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LOW-CARBON SMALL INDUSTRIES: STRATEGIES FOR EMISSION MITIGATION TO SUPPORT SUSTAINABLE TOURISM DEVELOPMENT IN BALI

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Abstract

Increasing carbon emissions from industrial activities has become a significant challenge in the development of sustainable mechanical engineering technologies, particularly for small industries supporting the tourism sector. Small industries in Bali play a strategic role in regional economic development; however, inefficient energy consumption, waste management practices, and production processes may contribute to increased carbon footprints. This study aims to analyze the influence of operational factors in small industries, including energy utilization, waste management, and production technology, on carbon emissions, as well as to develop an emission mitigation model to support sustainable tourism in Bali. This study employs a quantitative approach with an explanatory research design. Data were collected through questionnaires, field observations, and documentation involving 150 small industry operators in the tourism sector in Bali selected using purposive sampling. Data analysis was conducted using validity and reliability testing, descriptive analysis, and Structural Equation Modeling-Partial Least Squares (SEM-PLS). The results indicate that operational factors in small industries are associated with carbon emission levels and can serve as a foundation for developing strategies related to energy efficiency, waste management improvement, and the implementation of low-carbon production technologies. This study contributes to the advancement of mechanical engineering through an applicable low-carbon engineering approach to improve environmental efficiency and support the transformation of small industries toward sustainable production systems.

Keywords: Low-carbon industry; Carbon emissions; Energy efficiency; Green technology; Sustainable tourism.

INTRODUCTION

Climate change and increasing carbon emissions are major challenges in achieving sustainable development due to the growing dependence on energy-intensive economic activities and production processes. The industrial sector contributes significantly to greenhouse gas emissions through fossil fuel consumption, manufacturing activities, and waste generation. Therefore, the transition toward low-carbon production requires improved energy efficiency, environmentally friendly technologies, and sustainable production systems. From a mechanical engineering perspective, energy-efficient technologies and production optimization are essential for reducing carbon intensity while maintaining productivity. Sharma et al. (2026) emphasized that climate change mitigation requires integrated strategies involving technological innovation, resource efficiency, and sustainable production transformation. Furthermore, green innovation and environmental strategies improve environmental performance through optimized energy utilization and reduced ecological impacts Javed et al. (2024), while green technology supports industrial carbon efficiency through cleaner production systems (De Mello Santos et al., 2022).

Indonesia faces challenges in balancing economic growth and carbon emission reduction, requiring the involvement of various sectors, including small industries and micro, small, and medium enterprises (MSMEs). Although MSMEs contribute significantly to local economic activities, many small industries still experience limitations in adopting low-carbon technologies due to financial constraints, limited technological access, and inadequate environmental management capacity. Bhuyan (2024) highlighted that MSMEs in Asia face barriers in achieving carbon neutrality, particularly related to investment capability and technology adoption. Therefore,

developing low-carbon small industries is essential to integrate energy efficiency, waste management, and technological innovation into sustainable industrial practices.

The tourism sector is closely associated with carbon emissions through transportation, energy consumption, accommodation, and local creative industries. Bali, as one of the world's leading tourism destinations, has numerous small industries, including culinary businesses, handicrafts, and creative enterprises that support tourism activities. However, these industries may generate carbon emissions through energy use, fuel consumption, and inefficient waste management practices. Soratana et al. (2021) demonstrated that tourism activities contribute significantly to global carbon footprints through interconnected supply chains. Thus, sustainable tourism requires not only destination management but also the transformation of supporting industries toward efficient and low-carbon production systems.

Previous studies have examined the relationship between economic activities, green technology, and carbon emission reduction; however, most research remains focused on macro-level analyses, such as tourism growth, national energy consumption, and carbon emission trends. Xia et al. (2022) identified global tourism carbon emission drivers but did not specifically examine how operational activities of small industries within tourism supply chains influence carbon emissions. Moreover, green innovation studies have mainly focused on large enterprises with higher technological and investment capacities. Mazhar et al. (2024) highlighted that although small and medium-sized enterprises have considerable potential to reduce carbon footprints, low-carbon implementation remains constrained by technological limitations, resource availability, and environmental management capabilities. This indicates a research gap regarding carbon mitigation models specifically designed for small industries supporting tourism activities.

Based on this research gap, this study aims to analyze the influence of operational factors, including energy utilization, waste management, and production technology, on carbon emissions in small industries supporting the tourism sector in Bali. Using a quantitative approach, this study identifies relationships among variables and develops a carbon emission mitigation model suitable for small industry characteristics. The research contributes to mechanical engineering, particularly in energy engineering and sustainable production technologies, by expanding knowledge regarding operational factors, energy efficiency, green technology, and carbon emission mitigation. Practically, this study provides a foundation for developing a low-carbon small industry model that can support business actors and policymakers in designing emission reduction strategies based on local conditions, thereby strengthening sustainable production systems and low-carbon tourism development in Bali (Tang et al., 2025).

LITERATUR REVIEW

Previous studies have identified the transition toward low-carbon industries as an important topic in sustainable engineering due to increasing industrial greenhouse gas emissions. Existing literature emphasizes that low-carbon development requires the integration of energy efficiency, cleaner production systems, green technology adoption, and sustainable operational practices to reduce carbon intensity while maintaining productivity. In the context of mechanical engineering, emission mitigation is closely related to energy conversion efficiency, production process optimization, and technological innovation. Söderholm (2020) emphasized the importance of technological innovation, resource efficiency, and sustainable industrial transformation, while Sahoo et al. (2023) demonstrated that green innovation improves environmental performance through optimized resource utilization and reduced ecological impacts.

The existing literature also identifies energy consumption, production processes, and waste management as key factors influencing carbon emissions in industrial activities, including small-scale industries. Previous studies have shown that improving energy efficiency through optimized equipment utilization, efficient production systems, and environmentally friendly technologies can reduce emission intensity. However, research on small and medium enterprises indicates that the adoption of low-carbon technologies remains challenging due to limited financial resources, technological capability, and access to sustainable innovation. Olekanma et al. (2024) highlighted that small and medium enterprises in Asia face significant barriers in achieving carbon neutrality, particularly regarding investment limitations and access to low-carbon technologies. Furthermore, Baz & Zhu (2025) found that green technology innovation improves carbon emission efficiency by encouraging cleaner production processes and reducing dependence on high-carbon energy sources. Other studies have also emphasized that sustainable waste management practices, including waste reduction, recycling, and resource recovery, contribute to carbon footprint reduction and sustainable business development (Li et al., 2023).

Research on sustainable tourism has demonstrated that tourism-related activities contribute to carbon emissions through transportation, accommodation, energy consumption, and supporting industries. Previous

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literature suggests that sustainable tourism development requires integration between emission reduction strategies, technological improvement, and environmentally responsible operational practices. Zhang & Zhang (2021) identified that tourism carbon emissions are influenced by energy consumption patterns, tourism activities, and economic development. However, existing studies have primarily examined carbon emissions from tourism activities at a macro level, such as regional tourism growth, energy consumption patterns, and national emission trends, while the role of small industries as operational actors within tourism supply chains has received limited attention. In addition, previous studies on green technology and carbon mitigation have largely focused on large-scale industries with greater technological and financial capabilities, resulting in limited understanding of how small industries with resource constraints can implement practical low-carbon strategies (Wang & Zhang, 2025). Furthermore, few studies have integrated multiple operational factors, including energy utilization, waste management, and production technology, into a single empirical model to explain carbon emission reduction in small industries supporting tourism activities. Therefore, this study addresses these research gaps by analyzing the relationship between energy utilization, waste management, production technology, and carbon emissions in small industries supporting tourism in Bali. This approach contributes to the development of a low-carbon industrial model by integrating mechanical engineering perspectives with environmental sustainability principles.

METHOD

This study employed a quantitative approach with an explanatory research design to investigate the relationship between operational factors and carbon emissions in small industries supporting the tourism sector in Bali. The research model examined the influence of energy utilization (X1), waste management (X2), and production technology (X3) as independent variables on carbon emissions (Y) as the dependent variable. The study was conducted in Bali Province, Indonesia, focusing on small industries supporting tourism activities, including culinary businesses, handicraft industries, and creative enterprises. The population consisted of small industry operators whose operational activities involve energy consumption, production processes, and waste generation that may contribute to carbon emissions. Since the population size was unknown, this study applied a non-probability purposive sampling technique with criteria including business owners or managers who conduct operational activities, utilize energy resources, and generate production waste. Based on the Cochran formula, the minimum sample requirement was 100 respondents with a 10% error margin; however, to improve the reliability of the PLS-SEM analysis, this study targeted 150 respondents (Ali, 2026). The use of Partial Least Squares Structural Equation Modeling (PLS-SEM) was selected because it is suitable for analyzing predictive models involving multiple latent variables (Hair & Alamer, 2022).

Data were collected through questionnaires, field observations, and documentation studies. The research instrument was initially evaluated through expert judgment and a pilot test involving 30 respondents to assess validity and reliability. After meeting the required criteria, the final questionnaire was distributed to 150 small industry operators in Bali as the main sample for PLS-SEM analysis. The questionnaire measured energy utilization, waste management, production technology, and carbon emission conditions, with indicators consisting of electricity consumption, fuel usage, energy efficiency, waste separation, waste processing, waste reduction, environmentally friendly technology, production efficiency, fossil energy use, production waste, and operational efficiency. All variables were measured using a structured Likert-scale questionnaire, with indicators developed based on previous studies related to environmental management, green technology adoption, and carbon reduction practices in small and medium enterprises (Maqsood et al., 2022). The research procedure consisted of several stages, including problem identification, literature review, conceptual framework development, hypothesis formulation, instrument preparation, expert validation, pilot testing, data collection, statistical analysis, and interpretation of findings. The collected data were analyzed to identify operational factors affecting carbon emissions and develop a low-carbon mitigation model for small industries supporting sustainable tourism. The overall research procedure is illustrated in Figure 1.

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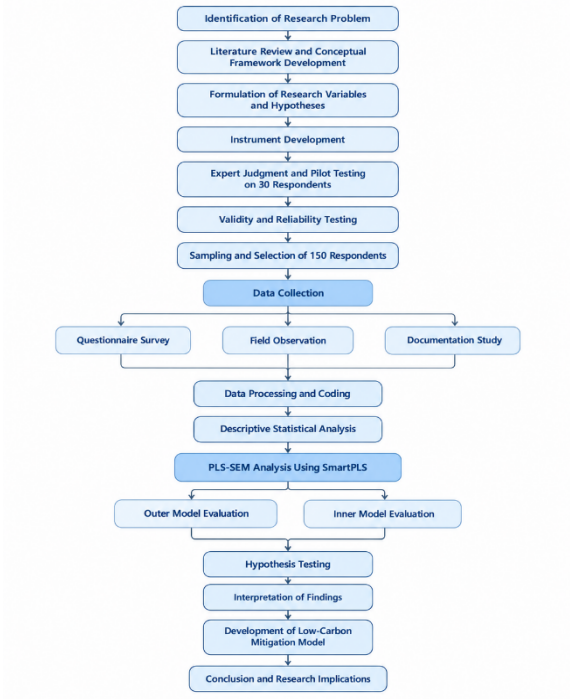


Figure 1. Research Flowchart

Data analysis was conducted using descriptive statistics and Partial Least Squares Structural Equation Modeling (PLS-SEM) with SmartPLS software. Before structural analysis, the research instrument was evaluated through validity and reliability testing, where validity was assessed using Pearson correlation with a significance level of $p < 0.05$, and reliability was evaluated using Cronbach's Alpha with a threshold value of $\alpha > 0.70$. The measurement model (outer model) was assessed based on loading factor (>0.70), Average Variance Extracted (AVE >0.50), Composite Reliability, Cronbach's Alpha (>0.70), and discriminant validity, while the structural model (inner model) was evaluated using path coefficients, t-statistics, p-values, and coefficient of determination (R^2). Hypothesis testing was performed using bootstrapping, where relationships were considered significant when t-statistics >1.96 and p-values <0.05. The use of PLS-SEM was selected because it is suitable for predictive analysis and examining complex relationships among latent constructs (Subhaktiyasa, 2024).

Furthermore, the evaluation of measurement and structural models follows established procedures for assessing reliability, validity, and predictive relationships in PLS-SEM analysis (Hair Jr et al., 2021). Based on the conceptual framework, this study proposes that operational factors influence carbon emissions in small industries supporting tourism in Bali. Energy utilization is expected to affect carbon emissions because inefficient energy consumption increases environmental impacts, while effective waste reduction and processing practices in waste management can minimize emission generation. Furthermore, environmentally friendly production technologies and efficient production processes are expected to reduce energy consumption and operational emissions. Therefore, the hypotheses are formulated as follows: H1: Energy utilization has a significant effect on carbon emissions in small industries supporting tourism in Bali; H2: Waste management has a significant effect on carbon emissions in small industries supporting tourism in Bali; H3: Production technology has a significant effect on carbon emissions in small industries supporting tourism in Bali.

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RESULTS AND DISCUSSION

Characteristics of Respondents

Table 1. Characteristics of Respondents

Characteristics	Category	Frequency	Percentage (%)
Business Sector	Culinary Industry	62	41.3
	Handicraft Industry	48	32.0
	Creative Industry	40	26.7
Business Duration	<5 years	36	24.0
	5–10 years	71	47.3
	>10 years	43	28.7

Table 1 presents the characteristics of the 150 respondents involved in this study. The respondents represented small industries supporting tourism activities in Bali, consisting of culinary businesses (41.3%), handicraft industries (32.0%), and creative industries (26.7%). In terms of business duration, most respondents had operated their businesses for 5–10 years (47.3%), followed by businesses operating for more than 10 years (28.7%) and less than 5 years (24.0%). These characteristics indicate that most respondents had sufficient operational experience to provide relevant information regarding energy utilization, waste management, production technology, and carbon emission practices. The diversity of business sectors strengthens the analysis because carbon emission issues in tourism-supporting industries occur across various operational activities.

Measurement Model Evaluation and Discussion of Construct Reliability

Table 2. Reliability and Convergent Validity Assessment

Construct	Loading Factor Range	Cronbach's Alpha	Composite Reliability	AVE
Energy Utilization (X1)	0.742–0.861	0.842	0.889	0.668
Waste Management (X2)	0.731–0.845	0.817	0.872	0.630
Production Technology (X3)	0.756–0.874	0.856	0.901	0.694
Carbon Emissions (Y)	0.764–0.883	0.869	0.910	0.717

The measurement model results show that all constructs achieved acceptable validity and reliability criteria. The loading factor values exceeded 0.70, while Cronbach's Alpha and Composite Reliability values were above the recommended threshold of 0.70, indicating strong internal consistency. The AVE values were also higher than 0.50, confirming convergent validity. These results indicate that the indicators used to measure energy utilization, waste management, production technology, and carbon emissions adequately represent the research constructs. This finding supports the suitability of the measurement model for further structural analysis using PLS-SEM, consistent with the methodological recommendations (Batra, 2025).

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Structural Model Analysis, Hypothesis Testing, and Discussion of Operational Factors Affecting Carbon Emissions

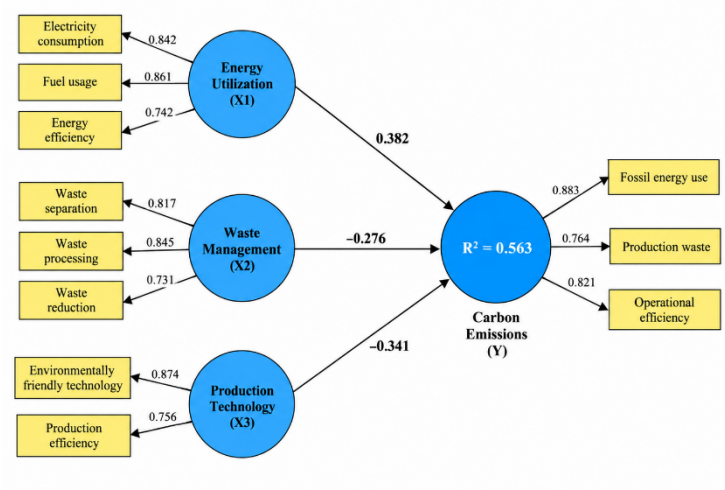


Figure 2. Structural Model Analysis of Operational Factors Influencing Carbon Emissions

Table 3. Path Coefficient and Hypothesis Testing Results

Hypothesis	Relationship	Path Coefficient	t-value	p-value	Decision
H1	Energy Utilization → Carbon Emissions	0.382	5.214	<0.001	Supported
H2	Waste Management → Carbon Emissions	-0.276	3.487	0.001	Supported
H3	Production Technology → Carbon Emissions	-0.341	4.126	<0.001	Supported

The structural model results presented in Figure 2 and Table 3 demonstrate that all proposed hypotheses are supported. Energy utilization has a positive and significant effect on carbon emissions ($\beta = 0.382$; $t = 5.214$; $p < 0.001$), indicating that increased energy consumption contributes to higher emission levels. This finding confirms H1 and suggests that inefficient energy utilization remains a critical factor influencing carbon intensity in small industries. The result is consistent with the low-carbon industry concept proposed by Bai et al. (2025), which emphasizes that energy efficiency and resource optimization are essential strategies for reducing industrial carbon emissions. Unlike previous studies that mainly focus on large-scale industries, this study provides evidence from small industries operating within tourism supply chains.

Waste management shows a negative and significant influence on carbon emissions ($\beta = -0.276$; $t = 3.487$; $p = 0.001$), supporting H2. This result indicates that improved waste management practices contribute to reducing carbon emissions through waste reduction, separation, and recycling activities. The finding demonstrates that operational environmental practices can directly support emission mitigation among small industries. This result supports Olekanma et al. (2024), who found that environmental management practices among small and medium enterprises can reduce carbon footprints despite limitations in financial resources and technological capacity. Therefore, improving waste management systems represents an important pathway toward sustainable industrial practices.

Production technology also has a negative and significant effect on carbon emissions ($\beta = -0.341$; $t = 4.126$; $p < 0.001$), confirming H3. The finding indicates that environmentally friendly technologies and efficient production processes contribute to reducing emission intensity. This result supports Zhang et al. (2021), who explained that green technology innovation improves carbon efficiency through cleaner production mechanisms. However, the adoption of advanced production technologies remains challenging for small industries due to investment limitations and restricted access to technology, as highlighted by (Ghobakhloo et al., 2022).

Model Explanatory Power and Implications for Low-Carbon Industrial Development

Table 4. Coefficient of Determination (R^2)

Endogenous Construct	R^2	Interpretation
Carbon Emissions (Y)	0.563	Moderate

The coefficient of determination indicates that energy utilization, waste management, and production technology explain 56.3% of the variation in carbon emissions among small industries supporting tourism in Bali. This finding demonstrates that operational factors represent important determinants of emission levels, although other external factors may contribute to the remaining variation. The result extends previous tourism carbon emission research, such as Wan et al. (2025), which examined emission drivers at a broader tourism system level. In contrast, this study provides a micro-level perspective by analyzing small industries as operational actors within tourism supply chains.

From a mechanical engineering perspective, the findings highlight the importance of sustainable production systems, energy efficiency strategies, and environmentally responsible technologies in reducing carbon emissions. The novelty of this research lies in integrating energy utilization, waste management, and production technology into a single low-carbon mitigation model specifically designed for small industries supporting tourism in Bali. Practically, the findings provide guidance for business owners and policymakers to develop emission reduction strategies through improved energy management, optimized waste handling, and technology adoption.

Nevertheless, this study has limitations. Carbon emissions were measured based on operational indicators rather than direct monitoring using emission measurement equipment. Furthermore, the research was limited to small industries in Bali, which may affect generalization to other tourism regions. Future studies should incorporate direct emission measurements, longitudinal approaches, and comparative studies across different tourism destinations to strengthen the understanding of low-carbon industrial transformation.

CONCLUSION

This study concludes that operational factors play an important role in influencing carbon emissions in small industries supporting tourism activities in Bali. The results of the PLS-SEM analysis demonstrate that energy utilization, waste management, and production technology significantly affect carbon emission levels. Energy utilization shows a positive and significant effect on carbon emissions, indicating that inefficient energy consumption increases emission intensity. Meanwhile, waste management and production technology have negative and significant effects, demonstrating that improved waste handling practices and the adoption of environmentally friendly production technologies can contribute to emission reduction. These findings confirm that operational improvements in energy efficiency, waste management, and sustainable production systems are essential components in developing low-carbon industries.

Theoretically, this study contributes to the development of mechanical engineering knowledge by providing an empirical model that integrates operational factors with carbon emission mitigation strategies at the small industry level. Unlike previous studies that mainly focused on large-scale industries or macro-level tourism emission analysis, this research highlights the role of small industries as operational actors within tourism supply chains. Practically, the findings provide a foundation for business actors and policymakers to implement low-carbon strategies through energy optimization, improved waste management systems, and environmentally responsible production technologies. However, this study is limited by the use of operational indicators rather than direct carbon emission measurements and its focus on small industries in Bali. Future research is recommended to incorporate direct emission monitoring, longitudinal analysis, and comparative studies across different tourism regions to strengthen the development of sustainable low-carbon industrial models.

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