP_name	BPO_AGE	Division	Occupation
R01	2	Cattle litter	RRF	48	Khulna	3
R02	2	Cattle litter	RRF	45	Khulna	3
R03	2	Cattle litter	RRF	52	Khulna	3
R04	2	Cattle litter	BCSIR	45	Khulna	7
R05	2	Cattle litter	RRF	45	Khulna	2
R06	2	Cattle litter	AID Foundation	45	Khulna	6
R07	2	Cattle litter	AID Foundation	38	Khulna	6
R08	2	Cattle litter	AID Foundation	55	Khulna	6
R09	4.8	Cattle litter	AID Foundation	35	Khulna	2
R10	2.4	Cattle litter	AID Foundation	50	Khulna	6
R11	1.25	Mixed with toilet	BCSIR	75	Rajshahi	3
R12	1.25	Mixed with toilet	Self	55	Rajshahi	1
R13	1.25	Cowdung and Toilet	BCSIR	60	Rajshahi	1
R14	2.4	Cowdung	BCSIR	73	Rajshahi	2
R15	3.2	Mixed with toilet	BCSIR	80	Rajshahi	7
R16	2.4	Cowdung	WAH Renewable En	41	Rajshahi	3
R17	2.4	Cowdung	WAH Renewable En	40	Rajshahi	6
R18	2.4	Cowdung	BCSIR	35	Rajshahi	1
R19	2.4	Cowdung	WAH Renewable En	42	Rajshahi	6
R20	1.25	Cowdung	WAH Renewable En	32	Rajshahi	2
R21	2.4	Cowdung	Sabuj Bangla Biogas	26	Rajshahi	2
R22	2.4	Cowdung	Sabuj Bangla Biogas	40	Rajshahi	2
R23	2.4	Cowdung	Sabuj Bangla Biogas	36	Rajshahi	6
R24	3.2	Cowdung	Sabuj Bangla Biogas	40	Rajshahi	2
R25	2.4	Cowdung	Sabuj Bangla Biogas	35	Rajshahi	2
R26	2.4	Cowdung	Sabuj Bangla Biogas	40	Rajshahi	2
R27	2.4	Cowdung	Sabuj Bangla Biogas	35	Rajshahi	1
R28	2	Cowdung	Sabuj Bangla Biogas	39	Rajshahi	2
R29	4.8	Cowdung	Sabuj Bangla Biogas	45	Rajshahi	2
R30	2.4	Cowdung	Sabuj Bangla Biogas	32	Rajshahi	1
R31	4.8	Cowdung	GHUSFUL	56	Chattogram	2
R32	4.8	Cowdung	ean Energy Foundati	50	Chattogram	1
R33	4.8	Cowdung	IDCOL	40	Chattogram	2
R34	2.4	Cowdung	GHUSFUL	42	Chattogram	2
R35	4.8	Cowdung	ean Energy Foundati	64	Chattogram	2
R36	2.4	Cowdung	IDCOL	42	Dhaka	2
R37	2.4	Cowdung	Thana Council	48	Dhaka	3
R38	4.8	Cowdung	Thana Council	55	Dhaka	2
R39	4.8	Cowdung	Self	42	Dhaka	2
R40	4.8	Cowdung	IDCOL	30	Dhaka	2
R41	3.2	Cowdung	PROKASH	45	Chattogram	1
R42	4.8	Cowdung	PROKASH	35	Chattogram	2
R43	2.4	Cowdung	PROKASH	65	Chattogram	2
R44	3.2	Cowdung	PROKASH	40	Chattogram	2
R45	2.4	Cowdung	PROKASH	32	Chattogram	2
R46	4.8	Cowdung	Grameen Shakti	57	Sylhet	2
R47	1.25	Mixed with toilet	Grameen Shakti	75	Rajshahi	3
R48	3.2	Cowdung	Grameen Shakti	35	Sylhet	2
R49	3.2	Cowdung	Jubo Unnoyan	46	Sylhet	2
R50	3.2	Cowdung	Grameen Shakti	36	Sylhet	2

Respondent_ID	Business	Education	Male_m	Female_m	BPC_period	BP_operation
R01		3	3	1	10	1
R02		4	2	2	12	1
R03		4	2	2	10	1
R04	Retired	6	3	1	10	1
R05	Grocer	3	4	1	10	1
R06		3	3	1	15	1
R07		4	2	3	15	1
R08		3	3	2	15	1
R09	Cow Farm	4	5	4	12	1
R10		5	3	1	15	2
R11		2	1	2	30	1
R12		7	1	5	14	2
R13		3	1	3	15	1
R14	Bread Factory	2	2	3	30	1
R15	Retired	6	4	5	15	1
R16		3	2	3	20	1
R17		3	1	4	17	1
R18		4	1	1	23	1
R19		2	1	3	16	1
R20		6	2	2	14	2
R21	Poultry	6	3	4	16	1
R22	Contructor	6	3	4	22	1
R23		6	2	3	18	1
R24	Broile Sale	4	3	2	15	1
R25	Hotel	5	3	1	19	1
R26	Construction Materia	3	4	4	21	1
R27		6	3	3	26	1
R28	Electrical Shop	3	2	1	10	1
R29	Dairy farm	8	3	5	21	1
R30		8	1	1	24	1
R31	Dairy Farm	3	2	4	23	1
R32		6	3	3	28	1
R33	Poultry Farm	4	6	4	15	1
R34	Ex NRB	3	3	2	18	1
R35	Dairy Farm	3	3	4	19	1
R36	Dairy Farm	4	6	6	30	1
R37		3	2	2	30	1
R38	Dairy Farm	2	2	3	30	1
R39	Dairy Farm	2	2	1	21	1
R40	Dairy Farm	2	2	1	30	1
R41		5	3	2	30	1
R42	Dairy Farm	4	3	3	30	1
R43	NGO	8	1	1	30	1
R44	Dairy Farm	5	3	3	30	1
R45	Dairy Farm	4	2	4	24	1
R46		8	12	0	25	1
R47		2	1	2	30	1
R48	Grocer	5	3	4	24	1
R49	Hardware	7	5	5	18	1
R50	Dairy	5	2	2	19	1

Respondent_ID	Y_Maintenance	Y_Renovation	Y_UseofGas	Y_S_n_burner	Y_SB_time	Raw_materials
R01	1	No	1	1	3.5	1
R02	1	No	1	1	2	1
R03	1	No	1	1	3.5	1
R04	1	No	1	1	3.5	1
R05	1	No	1	1	3.4	1
R06	1	No	1	1	3.5	1
R07	1	No	1	1	3.4	1
R08	1	No	1	1	3.2	1
R09	1	No	1	1	4	1
R10	1		1	1	3	1
R11	1	Yes	1	1	2	5
R12	2		1	1	1	5
R13	2	Yes	1	2	3	5
R14	1	Yes	1	1	4	1
R15	1		1	1	4	5
R16	2	No	1	1	2.5	1
R17	1		1	1	3	1
R18	1	No	1	1	3	1
R19	1	No	1	1	2	1
R20	1		1	1	2	1
R21	1		1	1	3	1
R22	1	No	1	1	3	1
R23	1		1	1	3	1
R24	1	Yes	1	2	4.5	1
R25	1	No	1	1	4	1
R26	1	No	1	2	4	1
R27	1		1	2	3	1
R28	1		1	1	3	1
R29	1		1	2	8	1
R30	1	No	1	3	2	1
R31	1	No	1	2	6	1
R32	1	Yes	1	1	4	1
R33	1	Yes	1	2	8	1
R34	1		1	1	4	1
R35	1		1	3	5	1
R36	1	No	1	3	3.5	1
R37	1	No	1	2	4	1
R38	1	No	1	1	6.5	1
R39	1	No	1	4	7	1
R40	1	No	1	1	6.2	1
R41	1	No	1	1	2	1
R42	1	No	1	1	7	1
R43	1	No	1	1	3	1
R44	1	No	1	2	4	1
R45	1	No	1	1	2	1
R46	1	No	1	1	7	1
R47	1	Yes	1	1	2	5
R48	1	No	1	1	3	1
R49	1	No	1	1	5	1
R50	1	No	1	2	4	1

Respondent_ID	Water	Slurry_pits	length	width	Depth	P_bound_e	P_shade_e
R01	2	1	3	3	6	2	2
R02	2	1	3	3	6	2	2
R03	2	1	3	3	6	2	1
R04	2	1	3	3	6	2	1
R05	2	1	3	1	6	2	1
R06	2	1	3	3	6	1	1
R07	2	1	3	3	6	1	2
R08	2	1	3	3	6	2	1
R09	2	1	3	3	6	1	2
R10	2	1	4	4	8	1	1
R11	2	1	1	2	2	2	2
R12	2	0				2	2
R13	2	1	2	2.5	2	2	2
R14	2	0				2	2
R15	2	0				2	2
R16	2	1	2	1.5	1.5	2	2
R17	1.5	1	2	1.5	2	2	2
R18	1.5	1	1.5	1.5	1.5	1	2
R19	2	1	1	0.5	1	2	2
R20	2	1	1	1	1	2	2
R21	1.5	1	150	150	125	2	2
R22	2	2	1	1	1	2	2
R23	2	0				2	2
R24	2	2	1.5	1.5	2	1	2
R25	2	2	1.5	1.5	2	1	2
R26	1.5	2	2	1.5	1.25	2	2
R27	2	1	1	1	2	2	2
R28	1.5	2	142	182	125	2	2
R29	1	2	2	1	2	2	2
R30	1.5	2	152	152	125	2	2
R31	2	0				2	2
R32	2	0				2	2
R33	2	0				2	2
R34	2	0				2	2
R35	2	0				2	2
R36	1	1	4.57	3.65	1.21	1	2
R37	2	1	3	3	3	2	2
R38	2	1	4	3	2	1	2
R39	2	0				2	2
R40	2	0				2	2
R41	1	1	10	5	4	1	2
R42	2	0				2	2
R43	2	1				2	2
R44	2	2	4	3	3	1	2
R45	2	0				2	2
R46	2	2	1.5	1	2	1	2
R47	2	1	1	2	2	2	2
R48	2	1	1.5	1.5	1	2	2
R49	2	1				2	2
R50	2	0				2	2

Respondent_ID	Gas_dis_pipe	Gas_Trans_m	Component	Princ_follow	Dis_WS	Toilet_a_BP
R01	2	2	2	2	2	2
R02	2	2	2	2	10	1
R03	2	2	2	2	20	2
R04	2	2	2	2	5	2
R05	2	2	2	2	5	2
R06	2	2	2	2	10	2
R07	2	2	2	2	10	2
R08	2	2	2	2	20	2
R09	2	2	2	2	20	2
R10	2	2	2	2	10	2
R11	2	2	2	2	2	3
R12	2	2	2	3	5	3
R13	2	2	2	2	3	3
R14	2	2	2	2	8	2
R15	2	2	2	3	3	3
R16	2	2	2	3	10	2
R17	2	2	2	2	8	2
R18	2	2	2	2	8	2
R19	2	2	2	2	5	2
R20	2	2	2	1	20	2
R21	2	2	2	2	15	2
R22	2	2	2	1	3	2
R23	2	2	2	3	3	2
R24	2	2	2	3	3	2
R25	2	2	2	3	4	2
R26	2	2	2	2	12	2
R27	2	2	2	3	6	2
R28	2	2	2	2	7	2
R29	2	2	2	1	15	2
R30	2	2	2	2	5	2
R31	2	2	2	1	3	2
R32	2	2	2	1	6	2
R33	2	2	2	1	3	2
R34	2	2	2	3	2	2
R35	2	2	2	3	3	2
R36	2	2	2	2	6	2
R37	2	2	5	2	5	2
R38	2	2	5	1	40	2
R39	2	2	2	1	10	2
R40	2	2	5	3	60	2
R41	2	2	5	3	8	2
R42	2	2	5	1	3	2
R43	2	2	2	3	20	2
R44	2	2	2	2	1	2
R45	2	2	2	2	8	3
R46	2	2	2	1	8	1
R47	2	2	2	2	2	3
R48	2	2	2	3	7	2
R49	2	2	2	3	3	2
R50	2	2	2	3	2	2

Respondent_ID	Social_taboos	Subsidy	N_A_OFS	SB_P	HealthB	ENVB
R01	2	2	2	2	2	2
R02	2	2	2	2	2	1
R03	2	1	2	2	2	2
R04	2	2	2	2	2	2
R05	2	2	2	2	2	2
R06	2	2	2	2	2	2
R07	2	2	2	2	2	2
R08	2	2	2	2	2	2
R09	2	2	2	2	2	2
R10	2	2	2	2	2	2
R11	1	1	2	2	2	2
R12	1	2	2	2	2	2
R13	1	1	2	2	2	2
R14	2	1	2	2	2	2
R15	1	1	2	2	2	2
R16	2	1	2	2	2	2
R17	2	1	2	2	2	2
R18	2	1	2	2	2	2
R19	2	1	2	2	2	2
R20	2	1	2	2	2	2
R21	2	1	2	2	2	2
R22	2	1	2	2	2	2
R23	2	1	2	2	2	2
R24	2	1	2	2	2	2
R25	2	1	2	2	2	2
R26	2	1	2	2	2	2
R27	2	1	2	2	2	2
R28	2	1	2	2	2	2
R29	2	2	2	2	2	1
R30	2	1	2	2	2	2
R31	2	1	2	2	2	2
R32	1	1	2	2	2	2
R33	2	1	2	2	2	2
R34	2	1	2	2	2	2
R35	2	1	2	2	2	2
R36	2	2	2	2	2	2
R37	2	2	2	2	2	2
R38	2	1	2	2	2	2
R39	2	2	2	2	2	2
R40	2	1	2	2	2	2
R41	2	1	2	2	2	2
R42	2	1	2	2	2	2
R43	2	2	2	2	2	2
R44	2	1	2	2	2	2
R45	1	1	2	2	2	2
R46	1	1	2	2	2	2
R47	1	1	2	2	2	2
R48	2	1	2	2	2	2
R49	2	1	2	2	2	2
R50	2	1	2	2	2	2

Respondent_ID	EconomicB	MfSP	MfEBPO	CfN	STE	Others_mribp
R01	2	2	1	2	1	2
R02	2	1	1	2	1	2
R03	1	1	1	2	1	2
R04	2	1	1	2	1	2
R05	2	1	1	2	1	2
R06	2	1	1	2	1	2
R07	2	1	1	2	2	2
R08	2	1	1	2	1	2
R09	2	1	1	2	1	2
R10	2	1	2	2	1	2
R11	2	1	2	2	2	2
R12	2	2	1	2	2	2
R13	2	1	2	2	2	2
R14	2	1	2	2	2	2
R15	2	1	2	2	2	2
R16	2	1	2	2	2	2
R17	2	1	2	2	2	2
R18	2	1	2	2	2	2
R19	2	1	2	2	2	2
R20	2	1	2	2	2	2
R21	2	1	2	2	2	2
R22	2	1	2	2	2	2
R23	2	1	2	2	2	2
R24	2	2	2	2	2	2
R25	2	1	2	2	2	2
R26	2	1	2	2	2	2
R27	2	1	2	2	2	2
R28	2	1	2	2	2	2
R29	2	1	2	2	2	2
R30	2	1	2	2	2	2
R31	2	1	2	2	2	2
R32	2	1	2	2	2	2
R33	2	1	2	2	2	2
R34	2	1	2	2	2	2
R35	2	1	2	2	2	2
R36	2	1	2	2	2	2
R37	2	1	2	2	2	2
R38	2	2	2	2	2	2
R39	2	1	2	2	2	2
R40	2	1	2	2	2	2
R41	2	1	2	2	2	2
R42	2	1	2	2	2	2
R43	2	1	2	2	2	2
R44	2	1	2	2	2	2
R45	1	1	1	2	2	2
R46	2	1	2	2	2	2
R47	2	1	2	2	2	2
R48	2	1	2	2	2	2
R49	2	1	2	2	2	2
R50	2	1	2	2	2	2

Respondent_ID	BP_constructor	StandardsetbySP	Trained_masons	Standard_CM	St_pipe_app	st_PlantDesign
R01	3	3	2	2	2	2
R02	3	3	2	2	2	2
R03	3	3	2	2	2	2
R04	3	3	2	2	2	2
R05	3	3	2	2	2	2
R06	2	3	2	2	2	2
R07	3	3	2	2	2	2
R08	4	3	2	2	2	2
R09	3	2	1	2	2	2
R10	4	3	2	2	2	2
R11	3	2	1	1	2	2
R12	3	2	1	2	2	2
R13	3	3	2	2	2	2
R14	3	3	2	2	2	2
R15	4	3	2	2	2	2
R16	3	3	2	2	2	2
R17	2	3	2	2	2	2
R18	2	3	2	2	2	2
R19	4	3	2	2	2	2
R20	1	3	2	2	2	2
R21	3	3	2	2	2	2
R22	4	3	2	2	2	2
R23	4	3	2	2	2	2
R24	3	2	1	1	2	2
R25	4	3	2	2	2	2
R26	3	2	1	2	2	2
R27	4	2	1	2	2	2
R28	2	1	2	2	2	2
R29	3	2	1	2	2	2
R30	3	3	2	2	2	2
R31	4	3	2	2	2	2
R32	3	3	2	2	2	2
R33	4	3	2	2	2	2
R34	4	3	2	2	2	2
R35	3	3	2	2	1	2
R36	3	3	2	2	2	2
R37	4	3	2	2	2	2
R38	3	3	2	2	2	2
R39	3	2	2	2	2	2
R40	4	3	2	2	2	2
R41	3	2	1	2	2	2
R42	1	3	2	2	2	2
R43	3	2	1	1	2	1
R44	4	3	2	2	2	2
R45	3	2	1	1	1	2
R46	3	2	1	1	1	2
R47	3	2	1	1	2	2
R48	2	2	1	2	2	2
R49	3	2	1	1	2	2
R50	2	3	2	2	2	2

Respondent_ID	DoNotKnow	Statisfied_fp	EGfCL_fs	TFFP_fs	EasyCook_fs	TSBT_fs
R01	1	2	2	1	1	2
R02	1	2	2	1	1	2
R03	1	2	1	2	1	2
R04	1	2	2	2	1	2
R05	1	2	2	2	1	2
R06	1	2	2	2	1	2
R07	1	2	1	2	1	2
R08	1	1				
R09	2	2	2	2	1	2
R10	1	2	1	1	1	2
R11	2	2	1	1	2	2
R12	2	1				
R13	1	2	1	2	1	2
R14	1	1				
R15	1	2	1	2	2	2
R16	1	2	1	1	1	2
R17	1	2	1	2	1	2
R18	1	2	1	2	1	2
R19	1	2	1	1	1	2
R20	1	3				
R21	1	2	1	1	2	2
R22	1	2	1	1	2	2
R23	1	2	1	2	1	2
R24	2	1				
R25	1	2	1	2	2	2
R26	2	2	1	2	1	2
R27	2	2	1	1	1	2
R28	1	2	1	2	2	2
R29	2	2	1	1	1	2
R30	1	2	1	2	1	2
R31	1	2	1	1	1	2
R32	1	2	1	1	2	1
R33	1	2	1	1	1	2
R34	1	2	1	1	1	2
R35	2	2	1	1	1	2
R36	1	2	1	2	1	2
R37	1	2	1	2	2	2
R38	1	2	1	2	1	2
R39	1	2	1	2	1	2
R40	1	2	1	2	1	2
R41	2	1				
R42	1	2	1	2	2	2
R43	2	2	1	2	2	2
R44	1	2	1	2	2	2
R45	2	2	1	1	1	2
R46	2	2	1	2	2	2
R47	2	2	1	1	2	2
R48	2	2	1	2	2	2
R49	2	2	1	2	2	2
R50	1	2	1	1	2	2

Respondent_ID	EconomicB_fs	HealthB_fs	SBP_fs	EnvBef_fs	WorkLR_fs	FGinGMT_fs
R01	2	2	2	2	1	2
R02	2	2	2	1	1	2
R03	1	2	2	2	1	2
R04	1	2	2	2	1	2
R05	1	2	2	2	1	2
R06	1	2	2	2	2	2
R07	2	2	2	2	1	2
R08						
R09	2	2	2	2	1	2
R10	2	2	2	2	1	2
R11	2	2	2	2	2	2
R12						
R13	2	2	2	2	2	2
R14						
R15	2	2	2	2	2	2
R16	2	2	2	2	2	2
R17	2	2	2	2	1	2
R18	2	2	2	1	2	2
R19	2	2	2	2	2	2
R20						
R21	1	2	2	2	2	2
R22	2	1	1	1	2	2
R23	2	2	2	2	2	2
R24						
R25	1	2	2	2	2	2
R26	2	2	2	2	2	2
R27	2	2	2	2	2	2
R28	1	2	2	2	2	2
R29	1	2	2	2	2	2
R30	1	2	2	2	2	2
R31	2	2	2	2	2	2
R32	2	1	2	2	2	2
R33	2	2	2	2	2	2
R34	2	2	2	2	2	2
R35	2	2	2	2	2	2
R36	2	2	2	2	2	2
R37	2	2	2	2	2	2
R38	2	2	2	2	2	2
R39	2	2	2	2	2	2
R40	2	2	2	2	2	2
R41						
R42	2	2	2	2	2	2
R43	2	2	2	2	2	2
R44	2	2	2	2	2	2
R45	1	1	1	2	1	2
R46	2	2	2	1	2	2
R47	2	2	2	2	2	2
R48	1	1	2	1	2	2
R49	1	2	2	1	2	2
R50	1	2	2	2	1	2

Respondent_ID	Others_fs	otherFeedM	waterAvailability	RequiredDungBP	QuantityRDBP	RTOM_BP
R01	2	1	1	1	90	3
R02	2	1	1	1	40	3
R03	2	1	1	1	60	5
R04	2	1	1	1	60	5
R05	2	1	1	1	40	3
R06	2	1	1	1	65	3
R07	2	1	1	2		3
R08		1	1	1	60	5
R09	2	1	1	2		3
R10	2	1	1	2		3
R11	2	3	1	1	50	3
R12		3	1			3
R13	2	3	1	1	25	3
R14		1	1	1	60	3
R15	2	3	1	2		3
R16	2	1	1	2		5
R17	2	1	1	2		5
R18	2	4	1	2		5
R19	2	1	1	1	30	1
R20		1	1	2		5
R21	2	1	1	2		3
R22	2	1	1	1	65	3
R23	2	1	1	1	60	3
R24		1	1	1	60	3
R25	2	1	1	1	60	3
R26	2	1	1	2		3
R27	2	1	1	1	60	3
R28	2	1	1	1	50	3
R29	2	1	1	1	120	3
R30	2	1	1	2		3
R31	2	1	1	2		5
R32	2	1	1	1	80	5
R33	2	1	1	2		5
R34	2	1	1	1	40	5
R35	2	1	1	1	80	5
R36	2	1	1	2		3
R37	2	1	1	2		3
R38	2	1	1	1	100	3
R39	2	1	1	2		3
R40	2	1	1	2		3
R41		1	1	1	85	3
R42	2	1	1	1	120	3
R43	2	1	1	1	60	3
R44	2	1	1	2		3
R45	2	1	1	2		5
R46	2	1	1	2		5
R47	2	3	1	1	50	3
R48	2	1	1	2		5
R49	2	1	1	2		5
R50	2	1	1	1	70	5

Respondent_ID	Tk_IDCOL	ExpenditureBP	Exp_HH_owner	Loan	Loan_from	Installment
R01	4000	34000	30000	1	1	1000
R02	4000	34000	30000	1	1	1000
R03	4000	29000	25000	1	1	1200
R04		25000	25000	2		
R05	4000	29000	25000	1	1	
R06	3800	33800	30000	1	1	1300
R07	3800	33800	30000	1	1	1300
R08	3800	33800	30000	1	1	1300
R09	8000	60000	52000	2		
R10	3800	33800	30000	1	1	1300
R11	7500	21500	14000	2		
R12		22000	22000	2		
R13		22000	22000	2		
R14	9000	21000	12000	2		
R15	7500	21500	14000	2		
R16	4000	29000	25000	1	1	1000
R17	4000	29000	25000	1	1	1000
R18	12000	29000	17000	2		
R19	7000	29000	22000	1	1	1000
R20	7000	27000	20000	2		
R21	4000	40000	36000	1	1	2000
R22	4000	40000	36000	1	1	6000
R23	4000	40000	36000	1	1	1750
R24	7500	41500	34000	2		
R25	4000	35000	29000	1	1	1772
R26	3000	34000	31000	1	1	1562
R27	3000	36000	33000	1	1	1667
R28	3000	35000	32000	1	1	1667
R29	4000	51000	47000	1	1	1250
R30	7500	42500	35000	2		
R31		82000	82000	2		
R32	9000	45000	36000	2		
R33	10000	80000	70000	2		
R34	5000	35000	30000	1	1	1000
R35		85000	85000	2		
R36	5000	68000	63000	2		
R37	10000	50000	40000	2		
R38	5000	50000	45000	2		
R39		60000	60000	2		
R40	10000	50000	40000	2		
R41	2500	67500	65000	2		
R42	5000	60000	55000	1	1	2750
R43	5000	35000	30000	2		
R44	4000	57000	53000	2		
R45	5000	45000	40000	2		
R46	2000	86000	84000	2		
R47	7500	21500	14000	2		
R48	4000	39000	35000	2		
R49	5000	32000	27000	2		
R50	4000	39000	35000	2		

Respondent_ID	num_instalm	Amount_loan	Training_om	ASS_BP_PO	Relation_PO	comfort_PO_cons
R01	30	28000	2	1	1	1
R02	30	25000	2	1	1	1
R03	24	23000	2	1	1	1
R04			2	1	1	
R05	24	22000	2	1	1	1
R06	26	30000	2	1	1	1
R07	26	30000	2	1	1	1
R08	26	30000	2	1	1	1
R09			2	1	1	1
R10	26	30000	2	1	1	1
R11			2	2	4	2
R12			2	2	4	
R13			2	2	4	2
R14			2	2	4	2
R15			2	2	1	1
R16	24	20000	2	2	1	1
R17	24	20000	2	2	1	1
R18			2	2	4	2
R19	24	20000	2	1	1	1
R20			2	2	2	2
R21	12	20000	2	1	1	1
R22	2	12000	2	1	1	1
R23	18	30150	2	1	1	1
R24			2	1	2	1
R25	18	30000	2	2	4	1
R26	18	25000	2	1	1	1
R27	18	25000	2	1	1	1
R28	18	25000	2	1	1	1
R29	24	25000	2	1	1	1
R30			2	2	4	1
R31			2	2	2	2
R32			2	2	1	1
R33			2	1	2	1
R34	22	20000	2	1	1	1
R35			2	1	1	1
R36			2	2	4	2
R37		20000	2	2	4	1
R38			2	2	4	1
R39		20000	2	2	4	
R40			2	2	4	1
R41		20000	2	2	1	1
R42	12	12000	2	1	1	1
R43		30150	1	1	1	1
R44			2	2	2	1
R45		30000	2	2	2	1
R46		25000	2	2	3	2
R47		25000	2	2	4	2
R48		25000	2	2	2	1
R49		25000	2	2	1	1
R50			2	2	2	1

Respondent_ID	comf_po_loan	CookTimeBefore	fuelcostBefore	lightcosbefore	cooktimeafter	fuelcostafter
R01	1	6	1200	250	4	700
R02	1	5	1800	200	4	1000
R03	1	5	1000	250	4	250
R04		6	1200	300	5	430
R05	1	4	1000	250	3.5	320
R06	1	4	1400	200	3.5	800
R07	1	4	1200	300	3	600
R08	1	6	1200	200	4	600
R09		6	3000	350	4	450
R10	1	5	1200	300	4.5	200
R11	2	4	2000	500	3.5	1600
R12		1	1500	0	0.5	1200
R13	2	4	2500	200	3	2100
R14	2	6	2000		4	500
R15	1	6	2500		5	1400
R16	1	4	2000		2.5	1000
R17	1	2.5	1500		2	400
R18		4	1800	350	3	750
R19	1	3	2000	300	2	980
R20	2	3	2500	500	2	2300
R21	1	4	3000	0	2.5	1900
R22	1	7	1800	200	5	800
R23	1	3	1000		2	200
R24	1	3	1800	300	2.5	450
R25	1	3.5	3000	250	3	1850
R26	1	6	5000	200	5	4050
R27	1	4	2000	300	3	1000
R28	1	5	1500	200	3	420
R29	1	8	5000	350	7	2080
R30	1	3	1000	300	2	0
R31	2	5	2400	500	3	0
R32	1	6	2800	0	4	0
R33	1	12	3000	200	8	100
R34	1	8	1000		5	0
R35	1	7	2950		5	0
R36	2	10	4000		6	3000
R37	2	6	1200	350	4	220
R38	2	6	2700	300	4	0
R39	2	8	3000	500	4	0
R40	2	6	2900	0	4	0
R41	2	4	2500	200	2.5	1000
R42	1	5	2500		4	0
R43	1	4	900		3	0
R44	2	3	1500		2	0
R45	2	5	1050	100	2	300
R46	2	10	10000		8	7000
R47	2	4	2000	500	3	1500
R48	2	2	1500		1.5	150
R49	2	7	5000	150	6	3600
R50	1	5	2000	100	4	550

Respondent_ID	fuelwood_before	fuelwood_after	save_fuel	Firewood	FWTk_kg	source_fuelwood
R01	360	0	1	360	2	2
R02	720	0	1	720	2	2
R03	400	0	1	400	2.5	2
R04	480	0	1	480	2.5	2
R05	400	0	1	400	2.5	2
R06	560	160	1	400	2.5	3
R07	480	240	1	240	2.5	2
R08	480	280	1	240	2.5	2
R09	560	240	1	320	2.5	2
R10						3
R11	250	0	1	2000	8	2
R12	1500	1000	1	200		3
R13	300	100	1	200		3
R14	250	0	1	250		3
R15	300	30	1	250		3
R16	400	60	1	340	5	2
R17	300	60	1	240	5	2
R18	200	20	1	180	10	3
R19	200	20	1	180	10	2
R20	350	350	1	185	9	3
R21	600	300	1	300	3.5	3
R22						3
R23	20	20	1	200	10	2
R24	300	150	1	150		3
R25	580	80	1	500	6	3
R26	1400	100	1	1300	3.5	2
R27	400	50	1	350	5	3
R28	300	0	1	300	5	3
R29	1000	0	1	1000	5	3
R30	250	0	1	250	4	3
R31	280	0	1	280	7.5	2
R32	130	0	1	130	7.5	2
R33	200	20	1	180	7.5	3
R34	140	10	1	130	7.5	2
R35	240	0	1	240	5	2
R36	800	0	1	800	5	3
R37	240	0	1	240	5	3
R38	800	0	1	800	2.5	3
R39	400	0	1	400	2.5	3
R40	80	0	1	80	2.5	3
R41	350	0	1	380	7.5	3
R42	350	0	1	350	7.5	3
R43	70	0	1	70	7.5	2
R44	70	0	1	70	7.5	3
R45	350	100	1	250	3	2
R46	2000	0	2	400	5	3
R47	250	0	1	2000	8	3
R48	400	50	1	350	3	2
R49	1300	300	1	1300	3.75	2
R50	250	0	1	250	3	3

Respondent_ID	TSFCPD_before	TSFCPD_after	EduFacility_after	SAPS_before	SAPS_after	Gas_sell
R01	1	0	1	1	1	2
R02	1	0	1	1	1	2
R03	1	0	1	1	1	2
R04	1	0	1	1	1	2
R05	1	0	1	1	1	2
R06	2	1	1	1	1	2
R07	1	0.5	1	1	1	2
R08	1	1	1	1	1	2
R09	2	1	1	1	1	2
R10	0	1	1	1	1	2
R11	1	0	3	3	3	2
R12	1	0	3	2	2	2
R13	1	0	3	2	2	2
R14	0	0	3	2	2	2
R15	1	0	3	2	2	2
R16	0.5	0.1	1	2	2	2
R17	1	0.2	3	2	2	2
R18	2	0.5	3	2	2	2
R19	1	0	3	2	2	2
R20	0	0	3	2	2	2
R21	1.5	0	3	2	2	2
R22	0	0	1	2	2	2
R23	0	0	3	2	2	2
R24	0	0	3	2	2	2
R25	1	0.5	3	2	2	2
R26	2	0	1	2	2	2
R27	1.5	0	3	2	2	2
R28	2	0	3	2	2	2
R29	0	0	1	2	1	1
R30	5	0	1	2	2	2
R31	1	0	3	2	2	2
R32	1	0	3	2	2	2
R33	1	0	3	2	2	2
R34	2	0	3	3	3	2
R35	2	0	3	2	2	1
R36	1	0.5	3	3	3	2
R37	1	0	3	3	3	2
R38	0	0	3	3	3	2
R39	0	0	3	2	2	2
R40	0	0	2	2	2	2
R41	2	0	3	3	3	2
R42	1	0	2	2	2	2
R43	1	0.5	1	2	2	2
R44	0	0	2	2	2	2
R45	1	0.5	3	2	2	2
R46	1	0	3	2	2	2
R47	1	0	3	3	3	2
R48	0.5	0	3	2	2	2
R49	5	7	3	2	2	2
R50	0.5	0	3	2	2	1

Respondent_ID	toiletHH_before	toiletHH_after	attatch_toilet	airpollution_before	airpollution_after	EyeInfec_before
R01	2	2	2	1	4	2
R02	2	2	2	1	4	2
R03	2	2	2	1	4	2
R04	2	2	2	1	4	2
R05	2	2	2	1	4	2
R06	2	2	2	1	3	2
R07	2	2	2	2	4	2
R08	2	2	2	2	2	2
R09	2	2	2	2	1	2
R10	1	1	2	4	4	3
R11	1	1	1	1	4	3
R12	1	1	1	3	4	3
R13	1	1	1	2	4	2
R14	1	1	2	3	4	3
R15	1	1	2	3	3	3
R16	1	1	2	2	3	2
R17	1	1	2	3	4	3
R18	1	1	2	3	3	3
R19	1	1	2	3	4	3
R20	1	1	2	3	4	3
R21	1	1	2	2	2	1
R22	1	1	2	2	2	2
R23	1	1	2	2	3	2
R24	1	1	2	2	3	2
R25	1	1	2	2	2	1
R26	2	2	2	2	2	1
R27	1	1	2	2	2	4
R28	1	1	2	2	2	1
R29	1	1	2	2	4	2
R30	1	1	2	3	4	3
R31	1	1	2	4	4	4
R32	1	1	2	4	4	4
R33	1	1	2	1	3	2
R34	2	2	2	1	4	3
R35	2	2	2	3	3	3
R36	2	2	2	2	3	2
R37	2	2	2	2	1	2
R38	2	2	2	3	3	3
R39	2	2	2	3	3	1
R40	2	2	2	2	2	3
R41	1	1	2	2	4	2
R42	1	1	2	2	3	2
R43	2	2	2	1	4	2
R44	2	2	2	2	3	2
R45	1	1	1	1	4	2
R46	1	1	1	1	4	2
R47	1	1	1	1	4	3
R48	2	2	2	2	3	2
R49	2	2	2	2	3	2
R50	2	2	2	2	2	2

Respondent_ID	EyeInf_after	respiratory_bef	respiratory_after	Typhoid_bef	Typhoid_after	Diarrhoea_bef
R01	4	3	3	3	3	3
R02	4	2	3	3	2	3
R03	4	2	4	2	3	2
R04	3	3	3	3	3	3
R05	2	3	3	3	3	3
R06	3	2	3	3	3	3
R07	3	2	3	3	3	3
R08	2	2	2	3	2	3
R09	3	2	3	2	2	2
R10	3	3	3	3	3	3
R11	4	3	4	3	4	3
R12	4	3	4	4	4	4
R13	4	2	4	3	3	1
R14	4	3	4			2
R15	3	3	3	3	3	1
R16	3	3	3	4	4	4
R17	3	3	3	3	4	3
R18	3	3	3	4	4	4
R19	4	2	4	4	4	4
R20	4	2	4	4	4	4
R21	3	1	3			3
R22	3	2	3			3
R23	4	1	4	4	4	4
R24	4	4	4	4	4	2
R25	3	4	4	4	4	2
R26	4	1	4	4	4	4
R27	4	4	4	4	4	2
R28	4	4	4	4	4	4
R29	4	2	4	4	4	4
R30	4	3	4	2	3	2
R31	4	4	4	4	4	2
R32	4	4	4	4	4	4
R33	4	1	4	4	4	4
R34	4	3	4	4	4	4
R35	4	3	4	4	4	4
R36	4	2	4	4	4	4
R37	1	2	1	2	2	2
R38	4	3	4	3	4	3
R39	4	1	4	3	3	3
R40	4	3	4	2	2	2
R41	4	2	4	3	3	3
R42	3	2	3	2	3	2
R43	3	2	3	3	4	3
R44	3	2	3	3	4	3
R45	4	2	4	2	3	2
R46	4	2	4	2	3	2
R47	4	3	4	3	4	3
R48	4	2	4	2	4	4
R49	3	2	3	2	2	2
R50	4	2	4	4	4	4

Respondent_ID	Diarrhoea_after	Abun_mosq_bef	Abun_mosq_after	NKFI_bef	NKFI_after	InitiativeTaken
R01	3	3	3	4	4	1
R02	3	3	3	4	4	1
R03	3	3	3	4	4	1
R04	3	3	3	4	4	1
R05	4	3	3	4	3	1
R06	3	2	4	4	4	2
R07	3	2	3	4	4	1
R08	2	3	3	4	4	1
R09	2	3	3	4	4	1
R10	3	3	2	4	4	2
R11	4	2	3	4	4	1
R12	4	3	4	4	4	1
R13	2	1	2	4	4	2
R14	4	2	3	3	4	1
R15	3	3	3	3	3	1
R16	4	3	4	4	4	1
R17	4	3	3	4	4	1
R18	4	4	4	4	4	2
R19	4	2	4	4	4	1
R20	4	2	4	4	4	1
R21	4	2	3	3	4	1
R22	4	2	3	3	4	2
R23	4	3	4	4	4	1
R24	4	4	4	4	4	1
R25	3	4	4	4	4	1
R26	4	4	4	4	4	2
R27	3	2	3	2	3	2
R28	4	3	4	4	4	1
R29	4	2	4	4	4	1
R30	3	3	4	2	3	1
R31	1	4	4	4	4	1
R32	4	4	4	4	4	1
R33	4	4	4	4	4	1
R34	4	4	4	4	4	1
R35	4	4	4	4	4	1
R36	4	3	4	4	4	1
R37	2	2	1	4	4	1
R38	4	3	4	3	4	1
R39	3	3	3	4	4	1
R40	2	2	2	4	4	2
R41	3	3	4	4	4	1
R42	3	2	4	4	4	1
R43	4	2	4	4	4	1
R44	4	2	4	4	4	1
R45	3	1	4	4	4	1
R46	3	1	4	4	4	1
R47	4	2	3	4	4	1
R48	4	1	3	4	4	1
R49	2	2	3	4	4	1
R50	4	2	4	4	4	1

Respondent_ID	DecisionTaken	Responsible	monitoring	Maintenance	Contact_CPO	Technical_known
R01	1	2	1	2	1	1
R02	1	2	1	2	1	1
R03	1	7	1	7	1	1
R04	1	7	1	7	1	1
R05	1	2	1	7	1	1
R06	2	2	1	2	1	1
R07	1	2	1	2	1	1
R08	1	1	1	1	1	1
R09	1	2	1	2	1	1
R10	2	2	1	2	1	1
R11	7	2	1	2	1	1
R12	1	8	1	7	1	1
R13	1	8	1	7	1	1
R14	7	2	1	1	8	1
R15	1	1	1	2	1	1
R16	7	2	1	2	8	8
R17	1	2	1	1	5	5
R18	7	2	2	1	5	5
R19	7	7	1	2	8	8
R20	1	1	1	1	8	8
R21	1	1	1	1	8	8
R22	7	2	2	2	8	8
R23	7	2	1	2	8	8
R24	7	1	1	7	8	8
R25	7	1	1	6	8	8
R26	7	2	1	2	8	8
R27	7	1	7	1	8	8
R28	1	2	1	2	8	8
R29	1	1	5	8	8	7
R30	7	1	5	1	8	7
R31	1	5	1	5	8	8
R32	7	1	1	1	8	8
R33	1	2	1	7	8	8
R34	7	7	1	1	8	8
R35	1	1	1	1	8	8
R36	7	1	1	1	8	8
R37	7	1	1	2	8	8
R38	7	1	1	1	8	8
R39	7	7	1	1	8	8
R40	7	2	5	2	8	8
R41	1	2	1	8	8	8
R42	7	7	1	8	8	8
R43	1	1	7	1	8	8
R44	1	2	1	8	8	8
R45	7	7	1	8	8	8
R46	7	7	1	8	8	8
R47	7	2	1	8	8	8
R48	1	7	1	8	8	8
R49	1	7	1	8	8	8
R50	1	2	1	5	5	5

Respondent_ID	Benifited	BenefitsDWG	CookTime_bf	CookTime_after	ChildEduTime_bf	ChildEduTime_af
R01	7	2	6	4	4	5
R02	7	2	5	4.5	3	3
R03	7	5	5	4	3	4
R04	7	2	6	5	4	5
R05	7	2	4	3.5	3	4
R06	7	2	4	3	4	4
R07	7	2	4	3.5	2	2
R08	7	2	6	4	2	2
R09	7	2	6	4	3	4
R10	7	2	5	4	6	6
R11	2	5	4	3.5		
R12	1	5	4	3	2	2
R13	1	5	4	3	2	2
R14	2	5	3	2		
R15	2	5	6	5		
R16	2	5	4	2.5	2	2
R17	7	5	2.5	2	2	2
R18	7	5	4	3	2	2
R19	7	2	3	2	1	2
R20	7	5	3	2	1	2
R21	7	5	4	2.5	2	2
R22	7	4	7	5	2	2
R23	7	4	3	2	3	3
R24	7	5	3	2.5	2	2
R25	7	5	3.5	3	3	3
R26	7	5	6	5	2	2
R27	7	5	4	3	2	2
R28	7	4	5	3	3	4
R29	4	5	8	7	3	3
R30	7	5	3	2		
R31	2	5	5	3	2	2
R32	7	1	6	4	3	3
R33	1	5	12	8	2	2
R34	7	5	8	5	2	2
R35	7	5	7	5	3	3
R36	7	2	10	6	3	3
R37	7	5	6	4	2	2
R38	7	5	6	4	2	2
R39	7	2	8	4		
R40	7	2	6	4	3	3
R41	7	5	4	2.5	2	2
R42	7	5	5	4	1	1
R43	7	2	4	3	0.5	0.5
R44	7	1	3	2	1	1
R45	7	5	5	2	1	1
R46	7	5	5	2	1	1
R47	2	5	4	3		
R48	7	5	2	1.5	1	1
R49	5	5	5	4	3	3
R50	2	5	5	4	2	2

Respondent_ID	OwnLand	MortgageLand	Cultivatedland	LivestkPop_bf	livestkpop_af	feedingmethod_bf
R01	200	0	180	3	3	1
R02	220	0	200	2	2	1
R03	316	0	290	1	2	1
R04	1134	0	929	2	4	1
R05	20	0	7	1	2	1
R06	83	0	66	4	7	1
R07	7	0	0	7	3	1
R08	121	0	99	3	3	
R09	31	0	5	3	3	1
R10	6	0	0	4	4	1
R11	150	0	145	4	2	2
R12	160	0	160	2	0	2
R13	200	0	160	2	2	1
R14	170	0	170	20	4	1
R15	220	0	220			
R16	190	0	190	3	1	1
R17	130	0	130	2	2	1
R18	90	0	90	2	2	1
R19	190	0	190	3	2	1
R20	60	0	60	3	3	1
R21	330	0	330	8	2	1
R22	400	0	400	5	5	1
R23	420	0	420	3	3	1
R24	150	0	0	2	5	1
R25	160	0	160	5	2	1
R26	460	0	460	2	3	1
R27	650	0	650	4	4	1
R28	65	0	65	2	2	1
R29	120	0	120	17	17	1
R30	50		50	3	3	1
R31	60	0	60	10	12	1
R32	35	0	35	12	8	1
R33	100	0	100	12	0	1
R34	30	0	30	8	2	1
R35	10	0	10	20	15	1
R36	66	0	66	4	6	1
R37	0	130	130	12	6	1
R38	50	160	210	18	11	1
R39				4	3	1
R40	65	0	65	7	4	1
R41	100	0	100	3	3	1
R42	30	200	230			1
R43	100	0	100	3	2	1
R44	74	0	74	9	3	1
R45	100	0	100	4	4	1
R46	100	0	100	6	6	1
R47	150	0	145	4	2	2
R48	50	0	50	4	3	1
R49	20	0	20	3	9	1
R50	50	0	50	4	9	1

Respondent_ID	feedingmethod_af	CSM_bf	CSM_af	useofBS	place_BS_use	AnimalHealth_bf
R01	1	1	1	1	1	1
R02	1	2	2	1	1	1
R03	1	2	1	1	1	1
R04	1	2	1	1	1	1
R05	1	2	2	1	1	1
R06	1	2	2	1	1	1
R07	1	1	1	2		1
R08		2	1	1	1	1
R09	1	1	1	2	2	1
R10	1	1	1	2		1
R11	1	2	2	1	1	4
R12	2	2	2	2		
R13	1	2	2	1	1	2
R14	1	2	2	1	1	2
R15				2		
R16	1	2	2	1	1	2
R17	1	2	2	1	1	2
R18	1	2	2	1	1	2
R19	1	2	2	1	1	3
R20	1	2	2			4
R21	1	2	2	2		2
R22	1	2	2	2		4
R23	1	2	2	2		2
R24	1	2	2	2	7	2
R25	1	2	2	2	1	3
R26	1	2	2	2		2
R27	1	2	2	2		4
R28	1	2	2	2		2
R29	1	2	2	2		2
R30	1	2	2	2		4
R31	1	2	2	2		1
R32	1	2	2	2		2
R33	1	2	2	2		2
R34	1	2	2	2		2
R35	1	2	2	2		2
R36	1	2	2	1	2	4
R37	1	2	2	1	1	2
R38	1	2	2	2		2
R39	1	2	2	2		2
R40	1	2	2	2		1
R41	1	2	2	2		4
R42	1	2	2			
R43	1	2	2	1	2	2
R44	1	2	2	1	7	2
R45	1	2	2	2		1
R46	1	2	2	1	2	2
R47	1	2	2	1	1	4
R48	1	2	2	2		2
R49	1	2	2	1	7	2
R50	1	2	2	1	1	2

Respondent_ID	AnimalHealth_af	FMS_before	FMS_after	EffectivenessBS	FuelCook_beforeBP1	FuelCook_beforeBP2
R01	1	1	1	1	1	2
R02	1	1	1	1	1	2
R03	1	2	1	1	1	2
R04	1	1	1	1	1	2
R05	1	1	1	1	1	2
R06	1	1	1	1	1	2
R07	1	1	1		1	3
R08	1	1	1	1	1	2
R09	1	1	1	1	1	2
R10	1	3	3		5	
R11	4	4	4	1	1	
R12					1	2
R13	1	2	1	1	1	2
R14	1	2	1	1	1	2
R15					7	
R16	1	4	4	1	1	2
R17	2	2	2	1	1	2
R18	2	2	2	1	1	2
R19	2	2	1	1	1	2
R20	4	4	4		8	
R21	2	2	2		1	2
R22	4	4	4		1	2
R23	2	2	2		1	2
R24	1	2	1		1	2
R25	2	2	2		1	2
R26	2	2	2		1	2
R27	4	4	4		1	3
R28	2	2	2	1	1	3
R29	1	2	1		1	2
R30	4	4	4		1	3
R31	1	2	2		1	8
R32	1	2	2		1	2
R33	2	2	2	1	1	2
R34	2	2	2		1	2
R35	1	2	1	1	1	2
R36	4	4	4	1	1	
R37	4	2	4	1	1	
R38	1	2	1		1	
R39	4	2	4		1	
R40	4	1	4		1	2
R41	4	4	4		1	
R42				1	1	8
R43	1	2	1	1	2	
R44	2	3	2	1	1	2
R45	1	1	1		1	2
R46	4	2	4	1	5	
R47	4	4	4	1	1	
R48	1	2	2		1	3
R49	2	2	2	1	1	
R50	2	2	2	1	1	2

Respondent_ID	SAHE_af	SAKE_bf	SAKE_af	SACSE_bf	SACSE_af	SoSE_bf
R01	1	3	1	2	2	2
R02	1	3	1	2	1	2
R03	1	3	1	2	2	2
R04	1	3	1	2	2	2
R05	2	3	1	2	2	2
R06	2	2	1	1	1	2
R07	2	2	1	2	1	1
R08	1	2	2	1	1	1
R09	1	2	1	2	1	2
R10	1	1	1	3	3	2
R11	1	2	1	2	2	4
R12	1	2	1	2	2	4
R13	1	2	1	3	2	3
R14	2	2	2	2	2	2
R15	2	2	2	2	2	2
R16	4	4	4	4	4	4
R17	1	2	1	2	2	2
R18	1	2	2	2	2	3
R19	1	3	1	2	2	2
R20	2	2	2	2	2	2
R21	1	1	1	2	2	2
R22	3	2	3	2	2	3
R23	1	3	2	3	2	3
R24	2	2	2	3	2	2
R25	2	2	2	2	2	2
R26	2	3	2	3	2	3
R27	2	2	2	3	2	3
R28	2	2	2	2	2	2
R29	4	2	4	2	3	2
R30	2	2	2	2	2	2
R31	1	2	1	2	1	2
R32	2	2	2	2	2	2
R33	2	2	2	2	2	2
R34	2	3	1	2	1	3
R35	1	2	1	2	1	2
R36	2	2	1	2	4	2
R37	2	2	2	2	2	2
R38	4	2	4	2	4	2
R39	2	2	2	2	2	2
R40	1	2	1	2	2	3
R41	4	2	1	3	2	3
R42	4	2	1	3	2	3
R43	1	3	1	3	2	2
R44	1	2	1	2	4	2
R45	1	2	1	3	2	3
R46	1	1	1	1	1	2
R47	1	2	1	2	2	4
R48	4	2	1	2	4	3
R49	2	2	2	2	2	2
R50	1	3	1	2	2	2

Respondent_ID	SoSE_af	SSE_bf	SSE_af	SoDWater	Distance_BP_DWS
R01	2	2	2	1	2
R02	2	2	2	1	10
R03	2	2	2	1	20
R04	2	2	2	1	5
R05	2	2	2	1	5
R06	4	2	4	1	10
R07	1	1	1	1	10
R08	1	1	1	1	20
R09	3	2	2	1	20
R10	2	2	2	1	10
R11	4	4	4	4	5
R12	4	4	4	1	7
R13	4	4	4	4	4
R14	2	2	2	1	4
R15	2	2	2	1	5
R16	4	4	4	1	6
R17	2	2	2	1	6
R18	2	2	4	1	6
R19	2	2	2	1	5
R20	2	4	4	1	20
R21	2	2	2	1	15
R22	3	2	3	1	3
R23	3	3	2	1	3
R24	3	2	3	1	3
R25	2	2	2	1	2
R26	2	2	2	1	12
R27	3	3	3	1	6
R28	2	2	2	1	7
R29	3	2	3	1	15
R30	2	2	2	1	5
R31	2	2	2	1	3
R32	2	3	2	1	6
R33	2	2	3	1	3
R34	2	3	2	3	2
R35	2	2	2	1	3
R36	4	2	2	1	6
R37	2	2	2	1	35
R38	4	2	4	1	40
R39	2	2	2	1	10
R40	3	3	3	1	60
R41	2	2	4	1	8
R42	2	2	4	1	3
R43	2	2	2	1	20
R44	4	2	4	1	1
R45	3	3	2	1	8
R46	2	2	2	1	8
R47	4	4	4	4	6
R48	2	3	2	1	7
R49	2	2	2	1	3
R50	2	2	2	1	2