Energy yield potentials from the anaerobic digestion of common animal manure in Bangladesh

1. Introduction

Bangladesh is one of the world's ten most populated countries with an estimated current population of 162 million and one of the highest population densities with an annual growth of 1.7% [1]. Bangladesh has a predominantly rural population, with over 60% of the workforce engaged in agriculture. The country's economy is still dependent on agriculture with rice, jute, tea, sugarcane, tobacco, and wheat as the chief crops [2]. Agriculture serves as the mainstay of the population contributing about 50% of the Gross Domestic Product (GDP). The predominantly agrarian economy is characterized by small-scale, fragmented farming. All the cultivable land is in use and the increasing population has reduced the average size of a smallholder farm in Bangladesh to 0.24 hectares. [3].

Globally more than 2.7 billion people (38% of the world’s population) are estimated to rely on the traditional use of solid biomass for cooking, typically using inefficient stoves or open fires in poorly ventilated spaces [4]. Developing Asia (Bangladesh, Nepal, India) and sub-Saharan Africa dominate the global totals. For example, 76% of people in Bangladesh live in rural areas and use mainly traditional stoves for cooking their three meals daily, and other heating purposes [5, 6]. Traditional energy includes fuel wood, agricultural residues, leaves and dried dung cake collected from the cattle. Using leaves, tender shoots and twigs as fodder is traditional in the villages [7], with some use of agricultural by-products, such as crop residues [8]. An estimate of traditional biomass fuels supplied in the year 2002/03 was 11,199 million tonnes of coal equivalent, mostly used for cooking. Use of these traditional fuels has a number of drawbacks including deforestation, depletion of organic matter in soil, air pollution, respiratory disease, time lost, labour-intensity and low efficiency [9]. Illnesses resulting from cooking and lighting fuel are estimated to cause the deaths of more women in some rural developing countries such as Bangladesh, than both malaria and tuberculosis [10].

Energy is a crucial input for socioeconomic development. In Bangladesh, about 96 million people (59%) do not have access to electricity [11] and most of the households heavily depend on biomass energy that accounts for 87% of their monthly energy consumption and about two-thirds of their energy expenditure [12]. Energy consumption per capita in Bangladesh is among the lowest in the world: the per capita electricity generation is 321 kWh. 83% of electricity is generated from natural gas [13], and only 3% of urban people have access to natural gas from centralised pipe lines. The rest of the population relies on traditional biomass fuel or liquefied petroleum gas (LPG) for cooking, but LPG is very expensive for the rural population [13].

Although cow dung and poultry litter are the most common animal manure for biogas feedstock in Bangladesh, rice straw, energy crops, food waste, and other agricultural waste also been used in some cases [14]. Most of the rural households of Bangladesh have 2 - 3 cattle whose quality is considered poor, and dung cake is used widely as the cooking fuel, with an inefficient burn which generally causes indoor air pollution. An alternative use of cow dung for the production of energy via biogas instead of combustion is the focus of this paper. Biogas is a combustible gas produced by anaerobic digestion (AD) and fermentation of organic materials by the action of methanogenic bacteria in a wet process: the dung is mixed with water and left to ferment in an enclosed vessel. The resultant gas which is emitted is mainly composed of methane (60 - 70%) and carbon dioxide (30 - 40%) – a very similar composition to piped gas in towns, which is derived from fossil fuels. Methane-based gas produces more heat than kerosene, fuel wood, charcoal and dung-cakes [15]. When biogas is used in suitably designed burners, it gives a clean, smokeless, blue flame, which is ideal for cooking. If biogas is used in specially designed lamps it gives a light similar to kerosene pressure lamps. Biogas can be used for other purposes such as electricity generation, refrigeration, space heating and running engines, but higher amounts of gas is required for those purposes than is available from typical households.

With most of the rural population living on smallholdings, the contribution to overall domestic national energy needs is potentially very significant [5]. However, it is very difficult for planners, policy makers and entrepreneurs to estimate potential contributions because there is very little data – reliable or not – from the field. Specially, reliable quantitative data for each source are reported to not be available [16]. The problem is that biogas production yields can vary hugely from laboratory values, depending on field parameters such as the actual dung production of the cattle (which depends on their condition); the regularity of the 'charging' of the feedstock into the digester; and the availability of water, and the conditions of the plant being used.

Better availability of reliable data and information on major biomass resources could help to build decision support tools (DST) for biomass and bioenergy potential for developing countries such as Bangladesh [13]. This can help stakeholders, government and decision-makers at regional, national or local levels to implement biogas plant facilities for sustainable development. However, the availability of reliable quantitative field data on waste and energy yields is reported to be scarce and unreliable in many developing countries [18]. In some countries this has led to exclusion from applying for funding through the Clean Development Mechanism [19] where the utilization of the biogas as a renewable energy could have in principle qualified to obtain certified emission reduction credits under the Kyoto protocol. Rigorous studies involving systematic consideration of field conditions are not usually found: in Bangladesh the operation manual from the company selling the digesters is used [20], and the nearest other reference is for data from Chinese field studies [21]. In 2015 The United Nations (UNs) implemented an agenda 2030 for sustainable development, which includes the 17 Sustainable Development Goals (SDG's**)**, among which is goal number 7 is "Ensure access to affordable, reliable, sustainable and modern energy for all" [22]. This goal can be justified by social inclusion, economic development and the environment viewpoint. Determination of energy yield potential of available biomass could help policy maker to implement this system by knowing the data inventory from both biomass and energy, thus contributing to reaching this SDG target.

The aim of this work is to fill the data gap by providing reliable field-based data relevant for decision making concerning domestic, small-medium sized biomass digesters using anaerobic digestion (AD) in Bangladesh. The goal is to obtain data which can then be reliably used to determine the country's national realistic biogas potential, both in terms of energy (kJ) and in numbers and percentages of households which could be affected. The main objectives are:

- To explore, in the field, which parameters might be significantly different to those assumed in calculations which scale up from farm level

- To determine actual field values of biogas and energy yields (methane content)
- To summarise the impact of the field data we find on national calculations which currently use key assumptions and unconfirmed grey literature

We achieve this by first carrying out a preliminary study to determine which parameters in the field need more careful study, and then obtaining them in the main study. We then compare them to informal data and go further to outline the immediate implications for national estimates and policy.

2. Methods

In order to ensure a good design of the main study, an exploratory preliminary field study was first carried out to determine the weakest parameters which needed further careful study in the field in order to obtain robust national figures, and which other parameter uncertainties needed to be formally noted by planners. This was followed by the main field studies to obtain key field data. Each of the separate methods used to obtain the primary field data are described below, as is the normalisation of the data with respect to temperature. The results for gas yields, composition and feedstock conditions are then compared to the informal literature [20] for Bangladesh, and AD systems in China [21].

2.1. Preliminary study

This was carried out several interviews with key informants from stakeholders with relevant expertise, resulting in immediate grounded knowledge and familiarity with field resources. These included key government and non-governmental organizations of Bangladesh; Grameen Shakti (GS), Advance Engineering (AE), Bangladesh Council for Scientific and Industrial Research (BCSIR), Netherland Development Organization (SNV) and Infrastructural Development Company Limited (IDCOL). These organizations are deeply involved with AD research and practice in Bangladesh. GS provided access to a number of AD sites for visits for this research. Advance Engineering provided the experimental AD plant site facilities for the rice straw feedstock investigation discussed below. GS also has a range of informative documents used in practice with sub-contractors and farmers concerning optimum management and setting up of small and medium-sized AD systems.

Field Work: Surveys and interviews with 11 farmers

After 2-3 rounds of discussions with the above key informants, it was understood that the main scenarios for AD use were small-medium scale use from cows in family smallholdings, and medium scale use from poultry farms. The parameters identified as being particularly uncertain and requiring field measurements were daily charges being used, gas yields, and gas compositions. It was decided to take preliminary data in the field to get a more precise understanding of any potential difficulties for the main field work. Grameen Shakti nominated 10 sites with small or medium AD plant with cow manure feedstock. They also nominated one site with a medium sized AD plant using poultry litter as feedstock. The first author visited the eleven sites and obtained from the farmer the plant size, number of cattle being used, and feeding frequency, leading to calculations of further information, all summarized in Table 1. Wider information on the operational conditions of the plant are summarised further below.

Table 1.
Data from preliminary field work on small-medium scale AD plant in Bangladesh. As the farmers were uncertain in most cases, an estimated weight of daily manure production was used [23]: the daily charge reported is an estimate from the farmers' report of charging every 'few' days.

Feed-stock	Location	Plant size (m^3 gas)	No. of animals	Assumed daily production [1] (kg/ day)	Daily charge equivalent [2] (kg)	Optimal reference daily charge [3] (kg)
Cow dung	Dhaka district (Savar)	14	17.5	15 [4]	262.5	378
Cow dung	Dhaka district (Savar)	14	17.5	15**Error! Bookmark not defined.**	262.5	378
Cow dung	Barisal district (Sadar)	3.2	5	10	50	87
Cow dung	Barisal district (Savar)	2.4	4	10	40	65
Cow dung	Manikgonj district (Singhair)	3	4	10	40	80
Cow dung	Manikgonj district (Singhair)	3.2	7	10	70	87
Cow dung	Manikgonj district (Singhair)	2.4	3	10	30	65
Cow dung	Manikgonj district (Singhair)	2.4	4	10	40	65
Cow dung	Manikgonj district (Singhair)	2.4	4	10	40	65
Cow dung	Manikgonj district (Singhair)	2.4	4	10	40	65
Poultry litter	Mymen-singh (Fulpur)	3.2	450	0.10	45	45

The total solid content of cow dung and poultry litter are 17% and 23% respectively [24] and have added water in 1:1 and 1:2 ratios respectively to keep the digester slurry

[1] Taken from GS field manual [23]
[2] The farmers reported they charged the system every 'few' days: this is a 'daily equivalent' averaged figure.

[33] This figure is related to the size of the digester: taken from the GS field manual [23]

[4] Estimated by farmer: the cattle in this case were a hybrid breed

around 8% TS [23]. Table 1 summarises the findings from this preliminary field work considering cow manure and poultry litter plant scenarios as discussed below.

Scenario 1: AD plant using cow manure from smallholdings

This scenario was reported by Grameen Shakti as being the most common and typical for small AD plant. Approximately 50% of the households of Bangladesh live in family groups which own 1-5 cows, [14] providing towards their daily milk needs. Typically, these cattle wander and feed in the vicinity of the smallholding, and their dung is picked up and carried back to a central location by a household member. Traditionally the dung is dried and then burned for energy, but here it is broken up slightly, mixed with water (1:1 – because the %TS of cow dung is 17 and this ratio keeps the slurry at around %TS 8, which is optimum of bacteria to digest in this condition) and fed into the household's AD tank, which is typically 2.4 m^3 in volume with a floating (or fixed) dome, and with a flexible hose pipe running from the top of the dome into the kitchen where it connects directly to a gas burner hob.

Scenario 2: AD plant using litter from a poultry farm

In Bangladesh there are large numbers of poultry farms serving local areas, typically with 1000-4000 birds. As each bird produces approximately 100 gm of litter each day, such poultry farms can easily regularly feed a medium, 3.2 m^3 AD plant [19]. This size of plant can in principle produce more energy (in MJ) per day, which is far more than the 44 MJ/day amount used by a typical household, and is usually used on site for farm activities.

Operational Findings from the preliminary field work surveys

The field work included not only surveys but also interviews with different stakeholders involved in running the plant. These yielded the following considerations important for noting generally, and for the design of our subsequent main study:

i. All of the AD systems were being fed insufficiently, ranging from less than half the amount recommended in the GS Operational Manual to the full amount. For our main study it would not be possible to properly correct the measured gas yield for improper amounts of feedstock charging, and so this highlighted that the main study would need to ensure that the charging was appropriate to the digester size. The fact that in the field the charging was sub-optimal would have to be treated as a separate aspect to be noted for national estimates.
ii. Farmers were not aware of the weight of the daily dung/litter production: it would be best to use a reference value for all indigenous cattle, e.g. as in the GS Field Operation Manual) rather than introduce untrustworthy estimates varying at each site, which would mask other variations being studied. In this way, our main study data would be more rigorous. The variation in the field would be noted as a separate factor for consideration by decision makers.
iii. The water ratio (amount of water mixed in with the dung as 1:1 normally) varied, as did the water content of the dung depending on how old it was. Thus,

this would need monitoring and probably supervision when trying to obtain reproducible field data of gas yields.

iv. Daily charging was not taking place, and in practice the frequency of charging was uncertain (the farmers did not give consistent answers). Since the gas yields would depend on regular charging so much, our main field study should design in some form of supervision or monitoring to make sure the frequency was known, and preferably regular, to produce reproducible results.

v. Because charging was inconsistent, it was not clear that useful gas yields could be measured, as they could vary with respect to charging time and regularity. In addition, attempts to measure yields would disrupt local gas use, and thus sites should be chosen with this in mind, to allow reproducible yield rates to be produced.

vi. During the preliminary study, we become familiar with an unexpected third common scenario for AD production which had not been mentioned in earlier studies or by the key informants: town market cattle straw. This is described below.

Scenario 3: AD plant using waste straw from town cattle markets

In larger towns it is normal to have markets where cattle are bought and sold. In these markets, the animals are kept in areas where rice straw is strewn for their bedding, and to absorb urine and manure produced on site. At the end of each day this straw and manure mixture is removed. Although there were not any existing AD plant using this as a feedstock, it was realised it had great potential not only for widespread and significant production, but for effective use, as the cattle were in towns, thus with larger numbers of potential users were nearby. This scenario was taken forward for further investigation in the main field study.

2.2. Design of the Main Field Work Methodology

The preliminary field work clearly indicated the need for supervised or at least monitoring of the AD plant in order to be clear of the conditions in which the gas yields were produced. Furthermore, this required such monitoring over several weeks, to allow the AD system to achieve an equilibrium state.

Three sites were then nominated by the NGO partner, one for each feedstock and scenario. For the cow dung case, a small scale plant of 2.4m^3 was used, on a smallholding with a cooperative farmer. For the poultry scenario, a medium plant of 4.8 m^3 was found on a poultry farm. In both cases the plant was already set up and going, but for 30 days the author visited every day for at least 2 hours to oversee daily charging. In the case of the third scenario, cattle market rice straw, there was no such facility existing, but a small-sized AD plant was found in the vicinity of a cattle market, and a worker was found to assist in clearing it out and setting it up from scratch using an initial charge of 1300 kg. It was then visited every day for supervision of the daily charging. Field observations were made for the following:

- Number of animals providing the feedstock
- Water ratio used
- Frequency of charging (daily was planned)
- Temperature

- Gas yields
- Gas composition (via samples for lab analysis)
- Total solids

Specific Methods used
Gas yields

The biogas yield was measured using two methods. In the first method, the plant was allowed to produce and store gas for 24 hours. Then the gas was released into a gas balloon through the gas meter. When the gas flow slowed down to a slow steady rate (from the activity of the microbes), the reading of the total gas measured was taken, giving a figure of the total gas produced over the previous 24 hours. The second approach was to measure the steady gas flow from the activity of the microbes, without gas storage. The gas flow reading was taken over 30 minute intervals for 3 hours and 6 measurements were recorded in each interval.
After the AD plant had achieved regular and monitored daily charging for 30 days, (resulting in equilibrium production and flow rates), primary data on the biogas yields were determined by using a portable digital gas flow meter (Figure 1) giving readings of litres per minute. Readings were taken in normal flow conditions every 30 minutes, for 3 hours each time.

Gas Composition

After the AD plant had achieved regular and monitored daily charging for 30 days, primary data on the biogas composition was obtained by collecting gas samples twice each day, for three days, from each plant. The biogas samples were collected with gas balloons and taken for analysis in BCSIR's laboratories in Dhaka. The amount of H_2S and CO was determined by using a digital gas analyser. Volume percentages of carbon dioxide were determined using an Orsat gas analyser (Figure 1), and by subtraction of these the methane volume percentage was deduced.

Figure 1: Digital Flow meter, Digital Gas Analyser and Orsat Gas Analyser

Total Solids

A sample of 15 kg of each feedstock was obtained after it had been mixed with water. From these, samples of 100 grams were taken and sun-dried for one day. The total solids were then measured by weighing the solids remaining after heating the sample at 105ºC until a constant weight was obtained:
$\%TS = (\text{Weight}_{\text{Dry pan + dry sample}} - \text{Weight}_{\text{dry pan}}) / (\text{Weight}_{\text{sample as received}}) \times 100\%$

2.3. Normalising for temperature variation

The gas yields of an anaerobic digester vary significantly with temperature. Previous work has documented these effects in the field in some detail [25], [26]. We thus prepared a method to normalise the field readings, taken in a given month at a given temperature, to any values reported in the literature which might be annual averages or at a specified but different temperature. To do this we first needed a known variation of gas yields for these types of AD systems with temperature, and to use that to estimate the production in each month for Bangladesh, to produce an annual or monthly average. Finally, the ratio of the gas yields expected at the field measurement and for the average month can be compared, to produce an approximate normalising ratio.

The case of AD in Tongliang in China provides documentation of biogas production at different temperatures. The daily production rate of biogas during winter (6 - 10°C) is 0.05 m^3; spring (16 - 22°C) is 0.1 - 0.2 m^3 and summer (22 - 23°C) is 0.20 - 0.33 m^3 [22] (see Figure 2).

This information can be combined with known temperature variations in Bangladesh to produce the relative estimated yields for each month, as shown in Table 2.

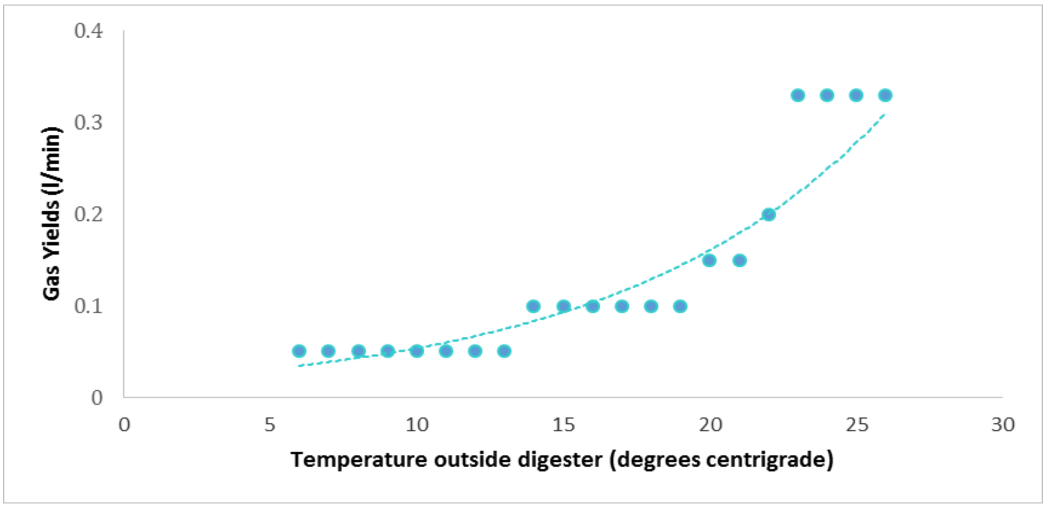

Figure 2. Gas yield variation of an anaerobic digester with temperature (based on [27]), including a trend line.

Table 2.
Estimated gas yields from an anaerobic digester in Bangladesh in order to model temperature variation through the year, using monthly minimum temperatures [28] and interpolating gas yields varying with temperature from [27].

Month	Minimum temperatures (degrees Centigrade)	Estimated yields (l/min)
January	13	0.07
February	14	0.08
March	16	0.11
April	24	0.25
May	25	0.28
June	25	0.28
July	26	0.33
August	26	0.33
September	26	0.33
October	25	0.28
November	19	0.15
December	15	0.11
Total Annual		2.6
Annually Averaged Monthly		0.217

Table 2 allows the field measurements made in any given month to be approximately related to the annual average of gas yields. This can be used as a rough temperature normalisation, since the temperature varies by month. Thus, if the temperature at the time of our measurements was 19 degrees Centigrade, shown to be appropriate for November in Table 2, then the gas yields in our study could be normalised to their expected annual average figure by using a Normalising Multiplier Ratio(NMR):
NMR = (Average annual yield rate) / (Yield for a given temperature and month)
NMR = (0.217)/(0.15) = 1.44

3. Results and Discussions

3.1 Normalised Daily Gas and Methane Yields

Table 3 below summarizes the data observed, measured, assumed and calculated. All measurements were taken after at least 30 days of supervised charging of feedstock at the recommended mass. The measurements were taken in February, with an outside temperature of 20 degrees centigrade, which when considered with the method of 2.3 produces a NMR of 1.27.

Table 3.

Data observed [O], measured [M], assumed [A], and calculated [C] on feedstock inputs, gas yields and composition. Since the daily feedstock was maintained as per the reference conditions of the plant manufacturer [20] in each case, the yields should represent optimal yields in the field.

Feed-stock type	AD plant size [O]	no. of animals [M]	Daily waste production[5] [A]	Daily AD feed-stock [C]	Ratio of water added [O]	Daily gas yield rates (l/min) [M]	Normalised[6] daily gas yield rates (l/min)	Methane content (%) [M]	Total Solids (%) [M]
Dung[7]	2.4 m^3	6 cows 1 calf	10kg/ cow 5kg/calf	65kg	1:1	1.20	1.52	59.9	19
Poul-Try**Error! Bookmark not defined.**	4.8m^3	6800 birds	0.1kg/ bird	68kg	1:2	1.10	1.40	61.6	23
Rice straw + cattle waste[8]	2.0 m^3	n/a	n/a	18kg[9]	1:4	1.37	1.74	74.4	45

[5] Taken from GS Field Operations Manual [23]

[6] Using a Normalising Multiplier of 1.27 to convert February temperature measurements to those for the annual average – see Section 2.3.

[7] Fixed dome

[8] Floating dome

[9] Taken from [14]

Yields and methane content

The results show that the new feedstock source considered, i.e. rice straw mixed with cattle dung, produces more gas per kg input that the two more well-known feedstocks of dung and poultry litter. Many studies indicated that the optimal C/N ratios in methane fermentation are 25-30:1 and this ratio also controls the pH value of the slurry [29]. The C/N ration of cow dung and poultry litter are less than this optimum amount but rice straw is much more than the optimum ratio and it could be up to 84:1 [30].

In Table 4 below we present comparisons of not only the yields but also their methane contents compared to the values in the GS Operations Manual (informal grey literature). This shows that we can confirm the overall relative production levels for the cow dung, but the poultry litter the results from this study are significantly less – only 40%.

Table 4.
A comparison of gas yields and methane contents for cow dung and poultry litter AD systems: this data and GS Field Manual [23].

	Feed stock (kg/cow)	Yield (m^3/kg)	% CH_4	MJ/m^3 CH_4	m^3/cow	MJ/Cow
This work	10	0.034	59.9	36.5	0.34	7.43
[20]	10	0.037	60	36.5	0.37	8.10
Ratio (this work/GS)					0.92	0.92
	Feed stock (kg/bird)	**Yield (m^3/kg)**	**% CH_4**	**MJ/m^3 CH_4**	**m^3/cow**	**MJ/bird**
This work	0.1	0.030	61.6	36.5	0.00	0.67
[20]	0.1	0.071	65	36.5	0.01	1.68
Ratio (this work/GS)					0.42	0.40

3.2. Factors Affecting the System

Our data overall indicates four factors which need to be considered when scaling up biogas potentials from individual farms to national levels. Incorrect quantities, mixing and regularity of feedstock, and possible plant problems. These are each discussed below.

3.2.1. Incorrect feedstock

From the eleven domestic biogas plants visited in the preliminary study reported here, our data showed that only one plant was fed with the recommended quantity of feedstock: in other words, 91% of them were significantly underfed. Under-feeding is the most commonly cited problem with AD in rural Bangladesh [31], confirmed by another survey result that was conducted by the Institute of Sustainable Development [32], which found that 83% of the plant were underfed, with 50% of them receiving less than half of the required dung. According to that survey, under-feeding usually occurs when the biogas plant owners sell a cow after the biogas plant is constructed.

Secondly, our first study data showed that incorrect mixing of dung was likely in many cases, and is a factor that would potentially greatly affect yields, because the appropriate mixing ratio of water and animal waste is a decisive factor for effective biogas yield [33]. It has previously been reported that a lack of proper training was an important reason of improper feeding (i.e. causing an excessive water/dung ratio) [32]. Proper mixing of slurry is also an important factor for proper bacterial activity: occasional stirring is required to help mix the manure, which will prevent the forming of crust (for cow dung) or slurry (for poultry manure) in the digester chamber.

Thirdly, our first study data showed that farmers were not charging their plant daily, as recommended, and indeed seemed to be charging them irregularly. This is not conducive to optimising gas yields, as the bacteria rely on regular feeding for stable growth and gas production. This could thus cause significant reductions and irregularities in gas production.

3.2.3. Plant problems

If there are unresolved or unmanaged problems with the AD plant, this can also affect gas yields, such as leaks or cracks or irregularities in the chambers. Some special characteristics of the feedstock can also affect the chambers, such as interior coating. In this study the biogas yield of poultry litter was 0.030 m^3/kg of feedstock whereas the GS field manual biogas yield rate is 0.071 m^3/kg of feedstock – less than half (Table 5). One possible reason might be due to the composition of animal food, as it was observed that the poultry farmer used food mixed with crushed mussel shells. These are rich in calcium, and make the egg shells hard and increase egg production. But crushed mussel shells can cause a compacted layer to form on the inside of the digester wall which affects bacterial activity and thus reduces biogas production. This hypothesis was not confirmed, and there could be other reasons, but as both independent comparator studies also showed higher yields per Total Solids (Table 5), it is likely that the problem was with our poultry AD plant system. This should be studied further if more exact figures are used for wider scaling up estimates e.g. of national capacity, and in the meantime all figures used with caution.

Table 5.

A comparison of biogas yields and total solids from this work with those of Gofran [23] and Hu [21], for cow dung and poultry litter. The figures for the new feedstock of rice straw + market cattle dung are compared.

	This study			Grameen Shakti			Hu DuRong	
	%TS	Biogas yield (m^3/kg Feedstock)	Biogas yield (m^3/kg TS)	%TS	Biogas yield (m^3/kg Feedstock)	Biogas yield (m^3/kg TS)	%TS	Biogas yield (m^3/kg TS)
Feed stock								
Cow dung	19	0.034	0.18	19.23	0.037	0.19	17	0.25
Poultry	23	0.030	0.13	23.82	0.071	0.33	25	0.33
Rice straw	45	0.142	0.32	n/a	n/a	n/a	n/a	n/a

Table 6.
Levels of CO_2, CO, H_2S and CH_4 measured from the biogas samples from cow dung, poultry litter and (rice straw with cattle dung), compared to values from two other studies [23], [21]

		Biogas elements			
		%CH_4	%CO_2	%CO	%H_2S
This study	Cow dung	59.9	42.1	0	0
This study	Poultry Litter	61.6	38.38	0	0.02
This study	Cattle market rice straw	74.4	25.57	0.0005	0
Gofran 2008	Cow dung	60	39.9	0	0.1
Gofran 2008	Poultry Litter	65	34.97	0	0.3
Hu 2006	Cow dung	50 – 77			
Hu 2006	Poultry Litter	60 – 65			

3.2.3. Data on cattle market straw

Data has been produced in this study for cattle market rice straw, which was unexpectedly found in the preliminary study to have good potential contribution to national planning o biogas resources. The field work indicated that the percentage of methane in the gas, the gas yield rates, and the yield rates per kg of total solids were all significantly higher than for dung or poultry litter feedstocks. The appropriate balance of nutrients is a critical factor in the anaerobic digestion process and optimum carbon to nitrogen ratios range from 25 to 35 [34], [35]. Untreated rice straw has a very low concentration of total nitrogen (i.e., <1% on a dry basis), [36] [37] and even less total phosphorus (i.e., 0.044% on dry basis) [37]. A typical C:N ratio for untreated rice straw is approximately 80 [38] and therefore an external source of nitrogen is essential for its digestion. Rice straw with a C:N ratio of 31 produced 4.5 times more biogas than rice husks with a C:N ratio of 81[38]. The significantly lower gas yield was attributed to the lower nitrogen concentration and higher lignin content in the rice husks compared to the rice straw [38]. Rice straw digested with cattle manure performed best with a C:N (non-lignin carbon to Kjeldahl nitrogen) ratio of 25 -35 yielding the highest methane production and lignin reduction [39], [40].

3.3 The Appropriate Use of This Data for National Planning and Decision-Making

This study has produced reliable field data of gas yields when the feedstock preparations are carried out according to the manufacturer's specification, as presented in Table 3. These represent the optimal yields that could be expected for cow manure, and could be used for scaling up calculations nationally with the understanding that they are upper limits, because of the other difficulties mentioned below. However, in the case of the poultry litter plant, the yield obtained in this study was so low as to suggest that the use of mussel shells in the feed might have created a crust inside the plant chamber walls which reduced its effectiveness, and therefore it cannot be stated whether the yield data is representative or not. Further studies would need to be carried out to ascertain if this represents a trend or anomaly.

However, all of the data in Table 3 has been produced using supervised feedstock preparation and charging. In actual fact, our preliminary study indicated that almost all plant are underfed, and likely to have incorrect water ratios and irregular and infrequent charging, all of which would reduce the gas yields – sometimes quite drastically. In extreme cases, the biological activity might reduce so far as to stop the useful production of gas. Thus, the actual yields available in the field are likely to range from zero up to those figures in Table 3.

In order to make effective national plans it is necessary to understand the impacts on wider energy provision and access, sustainable security of supply, and the potential social impacts e.g. on domestic life, and those all require the availability of reliable field data on common feeding scenarios, and the yields and compositions of the gas produced. This study has responded to that need for this field data, and the figures presented here have now been used in a further study to scope out those wider implications for Bangladesh [14]. In that study, surveys were undertaken in one district to determine the number of animals living on rural smallholdings and poultry farms, and the number of cattle markets, and using that information and the figures reported here, it was possible to calculate the maximum total optimal potential biogas energy from these feedstock types could meet the current cooking energy requirements of 30 million people in Bangladesh [14]. By comparing potential yields with household needs there was deemed to be potential for around 2 million domestic units, 340,000 medium units and 19,000 large units, as well as 500 very large units from the cattle markets that would be suited for larger users such as businesses, schools or hospitals in the towns where they occur [14].

While developed countries pursue the modern use of anaerobic digestion to combat the unmanageable growth of domestic organic post-consumer waste [41, 42], animal husbandry for increases in meat consumption and substitution for fossil fuels producing greenhouse gases [43], our studies focus on the potential for it to realistically simultaneously reduce indoor air pollution and provide access to secure energy supply to a significant part of the rural population of a developing country. Developing an efficient and sustainable biogas system for the rural Bangladesh is important not only for combat climate change but also an important solution to SDG Goal 7 "Ensure access to affordable, reliable, sustainable and modern energy for all". The multi-use potential of anaerobic digestion to assist with many of these present-day challenges perhaps deserves more attention to its overlapping co-benefits.

4. Conclusion

This study provide previously unavailable field data relating to the biogas and methane yields from supervised authentic anaerobic digesters using the most common animal manure in Bangladesh: cow dung, poultry litter and town cattle market straw which are found to produce biogas yields of 0.034, 0.030 and 0.142 m^3/kg respectively, with methane concentrations of 60% and 62% and 74% respectively. It also reports indications that in unsupervised plant issues with underfeeding, improper water mixing and irregular feeding are very common – all of which can significantly reduce yields. The figures above should thus be treated as maximum, optimum field values. The cow dung values are consistent with those published in grey literature and from China field work: the poultry value found here is approximately half and thus needs to be used with caution unless reconfirmed.

This results provide reliable data for use in national energy and investment planning, as they related directly to common scenarios of family smallholdings, common sized poultry farms, and town cattle markets in Bangladesh.

Acknowledgements
The authors received no financial support for the research, authorship, and/or publication of this article.

Declaration of conflicting interests
The authors declare no potential conflicts of interest with respect to the research, authorship and/or publication of this article.

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