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Measuring Carbon Emission Efficiency in a Developing Country: A Comparative Study of Sustainability Initiatives and Nonsustainability Initiatives of Manufacturing Firms

Jahira Debbarma[1] | Vikas Kumar[2] | Damilola Ekundayo[3]

[1]College of Business, Digital Transformation and Entrepreneurship, Birmingham City University, Birmingham, UK | [2]University of Portsmouth, Portsmouth, UK | [3]College of Built Environment, Birmingham City University, Birmingham, UK

Correspondence: Jahira Debbarma (jahira.debbarma@bcu.ac.uk)

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ABSTRACT

Improving carbon emission efficiency (CEE) is considered one of the most cost-effective ways to enhance sustainability and address climate change mitigation in developing countries like India. This study analyzes manufacturing firms' CEE of sustainability initiatives (SI) and nonsustainability initiatives (non-SI) and examines the effect of nationally determined contributions commitments on these firms. A nonradial slack-based model is adopted to assess efficiency over the period 2012–2022. Furthermore, the Tobit model is used to evaluate the influencing factors that promote the CEE of manufacturing firms. Findings reveal that most manufacturing firms in India, both in the SI and non-SI groups, are carbon inefficient due to pure carbon emission inefficiency. Results also indicate that workforce skills training (0.23%) and technological progress (0.14%) positively impact the CEE of manufacturing firms. In addition, SI firms support the Porter hypothesis, suggesting that strict emissions regulations improve efficiency and encourage innovation. Therefore, policymakers in developing countries should implement performance-based policies through trading programs and focus on skilled labor training and technological advancements to address climate change mitigation better and promote sustainability.

1 | Introduction

The sustainability issue has become a pressing concern in recent years, impacting developed and developing nations. The abnormal climate change driven by greenhouse gas emissions (mainly carbon dioxide [CO_2] emissions) is humanity's most urgent and widely recognized sustainability issue because it involves long-term, broad, and complicated processes. The manufacturing sector faces significant climate change threats and is a significant source of CO_2 emissions. For instance, manufacturing and construction were the third-largest contributors to global CO_2 emissions in 2021, accounting for 16.82% of global CO_2 emissions (Ritchie et al. 2024). As a result, it is crucial for this industry to enhance its carbon emission performance to mitigate risks associated with emission regulations and boost "climate change competitiveness" in meeting global climate targets.

Over the past two decades, the shift of manufacturing to developing regions has led these countries to contribute 95% of global emissions growth and account for 75% of total emissions in 2023 (Rooper 2024). As the second-largest developing country by economy, India has consistently ranked as the third-largest contributor to global CO_2 emissions since 2009, following China and the United States (Debbarma et al. 2022). Thus, improving India's CEE is critical for reducing its energy consumption and related CO_2 emissions from the perspective of developing countries. India ratified the Paris Agreement in 2016, committing to reduce the emissions intensity of gross domestic product (GDP) by 33%–35% by 2030 from 2005 levels, later strengthening its target to 45% in its 2022 NDC update (United Nations 2016; United Nations Climate Change 2022). This commitment underpins sectoral policies and market instruments to support low-carbon transformation. Nevertheless, it remains unclear whether Indian manufacturing firms have voluntarily reduced emissions in line with these goals or whether the measures will lead to sustainable low-carbon development. To date, limited studies have analyzed the efficiency of the Indian manufacturing industry from a CEE perspective.

In the Indian economy, the manufacturing sector accounted for 12.8% of the national GDP as of 2023 and provided employment to more than 27.3 million individuals (World Bank Group 2023; Sharma 2024). Furthermore, India is the world's fifth-largest manufacturer today, representing 3% of global manufacturing output (World Population Review 2024). India's manufacturing sector was valued at $64.37 billion when the country joined the World Trade Organization in 1995, growing substantially to $455.77 billion by 2023 (World Bank Group 2024). However, this period of rapid manufacturing growth has also contributed to a significant increase in the country's CO_2 emissions. For instance, following the energy sectors, the manufacturing and construction sectors ranked the second-largest contributor to CO_2 emissions in 2021, with 23.28% (Ritchie et al. 2024). As such, the manufacturing sectors play a pivotal role in addressing India's sustainability challenges from a developing country's perspective. India's substantial growth in manufacturing and CO_2 emissions offers a valuable opportunity to examine the efficiency of the manufacturing sector in developing nations within the context of the Paris Agreement's climate change mitigation efforts. Additionally, to address the pressing challenges posed by China's highly competitive costs, the Indian manufacturing sector must evolve toward a more environmentally competitive structure. As a result, the performance and sustainability of India's manufacturing industry are closely tied to the country's overall economic competitiveness, making it a primary focus of this study.

Several authors have attempted to address these issues by analyzing the energy efficiency measures and productivity growth and measuring environmental efficiency in India's industries (Mukherjee 2010; Debbarma et al. 2022; Choi et al. 2020). However, no study has thoroughly evaluated the CEE of India's manufacturing firms using firm-level data despite their significant contribution to global CO_2 emissions. Although studies have explored India's emissions mitigation potential, the link between NDCs and industry and the impact of its Paris Agreement commitments on sectors (Mandal and Madheswaran 2009; Singh et al. 2019; Mahapatra et al. 2021), a comprehensive sectoral analysis, remains limited. Besides, no study has evaluated the impact of emission policy (particularly NDC) on the CEE of manufacturing firms in India, nor have they compared the policy effects on the manufacturing industry (especially comparing the trend of policy effects on manufacturing between 2016 and 2022).

This study addresses the following research questions based on the preceding discussion and in the context of the sustainability of developing countries: *What is the current state of CEE among manufacturing firms in India? Is the current Indian emission policy contextually suitable? What are the primary sources of inefficiency, and how can the efficiency of these firms be enhanced?* This study seeks to answer these questions by analyzing CEE in India's manufacturing sector. Specifically, this study examines the impact of NDCs policy on CEE in India's manufacturing firms by comparing sustainability initiatives (SI) and nonsustainability initiatives (non-SI) firms and identifying the determinants of CEE (or sources of inefficiency). In various sustainability aspects, we focus on carbon emissions, which stem from the growing concern over global climate change and the significant role CO_2 plays in this issue. To estimate the CEE at the firm level, this study applies the Slacks-Based Measure of Data Envelopment Analysis (SBM-DEA) method, which has been used in prior research (Choi et al. 2012; Zhang and Choi 2013). Furthermore, econometric models are applied to identify the influencing factors that promote CEE in manufacturing firms.

This study makes several contributions that address gaps in existing literature while providing actionable insights for real-world applications. Theoretically, this research proposes a new definition of SI from the perspective of developing countries, defining it as an "umbrella concept" that includes long-term programs aimed at reducing environmental impact while promoting broader sustainability goals.Methodologically, the study employs a two-stage SBM-DEA model with undesirable output to evaluate, decomposing it into pure carbon emission efficiency (PCEE) and scale efficiency (SE), and applies the Tobit model to study the determinants of CE. This is the first empirical comparison of CEE between SI and non-SI manufacturing firms in India, using unique firm-level data from 2012 to 2022. Moreover, this study applied the Porter hypothesis to evaluate how NDCs influence Indian manufacturing firms' CEE, addressing an underexplored area in existing research. In terms of practical contributions, this study offers policy recommendations to aid the manufacturing sectors in transitioning towards a "greener" economy. This research is particularly valuable for policymakers aiming to balance industrial productivity with environmental responsibility in a developing country context.

This paper is structured as follows: Section 2 provides an overview of the literature review. Section 3 explains the materials and methods. Section 4 discusses the empirical results and discussions. Finally, Section 5 concludes the study with policy implications.

2 | Literature Review

2.1 | Overview of SIs

In recent decades, the practice of sustainability initiatives (SI) has gained prominence and become a subject of international discussion as sustainability issues have become global issues (Lam et al. 2020; Haque and Ntim 2022). Furthermore, the recent developments in business suggest that focusing solely on economic objectives is not a sustainable strategy if a firm's activity results in environmental damage or negatively impacts societal health (Choi et al. 2020). Consequently, in today's context, firms have begun addressing societal and environmental needs by implementing innovative sustainability practices. Before delving into SI firms, it is important to understand the concept of SI itself. SI has become increasingly important in applied social sciences (Chen et al. 2025; Sondekoppam et al. 2024; Lam et al. 2020). However, due to varying research objectives, experts have interpreted the concept of SI differently.

For example, according to Chen et al. (2025), SI can enhance a company's financial performance and play a crucial role in sustaining profitability and market size. Sondekoppam et al. (2024) define that SI encompasses both "bottom-up" and "top-down" approaches. Ismail et al. (2021) viewed that companies following the international SIs are more inclined to share life cycle assessment information and to disclose more details than others to uphold their legitimacy. On the other hand, Lam et al. (2020) use the term "SI" as an umbrella concept for all. This study defines SI as an "umbrella concept" encompassing long-term programs or projects within a firm aimed at reducing environmental impact while contributing to broader sustainability goals. These initiatives go beyond reducing environmental impact; they actively contribute to responsible resource use, engage stakeholders, and integrate ethical, social, and environmental considerations into core business operations. By promoting good governance and driving sustainability transitions, these initiatives ensure a firm's long-term success and competitiveness in the market while aligning with global sustainability objectives.

Postindependence development strategies in India have consistently prioritized industrialization as a crucial tool for sustained economic growth. The Indian government introduced the national manufacturing policy in 2011 to boost the global competitiveness of India's manufacturing sector (Jain and Solanki 2021). In 2014, the Indian government launched the 'Make in India' initiative, further highlighting the significance of the manufacturing industry (Make in India 2024). The Press Information Bureau (2024a) suggests that India's economy needs to generate nearly 7.85 million new jobs annually outside of agriculture by 2030 to accommodate the rising workforce and maintain employment stability. In this context, sustainability issues are particularly relevant in India, as the developing Asian continent is expected to become a major manufacturing hub over the next two decades, creating numerous opportunities. Various research approaches have been employed to analyze SI across different fields (Ismail et al. 2021; Haque and Ntim 2022). However, no studies have explored the CEE of manufacturing firms, particularly by comparing SI and non-SI firms. In the Indian context, energy-related CO_2 emissions in the industrial sector remain underexamined.

For instance, Garg and Kashav (2020) assessed SI in Indian railways using available literature and interview data, while Rajak et al. (2022) identified stakeholders' requirements and critical success factors for the SI in the Indian supply chain during the COVID-19 pandemic outbreak using the quality function deployment and best-worst methodology. Shyna and Ranganathan (2022) examined fairness and environmental sustainability in Indian corporations based on employee feedback. These studies demonstrate the growing importance of sustainability in both developed and emerging economies. However, the current literature lacks analysis of CEE in SI and non-SI firms in India, especially using time-series data. Thus, this study addresses this gap by investigating the CEE of Indian manufacturing firms, comparing SI and non-SI firms using unique time series data from 2012 to 2022.

2.2 | Low-Carbon Emission Policies of India

Since 2009, India has ranked as the third-largest CO_2 emitter globally. In response, India has prioritized energy efficiency and emission reduction, reflected in key policies like the National Action Plan for Climate Change (NAPCC) program, launched in 2008 (Press Information Bureau 2021). Table 1 summarizes India's key emission policies. The NAPCC program emphasizes developing a low-carbon society through eight submissions, including the National Mission on Strategic Knowledge for Climate Change (NMSKCC), which fosters data sharing and research collaboration, and the Green India Mission (GIM), aimed at enhancing green cover and achieving India's NDC target of sequestering 2.5 billion tonnes of carbon emissions between 2020 and 2030 (Table 1) (Department of Science and Technology 2024). However, the NAPCC lacks formal monitoring, evaluation processes, and effective market mechanisms to overcome organizational and economic barriers. Other key policies include the National Adaptation Fund for Climate Change (NAFCC), established in 2015, which supports climate adaptation projects but lacks fixed quantitative targets (Press Information Bureau 2024b).

Under its NDC commitment to the Paris Agreement, ratified in 2016, India pledged to reduce GDP emissions intensity by 33%–35% from 2005 levels by 2030 and further strengthened this target at COP26 in 2021(The National Archives 2024). The updated 2022 NDC includes mitigating 1 billion tonnes of CO_2 equivalent by 2030 and achieving net-zero emissions by 2070 (Table 1). These goals are supported by sectoral policies, regulatory measures, and market instruments to accelerate the transition to a low-carbon economy. The Paris Agreement supports the bottom-up approach to curb emissions and limit the temperature increase. However, the effect of these policies on manufacturing remains unknown in the Indian context. Despite this paradigm shift, the changes in the manufacturing industry may not be significant enough to enhance firms' efforts in CO_2 emission reduction. Consequently, evaluating the effect of India's NDC policy becomes a crucial research question.

This study examines the differences in policy impacts on SI and non-SI firms within the manufacturing sectors between 2016 and 2022. By assessing the changes in CEE, this study seeks to offer policy recommendations to improve emission efficiency within the industry. During the study period, due to strict government regulations, India's manufacturing industry experienced significant pressure to lower CO_2 emissions. Building on Porter's hypothesis (Porter and Linde 1995), which argues that stricter emission regulations can enhance firms' efficiency by encouraging more sustainable production practices, we propose the following hypothesis:

H_0. *The emission regulations in India have had no effect on the CEE of the manufacturing sector.*

TABLE 1 | Key emission policies in India.

Policies	Objectives	Targets and achievements	Approach
NAPCC, 2008	Mitigate the adverse impact of climate change.	• Comprises eight submissions with specific targets to reduce the economy's emission intensity. • Consequently, none of the renewable energy targets were achieved.	Multifaceted approach
NMSKCC under NAPCC, 2008	Enhance India's understanding of climate change and develop strategic knowledge to inform policy and adaptation/mitigation strategies.	• Focuses on generating knowledge to address climate change challenges.	Multidimensional approach
GIM under NAPCC, 2008	Safeguarding, restoring, and expanding India's green cover to address climate change.	• Achieving India's NDC goal of sequestrating 2.5 billion tonnes of "carbon emissions" between 2020 and 2030, as pledged to the UNFCCC. • The 10-year program, with a budget of 60,000 crores, has been significantly underfunded.	Holistic and integrated cross-sectoral approach
NAFCC, 2015	Support measures to address the adverse impacts of climate change adaptation.	• Lacks fixed quantitative targets. • Implemented on a project-based approach, with 30 projects approved across 27 states and UTs to date.	Strategic and participatory approach
Climate action plans by states	Address local climate change impacts and support national climate goals.	• Climate action plans vary across states based on specific challenges and priorities.	Comprehensive and participatory approach
NDC under Paris Agreement, 2015	Reduce national emissions and adapt to climate change effects.	• Achieved a 33% to 35% reduction in GDP emissions intensity by 2030, compared to 2005 levels. • Reduced GDP emissions intensity by 33% between 2005 and 2019. • In 2022, India revised its NDC, increasing the target to a 45% reduction by 2030, relative to 2005 level.	Implementing NDCs varies by country

2.3 | Methodological Approaches to Measuring CEE in Manufacturing

The concept of CEE highlights an economy's ability to transition to a less-carbon-intensive model without compromising production levels. In other words, CEE refers to the effectiveness with which an entity, such as a company, industry, or country, produces goods and services with the minimum possible carbon emissions compared to industry peers (Trinks et al. 2020). In this context, this study defines CEE as the degree to which a certain level of manufacturing output is produced while minimizing CO_2 emissions relative to direct sector peers. The fewer carbon emissions generated per unit of manufacturing output, the higher the level of CEE. Numerous studies have used the DEA method to assess the efficiency of manufacturing sectors by considering multiple inputs and outputs while also assessing efficiency changes when undesirable outputs are present at various levels (Yi et al. 2020; Im and Cho 2021; Cui and Chu 2023).

The traditional DEA method may overlook slack variables, potentially overestimating efficiency when nonzero slacks exist (Yi et al. 2020). To address this, the nonradial Slacks-Based Measure of Data Envelopment Analysis (SBM-DEA) has become popular, as it better captures inefficiencies by considering both input and output slacks (Debbarma et al. 2021). This approach is especially useful for analyzing reductions in undesirable outputs like CO_2 emissions. For example, Yi et al. (2020) applied the SBM-DEA model to assess the green innovation efficiency of panel data from 11 provinces and cities in China, using R&D personnel and R&D expenditure as inputs and Patents, sales revenue, and industrial environmental pollution as desirable and undesirable outputs, respectively. Similarly, Cui and Chu (2023) utilized the SBM model and Malmquist–Luenberger (ML) index model to measure the CEE in China's pharmaceutical manufacturing industry, considering asset investment, number of employees, and energy consumption as inputs and economic benefit and carbon dioxide as the desirable and undesirable outputs.

In India, efficiency analysis, particularly in the context of CEE, has been underexplored, and the application of DEA models is limited. Previous studies, such as Darji and Dahiya (2023), applied a DEA approach to examine the operational efficiency of textile manufacturing in the Indian state. Vijayalalitha et al. (2021) employed the Malmquist Productivity Index based on DEA to evaluate the total factor productivity performance of Indian manufacturing industries. However, studies using the SBM-DEA model to analyze CEE in Indian manufacturing firms are limited. Given India's status as the second-largest emerging economy after China and the third-largest emitter of CO_2, India warrants such an analysis. This study addresses this research gap by utilizing the SBM-DEA model, which incorporates undesirable output, to evaluate the CEE of India's manufacturing sector with firm-level data from 2012 to 2022. In addition, the study aims to assess the CEE of SI and non-SI firms within the framework of India's NDC policy under the Paris Agreement. To better understand the determinants of CEE (or sources of inefficiency) of manufacturing, the SBM-DEA model is further decomposed into two components: PCEE and SE. To calculate CEE using the SBM-DEA model, this study chose capital, employee, and energy as the relevant input variables, along with one desirable output variable—total income—and one undesirable output variable—CO_2 emissions (Table 2).

3 | Materials and Methods

3.1 | The SBM-DEA Model With Undesirable Output

In this paper, we apply the SBM-DEA model to calculate the CEE of manufacturing firms in India for the period 2012 to 2022. Unlike traditional radial efficiency measures that focus on proportional input and output adjustments, the SBM-DEA addresses input excess and output shortfalls (slack variables) (Choi et al. 2012; Yi et al. 2020; Streimikis et al. 2021). This SBM-DEA approach is effective for examining the reduction of undesirable outputs, such as CO_2 emissions (Lozano and Gutiérrez 2011; Zheng and Luo 2023; Cui and Chu 2023). As illustrated in Figure 1, the SBM model moves observations toward the most efficient point on the frontier, aiming to minimize the slack (Choi et al. 2012). The piecewise linear frontier in the figure represents the combinations of carbon emission and other inputs, with points on the frontier being technically efficient. Traditional radial efficiency measures would adjust point 'a' to point 'd' along the origin. However, SBM-DEA projects observations to the "furthest point" on the efficient frontier, such as point 'b'. While point 'b' may not reduce emissions as effectively as point 'd,' the emission slack (ES) is represented by 'ab', indicating the potential reduction from real carbon emission (RCE) to the target carbon emission (TCE). The SBM-DEA CEE is calculated by the ratio bk/ak (Zhang and Choi 2013).

We define efficiency as the ability to produce more output with fewer inputs. When undesirable outputs are present, efficient technologies generate more desirable outputs and fewer undesirable ones with minimal input usage (Chang et al. 2013). Consider that there are $n=1, \ldots, N$, manufacturing firms in India, where each firm operates with three key indicators—inputs, desirable outputs, and undesirable outputs. Each firm utilizes m input factors to produce $s1$ desirable outputs and $s2$ undesirable outputs, respectively. In this study, the input indicator consists of capital, employee, and energy, with total income representing the desirable output and CO_2 emissions as the undesirable output. Denoting these inputs, desirable output, and undesirable output by the metrics X, Y, and C respectively, the vectors can be defined as follows: $X=[x_{ij}]=[x_1, \ldots, x_n] \in R^{m\times n}$, $Y=[y_{ij}]=[y_1, \ldots, y_n] \in R^{s_1\times n}$, and $C=[C_{ij}]=[C_1, \ldots, C_n] \in R^{s_2\times n}$, where X, Y, and C are greater than 0. The multi-output production possibility set (PPS) can be described in Equation (1) as follows (Tone 2001; Chang et al. 2013):

$$P(x)=\{(Y,C)\,|\,x \text{ produce } (Y,C), \quad x \geq X\lambda, y \leq Y\lambda, C \geq C\lambda, \lambda \geq 0\} \tag{1}$$

where λ is the nonnegative multiplier vector, signifying the condition of constant returns to scale. Building on this PPS, Tone (2001) introduced the concept of SBM efficiency, a nonradial and nonoriented approach, defined in Equation (2), as follows (Zhang and Choi 2013; Sharma and Majumdar 2021):

$$p^* = \min \frac{1-\left(\frac{1}{m}\right)\sum_{i=1}^{m}\left(\frac{s_{i0}^-}{x_{i0}}\right)}{1+\left(\frac{1}{s_1}\right)\sum_{r_1=1}^{s_1}\left(\frac{s_{r_1 0}^y}{y_{r_1 0}}\right)} \quad \text{s. t.} \begin{cases} x_0 = X\lambda + s_0^- \\ y_0 = Y\lambda - s_0^y \\ s_0^- \geq 0, s_0^y \geq 0, \lambda \geq 0 \end{cases} \tag{2}$$

In Tone's original SBM-DEA model, undesirable outputs were not considered (Tone 2001). By extending Tone's SBM model and incorporating undesirable outputs into both the objective function and a separate constraint function, the SBM-DEA model with undesirable output can be expressed in Equation (3) as (Cooper et al. 2007; Sharma and Majumdar 2021):

$$\emptyset^* = min \frac{1-\left(\frac{1}{m}\right)\sum_{i=1}^{m}\left(\frac{s_{i0}^-}{x_{i0}}\right)}{1+\left(\frac{1}{s_1+s_2}\right)\left(\sum_{r_1=1}^{s_1}\left(\frac{s_{r_1 0}^y}{y_{r_1 0}}\right)+\sum_{r_2=1}^{s_2}\left(\frac{s_{r_2 0}^c}{C_{r_2 0}}\right)\right)} \quad \text{s. t.} \begin{cases} x_0 = X\lambda + s_0^- \\ y_0 = Y\lambda - s_0^y \\ c_0 = C\lambda + s_0^c \\ s_0^- \geq 0, s_0^y \geq 0, s_0^c \geq 0, \lambda \geq 0 \end{cases} \tag{3}$$

$i=1,2, \ldots, m$ represents the index of inputs.

$m=$ denotes the number of inputs.

$r_1=1,2, \ldots, s_1$ is the index for desirable (good) outputs.

$r_2=1,2, \ldots, s_2$ is the index of undesirable (bad) outputs.

s_1 is the number of desirable (good) outputs.

s_2 is the number of undesirable (bad) outputs.

s_0^- represents the overuse (or excesses) of inputs.

s_0^y is the shortage of desirable (good) outputs.

s_0^c indicates the overuse (or excesses) of undesirable outputs.

The subscript "0" refers to the decision-making unit (DMU) being evaluated for efficiency in this model.

λ is the nonnegative multiplier vector for constructing the PPS in a linear programming model.

Equation (3) represents a nonradial, nonoriented slacked-based measurement. A DMU is considered efficient when undesirable outputs are present if $\emptyset^*=1$, which indicates that all slack variables are 0, $(s_0^-=0, s^y=0, s^c=0)$. However, the

TABLE 2 | The application of DEA and econometric models in the manufacturing sector.

Author(s) and year	Field of research application	DEA methods		Econometric model	
		Variables	Models	Variables	Models
Cui and Chu (2023)	Pharmaceutical manufacturing industry in 30 provinces of China	Input: Asset investment, number of employees, and energy consumption Output: Economic benefit and carbon dioxide	SBM and Malmquis-Leuenberger index	Dependent: CEE Independent: Foreign investment, industrial agglomeration and intensity of environmental regulation, economic energy consumption and scientific and technological innovation.	Tobit model
Zheng and Luo (2023)	High-end equipment manufacturing industry	Input: Operating cost, net fixed assets, payroll payable to employees and R&D amount Output: Operating income and number of patent applications	Super-efficiency SBM model	Dependent: Operating efficiency Explanatory: Government subsidies	Tobit model
Meiryani et al. (2022)	Manufacturing companies in Indonesia (consumer goods sector)	Input: Capital, labor and salaries and wages Output: Revenue and return on equity	Two-stage DEA	Dependent: Technical efficiency Independent: Capital, labor, wage, revenue, return on equity and average salaries	Tobit model
Erena et al. (2021)	43 sub-sectors (large and medium manufacturing industries) in Ethiopia	Input: Fixed assets, number of employees, and cost of raw materials Output: Value-added, operating surplus and total sales.	DEA output-orientation (CCR & BCC)	Dependent: Technical efficiency score Independent: Capital expenditure, capital intensity, account-book ratio, skill intensity, industry size and advertising expense	Tobit model

(Continues)

TABLE 2 | (Continued)

Author(s) and year	Field of research application	DEA methods		Econometric model	
		Variables	Models	Variables	Models
Im and Cho (2021)	SMEs in the manufacturing and service industries in South Korea	Input: R&D personnel ratio, R&D headcount, total R&D costs and other innovation activity costs Output: Revenue and number of patent applications.	DEA	Dependent: Results of the CCR and BCC models Independent: Operation of an R&D department, external cooperation for technological innovation, external funding for technological innovation and implementation of organizational innovation.	Tobit model
Yi et al. (2020)	Manufacturing industry of the Yangtze River Economic Belt	Input: R&D personnel and R&D expenditure Output: Patents, sales revenue, and industrial environmental pollution	SBM-DEA	Dependent: Technical efficiency Explanatory: Government R&D subsidies and environmental regulation	Panel Tobit model
Zhou et al. (2019)	Manufacturing, agriculture, mining, Electricity/Gas/water production and supply, and transportation industry	Input: Capital, labor, and energy consumption Output: Industrial economic output and CO_2 emissions	Super-SBM-DEA	Dependent: Technological progress and CEE Explanatory: Economic scale, energy consumption structure, and oil prices.	Global Vector autoregressive
Sabli et al. (2019)	Plastic manufacturing firm in Malaysia	Input: Capital, laborers, and intermediate inputs Output: Total sales.	DEA	Dependent: Efficiency scores Explanatory: Capital-labour, information and communication technology expenditure, wages rate, R&D, training expenses, and firm size	Tobit model

(Continues)

TABLE 2 | (Continued)

Author(s) and year	Field of research application	DEA methods		Econometric model	
		Variables	Models	Variables	Models
Lin et al. (2018)	12 listed tourist equipment manufacturing companies	Input: R and D personnel, R and D expenditure Output: Number of patent applications, profit ratio of sales and total labor productivity.	DEA–Malmquist	Dependent: Malmquist index and its decompositions Independent: Government ownership, cooperation with academics, and cooperation with international corporations.	Tobit model
Ghondaghsaz et al. (2018)	17 manufacturing firms	Input: Cost of goods sold, fixed assets, and products spoiled. Output: Sales and market share.	DEA	Dependent: Efficiency scores Independent: Outsourcing, location of office, years of incorporation, experience of staff.	Bootstrapped Tobit model
Charoenrat and Harvie (2017)	Thai manufacturing SMEs	Input: Labour and capital Output: Output value added.	DEA	Dependent: Technical inefficiency scores Explanatory: Firm age and skilled labour	Two-limit Tobit model
Wang et al. (2016)	29 manufacturing industries in China	Input: Capital, labor, energy consumption, and technology Output: Gross industrial output value and total volume of industrial waste gas emission.	SBM-DEA	Dependent: Efficiency scores Independent: Industry scale, the openness degree and the energy structure.	Tobit model
Mujaddad and Ahmad (2016)	65 large scale manufacturing industries of Pakistan	Input: Capital, labour, industrial cost and nonindustrial cost Output: Contribution to GDP.	DEA double bootstrap	Dependent: Bias corrected efficiencies scores Independent: Average wage, size, and market size	Bootstrapped truncated regression model
Rezitis and Kalantzi (2016)	Greek food and beverages manufacturing industry	Input: Gross capital stock and man-hours worked Output: Output.	DEA	Dependent: Technical efficiency scores Explanatory: Sector size, capital productivity, labor productivity, labor intensity, capital intensity and growth	Bootstrapped truncated regressions and OLS regressions

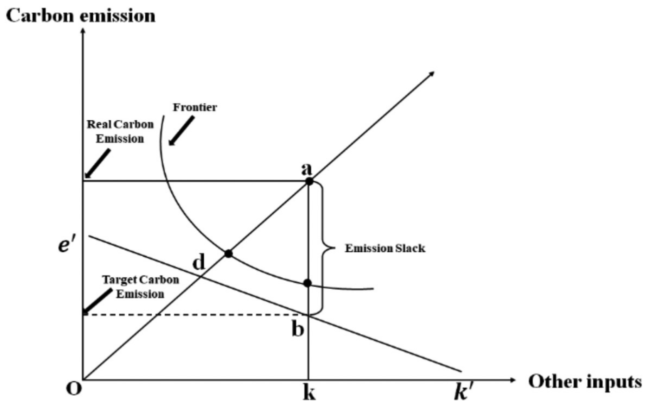

FIGURE 1 | Graphical illustration of radial efficiency vs nonradial SBM efficiency.

object Equation (3) is nonlinear. To achieve CEE, meaning the reduction of CO_2 emissions at the firm level within India's manufacturing sectors, the firm must reduce excess inputs and undesirable output while simultaneously addressing any shortfalls in desirable output. By applying Tone's transformation in Equation (3) and incorporating undesirable output into both the objective and constraint functions, an equivalent linear programming (LP) for t, φ, S^y, and S^c can be derived, as shown in Equation (4) as follows (Tone 2001; Choi et al. 2012):

$$
\begin{aligned}
r^* &= \min \quad t - \frac{1}{m}\sum_{i=1}^{m}\frac{s_{i0}^-}{x_{i0}} \\
1 &= t + \frac{1}{s_1+s_2}\left(\sum_{r_1=1}^{s_1}\frac{s_{r_10}^y}{y_{r_10}} + \sum_{r_2=1}^{s_2}\frac{s_{r_20}^c}{c_{r_20}}\right) \\
\text{S.T.} &\begin{cases} x_0 t = X\varphi + s_0^- \\ y_0 t = Y\varphi - s_0^y \\ C_0 t = C\varphi + s_0^c \\ s_0^- \ge 0, s_0^y \ge 0, s_0^c \ge 0, \varphi \ge 0, t > 0. \end{cases}
\end{aligned} \tag{4}
$$

The optimal solution for the linear programming model Equation (4) can be derived and is denoted as $(t^*, \varphi^*, S^{-*}, S^{y*}, S^{c*})$, where $p^* = t^*, \lambda^* = \frac{\varphi^*}{t^*}$, $s^{-*} = \frac{S^{-*}}{t^*}$, $s^{y*} = \frac{S^{y*}}{t^*}$, $s^{c*} = \frac{S^{c*}}{t^*}$ as described in Equation (3). The solution of $(t^*, \varphi^*, S^-, S^y, S^c)$ can be guaranteed by Equation (4) with $t^* > 0$. A similar approach for solving the SBM-DEA model with undesirable outputs has been detailed in the works of Zhou et al. (2006) and Lozano and Gutiérrez (2011). Meanwhile, the CEE of each manufacturing firm can be estimated by the ratio of TCE to RCE in Equation (5) as follows (Choi et al. 2012; Chang et al. 2013):

$$
\text{CEE} = \left(\frac{\text{TCE}}{\text{RCE}}\right) = \frac{(RCE - ES)}{RCE} = 1 - \frac{ES}{REI} \tag{5}
$$

where TCE is the target carbon emission, RCE is the real carbon emission, and ES is the emission slack. The concept of the “target-to-real ratio” was first introduced by Hu and Wang (2006) to measure energy efficiency and was later expanded by Zhou and Ang (2008) to include undesirable outputs of energy efficiency analysis. After estimating the emission slack using Equation (5), the CEE for each manufacturing firm is calculated. A notable strength of the SBM model used in this study is its capability to assess the efficiency of specific inputs and emissions, producing distinct results. By setting $\lambda = 1, P(x)$, it can be formulated using variable returns to scale (VRS) technology, as introduced by Banker et al. (1984). When calculating CEE under VRS technology, a PCEE score is obtained. Following the method outlined by Wei et al. (2011), total CEE from Equation (5) can be decomposed into PCEE and SE, as shown in Equation (6).

$$
\text{CEE} = \text{PCEE} \times \text{SE} \tag{6}
$$

Equation (6) helps distinguish whether inefficiency arises from inefficient operation and management, disadvantageous scale conditions, or a combination of both (Wei et al. 2011). A scale efficiency score of 1 signifies that a firm is operating at its optimal productive scale (i.e., most productive scale size) (Cooper et al. 2007).

Previous studies have used the Tobit model and other regression models to explore the factors influencing CEE in manufacturing firms and provide targeted policy insights (Table 2). For instance, Cui and Chu (2023) applied the SBM and ML index models to measure the CEE of the pharmaceutical manufacturing industry, then used a Tobit model to analyze its influencing factors. Similarly, Wang et al. (2016) employed a two-stage DEA and Tobit model to assess the environmental efficiency and its determinants across 29 manufacturing industries in China. Building on this, the current study uses an econometric model to identify the key factors influencing CEE.

3.2 | Input and Output Variables

To analyze the changes in CEE within Indian manufacturing industries, panel data were collected from 104 manufacturing firms (including SI and non-SI) in India over the period from 2012 to 2022. The dataset includes 43 SI firms and 61 non-SI firms, selected based on the consistency and availability of their data. The manufacturing sector was chosen for this study because it contributed 14.14% of the industry's GDP to the Indian economy in 2022 and was also ranked as the second-largest source of CO_2 emissions in 2021, with 23.28% (Ministry of Statistics and Programme Implementation 2024). The input variables consist of capital, employees, and energy, while the output variables consist of total income (desirable) and CO_2 emissions (undesirable). All data were sourced from the annual reports of Indian manufacturing companies, which are available on their respective websites (Debbarma et al. 2022). These reports offer detailed information on both input and output variables.

For capital input, data on total fixed assets were extracted from each company's annual reports from 2012 to 2022. Employee input was measured by the number of employees per head of the company. Regarding energy input and CO_2 emissions data, we have gathered data from power and fuel consumption rates (mainly electricity) of the company's annual reports at the macro level for both SI and non-SI companies, in accordance with the International Panel on Climate Change guidelines (Choi et al. 2020; Debbarma et al. 2022). Since companies do not provide standardized CO_2 emissions data in their annual reports, we

TABLE 3 | Descriptive statistics of the input and output variables.

Variables	Observation	Inputs/ outputs	Unit	Mean	Std. deviation	Minimum	Maximum
Full sample							
Capital	1144	Input	Million ₹	59546.62	284862.65	3.87	3396680.00
Employee	1144	Input	Person	4931.09	8792.03	6.00	71826.00
Energy	1144	Input	KWH	276751501.22	823009280.14	99354.00	8732303240.74
Total income	1144	Desirable Output	Million ₹	157312.00	647792.76	337.80	7327842.00
CO_2 emissions	1144	Undesirable Output	$kgCO_2e$	57346064.90	170416006.85	20573.23	1808198032.06
SI firms							
Capital	473	Input	Million ₹	133543.43	432385.21	3.87	3396680.00
Employee	473	Input	Person	6645.76	8581.81	6.00	34084.00
Energy	473	Input	KWH	531972683.15	1219352068.47	216000.00	8732303240.74
Total income	473	Desirable Output	Million ₹	350760.55	975294.05	337.80	7327842.00
CO_2 emissions	473	Undesirable Output	$kgCO_2e$	110250227.24	252463973.59	44727.12	1808198032.06
Non-SI firms							
Capital	671	Input	Million ₹	7384.92	11680.61	142.32	72038.80
Employee	671	Input	Person	3722.39	8743.53	77.00	71826.00
Energy	671	Input	KWH	96841487.73	172327551.90	99354.00	874880382.78
Total income	671	Desirable Output	Million ₹	20946.64	27298.41	496.25	169979.60
CO_2 emissions	671	Undesirable Output	$kgCO_2e$	20052966.86	35683866.17	20573.23	181161480.86

estimated CO_2 emissions by converting electricity consumption (measured in kWh) into $kgCO_2e$ using the following formula: CO_2e emissions (kg) = Electricity consumed (kWh) × Emission factor ($kgCO_2e$/kWh). The total income output was gathered based on the income generated by the companies' operations. As this study seeks to compare the CEE between SI and non-SI manufacturing firms in India, firms have been classified into these two categories accordingly.

In this study, we acknowledge that the SI firm actively engages in efforts to reduce its negative environmental and social impacts while enhancing its positive contributions to sustainability. On the other hand, a non-SI firm is a firm that does not prioritize sustainability considerations in its operations, products, or services. However, while many companies recognize sustainability as a unique competitive opportunity, not all effectively tackle the related opportunities and challenges. Some of these companies may focus more on short-term financial gains at the expense of long-term environmental and social sustainability. To classify companies, we analyzed their websites and reports. Companies with a dedicated section for sustainability or SIs in their reports or highlighting such efforts on their websites were categorized as SI firms. Those without such emphasis were classified as non-SI firms. These two groups may respond differently to government emission policies on emission reduction, which could result in more tailored insights and recommendations. Therefore, it is critical to assess the performance of both groups in terms of sustainability.

Table 3 provides the descriptive statistics of the sampled data, indicating considerable variation in input and output variables across the firms. Thus, evaluating whether larger input levels have a more significant impact on CEE is essential. A correlation matrix of the inputs and output variables is calculated to examine any significant relationship between these variables from 2012 to 2022. The results, presented in Table 4, reveal a positive correlation between inputs and output—meaning that as inputs increase or decrease, the corresponding outputs tend to follow suit. Given that capital and employees are critical factors in production, they are positively correlated with total income. Notably, there is a strong correlation between capital and total income (0.819**). Capital and energy consumption also show a significant relationship (0.562**), indicating that investment in energy-efficient technologies can influence a firm's energy use and improve efficiency (Debbarma et al. 2022). Moreover, the total income and CO_2 emissions are positively associated with

TABLE 4 | Correlation matrix of inputs and outputs.

Variables	Capital	Employee	Energy	Total income	CO_2 emissions
Capital	1.00				
Employee	0.375**	1.00			
Energy	0.562**	0.487**	1.00		
Total income	0.81**9	0.409**	0.694**	1.00	
CO_2 emissions	0.562**	0.487**	1.000**	0.693**	1.00

**Correlation is significant at the 0.01 level (2-tailed).

energy, with the relationship between energy and CO_2 emissions (1.000**) being particularly significant. These results underscore the relevance of analyzing data from a sustainability perspective, confirming that a CEE analysis in this context is appropriate.

4 | Empirical Results and Discussions

4.1 | Carbon Emission Efficiency Results

The SBM-DEA model is employed to assess the changes in the CEE of 104 manufacturing firms in India. As discussed in previous sections, we classified sample firms into two groups—SI firms and non-SI firms—and compared their CEE. Table 5 provides an empirical comparison of the average CEE and its decomposition for both SI and non-SI firms over a period of 11 consecutive years (2012–2022). The CEE index lies between zero and unity, with higher values indicating better emission efficiency. A firm with an index value of unity is considered to have optimal emission efficiency, operating on the production technology frontier.

The result of the average CEE reveals that most manufacturing firms, both in the SI and non-SI groups, are not operating in a carbon emission-efficient manner. This is largely due to their heavy reliance on their carbon-intensive energy resources in the production process. For example, in 2022, CEE scores ranged from 0.252 to 1 (Appendix 1), with the average scores for SI and non-SI firms being approximately 0.573 and 0.540, respectively. This suggests that SI firms could potentially reduce their carbon emissions by 42.7%, while non-SI firms could achieve a 46% reduction if they operated at optimal efficiency. These results indicate that neither group has yet reached an efficient emission regime, presenting significant opportunities for further emission reductions.

To assess the impact of India's NDC policy shift on CEE, especially between 2016 (when India ratified the Paris Agreement) and 2022 (when it updated its NDC), the study analyzed dynamic trends in CEE performance for SI and non-SI firms. The trends offer valuable insights for policymakers and businesses when negotiating carbon reduction targets with different groups. Figure 2 illustrates changes in CEE for SI and non-SI firms from 2012 to 2022 based on SBM-DEA calculations. SI firms showed a consistent upward trend in CEE, particularly after 2016, when India's first NDC commitment under the Paris Agreement introduced ambitious CO_2 reduction targets. Initially, SI firms had lower efficiency scores than non-SI firms in 2012, but by 2017, they surpassed non-SI firms, achieving the highest average efficiency by 2022. This improvement aligns with the Porter hypothesis, which suggests that stringent emission regulations drive innovation and efficiency, leading to more sustainable production practices (Porter and Linde 1995).

TABLE 5 | Comparison of average SBM-DEA and its decomposition.

	SI			Non-SI		
Year	SBM	PCEE	SE	SBM	PCEE	SE
2012	0.491	0.587	0.875	0.530	0.567	0.930
2013	0.467	0.549	0.892	0.529	0.566	0.929
2014	0.502	0.573	0.901	0.521	0.558	0.927
2015	0.498	0.583	0.884	0.513	0.555	0.918
2016	0.502	0.595	0.878	0.502	0.552	0.908
2017	0.502	0.586	0.883	0.502	0.557	0.904
2018	0.506	0.597	0.872	0.518	0.585	0.895
2019	0.528	0.600	0.898	0.517	0.601	0.880
2020	0.524	0.589	0.905	0.514	0.593	0.882
2021	0.522	0.576	0.925	0.523	0.600	0.888
2022	0.573	0.638	0.911	0.540	0.619	0.888
Average	0.510	0.588	0.893	0.519	0.578	0.904

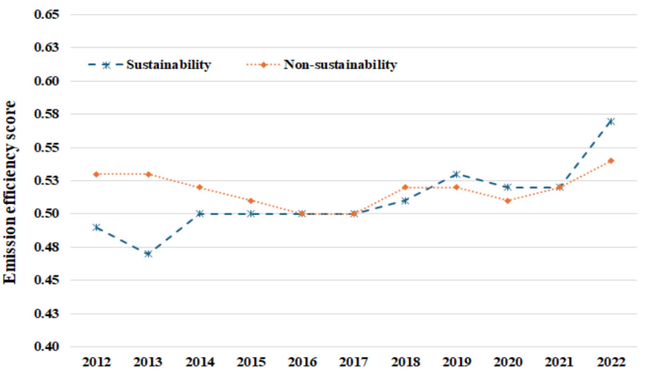

FIGURE 2 | Changes in the CEE of SI and non-SI firms.

In contrast, non-SI firms experienced slower and more inconsistent growth in CEE. From 2012 to 2016, non-SI firms performed better, but they faced a decline between 2016 and 2017, likely due to weaker responses to the NDC policy. Despite growing recognition of sustainable practices, Indian manufacturing firms face challenges such as inconsistent emission measurement guidelines, lack of national benchmarks, and limited managerial innovation (Debbarma et al. 2021). The non-SI firm should learn from SI firms by investing in SIs and practices to reduce its negative environmental and social impacts while enhancing its positive contributions to sustainability. Besides, policymakers should promote uniform progress through measures such as standardized emission guidelines, national benchmarking systems, and incentives for managerial innovation.

As mentioned earlier, we decomposed the SBM-DEA into two indices—PCEE and SE—to analyze the determinants of CEE (or sources of inefficiency) (Table 5 and Appendices 2 and 3). The PCEE is derived using VRS technology, while SE is determined as the ratio of CEE under CRS to that under VRS technology. On average, the SI group showed a higher PCEE index over the study period, indicating that their operational and management improvements contributed to better CEE. For instance, as of 2022, the average PCEE index for CEE among SI firms was 0.59, while non-SI firms showed an average PCEE value of 0.58, which is slightly lower than that of SI firms. Meanwhile, the average annual scale condition of SI is 0.893, while the SE of non-SI is 0.904. While SI firms' overall score is slightly lower than non-SI, their SE index shows a clear upward trend over the study period, suggesting that their scale condition performance has improved. On the contrary, the SE index for non-SI firms shows a downward trend, indicating a decline in their scale condition performance. Figures 3 and 4 show the trends in the PCEE index and SE index of the SBM-DEA model for both SI and non-SI firms between 2012 and 2022.

The average SE values for both SI and non-SI firms were higher than their respective PCEE values, suggesting that the main source of inefficiency is pure carbon emission inefficiency rather than scale inefficiency, with both groups exhibiting a significant degree of pure inefficiency. In other words, SE has been the main contributor to CEE, suggesting that SE had a more significant impact on improving CEE in Indian manufacturing firms. These findings align with those of Wei et al. (2011) and show that SE is a key driver of emission efficiency. To assess any significant differences

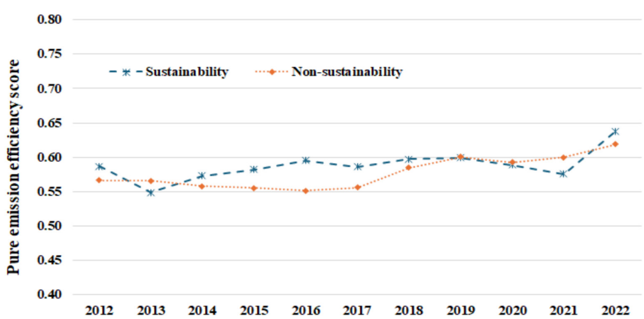

FIGURE 3 | Trends in the PEE of SI and non-SI firms.

between SI and non-SI firms in terms of SBM-DEA and its decompositions, the Wilcoxon-Mann–Whitney rank-sum test and Kolmogorov–Smirnov test were applied (Debbarma et al. 2022). As presented in Table 6, at a 95% confidence level, the null hypothesis is retained for SBM-DEA, PCEE, and SE, suggesting that these metrics are distributed similarly across both groups of Indian manufacturing firms. Both the SI and non-SI firms are mainly driven by SE, reflecting the importance of scale conditions. The kernel density plot in Figure 5 further supports the absence of any difference in the CEE and its decomposition distribution patterns between SI and non-SI firms.

4.2 | Factors Influencing Carbon Emission Efficiency of Manufacturing Firms

To better understand the factors influencing the CEE in manufacturing firms and offer more targeted policy implications, a third stage of evaluation is necessary to identify which aspects of SE influence CEE. Understanding these determinants is essential for gaining insights into the significant factors that affect the

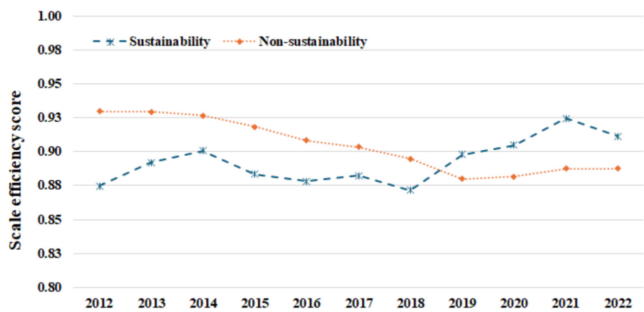

FIGURE 4 | Trends in the SE of SI and non-SI firms.

TABLE 6 | Nonparametric statistical test for SI and non-SI firms.

Test	Null hypothesis (Ho)	Statistics	*p*-value
Mann–Whitney U	SBM-DEA of SI = SBM- DEA of non-SI	1304.000	0.961
	PCEE of SI = PCEE of non- SI	1282.000	0.846
	SE of SI = SE of non- SI	1382.000	0.629
Kolmogorov–Smirnov	SBM-DEA of SI = SBM- DEA of non- SI	1.097	0.180
	PCEE of SI = PCEE of non- SI	0.988	0.283
	SE of SI = SE of non- SI	0.580	0.889

Note: The significance level is 0.05.

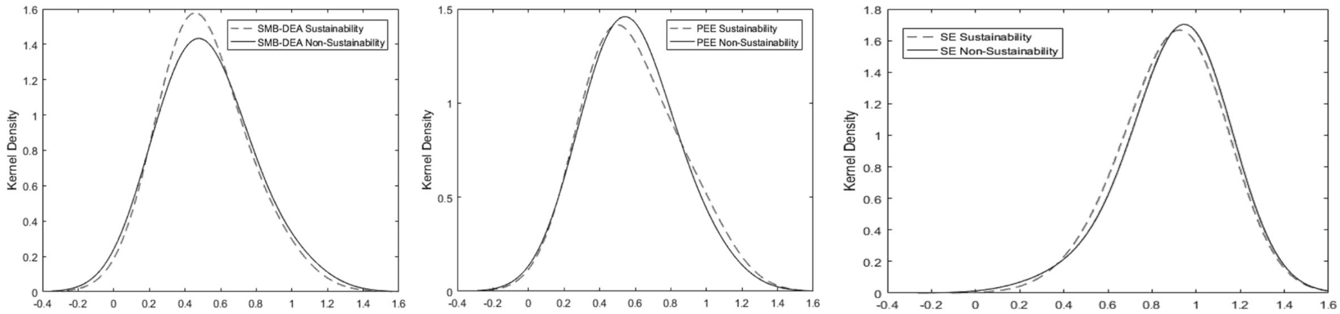

FIGURE 5 | Kernel density estimations for SI and non-SI firms.

long-term efficiency of manufacturing firms, which is crucial for sustainable development (He et al. 2018; Im and Cho 2021; Cui and Chu 2023). Further exploring the influencing factors is conducive to taking corresponding measures to improve the CEE. This analysis will also aid policymakers and businesses in determining the necessary actions to enhance scale conditions and combat climate change. An econometric model is used to identify the key factors influencing SE that contribute to CEE.

4.2.1 | Explanatory Variables

SE has been described using various factors such as labor productivity (LP), enterprise scale (ROA), technological progress (R&D), production planning and capacity management (PPCM), quality control and standardization (QCS), and workforce skills and training (WST), as highlighted in previous studies (Rezitis and Kalantzi 2016; Zhang et al. 2020; Zhou et al. 2019; Liu et al. 2012; Tayo Tene et al. 2021; Sabli et al. 2019). Reusing variables such as capital, employee, energy, total income, and CO_2 emission in the third stage of analysis may lead to significant estimation issues. Labor productivity, measured by the ratio of total income to the number of permanent employees, is a critical determinant of firm performance (Rezitis and Kalantzi 2016). Larger enterprises often invest in R&D, driving technological upgrades and resource efficiency (Zhang et al. 2020). However, overreliance on existing advantages can reduce innovation motivation, and internal conflicts may hinder progress. In this study, the total income and fixed assets ratio in a manufacturing industry represents the enterprise scale. Technological progress, driven by R&D expenditure, is widely regarded as a key factor in enhancing firm performance (Zhou et al. 2019).

Effective PPCM improves scale efficiency by optimizing resource allocation and maximizing production capacity, reducing waste and costs (Liu et al. 2012). Inventory from annual reports serves as an indicator of PPCM. QCS, measured by the International Organization for Standardization (ISO) certification, prevents nonconforming products, and enhances efficiency (Tayo Tene et al. 2021). Finally, WST drives innovation and regulatory compliance (Sabli et al. 2019). WST is quantified as 1 if the company provides training to employees and 0 otherwise. This information is obtained from the company's annual report. These six explanatory variables are used in the Tobit model for the third stage of analysis, with CEE scores from the first stage as the dependent variable. Data were collected from 104 firms' annual reports, and Table 7 provides the descriptive statistics for these variables. This study will not

TABLE 7 | Descriptive statistics for explanatory variables in manufacturing firms.

Explanatory variables	Unit	Mean
Labor productivity	The ratio of total income to the number of employees	43.66
Enterprise scale	The ratio of total income to the fixed assets (in Million ₹)	107.21
Technological progress	1 if the firm have invested in R&D, 0 otherwise	0.83
Production planning and capacity management	Million ₹	29464.34
Quality control and standardization	1 if the firm is certified with ISO standards, 0 otherwise	0.74
Workforce skills and training	1 if the firm provides training to the employees, 0 otherwise	0.98

categorize the manufacturing firms into two groups (between SI and non-SI firms) for the third stage of analysis. Instead, the data description and regression analysis will focus on overall manufacturing firms collectively, as the statistical test indicates no significant differences in their distribution between SI and non-SI firms.

4.2.2 | Econometric Model

To select the most appropriate model specification for analyzing the factors influencing SE in promoting CEE within manufacturing firms, two models were evaluated: (a) the ordinary least squares (OLS) model and (b) the Tobit model. The OLS regression model is expressed, as shown in Equation (7) as follows (Debbarma et al. 2022):

$$CEE = CONST + \gamma_1(LP) + \gamma_2(ES) + \gamma_3(R\&D) + \gamma_4(PPCM) + \gamma_5(QCS) + \gamma_6(WST) \quad (7)$$

TABLE 8 | Comparison of empirical results of OLS and Tobit models.

Dependent variable: CEE scores from the first stage of the SBM-DEA				
	OLS		Tobit model	
Explanatory variables	**Coefficient**	***t*-Statistics**	**Coefficient**	***t*-Statistics**
Labor productivity	0.0007866	4.07	0.000783	4.08
Enterprise scale (ROA)	−0.0000725	−1.61	−0.0000732	−1.64
Technological progress (R&D)	0.1413511	2.83	0.1444301	2.91
Production planning and capacity management	0.000000211	1.23	0.00000021	1.24
Quality control and standardization	−0.1446958	−3.27	−0.1470842	−3.34
Workforce skills and training	0.231306	1.86	0.2354262	1.91
_cons	0.2570009	2.02	0.2539567	2.01
Industry fixed effects	Yes		Yes	
SI/non-SI fixed effects	Yes		Yes	
Year fixed effects	Yes		Yes	
Year of observation	2022		2022	

where CEE is the dependent variable and the independent variables represent SE, including LP, ROA, R&D, PPCM, QCS, and WST. However, the Tobit model is more appropriate for analyzing CEE because the efficiency scores derived from the SBM-DEA model range between 0 and 1, making traditional OLS estimation unsuitable (Debbarma et al. 2021). Besides, the Tobit regression model has been widely used in research on efficiency and productivity analysis (Cui and Chu 2023; Debbarma et al. 2022), which provides an important reference for this study. Therefore, we define the econometric model in Equation (8), based on the Tobit regression model as follows:

$$Y_{it} = \beta^T x_{it} + \varepsilon_{it} \ \ (i = 1, \ldots, N; t = 1, \ldots, T)$$
$$\text{while} \begin{Bmatrix} \beta^T x_{it} + \varepsilon_{it} > 0 \\ 0 \ otherwise \end{Bmatrix} \tag{8}$$

Here, Y_{it} is the dependent variable, x_{it} is the explanatory variable, β^T is the vector of regression coefficients, and ε_{it} is the stochastic error term, assumed to follow a normal distribution, N (0, σ^2). The Tobit model, as expressed in Equation (9), is used to analyze the factors influencing CEE in the manufacturing sectors (Debbarma et al. 2022):

$$CEE_{it} = \beta_0 + \beta_1 LP_{it} + \beta_2 ES_{it} + \beta_3 R\&D_{it} + \beta_4 PPCM_{it} + \beta_5 QCS_{it} + \beta_6 WST_{it} + \varepsilon_{it} \tag{9}$$

where CEE represents the dependent variable (CEE measure of sample firms) and the subscripts *i* and *t* refer to the i^{th} firms in the sample and the study period, respectively. β_i are the coefficients, while SE, which includes LP, ROA, R&D, PPCM, QCS, and WST, serves as the explanatory variable. Finally, ε_{it} represents the stochastic error term.

4.2.3 | Estimation Results

Table 8 presents the regression analysis results, highlighting the coefficients and significance levels for each independent variable across the two models applied to Indian manufacturing firms. The table shows that the estimation results from the Tobit model differ from those of the OLS model in terms of both coefficients and significance levels. The Tobit model helps minimize bias and inconsistency when estimating unknown parameters, making it a more reliable method for identifying the influencing factors of CEE in Indian manufacturing firms (Debbarma et al. 2021). Consequently, the Tobit model has gained popularity for addressing methodological challenges in the second stage of DEA analysis (Debbarma et al. 2021). Therefore, Tobit regression was selected as the more appropriate method for this study, offering greater theoretical and practical relevance.

The influencing factors of SE in relation to CEE are shown in column (b) of Table 8. The result shows that LP, technological progress (R&D), PPCM, and WST have positively impacted CEE, while enterprise scale (ROA) and QCS are found to be negatively related to CEE. These findings align with economic realities (He et al. 2018; Sabli et al. 2019; Odei et al. 2024). Overall, the results show that WST (0.24) plays a crucial role in improving scale conditions and promoting CEE in manufacturing firms, as indicated by its high coefficient and significance level. This suggests that well-trained employees enhance operational efficiency and optimize resource use, which in turn boosts scale efficiency. Besides, skilled workers can operate complex machinery, streamline production processes, and implement best practices, leading to consistent output and reduced production costs (Odei et al. 2024). This expertise allows firms to leverage economies of scale better, as trained labor can handle increased production volumes with fewer errors and less waste.

Technological progress, as represented by R&D, ranked second in terms of its positive influence on the CEE, with a significantly positive coefficient. This indicates that manufacturing firms gained efficiency through R&D investments during the study period (Cui and Chu 2023). This may be due to pressure from the global market compelling firms to reduce carbon emissions, prompting them to invest heavily in R&D to enhance productivity and reduce emissions. Meanwhile, the negative coefficient for QCS indicates that these practices did not enhance manufacturing efficiency during the study. This finding differs from a previous study (Tayo Tene et al. 2021). Strict adherence to standards may prevent the adoption of energy-efficient technologies, hindering carbon emission improvements. Additionally, standardized procedures might not suit larger-scale operations or varying environmental conditions, leading to inefficiencies (Jeong and Lee 2022). While important, these practices can impose rigidity and hinder technological advancements. Therefore, policy suggestions for the manufacturing industry should focus on enhancing flexibility, promoting workforce skill development, and fostering innovation.

5 | Conclusions and Policy Implications

There is growing concern about sustainability issues like climate change mitigation at the global level. In 2016, India ratified the Paris Agreement, committing to its first NDCs to reduce global greenhouse gas emissions by 4.1% by 2030. It further strengthened this commitment in 2022 by setting an emissions intensity reduction target of 45% below 2005 levels by 2030. These policy efforts likely contributed to the turning point in 2005 that led to improvements in emission efficiency. However, the impact of these emissions policies on CEE in India's manufacturing sector has received limited attention, particularly in the context of developing countries. This study addresses this gap by examining CEE in India's manufacturing industry, comparing SI and non-SI firms, and assessing the effects of NDC policies on these firms.

This research contributes to the existing literature by addressing several research questions concerning Indian manufacturing sectors. Theoretically, this research proposes a new definition of SI from the perspective of developing countries, defining it as an "umbrella concept" that includes long-term programs aimed at reducing environmental impact while promoting broader sustainability goals." Methodologically, a two-stage SBM-DEA model with undesirable output is used to evaluate the CEE of 104 Indian firms from 2012 to 2022 and to analyze the determinants of the CEE (or sources of efficiency) measure. Furthermore, this study also employed the Tobit model to identify the influencing factors of SE that promote the CEE in Indian manufacturing firms. Moreover, this study applied the Porter hypothesis to evaluate how NDCs influence Indian manufacturing firms' CEE, addressing an underexplored area in existing research. In terms of practical contributions, this study offers policy recommendations to aid the manufacturing sectors in transitioning towards a "greener" economy. This study also highlights the significance of workforce skills and training and technological advancement, which were found to enhance CEE substantially. Furthermore, the study suggests the adaptation of performance-based policies (cap and trade) to promote both economic growth and environmental sustainability. This research is particularly valuable for policymakers aiming to balance industrial productivity with environmental responsibility in a developing country context.

This research highlights future research directions by highlighting its limitations. First, it focuses solely on India, thus excluding comparative analysis with other developing nations. Future research could expand the scope by incorporating cross-country comparisons of macro-level analysis across various industries to better understand heterogeneity in DEA results. Additionally, an empirical study could explore collaboration on carbon emission trading schemes (ETS) or energy-related initiatives among Southeast Asian countries. Finally, the current study's reliance on non-radial SBM approaches may limit statistical reliability; therefore, future research could consider more robust approaches, such as deterministic or stochastic frontier models, or using bootstrapping approaches to enhance empirical robustness.

Conflicts of Interest

The authors declare no conflicts of interest.

Data Availability Statement

All data were sourced from the annual reports of Indian manufacturing companies, which are available on their respective websites.

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Appendix 1

Emission Efficiency Scores for 104 Firms in India, 2012–2022

Firms ID	Firm type	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021	2022	Mean
Firm 1	Sustainability	0.3727	0.3702	0.3607	0.3651	0.3604	0.4104	0.4263	0.4324	0.4126	0.4386	0.4962	0.4041
Firm 2	Sustainability	0.4230	0.4207	0.4134	0.4211	0.4253	0.4356	0.4245	0.4317	0.4352	0.4339	0.4550	0.4290
Firm 3	Sustainability	0.3570	0.3517	0.3407	0.3398	0.3463	0.4173	0.4055	0.4028	0.3923	0.4216	0.5363	0.3919
Firm 4	Sustainability	0.2252	0.2453	0.2261	0.2404	0.2737	0.2704	0.2437	0.2422	0.2629	0.3215	0.3589	0.2646
Firm 5	Sustainability	0.4401	0.3808	0.3789	0.3795	0.3894	0.3991	0.4046	0.4146	0.4290	0.4385	0.4352	0.4082
Firm 6	Sustainability	0.3881	0.3792	0.4173	0.3710	0.3665	0.3576	0.3499	0.3696	0.3816	0.4197	0.3768	0.3798
Firm 7	Sustainability	0.4247	0.4628	0.4898	0.5799	0.5453	0.5808	0.5476	0.5359	0.5559	0.5710	1.0000	0.5722
Firm 8	Sustainability	0.3776	0.3376	0.3327	0.3442	0.3258	0.3530	0.4005	0.4065	0.3844	0.4671	0.3429	0.3702
Firm 9	Sustainability	0.4978	0.7431	0.6278	0.7001	0.7807	0.6575	1.0000	1.0000	1.0000	1.0000	1.0000	0.8188
Firm 10	Sustainability	0.5637	0.5145	0.5077	1.0000	1.0000	0.5411	0.5773	0.5779	0.4798	0.5142	0.5082	0.6168
Firm 11	Sustainability	0.8553	1.0000	1.0000	0.9353	0.8485	0.8057	0.8372	0.9730	0.8982	0.8130	1.0000	0.9060
Firm 12	Sustainability	0.5692	0.4826	0.5376	0.4818	0.4344	0.4885	0.4962	0.5735	0.5492	0.5607	0.5549	0.5208
Firm 13	Sustainability	0.4119	0.4242	0.4313	0.4258	0.4447	0.4172	0.4128	0.4402	0.4169	0.4249	0.4268	0.4252
Firm 14	Sustainability	1.0000	0.4843	0.5261	0.4879	0.4730	0.4693	0.4940	0.5189	0.5497	0.5329	0.5149	0.5501
Firm 15	Sustainability	0.3655	0.3795	0.3969	0.3835	0.3614	0.3468	0.3336	0.3645	0.3898	0.3803	0.3784	0.3709
Firm 16	Sustainability	0.3975	0.4064	0.4205	0.4153	0.4015	0.4064	0.4162	0.4635	0.4534	0.4636	0.4619	0.4278
Firm 17	Sustainability	0.6611	0.6844	0.7357	0.6624	0.6342	0.6151	0.6352	0.7275	0.6914	0.6381	0.8344	0.6836
Firm 18	Sustainability	0.4155	0.4080	0.4004	0.3064	0.3983	0.4119	0.3836	0.4063	0.4066	0.4211	0.4671	0.4023
Firm 19	Sustainability	0.3571	0.3187	0.2992	0.5385	0.6206	0.8012	0.8849	0.8109	0.7513	0.4132	0.8104	0.6005
Firm 20	Sustainability	0.7094	0.7150	0.7400	0.8253	0.8619	0.8723	0.8967	0.9354	0.9634	0.9804	1.0000	0.8636
Firm 21	Sustainability	0.9310	0.4668	1.0000	0.5828	0.5639	0.5654	0.5658	0.6018	0.5769	0.6342	0.7449	0.6576
Firm 22	Sustainability	0.4145	0.4177	0.4112	0.4243	0.3981	0.4505	0.4669	0.5347	0.4900	0.6119	0.6746	0.4813
Firm 23	Sustainability	0.7270	0.7302	0.7286	0.6846	0.7066	0.7679	0.8292	0.7691	0.8576	0.8778	0.8198	0.7726
Firm 24	Sustainability	0.4019	0.4175	0.4007	0.4450	0.4575	0.4646	0.5054	0.4961	0.5231	0.5164	0.5050	0.4667
Firm 25	Sustainability	0.3948	0.4109	0.4106	0.4184	0.3281	0.4423	0.4235	0.4177	0.4199	0.4232	0.4414	0.4119
Firm 26	Sustainability	0.3789	0.4378	0.4479	0.4399	0.3954	0.3924	0.4539	0.4756	0.4225	0.4347	0.4189	0.4271
Firm 27	Sustainability	0.4077	0.3964	0.4030	0.4232	0.4244	0.4311	0.4257	0.4085	0.4040	0.4017	0.4205	0.4133

Firms ID	Firm type	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021	2022	Mean
Firm 28	Sustainability	0.4227	0.4331	0.4082	0.4334	0.4458	0.4348	0.4283	0.4000	0.3781	0.3786	0.3888	0.4138
Firm 29	Sustainability	1.0000	1.0000	1.0000	1.0000	0.9044	0.9326	0.9608	1.0000	0.9736	0.8566	1.0000	0.9662
Firm 30	Sustainability	0.4497	0.4380	0.4235	0.4185	0.4192	0.3991	0.4115	0.3994	0.3848	0.3905	0.4001	0.4122
Firm 31	Sustainability	0.4236	0.4426	0.4803	0.4480	0.4593	0.4822	0.4775	0.4776	0.4777	0.4777	0.4778	0.4658
Firm 32	Sustainability	0.3796	0.3854	0.3818	0.3776	0.3843	0.4144	0.4061	0.4048	0.4102	0.4260	0.4575	0.4025
Firm 33	Sustainability	0.3214	0.3463	0.3389	0.3555	0.3588	0.3601	0.4242	0.2771	0.2358	0.3477	0.3436	0.3372
Firm 34	Sustainability	0.4841	0.5039	0.5090	0.5472	0.5600	0.5574	0.5754	0.6176	0.6121	0.8169	1.0000	0.6167
Firm 35	Sustainability	0.4180	0.4268	0.4328	0.4261	0.4197	0.4452	0.4426	0.4384	0.4082	0.4062	0.4069	0.4246
Firm 36	Sustainability	0.5105	0.5213	0.5511	0.7009	0.5882	0.6181	0.6115	0.6977	0.6899	0.6163	0.8491	0.6322
Firm 37	Sustainability	0.3725	0.3838	0.4128	0.4146	0.3907	0.4071	0.3758	0.3502	0.3585	0.3844	0.3917	0.3856
Firm 38	Sustainability	0.3165	0.3819	0.4110	0.4310	0.4213	0.4198	0.4517	0.4443	0.4532	0.4361	0.4498	0.4197
Firm 39	Sustainability	0.3686	0.3276	0.3237	0.3605	0.3677	0.3260	0.3261	0.3685	0.3976	0.3160	0.3443	0.3479
Firm 40	Sustainability	0.4120	0.4211	0.4201	0.4687	0.4765	0.4251	0.3996	0.3852	0.3569	0.3613	0.3700	0.4088
Firm 41	Sustainability	0.5695	0.6436	0.8388	0.4827	0.4927	0.5252	0.5299	0.5374	0.3432	0.3651	0.3903	0.5199
Firm 42	Sustainability	0.1986	0.1981	0.2647	0.3207	0.3450	0.2463	0.2339	0.5668	0.5449	0.3317	0.3691	0.3291
Firm 43	Sustainability	1.0000	0.4442	1.0000	0.6218	1.0000	1.0000	0.4391	0.6180	1.0000	1.0000	1.0000	0.8294
Firm 1	Nonsustainability	1.0000	1.0000	1.0000	0.9950	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	0.9995
Firm 2	Nonsustainability	1.0000	1.0000	1.0000	0.9230	0.6459	0.7093	0.6440	0.5866	0.5663	0.5562	0.5309	0.7420
Firm 3	Nonsustainability	0.2630	0.2356	0.2310	0.2355	0.2401	0.2366	0.2482	0.2601	0.2503	0.2789	0.5134	0.2721
Firm 4	Nonsustainability	0.2422	0.2554	0.2605	0.2663	0.2485	0.2574	0.2529	0.2551	0.2619	0.2684	0.2885	0.2597
Firm 5	Nonsustainability	0.3753	0.3703	0.3492	0.3597	0.3454	0.3311	0.3568	0.3824	0.3694	0.3461	0.3584	0.3586
Firm 6	Nonsustainability	0.5029	0.4908	0.4775	0.4953	0.5086	0.5334	0.5520	0.6065	0.6630	0.7795	0.7338	0.5767
Firm 7	Nonsustainability	0.7104	0.6869	0.5030	0.5004	0.5605	0.5959	0.5361	0.4617	0.5227	0.5837	0.6311	0.5720
Firm 8	Nonsustainability	0.6743	0.6342	0.6037	0.5867	0.5983	0.6585	0.6868	0.7356	0.8750	1.0000	1.0000	0.7321
Firm 9	Nonsustainability	0.5012	0.5002	0.5015	0.5008	0.4936	0.4864	0.5209	0.5375	0.5163	0.5682	0.5423	0.5154
Firm 10	Nonsustainability	0.3410	0.4089	0.3088	0.4221	0.4633	0.4751	0.5262	0.5782	0.5510	0.5242	0.5456	0.4677
Firm 11	Nonsustainability	0.3316	0.3386	0.3481	0.3560	0.3512	0.3391	0.3184	0.3234	0.3341	0.3378	0.2964	0.3341
Firm 12	Nonsustainability	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000
Firm 13	Nonsustainability	0.5224	0.6018	0.6055	0.6363	0.5722	0.5945	0.6060	0.6003	0.5416	0.4828	0.4682	0.5665
Firm 14	Nonsustainability	0.3357	0.3360	0.3041	0.2585	0.2547	0.2508	0.2527	0.2518	0.2522	0.2520	0.2521	0.2728

Firms ID	Firm type	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021	2022	Mean
Firm 15	Nonsustainability	0.4707	0.4958	0.5558	0.5254	0.5405	0.5329	0.5695	0.3872	0.4243	0.2966	0.5175	0.4833
Firm 16	Nonsustainability	0.5774	0.5795	0.6084	0.6462	0.6313	0.6542	0.6896	0.6731	0.6286	0.6600	0.6415	0.6354
Firm 17	Nonsustainability	0.3622	0.3943	0.2809	0.2942	0.2874	0.3212	0.3262	0.3472	0.3381	0.3290	0.3267	0.3279
Firm 18	Nonsustainability	0.5767	0.6066	0.6085	0.5679	0.5173	0.4666	0.4456	0.4374	0.4440	0.4808	0.4879	0.5127
Firm 19	Nonsustainability	0.3289	0.3869	0.4296	0.4224	0.5370	0.4138	0.4499	0.4385	0.3859	0.3837	0.4176	0.4177
Firm 20	Nonsustainability	1.0000	0.8332	1.0000	0.4664	0.4684	0.4705	0.5029	0.5072	0.5114	0.5370	0.5626	0.6236
Firm 21	Nonsustainability	0.8360	0.7881	0.8121	0.6931	0.5742	0.5101	0.4787	0.4797	0.5153	0.6844	0.7193	0.6446
Firm 22	Nonsustainability	0.5976	0.5952	0.5843	0.6150	0.5925	0.5475	0.5702	0.5503	0.5306	0.5404	0.5355	0.5690
Firm 23	Nonsustainability	0.6934	0.6318	0.5702	0.5489	0.5914	0.6339	0.6243	0.6141	0.6101	0.6181	0.5677	0.6094
Firm 24	Nonsustainability	0.7077	0.6377	0.6727	0.6842	0.6957	0.8147	1.0000	1.0000	1.0000	1.0000	1.0000	0.8375
Firm 25	Nonsustainability	0.4759	0.5144	0.4580	0.5095	0.5158	0.5220	0.4971	0.4933	0.5287	0.5170	0.5226	0.5049
Firm 26	Nonsustainability	0.5224	0.5333	0.5443	0.5730	0.5640	0.6073	0.5910	0.5603	0.5782	0.5066	0.5424	0.5566
Firm 27	Nonsustainability	0.4244	0.4074	0.3819	0.3884	0.3571	0.3271	0.3563	0.3740	0.3980	0.4236	0.4417	0.3891
Firm 28	Nonsustainability	0.4322	0.4103	0.5267	0.5000	0.4316	0.3607	0.3520	0.3564	0.3542	0.3553	0.3547	0.4031
Firm 29	Nonsustainability	1.0000	1.0000	0.4764	0.6006	0.5385	0.6323	0.7261	0.6890	0.8244	0.7567	0.7905	0.7304
Firm 30	Nonsustainability	0.8386	0.8102	0.8670	0.8630	0.8421	0.8800	0.9622	1.0000	1.0000	0.9264	1.0000	0.9081
Firm 31	Nonsustainability	0.3789	0.3736	0.3637	0.3362	0.2494	0.2592	0.2669	0.2738	0.2920	0.3094	0.2962	0.3090
Firm 32	Nonsustainability	0.4360	0.4077	0.3546	0.3811	0.3678	0.3745	0.4223	0.4101	0.4134	0.4306	0.3848	0.3984
Firm 33	Nonsustainability	0.2754	0.2799	0.2753	0.3129	0.2749	0.2824	0.3002	0.3183	0.2550	0.2799	0.2646	0.2835
Firm 34	Nonsustainability	0.3342	0.3363	0.3321	0.3404	0.3488	0.3318	0.3149	0.3231	0.3314	0.3369	0.3424	0.3338
Firm 35	Nonsustainability	0.5998	0.7215	0.8162	0.6246	0.6176	0.5298	0.5396	0.5226	0.5311	0.5268	0.5290	0.5962
Firm 36	Nonsustainability	0.3453	0.2901	0.3093	0.3348	0.3539	0.3617	0.3556	0.3517	0.3415	0.3791	0.3878	0.3464
Firm 37	Nonsustainability	0.9803	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	0.9982
Firm 38	Nonsustainability	0.7068	0.7197	0.8183	0.6558	0.5272	0.6023	0.6856	0.7057	0.6015	0.6997	0.9093	0.6938
Firm 39	Nonsustainability	0.5427	0.5729	0.6136	0.5933	0.6595	0.7126	0.7417	0.7744	0.7004	0.6244	0.6370	0.6520
Firm 40	Nonsustainability	0.4970	0.5105	0.5385	0.5244	0.5314	0.5279	0.5961	0.4597	0.4728	0.6537	0.5816	0.5358
Firm 41	Nonsustainability	0.2735	0.2731	0.2740	0.2721	0.2760	0.2680	0.2833	0.2482	0.2332	0.2696	0.3061	0.2706
Firm 42	Nonsustainability	0.4489	0.4489	0.4689	0.5415	0.5484	0.5630	0.5601	0.5774	0.6049	0.5912	0.5981	0.5410
Firm 43	Nonsustainability	0.8899	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	0.9081	1.0000	1.0000	1.0000	0.9816
Firm 44	Nonsustainability	0.6523	0.6650	0.6246	0.5498	0.5423	0.5429	0.5462	0.6385	0.6651	0.5740	0.6651	0.6060

Firms ID	Firm type	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021	2022	Mean
Firm 45	Nonsustainability	0.5274	0.5270	0.4668	0.5217	0.5556	0.6469	0.6377	0.6423	0.6400	0.6411	0.6406	0.5861
Firm 46	Nonsustainability	0.4863	0.4304	0.4582	0.4443	0.4512	0.4312	0.4051	0.4290	0.4170	0.5618	0.7215	0.4760
Firm 47	Nonsustainability	0.6681	0.5524	0.5501	0.5546	0.5453	0.5323	0.5149	0.5497	0.4802	0.5209	0.5006	0.5426
Firm 48	Nonsustainability	0.2949	0.2953	0.2946	0.2961	0.2931	0.2990	0.3050	0.3061	0.3073	0.2969	0.2867	0.2977
Firm 49	Nonsustainability	0.6453	0.6842	0.7007	0.7171	0.7354	0.7536	0.5572	0.4844	0.5437	0.4724	0.4011	0.6086
Firm 50	Nonsustainability	0.5772	0.7056	0.5678	0.7723	0.6802	0.5920	0.9317	0.8945	0.6796	0.6433	0.5903	0.6940
Firm 51	Nonsustainability	0.3745	0.3262	0.3519	0.3775	0.3640	0.3910	0.4180	0.4813	0.4358	0.3903	0.4125	0.3930
Firm 52	Nonsustainability	0.5379	0.5337	0.5421	0.4784	0.4931	0.4639	0.5226	0.5649	0.5235	0.5806	0.6384	0.5345
Firm 53	Nonsustainability	0.5431	0.3207	0.3180	0.3233	0.3287	0.3209	0.3339	0.3399	0.3369	0.3384	0.3376	0.3492
Firm 54	Nonsustainability	0.2821	0.2807	0.2836	0.2778	0.2894	0.2664	0.3130	0.3620	0.3416	0.3213	0.3514	0.3063
Firm 55	Nonsustainability	0.4117	0.5343	0.6568	0.6392	0.6745	0.5010	0.4946	0.5074	0.4876	0.4453	0.4745	0.5297
Firm 56	Nonsustainability	0.2929	0.2806	0.2973	0.2891	0.2932	0.2772	0.2348	0.2601	0.2434	0.3036	0.2940	0.2787
Firm 57	Nonsustainability	0.3595	0.3783	0.3554	0.3269	0.3354	0.3403	0.3356	0.3309	0.3083	0.3095	0.3094	0.3354
Firm 58	Nonsustainability	0.4638	0.4911	0.4502	0.4654	0.4457	0.4834	0.4581	0.5280	0.5226	0.5110	0.5316	0.4864
Firm 59	Nonsustainability	0.2224	0.2245	0.2284	0.2209	0.2363	0.2475	0.2735	0.2621	0.2578	0.2775	0.2826	0.2485
Firm 60	Nonsustainability	0.2641	0.2601	0.2675	0.2934	0.2771	0.2767	0.2775	0.2759	0.2790	0.3095	0.3227	0.2821
Firm 61	Nonsustainability	0.3632	0.3684	0.3580	0.3788	0.3376	0.2979	0.3176	0.3290	0.3326	0.3317	0.3324	0.3407
Sustainability initiative firms		0.4911	0.4671	0.5019	0.4983	0.5023	0.5015	0.5055	0.5282	0.5238	0.5224	0.5726	0.5104
Nonsustainability initiative firms		0.5298	0.5291	0.5214	0.5127	0.5016	0.5023	0.5178	0.5171	0.5140	0.5233	0.5397	0.5190

Appendix 2

Pure Emission Efficiency Scores for 104 Firms in India, 2012–2022.

Firms ID	Firm type	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021	2022	Mean
Firm 1	Sustainability	0.4889	0.4700	0.4562	0.4328	0.4167	0.4926	0.5316	0.5606	0.5327	0.5644	0.6752	0.5111
Firm 2	Sustainability	0.4230	0.4207	0.4134	0.4211	0.4253	0.4356	0.4245	0.4317	0.4352	0.4339	0.4550	0.4290
Firm 3	Sustainability	0.4763	0.4454	0.4838	0.4853	0.4921	0.5024	0.5153	0.5083	0.4872	0.5311	0.6709	0.5089
Firm 4	Sustainability	0.4617	0.5026	0.4636	0.4924	0.5618	0.5529	0.5022	0.4911	0.4766	0.3215	0.4528	0.4799
Firm 5	Sustainability	0.5694	0.3808	0.3789	0.3795	0.3894	0.3991	0.4046	0.4146	0.4290	0.4385	0.4352	0.4199
Firm 6	Sustainability	0.3606	0.3792	0.4496	0.5604	0.5423	0.5200	0.5108	0.5437	0.5629	0.6120	0.6007	0.5129

Firms ID	Firm type	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021	2022	Mean
Firm 7	Sustainability	0.4247	0.4628	0.4898	0.5799	0.5453	0.5808	0.5476	0.5359	0.5559	0.5710	1.0000	0.5722
Firm 8	Sustainability	0.3776	0.3376	0.3327	0.3442	0.3258	0.3530	0.4097	0.4218	0.3844	0.4671	0.4021	0.3778
Firm 9	Sustainability	1.0000	1.0000	0.6744	0.7558	0.9951	0.7163	1.0000	1.0000	1.0000	1.0000	1.0000	0.9220
Firm 10	Sustainability	0.5838	0.5145	0.5077	1.0000	1.0000	0.5411	0.8168	0.8395	0.4798	0.5142	0.5082	0.6641
Firm 11	Sustainability	0.8553	1.0000	1.0000	0.9353	0.8485	0.8057	0.8372	0.9730	0.8982	0.8130	1.0000	0.9060
Firm 12	Sustainability	0.5692	0.4826	0.5376	1.0000	1.0000	0.8321	0.9129	0.7980	0.7942	0.8393	1.0000	0.7969
Firm 13	Sustainability	0.4119	0.4242	0.4313	0.4258	0.4447	0.4172	0.4128	0.4402	0.4169	0.4249	0.4268	0.4252
Firm 14	Sustainability	1.0000	1.0000	0.8725	0.7562	0.7391	0.6111	0.6275	0.6854	0.8120	0.7775	0.7124	0.7812
Firm 15	Sustainability	0.3655	0.3795	0.3969	0.5054	0.4451	0.4368	0.4222	0.4573	0.4957	0.4351	0.4377	0.4343
Firm 16	Sustainability	0.3975	0.4064	0.4205	0.4153	0.4015	0.4064	0.4162	0.4635	0.4534	0.4636	0.4619	0.4278
Firm 17	Sustainability	0.6611	0.6844	0.7357	0.6624	0.6342	0.6151	0.6352	0.7275	0.6914	0.6381	0.8344	0.6836
Firm 18	Sustainability	0.4155	0.4080	0.4004	0.3064	0.3983	0.4119	0.3836	0.4063	0.4066	0.4211	0.4671	0.4023
Firm 19	Sustainability	0.4768	0.3788	0.3763	0.6582	0.7694	0.9863	1.0931	1.0000	0.9273	0.5097	1.0000	0.7433
Firm 20	Sustainability	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000
Firm 21	Sustainability	0.9310	0.4668	1.0000	0.5828	0.5639	0.5654	0.5658	0.6018	0.5769	0.7189	0.8888	0.6784
Firm 22	Sustainability	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	0.9949	0.8473	1.0000	1.0000	0.9857
Firm 23	Sustainability	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	0.9835	1.0000	0.9985
Firm 24	Sustainability	1.0000	0.4175	0.4007	0.7253	1.0000	1.0000	0.9373	0.8480	1.0000	0.8613	0.7941	0.8167
Firm 25	Sustainability	0.5221	0.5434	0.5437	0.5365	0.4241	0.6208	0.5447	0.5468	0.5523	0.5338	0.5908	0.5417
Firm 26	Sustainability	0.3789	0.4378	0.4479	0.4399	0.3954	0.3924	0.4539	0.4756	0.4225	0.4347	0.4189	0.4271
Firm 27	Sustainability	0.4077	0.3964	0.4030	0.4232	0.4244	0.4311	0.4257	0.4085	0.4040	0.4017	0.4205	0.4133
Firm 28	Sustainability	0.4227	0.4331	0.4082	0.4334	0.4667	0.4977	0.4283	0.4000	0.3781	0.3786	0.3888	0.4214
Firm 29	Sustainability	1.0000	1.0000	1.0000	1.0000	0.9044	0.9326	0.9608	1.0000	0.9736	0.8566	1.0000	0.9662
Firm 30	Sustainability	0.4497	0.4380	0.4235	0.4185	0.4192	0.3991	0.4115	0.3994	0.3848	0.3905	0.4001	0.4122
Firm 31	Sustainability	0.6988	0.6663	0.7023	0.4480	0.4593	0.4822	0.4775	0.4776	0.4777	0.4777	0.4778	0.5314
Firm 32	Sustainability	0.3796	0.3854	0.3818	0.3776	0.3843	0.4144	0.4061	0.4048	0.4102	0.4260	0.4575	0.4025
Firm 33	Sustainability	0.3214	0.3463	0.3389	0.3555	0.3588	0.3601	0.7326	0.3172	0.3247	0.3477	0.3690	0.3793
Firm 34	Sustainability	0.4841	0.5039	0.5090	0.5472	0.5600	0.5574	0.5754	0.6176	0.6121	0.8169	1.0000	0.6167
Firm 35	Sustainability	0.4180	0.4268	0.4328	0.4505	0.4197	0.4452	0.4426	0.4598	0.4082	0.4062	0.4069	0.4288
Firm 36	Sustainability	1.0000	1.0000	1.0000	0.8000	0.6610	0.6817	0.6983	0.7707	0.7500	0.6767	0.8910	0.8118
Firm 37	Sustainability	0.3725	0.3838	0.4128	0.4146	0.3907	0.4071	0.3758	0.3502	0.3585	0.3844	0.3917	0.3856

Firms ID	Firm type	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021	2022	Mean
Firm 38	Sustainability	0.3165	0.3819	0.4110	0.4310	0.4213	0.4198	0.4517	0.4443	0.4532	0.4361	0.4498	0.4197
Firm 39	Sustainability	0.3686	0.3276	0.3237	0.3605	0.3896	0.4231	0.4308	0.4544	0.4935	0.4003	0.4171	0.3990
Firm 40	Sustainability	0.4120	0.4211	0.4201	0.4687	0.4765	0.4251	0.3996	0.3852	0.3569	0.3613	0.3700	0.4088
Firm 41	Sustainability	0.5695	0.6436	0.8388	0.4827	0.4927	0.5252	0.5299	0.5374	0.3432	0.3651	0.3903	0.5199
Firm 42	Sustainability	0.4590	0.4694	0.4294	0.6178	0.6077	0.6040	0.5928	0.5668	0.5449	0.3317	0.3691	0.5084
Firm 43	Sustainability	1.0000	0.4442	1.0000	0.6218	1.0000	1.0000	0.4391	0.6180	1.0000	1.0000	1.0000	0.8294
Firm 1	Nonsustainability	1.0000	1.0000	1.0000	0.9950	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	0.9995
Firm 2	Nonsustainability	1.0000	1.0000	1.0000	0.9230	0.6459	0.7093	0.6440	0.5866	0.5663	0.5562	0.5309	0.7420
Firm 3	Nonsustainability	0.3011	0.2877	0.2850	0.2865	0.2881	0.2858	0.2935	0.3012	0.2974	0.3402	0.5134	0.3164
Firm 4	Nonsustainability	0.3225	0.3389	0.3453	0.3493	0.3301	0.3397	0.3349	0.3373	0.3333	0.3294	0.3650	0.3387
Firm 5	Nonsustainability	0.3753	0.3703	0.3492	0.3597	0.3454	0.3311	0.3568	0.3824	0.3694	0.3564	0.3629	0.3599
Firm 6	Nonsustainability	0.5029	0.4908	0.4775	0.4953	0.5086	0.5334	0.5520	0.6065	0.6630	0.7795	0.7338	0.5767
Firm 7	Nonsustainability	0.7104	0.6869	0.5030	0.5004	0.5605	0.5959	0.5361	0.4617	0.5227	0.5837	0.6311	0.5720
Firm 8	Nonsustainability	0.6743	0.6342	0.6037	0.5867	0.5983	0.6585	0.6868	0.7356	0.8750	1.0000	1.0000	0.7321
Firm 9	Nonsustainability	0.5012	0.5002	0.5015	0.5008	0.4936	0.4864	0.5209	0.5375	0.5163	0.5682	0.5423	0.5154
Firm 10	Nonsustainability	0.3410	0.4089	0.3088	0.4221	0.4634	0.5046	0.5529	0.6012	0.5953	0.5894	0.6152	0.4912
Firm 11	Nonsustainability	0.3735	0.3944	0.4053	0.4273	0.4252	0.4418	0.4284	0.4524	0.4437	0.4388	0.4033	0.4213
Firm 12	Nonsustainability	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000
Firm 13	Nonsustainability	0.5362	0.6730	0.6055	0.6363	0.5722	0.5945	0.6060	0.6003	0.5416	0.4828	0.4682	0.5742
Firm 14	Nonsustainability	0.3357	0.3360	0.3359	0.3359	0.3369	0.3380	0.3375	0.3377	0.3376	0.3377	0.3376	0.3370
Firm 15	Nonsustainability	0.6154	0.5850	0.6297	0.6074	0.6185	0.6129	0.9065	1.0000	0.8362	0.4725	0.5805	0.6786
Firm 16	Nonsustainability	0.5774	0.5795	0.6084	0.6462	0.6313	0.6542	0.6896	0.6731	0.6286	0.6600	0.6415	0.6354
Firm 17	Nonsustainability	1.0000	1.0000	0.8506	0.8915	0.8903	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	0.9666
Firm 18	Nonsustainability	0.5767	0.6066	0.6085	0.5679	0.5173	0.4666	0.4456	0.4374	0.4440	0.4808	0.4879	0.5127
Firm 19	Nonsustainability	0.3312	0.3904	0.4296	0.4296	0.5370	0.4138	0.4499	0.5177	0.4180	0.4261	0.7553	0.4635
Firm 20	Nonsustainability	1.0000	0.8332	1.0000	0.4664	0.4684	0.4705	0.5029	0.5072	0.5114	0.5370	0.5626	0.6236
Firm 21	Nonsustainability	0.8360	0.7881	0.8121	0.6931	0.5742	0.5101	0.4787	0.4797	0.5153	0.6844	0.7193	0.6446
Firm 22	Nonsustainability	0.6393	0.6353	0.6196	0.6532	0.6970	0.6330	0.6650	0.6453	0.6256	0.6354	0.6305	0.6436
Firm 23	Nonsustainability	0.6934	0.6318	0.5702	0.5489	0.5914	0.6339	0.6243	0.6141	0.6101	0.6181	0.5677	0.6094
Firm 24	Nonsustainability	0.7077	0.6377	0.6727	0.6842	0.6957	0.8147	1.0000	1.0000	1.0000	1.0000	1.0000	0.8375
Firm 25	Nonsustainability	0.4759	0.5144	0.4580	0.5095	0.5158	0.5220	0.4971	0.5168	0.5287	0.5228	0.5226	0.5076

Firms ID	Firm type	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021	2022	Mean
Firm 26	Nonsustainability	0.5224	0.5333	0.5443	0.5730	0.6017	0.6412	0.6007	0.5603	0.5782	0.5066	0.5424	0.5640
Firm 27	Nonsustainability	0.5103	0.4074	0.3819	0.3884	0.3571	0.3271	0.3563	0.3740	0.3980	0.4236	0.4417	0.3969
Firm 28	Nonsustainability	0.4871	0.4364	0.5267	0.5000	0.4316	0.3607	0.3520	0.3564	0.3542	0.3553	0.3547	0.4105
Firm 29	Nonsustainability	1.0000	1.0000	0.4764	0.6006	0.5385	0.6323	0.7261	0.6890	0.8244	0.7567	0.7905	0.7304
Firm 30	Nonsustainability	0.8386	0.8102	0.8670	0.8630	0.8421	0.8800	0.9622	1.0000	1.0000	0.9264	1.0000	0.9081
Firm 31	Nonsustainability	0.3948	0.4126	0.4278	0.4012	0.4087	0.4327	0.4564	0.4800	0.5194	0.5588	0.5834	0.4614
Firm 32	Nonsustainability	0.5251	0.5234	0.5215	0.5224	0.5220	0.5222	0.7340	0.9459	0.9665	1.0000	1.0000	0.7075
Firm 33	Nonsustainability	0.3255	0.3302	0.3208	0.3807	0.3560	0.3589	0.3924	0.4117	0.3143	0.3647	0.3400	0.3541
Firm 34	Nonsustainability	0.3884	0.3897	0.3871	0.3923	0.3976	0.3793	0.3611	0.3628	0.3644	0.3670	0.3696	0.3781
Firm 35	Nonsustainability	0.5998	0.7215	0.8162	0.6246	0.6176	0.5298	0.5396	0.5226	0.5311	0.5268	0.5290	0.5962
Firm 36	Nonsustainability	0.3453	0.2901	0.3093	0.3348	0.3539	0.3617	0.3556	0.3517	0.3479	0.4002	0.4093	0.3509
Firm 37	Nonsustainability	0.9803	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	0.9982
Firm 38	Nonsustainability	0.7889	0.8155	0.9174	0.7636	0.6437	0.7196	0.7842	0.7981	0.6738	0.7554	0.9466	0.7824
Firm 39	Nonsustainability	0.5427	0.5729	0.6136	0.5933	0.6595	0.7257	0.7417	0.7764	0.7004	0.6244	0.6370	0.6534
Firm 40	Nonsustainability	0.5866	0.6092	0.6293	0.6192	0.6243	0.6217	0.9109	1.0000	1.0000	0.9887	1.0000	0.7809
Firm 41	Nonsustainability	0.3412	0.3401	0.3423	0.3380	0.3466	0.3293	0.3639	0.3415	0.3538	0.4096	0.4654	0.3611
Firm 42	Nonsustainability	0.4489	0.4489	0.4689	0.5415	0.5484	0.5630	0.5601	0.5774	0.6049	0.5912	0.5981	0.5410
Firm 43	Nonsustainability	0.8899	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	0.9081	1.0000	1.0000	1.0000	0.9816
Firm 44	Nonsustainability	0.6523	0.6650	0.6246	0.5498	0.5423	0.5429	0.5462	0.6385	0.6651	0.5740	0.6651	0.6060
Firm 45	Nonsustainability	0.5274	0.5270	0.4668	0.5217	0.5556	0.6469	0.6377	0.6423	0.6400	0.6411	0.6406	0.5861
Firm 46	Nonsustainability	0.4916	0.4389	0.4652	0.4520	0.4586	0.4885	0.5183	0.5455	0.5319	0.6701	0.8083	0.5335
Firm 47	Nonsustainability	0.6904	0.5725	0.5668	0.5783	0.5553	0.5323	0.5149	0.5497	0.4802	0.5209	0.5006	0.5511
Firm 48	Nonsustainability	0.3191	0.3194	0.3187	0.3201	0.3174	0.3229	0.3285	0.3290	0.3296	0.3245	0.3195	0.3226
Firm 49	Nonsustainability	0.6453	0.6842	0.7007	0.7171	0.7354	0.7536	0.5572	0.4844	0.5437	0.4724	0.4011	0.6086
Firm 50	Nonsustainability	0.5943	0.7056	0.5792	0.7780	0.7044	0.6309	1.0000	1.0000	0.6963	0.6433	0.5903	0.7202
Firm 51	Nonsustainability	0.3745	0.3262	0.3519	0.3775	0.3640	0.3910	0.4180	0.4813	0.4358	0.3903	0.4125	0.3930
Firm 52	Nonsustainability	0.5379	0.5337	0.5421	0.5506	0.5657	0.5354	0.5960	0.6490	0.6369	0.7012	0.7655	0.6013
Firm 53	Nonsustainability	0.5431	0.3207	0.3180	0.3233	0.3287	0.3209	0.3366	0.3404	0.3385	0.3394	0.3390	0.3499
Firm 54	Nonsustainability	0.3629	0.3625	0.3633	0.3617	0.3648	0.3586	0.3710	0.3834	0.3623	0.3411	0.3728	0.3640
Firm 55	Nonsustainability	0.4117	0.5343	0.6568	0.6392	0.6745	0.5010	0.4946	0.5074	0.4876	0.4453	0.4745	0.5297
Firm 56	Nonsustainability	0.3894	0.4442	0.4788	0.4615	0.4702	0.5675	0.6648	0.7746	0.7174	0.9587	1.0000	0.6297

Firms ID	Firm type	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021	2022	Mean
Firm 57	Nonsustainability	0.3595	0.3783	0.3685	0.3587	0.3738	0.3792	0.3738	0.3684	0.3433	0.3182	0.3307	0.3593
Firm 58	Nonsustainability	0.4638	0.4911	0.4502	0.4654	0.4457	0.4834	0.4581	0.5280	0.5226	0.5110	0.5316	0.4864
Firm 59	Nonsustainability	0.3037	0.3066	0.3121	0.3016	0.3234	0.2914	0.2735	0.2969	0.3207	0.3397	0.3454	0.3105
Firm 60	Nonsustainability	0.4562	0.4379	0.4744	0.6555	0.8366	0.8354	0.8379	0.8329	0.8429	0.9357	0.7500	0.7178
Firm 61	Nonsustainability	0.4999	0.5055	0.4942	0.5169	0.4714	0.4259	0.4487	0.5103	0.5719	0.5411	0.5565	0.5038
Sustainability initiative firms		0.5868	0.5491	0.5732	0.5826	0.5952	0.5861	0.5973	0.5995	0.5887	0.5759	0.6380	0.5884
Nonsustainability initiative firms		0.5667	0.5659	0.5584	0.5554	0.5515	0.5565	0.5850	0.6008	0.5931	0.6004	0.6194	0.5775

Appendix 3

Scale efficiency scores for 104 firms in India, 2012–20,122.

Firms ID	Firm type	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021	2022	Mean
Firm 1	Sustainability	0.7624	0.7877	0.7906	0.8436	0.8648	0.8332	0.8020	0.7713	0.7745	0.7772	0.7349	0.7947
Firm 2	Sustainability	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000
Firm 3	Sustainability	0.7495	0.7897	0.7042	0.7001	0.7038	0.8306	0.7868	0.7926	0.8051	0.7937	0.7994	0.7687
Firm 4	Sustainability	0.4878	0.4879	0.4877	0.4882	0.4872	0.4892	0.4852	0.4931	0.5516	1.0000	0.7926	0.5682
Firm 5	Sustainability	0.7729	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	0.9794
Firm 6	Sustainability	1.0763	1.0000	0.9283	0.6621	0.6759	0.6878	0.6850	0.6798	0.6779	0.6858	0.6272	0.7624
Firm 7	Sustainability	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000
Firm 8	Sustainability	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	0.9774	0.9636	1.0000	1.0000	0.8528	0.9813
Firm 9	Sustainability	0.4978	0.7431	0.9310	0.9263	0.7846	0.9180	1.0000	1.0000	1.0000	1.0000	1.0000	0.8910
Firm 10	Sustainability	0.9656	1.0000	1.0000	1.0000	1.0000	1.0000	0.7068	0.6883	1.0000	1.0000	1.0000	0.9419
Firm 11	Sustainability	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000
Firm 12	Sustainability	1.0000	1.0000	1.0000	0.4818	0.4344	0.5871	0.5435	0.7187	0.6915	0.6681	0.5549	0.6982
Firm 13	Sustainability	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000
Firm 14	Sustainability	1.0000	0.4843	0.6030	0.6452	0.6400	0.7679	0.7872	0.7570	0.6770	0.6854	0.7228	0.7063
Firm 15	Sustainability	1.0000	1.0000	1.0000	0.7588	0.8120	0.7939	0.7901	0.7972	0.7865	0.8742	0.8646	0.8616
Firm 16	Sustainability	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000
Firm 17	Sustainability	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000

Firms ID	Firm type	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021	2022	Mean
Firm 18	Sustainability	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000
Firm 19	Sustainability	0.7490	0.8412	0.7951	0.8181	0.8066	0.8124	0.8095	0.8109	0.8102	0.8106	0.8104	0.8067
Firm 20	Sustainability	0.7094	0.7150	0.7400	0.8253	0.8619	0.8723	0.8967	0.9354	0.9634	0.9804	1.0000	0.8636
Firm 21	Sustainability	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	0.8822	0.8381	0.9746
Firm 22	Sustainability	0.4145	0.4177	0.4112	0.4243	0.3981	0.4505	0.4669	0.5374	0.5784	0.6119	0.6746	0.4896
Firm 23	Sustainability	0.7270	0.7302	0.7286	0.6846	0.7066	0.7679	0.8292	0.7691	0.8576	0.8926	0.8198	0.7739
Firm 24	Sustainability	0.4019	1.0000	1.0000	0.6135	0.4575	0.4646	0.5392	0.5850	0.5231	0.5995	0.6360	0.6200
Firm 25	Sustainability	0.7562	0.7563	0.7552	0.7798	0.7736	0.7124	0.7774	0.7639	0.7603	0.7928	0.7471	0.7614
Firm 26	Sustainability	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000
Firm 27	Sustainability	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000
Firm 28	Sustainability	1.0000	1.0000	1.0000	1.0000	0.9551	0.8737	1.0000	1.0000	1.0000	1.0000	1.0000	0.9844
Firm 29	Sustainability	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000
Firm 30	Sustainability	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000
Firm 31	Sustainability	0.6062	0.6643	0.6839	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	0.9049
Firm 32	Sustainability	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000
Firm 33	Sustainability	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	0.5790	0.8736	0.7263	1.0000	0.9312	0.9191
Firm 34	Sustainability	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000
Firm 35	Sustainability	1.0000	1.0000	1.0000	0.9458	1.0000	1.0000	1.0000	0.9534	1.0000	1.0000	1.0000	0.9908
Firm 36	Sustainability	0.5105	0.5213	0.5511	0.8761	0.8899	0.9068	0.8757	0.9053	0.9198	0.9107	0.9530	0.8018
Firm 37	Sustainability	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000
Firm 38	Sustainability	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000
Firm 39	Sustainability	1.0000	1.0000	1.0000	1.0000	0.9438	0.7707	0.7571	0.8110	0.8057	0.7894	0.8255	0.8821
Firm 40	Sustainability	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000
Firm 41	Sustainability	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000
Firm 42	Sustainability	0.4328	0.4220	0.6164	0.5192	0.5678	0.4077	0.3945	1.0000	1.0000	1.0000	1.0000	0.6691
Firm 43	Sustainability	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000
Firm 1	Nonsustainability	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000
Firm 2	Nonsustainability	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000
Firm 3	Nonsustainability	0.8736	0.8189	0.8104	0.8220	0.8336	0.8278	0.8457	0.8635	0.8417	0.8198	1.0000	0.8506
Firm 4	Nonsustainability	0.7510	0.7537	0.7544	0.7625	0.7529	0.7577	0.7553	0.7565	0.7856	0.8148	0.7904	0.7668

Firms ID	Firm type	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021	2022	Mean
Firm 5	Nonsustainability	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	0.9711	0.9874	0.9962
Firm 6	Nonsustainability	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000
Firm 7	Nonsustainability	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000
Firm 8	Nonsustainability	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000
Firm 9	Nonsustainability	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000
Firm 10	Nonsustainability	1.0000	1.0000	1.0000	1.0000	0.9997	0.9415	0.9516	0.9618	0.9256	0.8893	0.8869	0.9597
Firm 11	Nonsustainability	0.8880	0.8585	0.8588	0.8332	0.8261	0.7674	0.7431	0.7148	0.7529	0.7698	0.7348	0.7952
Firm 12	Nonsustainability	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000
Firm 13	Nonsustainability	0.9743	0.8943	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	0.9881
Firm 14	Nonsustainability	1.0000	1.0000	0.9051	0.7697	0.7558	0.7420	0.7489	0.7454	0.7472	0.7463	0.7467	0.8097
Firm 15	Nonsustainability	0.7648	0.8475	0.8826	0.8650	0.8738	0.8694	0.6283	0.3872	0.5074	0.6276	0.8915	0.7405
Firm 16	Nonsustainability	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000
Firm 17	Nonsustainability	0.3622	0.3943	0.3302	0.3300	0.3228	0.3212	0.3262	0.3472	0.3381	0.3290	0.3267	0.3389
Firm 18	Nonsustainability	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000
Firm 19	Nonsustainability	0.9930	0.9910	1.0000	0.9833	1.0000	1.0000	1.0000	0.8469	0.9233	0.9007	0.5529	0.9265
Firm 20	Nonsustainability	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000
Firm 21	Nonsustainability	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000
Firm 22	Nonsustainability	0.9347	0.9369	0.9432	0.9416	0.8500	0.8649	0.8575	0.8528	0.8481	0.8504	0.8493	0.8845
Firm 23	Nonsustainability	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000
Firm 24	Nonssustainability	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000
Firm 25	Nonsustainability	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	0.9545	1.0000	0.9891	1.0000	0.9949
Firm 26	Nonsustainability	1.0000	1.0000	1.0000	1.0000	0.9373	0.9471	0.9838	1.0000	1.0000	1.0000	1.0000	0.9880
Firm 27	Nonsustainability	0.8316	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	0.9847
Firm 28	Nonsustainability	0.8872	0.9402	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	0.9843
Firm 29	Nonsustainability	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000
Firm 30	Nonsustainability	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000
Firm 31	Nonsustainability	0.9596	0.9056	0.8501	0.8379	0.6102	0.5991	0.5848	0.5705	0.5621	0.5537	0.5077	0.6856
Firm 32	Nonsustainability	0.8303	0.7790	0.6799	0.7295	0.7047	0.7171	0.5753	0.4335	0.4277	0.4306	0.3848	0.6084
Firm 33	Nonsustainability	0.8460	0.8476	0.8583	0.8218	0.7723	0.7869	0.7651	0.7733	0.8112	0.7675	0.7783	0.8026
Firm 34	Nonsustainability	0.8605	0.8629	0.8581	0.8677	0.8774	0.8747	0.8720	0.8906	0.9093	0.9179	0.9266	0.8834

Firms ID	Firm type	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021	2022	Mean
Firm 35	Nonsustainability	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000
Firm 36	Nonsustainability	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	0.9817	0.9472	0.9475	0.9888
Firm 37	Nonsustainability	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000
Firm 38	Nonsustainability	0.8960	0.8826	0.8920	0.8589	0.8191	0.8369	0.8743	0.8843	0.8928	0.9263	0.9606	0.8840
Firm 39	Nonsustainability	1.0000	1.0000	1.0000	1.0000	1.0000	0.9819	1.0000	0.9973	1.0000	1.0000	1.0000	0.9981
Firm 40	Nonsustainability	0.8471	0.8380	0.8557	0.8469	0.8513	0.8491	0.6544	0.4597	0.4728	0.6612	0.5816	0.7198
Firm 41	Nonsustainability	0.8017	0.8028	0.8006	0.8050	0.7962	0.8138	0.7785	0.7269	0.6590	0.6583	0.6576	0.7546
Firm 42	Nonsustainability	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000
Firm 43	Nonsustainability	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000
Firm 44	Nonsustainability	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000
Firm 45	Nonsustainability	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000
Firm 46	Nonsustainability	0.9893	0.9806	0.9849	0.9828	0.9839	0.8827	0.7815	0.7865	0.7840	0.8383	0.8926	0.8988
Firm 47	Nonsustainability	0.9676	0.9648	0.9705	0.9590	0.9820	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	0.9858
Firm 48	Nonsustainability	0.9243	0.9245	0.9242	0.9248	0.9236	0.9260	0.9285	0.9304	0.9323	0.9149	0.8974	0.9228
Firm 49	Nonsustainability	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000
Firm 50	Nonsustainability	0.9712	1.0000	0.9803	0.9927	0.9656	0.9384	0.9317	0.8945	0.9761	1.0000	1.0000	0.9682
Firm 51	Nonsustainability	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000
Firm 52	Nonsustainability	1.0000	1.0000	1.0000	0.8690	0.8716	0.8664	0.8769	0.8705	0.8219	0.8280	0.8340	0.8944
Firm 53	Nonsustainability	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	0.9922	0.9985	0.9953	0.9969	0.9961	0.9981
Firm 54	Nonsustainability	0.7775	0.7743	0.7806	0.7680	0.7932	0.7429	0.8436	0.9443	0.9431	0.9420	0.9425	0.8411
Firm 55	Nonsustainability	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000
Firm 56	Nonsustainability	0.7523	0.6318	0.6209	0.6263	0.6236	0.4884	0.3532	0.3358	0.3394	0.3167	0.2940	0.4893
Firm 57	Nonsustainability	1.0000	1.0000	0.9644	0.9113	0.8973	0.8974	0.8978	0.8983	0.8981	0.9727	0.9354	0.9339
Firm 58	Nonsustainability	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000
Firm 59	Nonsustainability	0.7325	0.7322	0.7317	0.7322	0.7307	0.8492	1.0000	0.8828	0.8040	0.8167	0.8180	0.8027
Firm 60	Nonsustainability	0.5789	0.5939	0.5639	0.4475	0.3312	0.3312	0.3312	0.3313	0.3310	0.3308	0.4302	0.4183
Firm 61	Nonsustainability	0.7266	0.7287	0.7245	0.7328	0.7162	0.6995	0.7078	0.6447	0.5815	0.6131	0.5973	0.6793
Sustainability initiative firms		0.8749	0.8921	0.9006	0.8836	0.8782	0.8825	0.8718	0.8978	0.9049	0.9245	0.9113	0.8929
Nonsustainability initiative firms		0.9299	0.9293	0.9266	0.9184	0.9082	0.9036	0.8949	0.8801	0.8819	0.8876	0.8877	0.9044