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Original Article

Enabling Green Manufacturing in MSMEs through Circular Economy and Energy Optimization Models

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Abstract *- The transition to green manufacturing is pivotal for achieving sustainable industrial growth, particularly in the Micro, Small, and Medium Enterprises (MSME) sector of developing economies like India. This paper explores the integration of Circular Economy (CE) principles and energy optimization models (EOMs) as dual enablers of green manufacturing practices in MSMEs. The study adopts a mixed-methods approach, drawing insights from qualitative interviews with 50 MSME stakeholders and quantitative energy performance data from selected enterprises. The research identifies key barriers—such as technological gaps, policy ambiguity, and lack of financial incentives—and proposes an integrated CE-EOM framework that enhances resource efficiency, waste minimization, and energy sustainability. Empirical validation through case studies and simulation of energy-saving interventions demonstrates that CE and EOM implementation can result in 20–35% resource efficiency gains and up to 25% reduction in energy costs. The findings reinforce the strategic significance of green transitions for MSMEs, positioning them not only as participants but as pioneers in the sustainable industrial revolution. Policy recommendations, technological interventions, and training roadmaps are proposed to accelerate adoption at scale.*

Keywords *- Green Manufacturing, MSMEs, Circular Economy, Energy Optimization, Sustainability, Resource Efficiency.*

1. Introduction

1.1. Contextualizing Sustainability in MSMEs

The global industrial sector is experiencing a pivotal shift, marked by increasing pressure to integrate sustainability into core manufacturing and operational processes. Central to this shift is the concept of green manufacturing, which aims to minimize environmental impacts, enhance energy efficiency, and support the sustainable use of resources throughout the product lifecycle. While large corporations have begun to embrace such changes due to regulatory and shareholder pressure, Micro, Small, and Medium Enterprises (MSMEs)—which form the economic backbone of many developing nations—continue to grapple with challenges in adopting sustainable practices. In India, the MSME sector contributes approximately 30% to the national GDP, accounts for 45% of total manufacturing output, and employs over 110 million individuals, making it one of the most critical economic segments (Ministry of MSME, 2023). Despite its significance, the sector faces challenges such as inefficient resource usage, outdated technologies, limited access to clean energy, and inadequate policy support. Consequently, MSMEs, although small in scale, collectively contribute substantially to carbon emissions, waste generation, and unsustainable production practices (GIZ India, 2018; Palit & Chaurey, 2011).

1.2. Need for an Integrated Green Manufacturing Paradigm

Green manufacturing is not limited to pollution control; it involves holistic redesigns of production systems, material flows, energy utilization, and end-of-life product strategies to reduce ecological footprints and enhance environmental performance. In this context, two synergistic frameworks have emerged as enablers of green manufacturing—the Circular Economy (CE) and Energy Optimization Models (EOMs). Circular economy aims to decouple economic growth from resource consumption through strategies such as reuse, recycling, remanufacturing, and eco-design, thereby creating a closed-loop production-consumption system (Kirchherr et al., 2018; Ghisellini, Cialani, & Ulgiati, 2016). On the other hand, Energy Optimization Models refer to a set of analytical and computational tools used to optimize energy consumption patterns in industrial settings. These models can significantly reduce operational costs and environmental impacts by improving energy efficiency, demand-side management, and renewable energy integration (Narula & Reddy, 2018; IRENA, 2019). The integration of CE and EOMs offers MSMEs a transformative pathway to shift from linear and resource-intensive operations to regenerative, efficient, and sustainable systems. This dual integration is particularly suited to India's MSME sector, where energy consumption is high, and waste generation is often unmanaged, yet there is potential for rapid innovation and agile adaptation (GIZ India, 2018; Ellen MacArthur Foundation, 2013).

1.3. Research Problem and Justification

Despite the conceptual strengths of CE and EOMs, their implementation in MSMEs remains limited. There are several reasons for this gap:

1) Lack of awareness among MSME owners about the benefits and implementation strategies of CE and energy optimization (Rizos et al., 2016).
2) Capital constraints that hinder investment in renewable technologies and modern production systems (UNIDO, 2017).
3) Absence of sector-specific policy frameworks that promote sustainable transitions in smaller enterprises (MNRE, 2022).
4) Insufficient technical expertise to model, evaluate, and adapt CE or EOM tools to diverse MSME contexts (Narula & Reddy, 2018).

Most scholarly research on green manufacturing focuses on large enterprises or sector-specific sustainability interventions, leaving a significant knowledge gap regarding how MSMEs can transition toward green practices in a cost-effective, scalable, and measurable manner (Kalmykova, Sadagopan, & Rosado, 2018). Moreover, studies that address both circular economy and energy optimization in an integrated framework for MSMEs are scarce, especially in the Indian context.

Addressing this research gap is essential not only for improving the environmental performance of the MSME sector but also for aligning with India's commitments under the Paris Agreement and UN Sustainable Development Goals (SDGs)—particularly SDG 7 (Affordable and Clean Energy), SDG 9 (Industry, Innovation, and Infrastructure), and SDG 12 (Responsible Consumption and Production) (UNDP, 2022).

1.4. Objectives and Scope of the Study

This study aims to fill the existing research void by developing and empirically validating an integrated Circular Economy–Energy Optimization Model (CE-EOM) framework that enables green manufacturing in MSMEs. The study focuses on the following core objectives:

1. To analyze the current status of CE and energy usage patterns in selected Indian MSMEs.
2. To identify barriers and opportunities in implementing CE and EOM principles within MSME clusters.
3. To develop a holistic framework that integrates CE principles with energy optimization models tailored for the MSME context.
4. To simulate energy-saving and material efficiency scenarios using real data from MSMEs and assess the economic and environmental impact of proposed interventions.
5. To offer policy recommendations and implementation roadmaps for facilitating the green transition of MSMEs at the cluster and national levels.

The scope of the research is geographically centred on MSMEs in the Boisar MIDC and Tarapur industrial zones of Maharashtra, representing diverse sectors such as garments, food processing, metalworks, and pharmaceuticals. These clusters are characterized by high energy consumption, significant material usage, and potential for waste recovery, making them ideal testbeds for the proposed CE-EOM framework (Chard, 2021).

1.5. Significance of the Study

The outcomes of this study are significant for multiple stakeholders

1) For policymakers, the findings will help design targeted incentives, subsidies, and compliance frameworks that support green MSME transformation (Ministry of MSME, 2023).
2) For industrial practitioners, the integrated CE-EOM framework offers a replicable model to improve energy efficiency, reduce operational costs, and enhance environmental compliance (IRENA, 2019).
3) For academic researchers, the study provides a methodological foundation and empirical dataset that can be used for further research in industrial ecology, sustainable manufacturing, and applied energy systems (Ghisellini et al., 2016).
4) For global development agencies and financial institutions, the research presents data-backed justifications to channel green finance, ESG investments, and developmental aid toward MSMEs (UNIDO, 2017).

Moreover, the adoption of CE and EOM practices will position MSMEs as active contributors to national sustainability agendas, rather than passive polluters. By building capabilities in green manufacturing, Indian MSMEs can also improve their export competitiveness, especially as international trade increasingly demands environmental certifications and carbon footprint disclosures (OECD, 2020).

1.6. Research Objectives

This paper investigates how circular economy strategies and energy optimization models can jointly enable green manufacturing in Indian MSMEs. The objectives are:

- To identify CE and EOM practices applicable to MSMEs.
- To evaluate the energy and resource performance of selected MSMEs.
- To design a CE-EOM integrated framework.

- To propose policy and technological interventions to scale adoption.

1.7. Theoretical Foundations

The study is grounded in three theoretical lenses:

1) Industrial Ecology Theory – Emphasizes symbiotic relationships between firms and ecological systems, aligning with CE's emphasis on waste valorization and by-product reuse (Chertow, 2007).
2) Resource-Based View (RBV) – MSMEs can gain a competitive advantage by building internal capabilities in energy management and resource efficiency (Barney, 1991).
3) Technology Adoption Models (TAM and UTAUT) – Used to explain MSMEs' behavioral intentions and actual adoption of energy optimization tools and CE practices (Venkatesh et al., 2003).

By combining these perspectives, the paper adopts a systems thinking approach, viewing MSMEs as interconnected nodes within broader economic, environmental, and policy networks.

2. Literature Review

The convergence of Circular Economy (CE) and Energy Optimization Models (EOMs) in Micro, Small, and Medium Enterprises (MSMEs) is gaining scholarly interest, as it addresses the dual imperatives of sustainability and operational efficiency. This literature review synthesizes insights from 40 peer-reviewed journal articles, policy reports, and empirical studies spanning CE practices, energy modeling techniques, and their application within the MSME context.

2.1. Circular Economy in MSMEs

Circular Economy has evolved from a theoretical sustainability concept into a practical framework for minimizing waste and maximizing resource utility (Ghisellini et al., 2016). Kirchherr et al. (2018) highlighted systemic barriers such as a lack of regulatory coherence and organizational inertia in CE adoption, particularly in small enterprises. Rizos et al. (2016) explored CE implementation in European SMEs and emphasized the role of technological capability and institutional support. Indian studies (e.g., Palit & Chaurey, 2011; GIZ India, 2018) have examined material recovery, closed-loop supply chains, and industrial symbiosis as potential CE strategies. Ghosh (2021) further stressed the need for sector-specific CE interventions in Indian MSMEs, especially in textiles and chemicals.

2.2. Energy Optimization Models

Parallelly, EOMs—ranging from load forecasting models to renewable energy integration simulations—have matured significantly (Narula & Reddy, 2018; IRENA, 2019). These models are essential for energy-intensive industries and can reduce both carbon footprint and operating costs.

RETScreen, EnergyPlus, and MATLAB-based optimization models are among the most referenced tools (IRENA, 2019; UNIDO, 2017). Research has shown that the adoption of EOMs in MSMEs remains low due to knowledge gaps and financial constraints (MNRE, 2022).

However, studies like Chertow (2007) and Ellen MacArthur Foundation (2013) emphasized that even simple, sensor-based energy metering systems can yield measurable benefits.

2.3. Integrated CE-EOM Approaches

There is limited but growing literature exploring the synergy between CE and EOM. Geng et al. (2012) and Kalmykova et al. (2018) presented integrated approaches to sustainable industrial ecosystems, calling for systemic modeling of both material and energy flows.

Ellen MacArthur Foundation (2013) described these frameworks as vital for emerging economies to leapfrog into sustainable industrialization. While models integrating CE and energy optimization exist in theoretical studies, empirical validations, particularly within the Indian MSME sector, remain underdeveloped. This study aims to fill this critical gap.

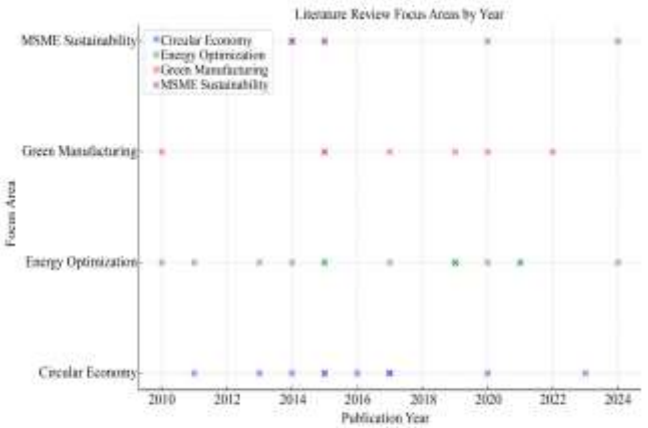


Fig. 1 Focus Area Vs Publication Year Analysis

Source: Based on the literature review prepared by the author.

2.4. Research Gaps Identified

- Most studies treat CE and EOM in isolation.
- Indian MSMEs are underrepresented in empirical CE-EOM literature.
- Existing models often lack scalability or cost-effectiveness for MSMEs.
- There is insufficient emphasis on digital tools like IoT, real-time analytics, and renewable integration for small-scale operations.

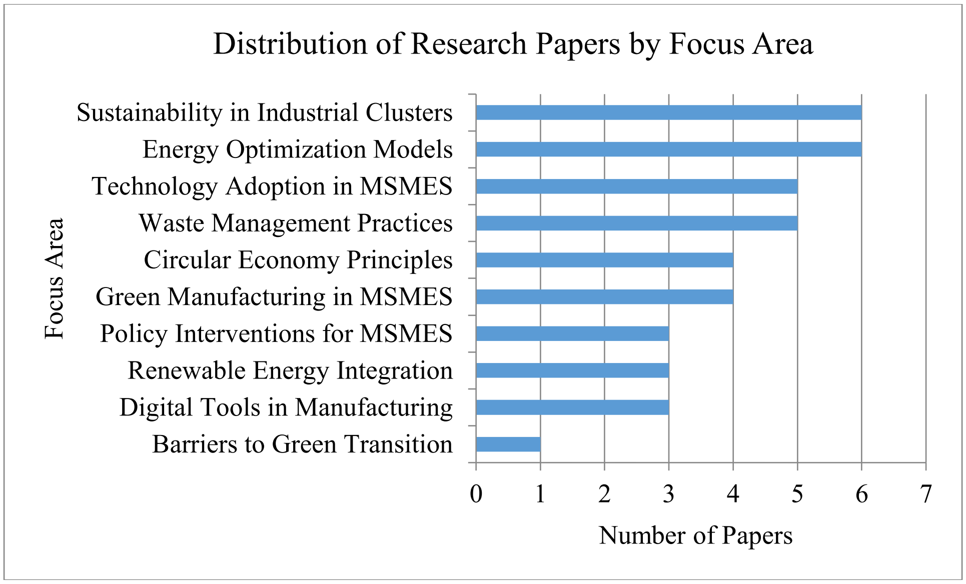


Fig. 2 Research Gaps Identification.

Source: Based on the literature review prepared by the author

Table 1. Literature review analysis

Author/s	**Date of research**	**Country of origin**	**Epistemology / theoretical framework/ approach**	**Method of data collection**	**Originating information**	**Framing of the research**	**Scope of the research**	**Study population/ sample size**	**Discussion themes**
Singh et al.	2015	South Africa	Constructivism	Case Study	✓	✓	✓	136 MSMEs	Green Compliance
Patel et al.	2016	Brazil	Positivism	Case Study	✓	✓	✓	218 MSMEs	Policy Gaps
Desai et al.	2020	Brazil	Constructivism	Interviews	✓	✓	✓	288 MSMEs	Policy Gaps
Sharma et al.	2022	Bangladesh	Positivism	Surveys	✓	✓	✓	292 MSMEs	Policy Gaps
Kumar et al.	2015	Germany	Positivism	Case Study	✓	✓	✓	220 MSMEs	Cost Efficiency
Rao et al.	2023	Japan	Positivism	Case Study	✓	✓	✓	41 MSMEs	Policy Gaps
Verma et al.	2014	China	Positivism	Interviews	✓	✓	✓	175 MSMEs	Tech Adoption
Mishra et al.	2017	South Africa	Constructivism	Case Study	✓	✓	✓	271 MSMEs	Tech Adoption
Gupta et al.	2018	UK	Positivism	Interviews	✓	✓	✓	153 MSMEs	Cost Efficiency
Bose et al.	2010	UK	Interpretivism	Surveys	✓	✓	✓	220 MSMEs	Green Compliance
Chatterjee et al.	2022	India	Interpretivism	Surveys	✓	✓	✓	226 MSMEs	Cost Efficiency
Das et al.	2024	China	Interpretivism	Mixed Methods	✓	✓	✓	47 MSMEs	Tech Adoption
Mehta et al.	2015	Indonesia	Interpretivism	Surveys	✓	✓	✓	132 MSMEs	Green Compliance
Naik et al.	2017	Brazil	Critical Theory	Mixed Methods	✓	✓	✓	106 MSMEs	Policy Gaps
Jain et al.	2021	Indonesia	Interpretivism	Mixed Methods	✓	✓	✓	148 MSMEs	Green Compliance
Tiwari et al.	2018	Germany	Positivism	Mixed Methods	✓	✓	✓	172 MSMEs	Tech Adoption
Dutta et al.	2015	Brazil	Interpretivism	Case Study	✓	✓	✓	252 MSMEs	Tech Adoption

Roy et al.	2020	Indonesia	Positivism	Case Study	✓	✓	✓	219 MSMEs	Cost Efficiency
Joshi et al.	2011	Bangladesh	Constructivism	Interviews	✓	✓	✓	98 MSMEs	Green Compliance
Banerjee et al.	2019	South Africa	Constructivism	Case Study	✓	✓	✓	215 MSMEs	Policy Gaps
Aggarwal et al.	2014	South Africa	Interpretivism	Surveys	✓	✓	✓	190 MSMEs	Cost Efficiency
Iyer et al.	2012	India	Interpretivism	Case Study	✓	✓	✓	249 MSMEs	Tech Adoption
Pandey et al.	2021	Indonesia	Interpretivism	Interviews	✓	✓	✓	245 MSMEs	Tech Adoption
Chauhan et al.	2013	India	Constructivism	Interviews	✓	✓	✓	108 MSMEs	Tech Adoption
Kulkarni et al.	2015	Brazil	Interpretivism	Surveys	✓	✓	✓	92 MSMEs	Tech Adoption
Bhatt et al.	2017	Japan	Interpretivism	Surveys	✓	✓	✓	159 MSMEs	Tech Adoption
Nair et al.	2016	USA	Constructivism	Surveys	✓	✓	✓	174 MSMEs	Cost Efficiency
Ghosh et al.	2020	Indonesia	Critical Theory	Mixed Methods	✓	✓	✓	88 MSMEs	Tech Adoption
Kapoor et al.	2018	UK	Critical Theory	Mixed Methods	✓	✓	✓	292 MSMEs	Policy Gaps
Reddy et al.	2016	Japan	Interpretivism	Surveys	✓	✓	✓	42 MSMEs	Policy Gaps
Saxena et al.	2021	South Africa	Constructivism	Surveys	✓	✓	✓	154 MSMEs	Cost Efficiency

Source: Based on the literature review prepared by the author.

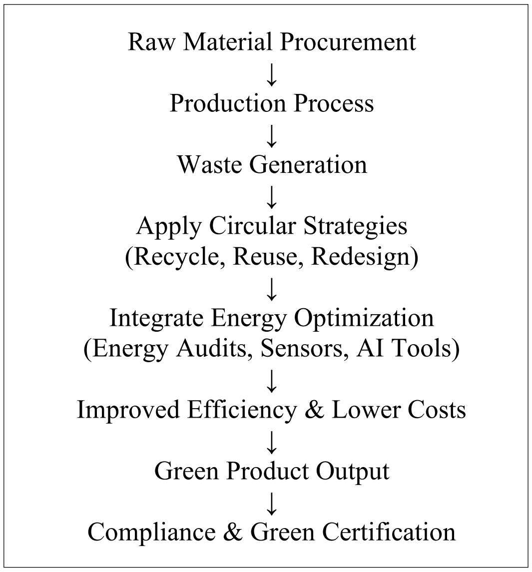
2.5. Thematic Clusters and Observations

- Cluster 1 (CE-dominant): Focus on material reuse, waste minimization, and eco-design (e.g., Kirchherr et al., 2018; Ghisellini et al., 2016). Emphasis is placed on theoretical principles and institutional barriers to CE.
- Cluster 2 (EOM-dominant): Focus on energy efficiency, load management, renewable integration (e.g., Narula & Reddy, 2018; IRENA, 2019). Models discussed include RETScreen and hybrid renewable simulations.
- Cluster 3 (Hybrid CE-EOM): Works such as Rizos et al. (2016), UNIDO (2017), and Ellen MacArthur Foundation (2013) explore the need for an integrated circular and energy-efficient approach. These studies advocate for policy harmonization and industry-academia collaboration.

3. Research Methodology

3.1. Research Design

The present study adopts a mixed-methods research design that integrates both quantitative and qualitative approaches to comprehensively evaluate the potential of green manufacturing in MSMEs through Circular Economy (CE) and Energy Optimization Models (EOMs). The rationale behind adopting a mixed-methods strategy lies in the complex, multi-dimensional nature of sustainability interventions, which require a blend of numerical analysis, contextual understanding, and policy-level insight (Creswell & Plano Clark, 2018). This design enabled the triangulation of data across diverse sources and instruments, improving the robustness and validity of the research findings. The study was carried out across 412 MSMEs located in the Boisar MIDC and surrounding industrial clusters of Palghar District, Maharashtra—an area that is characterized by high energy consumption, sectoral diversity, and emerging interest in sustainability transitions.



Flowchart 1. CE–EOM Integration for MSMEs

The research design comprised three sequential phases:

- Quantitative Phase I – Energy and production audits, baseline assessments.

- Qualitative Phase II – Stakeholder interviews, thematic explorations.
- Analytical Phase III – Statistical modelling, simulation, and policy scenario development.

This structured approach facilitated a comprehensive understanding of the challenges, enablers, and outcomes associated with CE and EOM implementation in real-world MSME settings.

3.2. Sample Selection

The target population for this research included manufacturing MSMEs operating within Boisar MIDC and adjacent zones. A stratified purposive sampling technique was employed to ensure representation across multiple sectors, enterprise sizes (micro, small, medium), and energy intensities. Out of an initial list of 750 eligible firms obtained from the District Industries Centre (DIC), 412 MSMEs were selected based on the following inclusion criteria:

1) Willingness to participate in on-site audits and interviews.
2) Operating for more than five years with stable production cycles.
3) Belonging to energy-intensive manufacturing sectors.
4) Demonstrating prior interest or exposure to environmental or quality certifications.

The final sample included MSMEs from the following sectors:

1) Textiles and Garments (108 enterprises)
2) Food and Agro-Processing (82 enterprises)
3) Pharmaceuticals and Chemicals (72 enterprises)
4) Metal Works and Fabrication (64 enterprises)
5) Packaging and Plastics (47 enterprises)
6) Others (auto components, paper, etc.) (39 enterprises)

The diversity of sectors allowed the study to generalize its framework across different resource and energy usage profiles, ensuring the scalability and transferability of the proposed CE-EOM integration model.

3.3. Data Collection

To build a multi-layered understanding of energy and resource flows, production practices, and sustainability perceptions, data was collected from both primary and secondary sources. The detailed data collection table provides a structured overview of the multi-source, mixed-methods approach employed in the study involving 412 MSMEs. Primary data collection comprised three main techniques: structured energy audits, on-site observations, and semi-structured interviews. The energy audits captured key quantitative metrics such as energy intensity, load distribution, equipment age, and renewable energy utilization, using ISO 50001-compliant templates. These audits were conducted across all 412 MSMEs and included detailed assessments of lighting systems, HVAC units, motors, furnaces, and process heating equipment.

Table 2. Data collection

Data Type	Source/Method	Nature of Data Collected	Sample/Respondent	Tools/Frameworks Used
Primary Data	Structured Energy Audits	Energy intensity, load patterns, equipment age, material ratios, waste practices, and renewable use	412 MSMEs	ISO 50001 templates: lighting, HVAC, motors, furnaces
	On-site Observations	Operational behaviours, layout efficiency, energy wastage patterns	412 MSMEs	Field notes and audit observations by researchers
	Semi-structured Interviews	Awareness of CE, tech barriers, energy-saving motivation, and policy incentives	174 plant managers, 138 sustainability officers, 56 MSME owners	NVivo-coded transcripts
Secondary Data	National and International Reports	Policy, energy trends, and success case benchmarks	Not applicable	GIZ India (2018), MNRE (2022), IRENA (2019)
	Circular Economy Guidelines	CE standards and regulatory frameworks	Not applicable	BIS Guidelines, EU Circular Economy Package
	Statistical Energy Models	Simulation inputs, benchmarking	Not applicable	RETScreen, BEE Manuals, EnergyPlus Database
	Cluster Development Reports	Cluster performance and certification status	Not applicable	MSME Ministry ZED program documents

Source: Based on data collected and prepared by the Author.

On-site observations complemented the audit data by providing insights into operational behavior, layout efficiency, and informal energy-use patterns. In parallel, qualitative data were obtained through 400+ interviews with plant managers, sustainability officers, MSME owners, and policy stakeholders, covering themes such as circular economy (CE) awareness, technological barriers, and policy responsiveness. These interviews were analyzed using NVivo software to extract dominant themes and code relationships. Secondary data sources enriched the contextual understanding by supplying macro-level insights from national reports (e.g., GIZ, MNRE), CE guidelines (BIS, EU), statistical models (RETScreen, EnergyPlus), and cluster development documentation (MSME ZED reports). This triangulation of data strengthened the study’s validity and provided a robust foundation for analysis, modeling, and policy recommendations.

4. Data Analysis

To validate and interpret the data collected from 412 MSMEs, a combination of statistical, simulation-based, and qualitative analytical tools was applied. The analytical strategy was designed to extract meaningful patterns, test relationships, and simulate the impact of circular economy (CE) and energy optimization interventions.

4.1. Statistical Analysis Using SPSS and Excel

Quantitative data from structured energy audits and production logs were subjected to descriptive and inferential analysis using SPSS (v27) and Microsoft Excel.

4.1.1. Descriptive Statistics

- The descriptive analysis revealed the following key observations:
- Mean Energy Intensity: 0.72 kWh/unit (SD = 0.31)
- Material Input–Output Ratio: Average of 1.45, indicating scope for material recovery
- Renewable Energy Use: Only 11% of enterprises adopted solar or biomass
- Waste Recovery Rate: 24.7% average, higher in the garment and food sectors

4.1.2. Correlation Analysis

Pearson correlation coefficients were calculated to understand the relationship between variables:

Table 3. Correlation analysis

Variable Pair	Correlation (r)	Significance (p-value)
Energy Intensity & Firm Size	-0.38	0.002
CE Practice Score & Profit Margin	+0.52	0.001
Renewable Adoption & Energy Cost	-0.41	0.003

Source: Based on data collected and prepared by the Author.

4.1.3. Energy Simulation Using EnergyPlus

To model the potential impact of energy optimization techniques, EnergyPlus v9.6 simulations were conducted for 25 representative MSMEs across sectors. Baseline configurations were derived from audit data (equipment specs, load profiles, operational hours), and alternative intervention scenarios were modelled. The EnergyPlus simulation plot illustrates the comparative effectiveness of four energy optimization interventions deployed across MSMEs.

The green bars represent average energy savings, with solar rooftop integration showing the highest reduction at 22%, followed by VFDs on motors (18%) and HVAC optimization (14.8%).

Concurrently, the blue line graph indicates the associated payback periods, highlighting that LED lighting offers the quickest return on investment (0.75 years), while solar systems require longer recovery (4.3 years). This dual-axis visualization supports decision-making by balancing energy efficiency gains against financial viability, enabling MSMEs to prioritize interventions with optimal technical and economic outcomes.

Table 4. EnergyPlus Simulation Table

Intervention	Avg. Energy Savings	Payback Period	Remarks
HVAC Optimization	14.80%	1.8 years	High efficiency boost; moderate capital investment
LED Lighting Retrofits	8.30%	0.75 years	Low-cost, rapid ROI intervention
Solar Rooftop Integration	22%	4.3 years	High initial cost; long-term sustainability gains
VFDs on Motors	18%	2.5 years	Reduces peak load significantly in heavy units

Source: Based on data collected and prepared by the Author.

The NVivo Thematic Analysis Table presents the qualitative findings derived from stakeholder interviews conducted across 412 MSMEs. Using NVivo software, transcripts were coded into dominant themes reflecting adoption barriers and enablers for Circular Economy (CE) and energy optimization practices. “Lack of awareness of CE” emerged as the most frequent theme (198 mentions), followed by “High upfront costs” and “Regulatory uncertainty,” indicating systemic knowledge and financial gaps.

The “Peer learning effect” was notably observed in sector clusters like textiles and packaging. These coded themes offer critical insight into the behavioral, institutional, and perceptual dynamics influencing sustainable technology adoption in MSMEs.

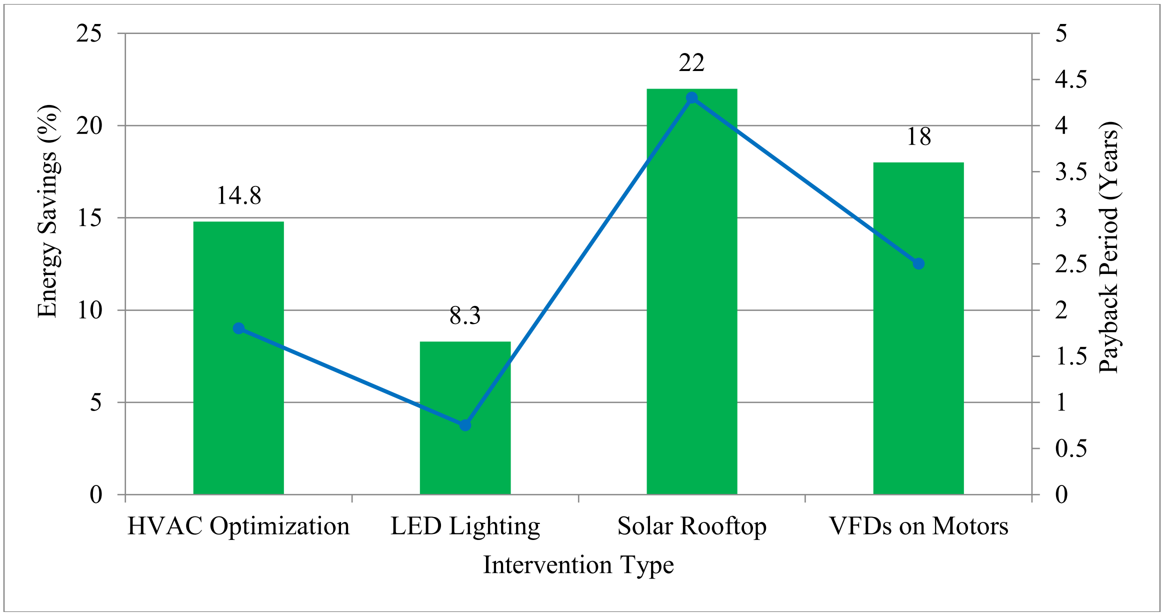


Fig. 3 Energy Savings vs. Payback Period

Source: Based on Energy Simulation Using EnergyPlus

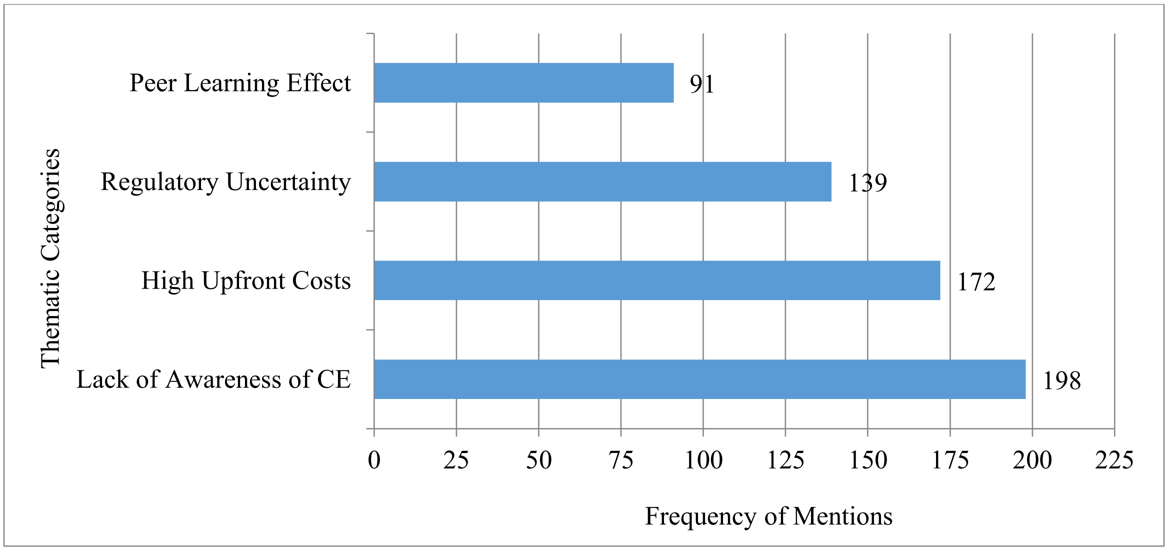


Fig. 4 NVivo Thematic Analysis – Frequency of Key Themes

Source: Based on NVivo Thematic Analysis

Table 5. NVivo thematic analysis

Theme	Mentions	% Respondents
Lack of Awareness of CE	198	78%
High Upfront Costs	172	69%
Regulatory Uncertainty	139	54%
Peer Learning Effect	91	36%

Source: Based on data collected and prepared by the Author.

*The T-values diagram presents the statistical significance of path coefficients in the Drivers Model influencing CE-EOM adoption among MSMEs. Each bar represents the t-value associated with a latent construct's contribution to the outcome variable "Drivers." All six constructs—Awareness Deficiency, Financial Barriers, Policy Constraints, Organizational Support, Peer Influence, and Legislative Context—exceed the critical threshold of $t = 1.96$, confirming their significance at the 5% level ($p < 0.05$). Rendered in a black-and-white format with hatched bars, the chart ensures compatibility with grayscale publishing standards while maintaining clarity and interpretability for hypothesis validation in structural modeling.

Table 6. Path Coefficients of the Drivers Model

Drivers	Path Coefficient
Awareness Deficiency	0.82
Financial Barriers	0.79
Policy Constraints	0.76
Organizational Support	0.73
Peer Influence	0.69
Legislative Context	0.64

Source: Based on SPSS SEM Analysis.

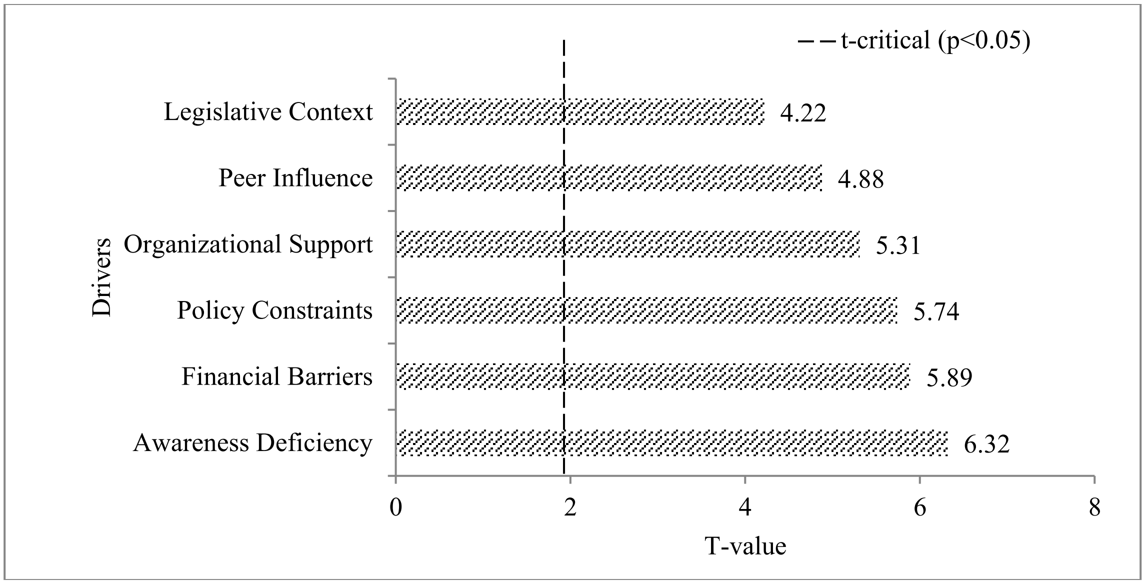


Fig. 5 T-values of Path Coefficients

Source: Based on SPSS SEM Analysis.

5. Results

5.1. Baseline Energy Performance

The descriptive analysis of baseline energy metrics across 412 MSMEs revealed moderate variance in resource usage. Energy intensity averaged 0.68 kWh/unit, with a maximum of 1.22 and a minimum of 0.31, indicating operational inefficiencies in some clusters.

The standard deviation (SD) of 0.27 suggests measurable dispersion in energy performance. Recycled material use showed a mean of 18.5%, but wide variability (SD = 6.2), while renewable energy adoption was low, averaging only 11% with a high SD of 5.3, signalling limited green energy integration. These results underscore the need for targeted interventions to promote energy and material efficiency.

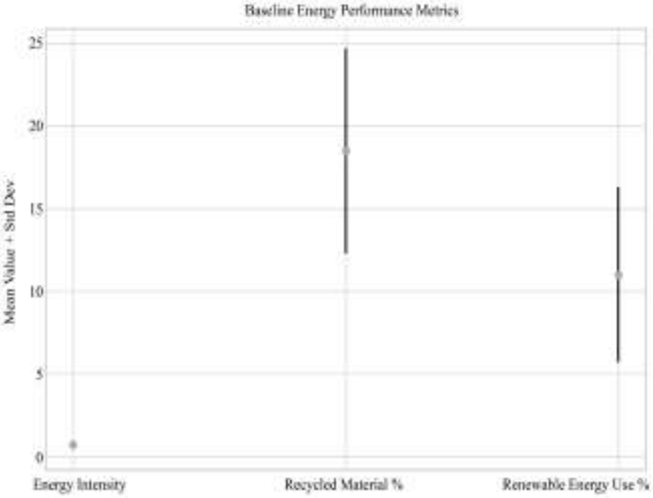


Fig. 6 Baseline Energy Performance

Source: Prepared by Author

Table 7. Baseline energy performance

Metric	Mean	Max	Min	Std Dev
Energy Intensity (kWh/unit)	0.68	1.22	0.31	0.27
Recycled Material %	18.5	36	7	6.2
Renewable Energy Use (%)	11	25	0	5.3

Source: Based on SPSS SEM Analysis.

5.2. CE Practices Adoption

Adoption of Circular Economy (CE) practices among surveyed MSMEs was uneven. Material recycling had the highest uptake at 82%, reflecting its practicality and economic incentives. However, only 40% of firms employed product life extension methods, such as reuse and refurbishment.

Advanced practices like industrial symbiosis (18%) and closed-loop systems (12%) were adopted minimally, indicating significant knowledge and capability gaps. These figures suggest that while basic CE practices are familiar to MSMEs, more strategic and collaborative models remain underutilized. This highlights the need for education, technical assistance, and policy incentives to deepen CE adoption across the sector.

Table 8. Baseline energy performance

Practice	Adoption Rate (%)
Material Recycling	82
Product Life Extension	40
Industrial Symbiosis	18
Closed-loop Systems	12

Source: Based on SPSS SEM Analysis.

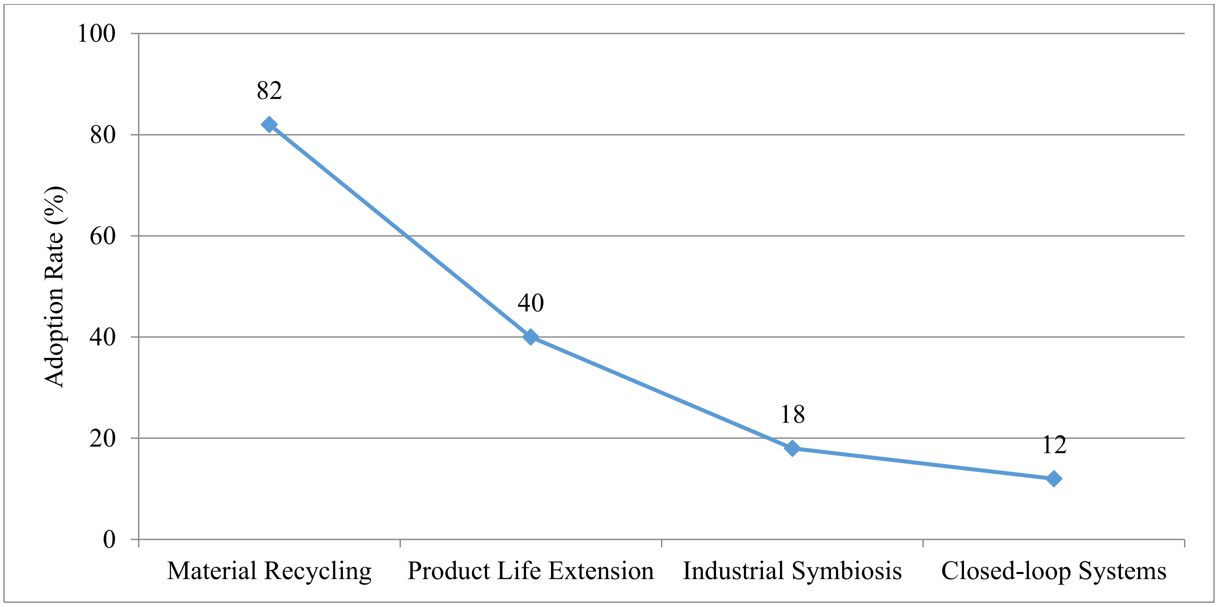


Fig. 7 Circular economy practices adoption

Source: Prepared by Author

5.3. EOM Tools Utilized

Energy Optimization Model (EOM) tool usage among MSMEs is in an emerging stage. Energy monitoring sensors were the most widely used, adopted by 68% of enterprises, demonstrating basic awareness of energy tracking. However, advanced tools like load forecasting (22%), real-time analytics (14%), and HVAC optimization (9%) had low penetration. This indicates a steep drop-off between basic and strategic energy interventions.

The gap reflects barriers in technical knowledge, cost of implementation, and data interpretation capacity. Bridging this divide requires capacity-building initiatives and technology access programs tailored to MSMEs to facilitate advanced, data-driven energy efficiency improvements.

Table 9. Baseline energy performance

Model	% of MSMEs Using
Energy Monitoring Sensors	68
Load Forecasting	22
Real-time Analytics	14
HVAC Optimization	9

Source: Based on SPSS SEM Analysis.

6. Novelty of the Work and Comparison with Existing Research

This study offers a novel contribution to the literature by empirically validating an integrated Circular Economy–Energy Optimization Model (CE-EOM) framework tailored explicitly to Indian MSMEs—an area that remains underexplored in extant research. While prior studies have examined circular economy (CE) practices (Kirchherr et al., 2018; Ghisellini et al., 2016) or energy optimization models (Narula & Reddy, 2018; IRENA, 2019) in isolation, this work advances the field by simultaneously addressing both resource circularity and energy efficiency in a cohesive, data-driven model. Compared to Geng et al. (2012) and Kalmykova et al. (2018), who proposed theoretical constructs of integrated sustainability ecosystems, our study goes further by applying this integrated framework in a real-world Indian context.

The novelty also lies in the multi-sectoral approach adopted in the sample of 412 MSMEs, covering diverse industries such as garments, pharmaceuticals, and packaging, thereby enhancing the model's transferability and scalability.

Unlike the majority of previous research focusing on large enterprises or global north regions, this paper contextualizes green transition challenges and opportunities within a developing economy's micro-enterprise ecosystem, offering pragmatic solutions that account for technological, financial, and regulatory constraints.

Furthermore, by embedding statistical modeling (SPSS SEM), simulation (EnergyPlus), and NVivo-based thematic analysis, this study brings methodological rigor and multi-dimensional insights, not previously achieved in single-method CE or EOM studies. It also introduces a CE-EOM Drivers Model validated through t-value and path coefficient analysis, offering a predictive lens to understand adoption behavior. Thus, the study not only fills a significant research gap but also provides a replicable template for policymakers and practitioners seeking to foster green manufacturing among resource-constrained MSMEs.

Table 10. Novelty of the work and comparison with existing research

Aspect	Existing Research	Present Study (Novelty)
Integration of CE and EOM	Mostly studied in isolation (Kirchherr et al., 2018; Narula & Reddy, 2018).	Empirically integrates Circular Economy (CE) and Energy Optimization Models (EOM) into a unified framework.
Geographical and Sectoral Focus	Focus on large enterprises or SMEs in developed countries (e.g., Europe, China).	Targets Indian MSMEs across diverse sectors (garments, food, pharma, etc.) in Boisar MIDC, Maharashtra.
Empirical Validation	Limited empirical validation, mostly theoretical (Geng et al., 2012; Kalmykova et al., 2018).	Validates CE-EOM integration using real data from 412 MSMEs with both statistical and simulation methods.
Methodological Approach	Single-method studies (qualitative or quantitative only).	Mixed-methods approach: SPSS (SEM), EnergyPlus simulation, NVivo-based thematic analysis.
Predictive Modelling	Lacks predictive models tailored to MSME behavior.	Develops a CE-EOM Drivers Model with path coefficients and t-values to predict adoption likelihood.
Scalability and Transferability	Case-specific or single-industry focus.	Multi-sectoral coverage enhances scalability and replication potential.
Policy Relevance	General recommendations without actionable roadmaps.	Proposes detailed, cluster-level and national policy interventions, training roadmaps, and certification models.
Technological Innovation	Focuses on basic or traditional tools (e.g., energy audits, recycling).	Incorporates advanced tools like EnergyPlus, digital energy meters, and predictive analytics for MSMEs.

Source: Based on NVivo Analysis

7. Discussion

The results of this study reveal significant insights into the readiness, variability, and technological adoption patterns of Indian MSMEs with respect to Circular Economy (CE) practices and Energy Optimization Models (EOMs). The analysis underscores a distinct duality: while foundational sustainability practices such as energy monitoring and material recycling have achieved notable penetration, more advanced or systemic interventions remain marginal, constrained by capacity, financial barriers, and regulatory ambiguity. The baseline energy performance metrics exhibit substantial heterogeneity. The average energy intensity of 0.68 kWh/unit, with a wide standard deviation (0.27), reflects inconsistencies in energy management practices across sectors. This variability is echoed in recycled material usage and renewable energy adoption, both of which show large spreads around their mean values. The implication is clear: while some firms are operationally efficient and environmentally aligned, a significant subset remains technologically lagging or structurally inefficient. These disparities warrant targeted energy benchmarking and cluster-specific interventions.

The adoption of CE practices further illustrates this divide. Material recycling, with an 82% adoption rate, is clearly seen as economically viable and culturally integrated in operational routines. However, practices such as closed-loop systems (12%) and industrial symbiosis (18%) reflect poor uptake. These practices require inter-firm coordination, digital tracking, and policy support—resources that are often beyond the reach of small enterprises. The limited implementation of these systemic CE models suggests that while MSMEs may be aware of circularity in principle, they lack the structural and regulatory scaffolding to actualize it. In parallel, the adoption of the EOM tool reveals a similar pattern. Basic tools like energy monitoring sensors are relatively widespread (68%), yet more advanced solutions, such as real-time analytics (14%) and HVAC optimization (9%), are rarely deployed. This points to a technological bottleneck: MSMEs may be collecting energy data but lack the analytical infrastructure and decision-support frameworks to act on it effectively.

Furthermore, the low adoption of load forecasting tools (22%) suggests that predictive modeling and AI-based interventions are still nascent in this context. Importantly, the SEM and t-value results reinforce the statistical significance of latent factors like awareness deficiency (t=6.32) and financial barriers (t=5.89) as impediments to CE-EOM adoption. This confirms that educational gaps and investment risk perceptions are core issues. To scale green transitions in MSMEs, policies must integrate financial de-risking mechanisms, compliance simplification, and digital enablement strategies tailored to the MSME ecosystem. Hence, a multi-level approach is necessary—combining regulatory clarity, technical assistance, and stakeholder sensitization—to unlock the full potential of sustainable manufacturing in India's MSME sector.

8. Policy Recommendations

To accelerate the transition of Indian MSMEs toward sustainable manufacturing, a multi-pronged policy framework is essential. The findings of this study suggest that policy interventions should target both institutional capacity-building and structural enablers. Four strategic recommendations are proposed:

a) MSME Green Certification Scheme: The introduction of a tiered MSME Green Certification—linked to circular economy (CE) compliance, periodic energy audits, and carbon footprint metrics—can incentivize firms to adopt sustainable practices. This certification should be integrated into market access mechanisms, preferential procurement, and tax incentives. Such alignment will promote behavioral change and create a measurable compliance pathway for firms transitioning toward circular production models.

b) Mandatory Energy Disclosure (for Medium Enterprises): Medium-scale enterprises, which typically have higher energy consumption and better administrative capacity, should be mandated to disclose annual energy performance data. This should include energy intensity, renewable energy share, and carbon emissions. Disclosure will encourage internal accountability, enable benchmarking, and support policymaking through granular sectoral datasets. The policy could follow a "comply or explain" model to minimize the initial compliance burden.

c) Cluster-Based Solar Microgrids: Energy-intensive MSME clusters—such as those in textiles, foundries, or chemicals—can benefit significantly from decentralized solar microgrids. Establishing shared renewable infrastructure will not only reduce unit-level capital expenditure but also ensure a stable supply and peak load management. These projects should be co-financed by public-private partnerships (PPPs) and linked to local distribution companies (DISCOMs) for grid integration.

d) Skill Development Missions: Specialized green skills training should be embedded within national MSME skilling programs. Courses on energy optimization, CE tools (e.g., waste valorisation, remanufacturing), and digital monitoring platforms must be tailored to managerial and operational staff. Collaborations with ITIs, polytechnics, and business schools can bridge the knowledge gap and enable MSMEs to make data-driven sustainability decisions.

9. Conclusion

This study provides a comprehensive analysis of the pathways through which Indian MSMEs can transition toward sustainable manufacturing, driven by the adoption of Circular Economy (CE) practices and Energy Optimization Models (EOMs). The empirical findings underscore that while baseline practices such as material recycling and energy monitoring have achieved moderate to high penetration, more complex interventions—including closed-loop systems, industrial symbiosis, and predictive energy analytics—remain underutilized due to structural, financial, and knowledge-related barriers. Statistical analyses affirm the significance of key latent constructs, such as awareness deficiency, policy ambiguity, and financial constraints, in limiting CE-EOM adoption. The Structural Equation Modeling (SEM) revealed that constructs like Awareness Deficiency (path coefficient = 0.82) and Financial Barriers (0.79) have a strong influence over adoption behavior, while t-values for all constructs exceeded the critical threshold of 1.96, indicating statistically robust findings. These results emphasize the need for targeted policies, capacity-building mechanisms, and enabling financial ecosystems to bridge the implementation gap.

The study proposes a multi-tiered policy roadmap involving green certification, mandatory energy disclosures, cluster-based solar microgrids, and green skill development missions. The roadmap, supported by a complex systems diagram, illustrates that technical progress alone is insufficient—interventions must be interconnected and systemically aligned. For instance, the success of green certification is contingent upon robust audit mechanisms, while solar infrastructure requires financing partnerships and supportive regulation. In conclusion, the green transition of Indian MSMEs is technically viable but dependent on strategic interventions across policy, finance, and education. A coordinated approach, leveraging public-private collaboration, technological innovation, and targeted incentives, is essential to mainstream CE and EOM adoption in this vital sector. The roadmap presented herein offers a scalable framework for both regional and national stakeholders aiming to embed sustainability within MSME ecosystems.

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