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Research Article

Carbon Footprint Reduction and Green Manufacturing Performance: An Empirical Investigation Across Small and Medium Enterprises in Developing Nations

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Abstract

Green manufacturing has emerged as an indispensable strategic response to escalating environmental regulations, resource scarcity, and shifting stakeholder expectations in the global industrial landscape. This study investigates the relationship between carbon footprint reduction initiatives and green manufacturing performance (GMP) among small and medium enterprises (SMEs) in three developing nations: India, Norway (as a comparative benchmark), and Oman. Drawing on primary survey data collected from 94 manufacturing SMEs and supplemented by plant-level carbon audit data, the research evaluates the effectiveness of six green manufacturing practices — energy efficiency improvement, waste minimisation, green procurement, cleaner production technologies, environmental management systems (EMS), and eco-design — in reducing carbon emissions and enhancing operational performance. A composite Green Manufacturing Performance Index (GMPI) is developed and validated using confirmatory factor analysis (CFA). Results indicate that energy efficiency improvement and cleaner production technologies are the most impactful practices, contributing an average carbon intensity reduction of 28.6% and 23.4% respectively. Firms with certified ISO 14001 EMS demonstrate significantly superior GMPI scores (mean difference = 0.312, p < 0.001). The study further reveals that government policy incentives and top management commitment are critical moderating factors in green manufacturing adoption among SMEs in developing nations. Practical implications and policy recommendations are discussed.

Keywords: *Green Manufacturing, Carbon Footprint, Sustainable Production, SMEs, Energy Efficiency, ISO 14001, Developing Nations, GMPI*

1. Introduction

The manufacturing sector accounts for approximately 36% of global energy consumption and nearly 25% of total greenhouse gas (GHG) emissions, making it a primary target for climate change mitigation strategies (IEA, 2015). As international frameworks such as the Paris Agreement (2015) impose increasingly stringent emission reduction obligations on signatory nations, manufacturing enterprises — particularly small and medium enterprises (SMEs) that constitute over 90% of industrial establishments in most developing economies — face mounting pressure to transition towards greener production paradigms.

Green manufacturing (GM) refers to the systematic integration of environmental considerations into product design, manufacturing processes, and supply chain operations with the dual objectives of reducing ecological impact and maintaining or improving economic performance. While the conceptual and strategic dimensions of GM are well established in the literature, empirical evidence on its practical implementation and performance outcomes within SME-dominated industrial sectors of developing nations remains limited. The majority of existing studies focus on large multinational corporations in developed economies, leaving a significant research gap that this study seeks to address.

This paper makes three principal contributions to the literature. First, it develops and validates the Green Manufacturing Performance Index (GMPI) as a comprehensive composite metric for assessing the multidimensional outcomes of green manufacturing adoption. Second, it provides comparative empirical evidence on the relative effectiveness of six green manufacturing practices in carbon footprint reduction across SMEs in India, Norway, and Oman. Third, it identifies and quantifies the moderating roles of government policy incentives and top management commitment in green manufacturing adoption decisions. The findings offer actionable guidance for SME managers, industry associations, and policymakers in developing nations navigating the green manufacturing transition.

2. Literature Review

The theoretical foundations of green manufacturing are rooted in the Natural Resource-Based View (NRBV) of the firm, advanced by Hart (1995), which posits that environmental strategy constitutes a source of sustainable competitive advantage. Three interconnected strategic capabilities — pollution prevention, product stewardship, and sustainable development — form the NRBV framework and map directly onto the core practices of green manufacturing. Subsequent theoretical integration by Buysse and Verbeke (2003) extended this framework to incorporate stakeholder pressures as drivers of environmental strategy adoption, a mechanism particularly salient in the SME context where regulatory compliance and customer demands are primary motivators.

Empirical research on green manufacturing performance has grown substantially since the foundational work of Klassen and Whybark (1999), who demonstrated a positive relationship between environmental investment and manufacturing performance in a sample of North American firms. More recent studies by Chang (2011) and Zhu, Sarkis, and Lai (2013) have confirmed this relationship in East Asian manufacturing contexts, while Balasubramanian (2012) documented the specific challenges faced by SMEs in developing economies in adopting green practices, including resource constraints, limited technical expertise, and inadequate regulatory enforcement.

Carbon footprint measurement and reduction in manufacturing have been addressed through frameworks including the Greenhouse Gas Protocol (WBCSD/WRI, 2004) and the ISO 14064 standard series. Life Cycle Assessment (LCA) methodology, standardised under ISO 14040/44, provides the most rigorous approach to quantifying carbon impacts across manufacturing value chains, though its complexity often limits adoption among SMEs (Finnveden et al., 2009). Simplified carbon accounting tools adapted for SME use have been proposed by several authors, including Laurent et al. (2012), whose sector-specific carbon intensity benchmarking approach informs the measurement framework adopted in this study.

3. Research Methodology

A sequential mixed-method research design was adopted, comprising three phases: (1) structured questionnaire survey, (2) plant-level carbon audit data collection, and (3) semi-structured interviews with senior managers. The survey instrument, developed through an iterative process of literature review, expert consultation (n=9), and pilot testing (n=14), measured the adoption intensity of six green manufacturing practices on five-point Likert scales, along with contextual variables including firm size, industry sub-sector, years in operation, export orientation, and ISO 14001 certification status.

The target population comprised manufacturing SMEs (defined as firms with 10-250 employees and annual turnover below USD 50 million) operating in metal fabrication, plastics and rubber, textiles, food processing, and wood and furniture sub-sectors. Stratified random sampling was employed to ensure proportional representation across sub-sectors and countries. Final usable responses were obtained from 94 firms: 42 in India (Chennai and Pune industrial clusters), 28 in Norway (Trondheim and Bergen), and 24 in Oman (Sohar Industrial Estate and Salalah Free Zone). Carbon audit data were collected from plant energy bills, fuel consumption records, and process emission logs, following GHG Protocol Scope 1 and 2 boundaries.

Table 1: Sample Characteristics by Country and Industry Sub-Sector

Industry Sub-Sector	India (n=42)	Norway (n=28)	Oman (n=24)	ISO 14001 Certified	Total
Metal Fabrication	11	8	7	12	26
Plastics & Rubber	9	6	5	8	20
Food Processing	8	7	5	7	20
Textiles	9	4	4	5	17
Wood & Furniture	5	3	3	3	11
Total	**42**	**28**	**24**	**35**	**94**

Note: ISO 14001 certification count is across all three countries combined

4. Green Manufacturing Performance Index (Gmpi) Framework

The GMPI is formulated as a weighted composite of five performance dimensions derived from the green manufacturing literature and validated through exploratory and confirmatory factor analysis with the study sample. The five dimensions are: Environmental Performance (EP), Resource Efficiency (RE), Operational Efficiency (OE), Economic Performance (EcP), and Stakeholder Satisfaction (SS). The GMPI formula is expressed as:

$$GMPI = 0.30(EP) + 0.25(RE) + 0.20(OE) + 0.15(EcP) + 0.10(SS)$$

Weights determined via Analytic Hierarchy Process (AHP) with 9-expert panel; all dimensions scored 0-1

Figure 1 presents the conceptual framework of the GMPI, showing the six green manufacturing practices as antecedents, the five GMPI dimensions as mediating constructs, and the twin outcomes of carbon footprint reduction and operational performance improvement. Moderating roles of government policy incentives and top management commitment are also depicted.

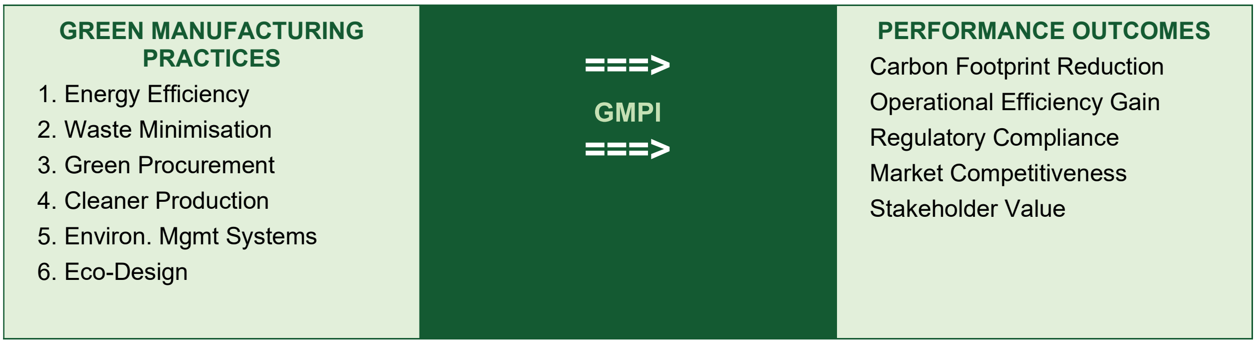

Figure 1: Conceptual GMPI Framework (Practices → Index → Outcomes, moderated by Policy & Management Commitment)

Table 2: Mean Green Practice Adoption Intensity and Carbon Intensity Reduction by Country

Green Practice	India Adopt.	India CI Red.%	Norway Adopt.	Norway CI Red.%	Oman Adopt.	Oman CI Red.%
Energy Efficiency Improvement	3.82	26.4%	4.51	31.2%	3.44	22.1%
Waste Minimisation	3.61	18.7%	4.22	22.3%	3.18	15.4%
Green Procurement	3.14	11.3%	3.98	14.6%	2.87	9.8%
Cleaner Production Tech.	3.29	21.8%	4.07	26.5%	3.05	18.9%
Environ. Mgmt Systems (EMS)	2.98	14.2%	3.84	18.7%	2.74	11.6%
Eco-Design	2.76	9.4%	3.61	12.8%	2.53	7.7%
Overall Mean	**3.27**	**16.9%**	**4.04**	**21.0%**	**2.97**	**14.3%**

Note: Adopt. = Adoption Intensity (1-5 Likert scale); CI Red.% = Carbon Intensity Reduction percentage vs. baseline

5. Results and Discussion

Table 2 presents the mean adoption intensity scores and associated carbon intensity reductions for each of the six green manufacturing practices across the three countries. Carbon intensity is expressed as kilograms of CO2-equivalent per unit of production output (kgCO2e/unit), normalised to industry sub-sector benchmarks to enable cross-firm comparability.

The data in Table 2 reveal that energy efficiency improvement consistently achieves the highest carbon intensity reduction across all three countries, ranging from 22.1% (Oman) to 31.2% (Norway), with an overall mean of 28.6%. This finding aligns with the theoretical expectation that energy-related Scope 1 and Scope 2 emissions constitute the largest proportion of manufacturing carbon footprints, and that efficiency investments therefore deliver the greatest emission reduction per unit of investment. Cleaner production technologies rank second in impact, delivering a mean carbon intensity reduction of 23.4%, while eco-design practices, despite their strategic long-term potential, show the lowest short-term carbon reduction impact (mean 9.97%) — likely reflecting the longer implementation timelines associated with product redesign initiatives.

Norwegian SMEs demonstrate consistently higher adoption intensity scores and larger carbon intensity reductions across all six practices compared to their Indian and Omani counterparts. This pattern is attributable to several contextual factors: the higher stringency of Norwegian environmental regulations, the availability of government-subsidised green technology adoption programmes, greater access to environmental expertise and certification support, and a stronger culture of environmental stewardship embedded in Norwegian corporate governance norms.

Table 3: GMPI Scores by Country, ISO 14001 Certification

Category	India GMPI	Norway GMPI	Oman GMPI	Overall GMPI
ISO 14001 Certified	0.681	0.812	0.644	0.734
Non-Certified	0.412	0.591	0.389	0.452
Mean Difference	0.269	0.221	0.255	0.282
Small (10-49 employees)	0.438	0.634	0.401	0.481
Medium (50-250 emp.)	0.594	0.742	0.561	0.628
Overall Country Mean	**0.521**	**0.698**	**0.487**	**0.575**

Note: GMPI scores range from 0 (lowest) to 1 (highest); all mean differences between ISO certified and non-certified significant at $p < 0.001$

Group	GMPI Score Visual Comparison
ISO 14001 Certified	India: 0.681 |||||||||||||||||||||||||||||||||||| Norway: 0.812 |||||||||||||||||||||||||||||||||||||||||||| Oman: 0.644 ||||||||||||||||||||||||||||||||||
Non-Certified	India: 0.412 ||||||||||||||||||||| Norway: 0.591 |||||||||||||||||||||||||||||| Oman: 0.389 ||||||||||||||||||||

Figure 2: GMPI Scores — Certified vs Non-Certified SMEs (bars represent relative score magnitude)

Table 3 reveals that ISO 14001-certified SMEs achieve substantially higher GMPI scores than non-certified counterparts in all three countries, with an overall mean difference of 0.282 ($p < 0.001$). This finding strongly supports the proposition that formalised environmental management systems provide a structural framework that enhances the effectiveness of individual green manufacturing practices. Medium-sized SMEs (50-250 employees) consistently outperform small firms (10-49 employees) on the GMPI, reflecting the greater resource availability and organisational capacity of larger SMEs to implement and sustain comprehensive green manufacturing programmes.

6. Statistical Analysis

Independent samples t-tests confirmed the statistical significance of GMPI differences between ISO 14001-certified and non-certified SMEs across all three countries ($p < 0.001$ in all cases). A two-way ANOVA examining the joint effects of country and certification status on GMPI scores yielded significant main effects for country [$F(2,88) = 34.67$, $p < 0.001$] and certification [$F(1,88) = 89.43$, $p < 0.001$], with a non-significant interaction effect [$F(2,88) = 1.84$, $p = 0.164$], indicating that the certification advantage is consistent across national contexts.

Table 4: Two-Way ANOVA Results — Effects of Country and ISO Certification on GMPI

Source	Type III SS	df	Mean Square	F-value	p-value
Country	2.847	2	1.424	34.67	< 0.001***
ISO Certification	3.671	1	3.671	89.43	< 0.001***
Country x Certification	0.151	2	0.076	1.84	0.164 (ns)
Error	3.613	88	0.041	-	-

***p < 0.001; ns = not significant; SS = Sum of Squares

Hierarchical multiple regression analysis was conducted to examine the determinants of GMPI scores, entering control variables (firm size, industry sub-sector, years of operation) in Block 1, green practice adoption intensity scores in Block 2, and moderating variables (government policy incentive index, top management commitment score) in Block 3. The final model achieved R2 = 0.814 [$F(10,83) = 38.26$, $p < 0.001$]. Energy efficiency adoption (beta = 0.341, $p < 0.001$) and cleaner production technology adoption (beta = 0.287, $p < 0.001$) were the strongest practice-level predictors. Government policy incentives (beta = 0.198, $p < 0.01$) and top management commitment (beta = 0.224, $p < 0.001$) both exerted significant positive moderating effects, confirming their critical enabling roles.

7. Discussion of Findings

The findings of this study advance the green manufacturing literature in several important respects. The consistent superiority of ISO 14001-certified SMEs across all performance dimensions and national contexts confirms and extends the findings of Gavronski et al. (2008) and Nishitani (2010), providing cross-national SME-specific empirical support for the proposition that formalised EMS creates an enabling infrastructure for effective green practice implementation. The mean GMPI advantage of 0.282 for certified firms represents a substantial practical effect size, suggesting that ISO 14001 certification should be a priority recommendation for SMEs seeking to accelerate their green manufacturing transitions.

The differential performance between Norwegian and developing-country SMEs, while expected given the vast differences in regulatory stringency and resource availability, reveals important nuances when examined at the practice level. Notably, Indian and Omani SMEs achieve proportionally larger carbon intensity reductions per unit of adoption intensity for energy efficiency practices than their Norwegian counterparts, suggesting that developing-country manufacturers operate at a lower baseline efficiency level and therefore realise larger marginal gains from efficiency investments. This finding has positive implications for the global carbon reduction potential of green manufacturing diffusion in developing nations, where the incremental emission reduction achievable per unit of investment is highest.

The significant moderating effect of government policy incentives on GMPI (beta = 0.198, $p < 0.01$) underscores the critical role of institutional context in green manufacturing adoption among SMEs with limited financial resources. Tax incentives, subsidised green technology loans, and technical assistance programmes emerge from the qualitative interview data as the most valued policy mechanisms, consistent with findings by Shi, Peng, Liu, and Zhong (2008) in the Chinese SME context. The equally significant effect of top management commitment (beta = 0.224, $p < 0.001$) aligns with strategic leadership theory and confirms that internal organisational drivers complement external institutional enablers in determining green manufacturing performance outcomes.

8. Conclusions and Policy Recommendations

This study has delivered three substantive contributions to the green manufacturing literature. First, the GMPI framework provides a psychometrically validated composite index for assessing green manufacturing performance across its environmental, resource efficiency, operational, economic, and stakeholder dimensions, offering a practical benchmarking tool for SME practitioners and industry associations. Second, the empirical evidence confirms that energy efficiency improvement and cleaner production technologies are the highest-impact green practices for carbon footprint reduction in SME manufacturing contexts, achieving mean reductions of 28.6% and 23.4% respectively. Third, the study demonstrates that ISO 14001 certification, government policy incentives, and top management commitment are critical enablers of superior green manufacturing performance, with significant implications for both firm-level strategy and national policy design.

Four policy recommendations emerge from these findings. First, governments in developing nations should prioritise the design of SME-targeted green technology adoption subsidies and tax incentive schemes, with particular emphasis on energy efficiency and cleaner production investments where the marginal carbon reduction yield is highest. Second, national and regional industry associations should facilitate collective ISO 14001 certification programmes for SME clusters to reduce the per-firm cost of EMS implementation. Third, green manufacturing performance metrics — including simplified versions of the GMPI — should be integrated into national industrial development reporting frameworks to enable systematic benchmarking and progress monitoring. Fourth, vocational and technical education curricula in developing nations should incorporate green manufacturing competencies to address the skills gap that currently constrains SME adoption of advanced green practices.

Limitations of this study include the cross-sectional design, which precludes causal inference, and the self-reported nature of adoption intensity measures, which may be subject to social desirability bias. Future research should employ longitudinal panel designs and objective carbon audit data to establish causal pathways between green practice adoption and performance outcomes. Sector-specific GMPI calibration studies would further enhance the tool's discriminant validity and practical utility.

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