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The Impact of Green Manufacturing on Operational and Environmental Performance in Pharmaceutical Industries

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Abstract: The pharmaceutical industry in Indonesia has experienced significant growth in the post-pandemic period. However, this growth has also increased the generation of hazardous and toxic waste, creating environmental management challenges. This study examines the effect of green manufacturing on operational and environmental performance in pharmaceutical companies in the Jabodetabek region, with firm size as a moderating variable. A quantitative approach was employed using Partial Least Squares Structural Equation Modeling (PLS-SEM) with SmartPLS 4. Data were collected from 100 managers, supervisors, and senior staff with at least three years of work experience. The results show that green manufacturing positively and significantly affects operational performance and environmental performance. Operational performance also has a significant positive effect on environmental performance. Firm size significantly moderates the relationship between green manufacturing and operational performance but does not moderate the relationship between green manufacturing and environmental performance. These findings highlight the importance of green manufacturing in improving operational efficiency and environmental sustainability in the pharmaceutical industry.

Keywords: environmental performance, green manufacturing, operational performance, pharmaceutical industry, SEM-PLS.

INTRODUCTION

The pharmaceutical industry in Indonesia has experienced significant growth in recent years. In 2021, the industry recorded a growth rate of 10.81%, with a market value reaching IDR 90–95 trillion (Gabungan Perusahaan Farmasi Indonesia [GPFI], 2022). Furthermore, the chemical, pharmaceutical, and traditional medicine manufacturing sector continued its post-pandemic recovery, contributing a growth rate of 5.86% to Indonesia's Gross Domestic Product (GDP) in 2024 (BPS, 2024a). However, rapid industrial growth is often accompanied by increasing production waste and environmental degradation. Pharmaceutical waste is classified as hazardous waste when it contains toxic compounds such as antibiotics, hormones, steroids, and heavy metals (Shukla et al., 2017). According to Indonesia Environmental

Statistics, the healthcare sector generates hundreds of thousands of tons of hazardous waste annually, yet only a small proportion is properly managed. This management gap became particularly evident in 2022, when only approximately 6.7% of the 726,817 tons of hazardous waste generated was successfully treated (BPS, 2024b). The consequences of inadequate waste management have already been observed through the detection of high concentrations of pharmaceutical compounds, particularly paracetamol, in the waters of Jakarta Bay (Teguh, 2021).

Given the substantial gap between hazardous waste generation and waste treatment, pharmaceutical companies need to adopt environmentally sustainable production approaches such as green manufacturing. Green manufacturing offers a comprehensive solution that considers not only the final product but also the environmental impacts associated with every stage of the production process (Rehman et al., 2016). The concept integrates product design, operational processes, manufacturing planning, and production control to minimize environmental waste throughout the product life cycle (Govindan et al., 2015). In practice, green manufacturing emphasizes efficient material utilization through the implementation of the 6R principles: reduce, reuse, recycle, recover, redesign, and remanufacture(Jawahir & Dillon, 2007). Through eco-design practices, the use of sustainable raw materials, and recyclable packaging, green manufacturing has been shown to reduce resource depletion and support environmental sustainability (Leong et al., 2019).

From a theoretical perspective, green manufacturing contributes directly to both operational and environmental performance. Previous studies have reported that green manufacturing positively affects operational performance by reducing long-term production costs through more efficient energy and material utilization (Paul et al., 2014). Lower resource waste, fewer operational errors, and reduced machine downtime enable firms to improve productivity while maintaining cost efficiency, thereby enhancing competitiveness (Eshikumo & Odock, 2017). In addition, green manufacturing improves environmental performance by reducing solid and liquid waste, lowering carbon emissions, and minimizing the use of hazardous materials (Sezen & Çankaya, 2013). Effective environmental management is further supported by the implementation of ISO 14001:2015, which provides organizations with guidelines for managing environmental aspects and ensuring compliance with environmental regulations (Massoud et al., 2015).

Despite its potential benefits, the implementation of green manufacturing in Indonesia's pharmaceutical industry remains challenging. Many pharmaceutical companies are still at an early stage of adoption, focusing primarily on small-scale energy efficiency initiatives and packaging waste reduction programs. The adoption of advanced technologies, such as integrated water recycling systems and biodegradable raw materials, remains limited due to high initial investment costs and technological constraints.

Empirical data from the Ministry of Industry of the Republic of Indonesia indicates a slow progression, where less than 10% of national pharmaceutical formulation plants have formally acquired the Green Industry Certification. This sluggish adoption is primarily driven by high capital barriers and compliance complexities within local medicine supply networks (Ricardianto et al., 2022). Nevertheless, pioneering large-scale pharmaceutical firms in Indonesia have demonstrated measurable outcomes. A technical study on Indonesian pharma plants reveals that the Heating, Ventilation, and Air Conditioning (HVAC) systems alone consume up to 55.56% of the entire facility's electrical energy(Ali et al., 2023). By targeting these utility sectors through energy-efficient upgrades, major state-owned and private pharmaceutical enterprises successfully contributed to an average of 5% to 12% reduction in greenhouse gas emissions and operational utility costs annually (Ali et al., 2023).

Furthermore, the widespread use of hazardous and toxic substances in pharmaceutical production complicates the substitution of conventional materials with environmentally

friendly alternatives. This challenge is compounded by the inherent contradictory requirements within the sector, where enhancing eco-friendly attributes or biodegradability might potentially compromise drug stability and medical efficacy (Belal et al., 2025). In addition, empirical studies examining the implementation and impact of green manufacturing within the pharmaceutical sector remain limited, particularly in developing countries such as Indonesia. This scarcity highlights the need for broader systematic evaluations, as global literature syntheses emphasize that proactive integration of eco-friendly sourcing and sustainable operations holds immense promise for minimizing the environmental footprint of pharmaceutical supply chains (Ezekiel St Paul, 2024). Nevertheless, evidence from other developing economies underscores that integrating green components across the supply chain functions yields positive advancements in the overall environmental efficiency of pharmaceutical firms (Almasarweh, 2022).

Therefore, this study aims to examine how green manufacturing affects both operational performance and environmental performance in the pharmaceutical industry. The Jabodetabek region was chosen because it is the heart of Indonesia's pharmaceutical sector, hosting about 45% of the country's drug manufacturers. While many studies have discussed green manufacturing in general factories, research focusing on the highly regulated pharmaceutical sector is still very rare. This study fills this gap by showing how green practices work under strict medical safety and government rules. Additionally, this study provides a new scientific contribution by adding 'firm size' as a moderating variable. This helps explain how company size creates different challenges and speeds between small and large companies in adopting green practices. This study employs the Structural Equation Modeling–Partial Least Squares (SEM-PLS) approach to analyze the proposed relationships. The findings are expected to provide strategic insights for pharmaceutical industry decision-makers in developing sustainable green manufacturing practices and strengthening long-term green competitiveness.

METHODS

This study employed a quantitative approach using Structural Equation Modeling–Partial Least Squares (SEM-PLS) to examine the relationships between green manufacturing, operational performance, and environmental performance in pharmaceutical companies. The research was conducted among pharmaceutical manufacturing companies operating in the Jabodetabek region, Indonesia. Respondents were selected through purposive sampling based on the criterion of having a minimum of three years of experience in the pharmaceutical industry. A total of 100 respondents, consisting of managers, supervisors, and senior staff, participated in the study.

The basis for determining this sample size follows the inverse square root method proposed by Hair et al. (2021). Assuming a minimum path coefficient of 0.25, the required minimum sample size was calculated to be 100 respondents. Furthermore, SEM-PLS was chosen as the analysis method because the proposed model involves multiple latent constructs measured by several indicators and aims to predict the relationships among these constructs. Additionally, SEM-PLS is highly suitable for studies with relatively moderate sample sizes and does not require strict multivariate normality assumptions (Hair et al., 2021). The collected data were subsequently analyzed using SmartPLS 4 software.

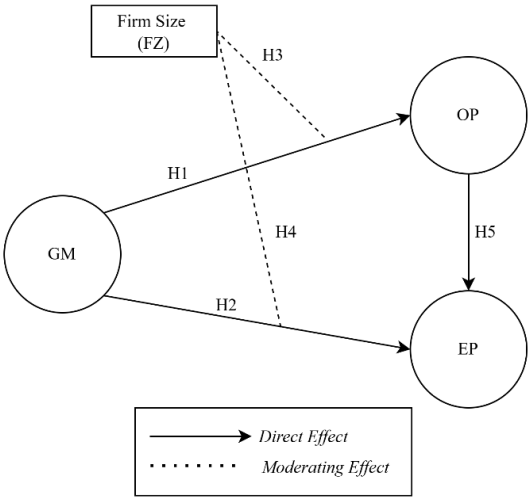


Figure 1. Research Framework Using SEM-PLS
Source: Research Results

Figure 1 presents the proposed research model. Green manufacturing is hypothesized to have a positive effect on operational performance and environmental performance. In addition, operational performance is expected to positively influence environmental performance. Firm size is also proposed as a moderating variable in the relationships between green manufacturing and both performance outcomes.

Research data were collected through a questionnaire survey using a five-point Likert scale ranging from 1 (strongly disagree) to 5 (strongly agree). The research model consists of four variables: green manufacturing (GM) as the independent variable, operational performance (OP) and environmental performance (EP) as the dependent variables, and firm size (FZ) as the moderating variable. The variables and their corresponding indicators are presented in Table 1.

Table 1. Research Variables and Indicators

Variable	Indicator	
;(GM) Green Manufacturing	(GM01) Eco-design implementation (GM02) Energy-efficient technology adoption (GM03) Eco-friendly raw material usage (GM04) Low-waste and low-energy production (GM05) Sustainable packaging implementation (GM06) Sustainable supplier selection (GM07) Employee green training & awareness (GM08) Routine environmental monitoring	Afum et al. (2020); Belal et al. (2025); Eshikumo & Odock (2017); Leong et al. (2019)
(OP) Operational Performance	(OP01) On-time delivery / lead time efficiency (OP02) Production output targets fulfillment (OP03) Consistent product quality standard (OP04) Labor productivity enhancement (OP05) Process efficiency & waste minimization (OP06) Workplace accident risk reduction	Inman & Green (2018); Santos et al. (2019)
(EP) Environmental Performance	(EP01) Emission reduction level (EP02) Energy conservation rate (EP03) Water usage optimization (EP04) Hazardous chemical reduction (EP05) Environmental regulatory compliance	Almasarweh (2022); Inman & Green (2018); Massoud et al. (2015)
(FZ) Firm Size	(FZ01) Total number of employees (FZ02) Annual corporate revenue	Gupta & Nagpal (2020)

Source: Research data

Data analysis was conducted using SmartPLS 4 software through three main stages. The first stage involved the assessment of the measurement model (outer model) to evaluate construct validity and reliability using outer loadings, Average Variance Extracted (AVE), Composite Reliability (CR), and the Heterotrait–Monotrait Ratio (HTMT). The second stage focused on the evaluation of the structural model (inner model) to examine the relationships among variables through path coefficients and coefficients of determination (R^2). Finally, a bootstrapping procedure was performed to test the significance of the proposed hypotheses based on t-statistics and p-values.

RESULTS AND DISCUSSION

Respondent Profile

Respondent characteristics were analyzed to describe the profile of the study sample. The characteristics included company location, number of employees, company revenue, work experience, job position, and educational attainment. The respondents exhibited diverse demographic and organizational backgrounds, reflecting variations in experience, educational qualifications, and company size. Such diversity enhances the representativeness of the sample and provides a broader perspective on the implementation of green manufacturing practices in the pharmaceutical industry. Specifically, the 100 respondents in this study strongly represent the pharmaceutical industry population for two major reasons. First, geographically, the sample covers all key manufacturing zones in the Jabodetabek region, with Jakarta (34%) and Bekasi (25%) acting as the primary clusters. This balanced distribution across multiple cities ensures that the data captures the entire region's characteristics without any local bias. Second, structurally, 90% of the surveyed participants work in medium to large-scale drug companies, with 54% employing over 500 people. Since large and medium enterprises are the main production engines and volume drivers in this industry, focusing on these segments provides a highly realistic and accurate reflection of the current state of operations. The detailed respondent profile is presented in Table 2.

Table 2. Characteristics of Respondents

Characteristics	Category	Frequency	Percentage
Location	Jakarta	34	34%
	Bogor	20	20%
	Depok	6	6%
	Tangerang	15	15%
	Bekasi	25	25%
Number of Employees	1 - 100 People	10	10%
	101 - 500 People	36	36%
	> 500 People	54	54%
Annual Corporate Revenue	< IDR 2.5 Billion	2	2%
	IDR 2.5 Billion - IDR 50 Billion	29	29%
	IDR 50 Billion	69	69%
Work Experience	3 - 5 Years	32	32%
	6 - 10 Years	50	50%
	> 10 Years	18	18%
Position	Manager	14	14%
	Supervisor	32	32%
	Senior Staff	54	54%
Educational Background	Diploma	5	5%
	Apothecary Professional Degree	11	11%
	Bachelor's Degree	67	67%
	Master's Degree	17	17%

Source: Research data

Table 2 shows that the respondents were predominantly located in Jakarta (34%) and Bekasi (25%). Most respondents were employed by companies with more than 500 employees (54%) and annual revenues exceeding IDR 50 billion (69%), indicating that large pharmaceutical firms were well represented in the sample. Regarding work experience, half of the respondents had between 6 and 10 years of professional experience (50%). Senior staff constituted the largest proportion of respondents (54%), while the majority held a bachelor's degree as their highest educational qualification (67%).

Descriptive Statistics

Descriptive statistics were employed to examine the levels of green manufacturing implementation, operational performance, and environmental performance among the pharmaceutical companies included in this study. The mean score was used to assess the extent to which each indicator was implemented, while the standard deviation was used to evaluate the dispersion of respondents' perceptions. The results of the descriptive analysis for each research indicator are presented in Table 3.

Table 3 Descriptive Analysis of Research Indicators

Indicator	Mean	Standard Deviation
(GM01) Eco-design implementation	3.22	0.94
(GM02) Energy-efficient technology adoption	3.27	0.90
(GM03) Eco-friendly raw material usage	3.32	0.89
(GM04) Low-waste and low-energy production	3.75	0.75
(GM05) Sustainable packaging implementation	3.38	0.90
(GM06) Sustainable supplier selection	3.93	0.86
(GM07) Employee green training & awareness	4.08	1.03
(GM08) Routine environmental monitoring	4.50	0.73
(OP01) On-time delivery / lead time efficiency	4.04	0.79
(OP02) Production output targets fulfillment	4.35	0.75
(OP03) Consistent product quality standard	4.45	0.73
(OP04) Labor productivity enhancement	4.08	0.83
(OP05) Process efficiency & waste minimization	3.90	0.90
(OP06) Workplace accident risk reduction	4.50	0.73
(EP01) Emission reduction level	3.57	0.86
(EP02) Energy conservation rate	3.69	0.80
(EP03) Water usage optimization	4.09	0.74
(EP04) Hazardous chemical reduction	3.93	0.74
(EP05) Environmental regulatory compliance	4.58	0.66

Source: Research data

The descriptive analysis results presented in Table 3 indicate that most indicators achieved mean scores above 3.50, suggesting a relatively high level of green manufacturing implementation among the pharmaceutical companies surveyed. Within the green manufacturing construct, routine environmental monitoring (GM08) recorded the highest mean score (4.50), while eco-design implementation (GM01) exhibited the lowest mean score (3.22). For operational performance, workplace accident risk reduction (OP06) achieved the highest mean score (4.50), whereas process efficiency and waste minimization (OP05) showed the lowest mean score (3.90). Regarding environmental performance, environmental regulatory compliance (EP05) recorded the highest mean score (4.58), while emission reduction level (EP01) had the lowest mean score (3.57).

These findings suggest that pharmaceutical companies demonstrate a strong commitment to workplace safety, environmental compliance, and routine environmental monitoring. However, greater attention is needed to strengthen eco-design practices, improve energy

efficiency, and further reduce emissions to enhance the overall effectiveness of green manufacturing implementation.

Measurement Model Assessment

The measurement model (outer model) was evaluated to assess the validity and reliability of the constructs used in this study. The evaluation was conducted systematically using SmartPLS 4 software. In the first stage, indicator reliability was assessed based on outer loading values. Following the recommendation of Hair et al. (2021), indicators with outer loading values below the recommended threshold of 0.70 were considered for removal from the model. The results of the initial outer loading assessment are presented in Table 4.

Table 4 Outer Model Evaluation Results (Stage 1)

Indicator	Green Manufacturing	Operational Performance	Environmental Performance	Firm Size
GM01	0.725			
GM02	0.801			
GM03	0.749			
GM04	0.731			
GM05	0.695			
GM06	0.822			
GM07	0.664			
GM08	0.679			
OP01		0.817		
OP02		0.771		
OP03		0.789		
OP04		0.811		
OP05		0.814		
OP06		0.720		
EP01			0.817	
EP02			0.817	
EP03			0.823	
EP04			0.679	
EP05			0.694	
FZ01				0.914
FZ02				0.924

Source: Research data

Based on Table 4, several indicators had outer loading values below the recommended threshold of 0.70, there are GM05 (0.695), GM07 (0.664), GM08 (0.679), EP04 (0.679), and EP05 (0.694). The theoretical justification for removing these indicators rests on convergent validity requirements. According to Hair et al. (2021), an outer loading below 0.70 implies that the latent construct explains less than 50% of the indicator's variance, as the square of the loading value falls below 0.50. Retaining these weak indicators would increase error variance, which directly lowers the Average Variance Extracted (AVE) and compromises the overall internal consistency reliability of the measurement model.

Therefore, these indicators were considered unable to adequately represent their respective constructs and were removed from the research model. After excluding the indicators that did not meet the validity requirement, the model was re-estimated to obtain a final measurement model that satisfied the required validity and reliability criteria. The measurement model was then evaluated to assess the validity and reliability of the constructs used in this study. The evaluation was based on the values of Average Variance Extracted (AVE), Composite Reliability (CR), and Cronbach’s Alpha. The results of the measurement model assessment are presented in Table 5.

Table 5 Convergent Validity and Reliability Assessment

Construct	AVE	Composite Reliability	Cronbach's Alpha
GM	0.641	0.899	0.860
OP	0.620	0.894	0.822
EP	0.738	0.907	0.877
FZ	0.844	0.915	0.816

Source: Research data

Based on Table 5, all constructs achieved AVE values above the recommended threshold of 0.50, indicating that each construct was able to explain more than 50% of the variance of its indicators. In addition, the Composite Reliability (CR) and Cronbach's Alpha values for all constructs exceeded the minimum recommended value of 0.70. These results demonstrate that all constructs satisfied the recommended criteria for convergent validity and reliability.

In addition to convergent validity and reliability, the measurement model was evaluated for discriminant validity to ensure that each construct was empirically distinct from the other constructs in the study. Discriminant validity was assessed using the Heterotrait–Monotrait ratio (HTMT). The results of the HTMT analysis are presented in Table 6.

Table 6 Discriminant Validity Assessment (HTMT)

Construct Variable	*Green Manufacturing*	Environmental Performance	Operational Performance	Firm Size
Green Manufacturing				
Environmental Performance	0.834			
Operational Performance	0.639	0.760		
Firm Size	0.303	0.453	0.354	

Source: Research data

As shown in Table 6, all HTMT values were below the recommended threshold of 0.85. These findings indicate that the constructs are sufficiently distinct from one another and represent different underlying concepts. Therefore, the measurement model demonstrates adequate discriminant validity.

Structural Model Assessment

After confirming the validity and reliability of the measurement model, the structural model was evaluated to examine the hypothesized relationships among the research constructs. Bootstrapping analysis was performed using SmartPLS to estimate path coefficients and assess the statistical significance of the proposed relationships through t-statistics and p-values. The results of the structural model assessment are presented in Figure 2.

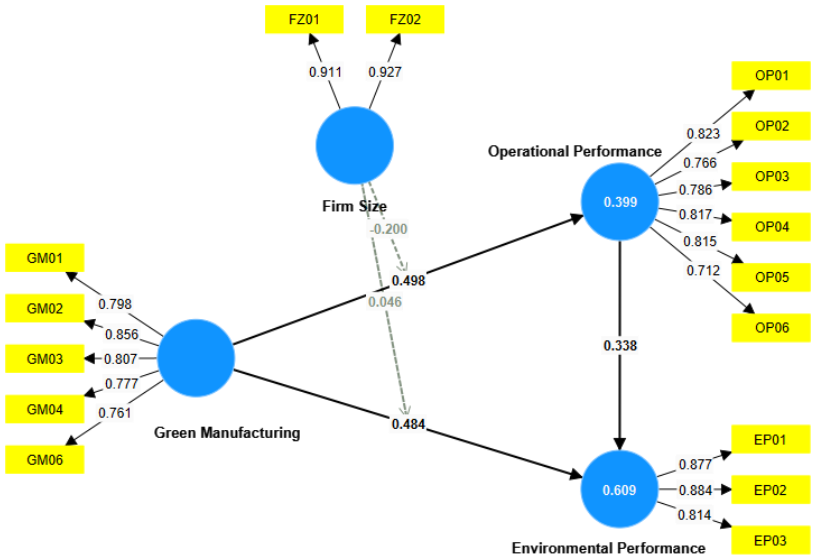


Figure 2 Structural Model Results

Source: Research data

Figure 2 illustrates the relationships among the constructs in the research model, along with the path coefficients and coefficients of determination (R^2). Green manufacturing was found to have a positive effect on operational performance ($\beta = 0.498$) and environmental performance ($\beta = 0.484$). In addition, operational performance positively influenced environmental performance ($\beta = 0.338$). Regarding the moderating effects, firm size moderated the relationship between green manufacturing and operational performance ($\beta = -0.200$), whereas its moderating effect on the relationship between green manufacturing and environmental performance was relatively weak ($\beta = 0.046$). In addition to examining the direction and strength of the relationships among the constructs, the structural model was evaluated using the coefficient of determination (R^2). The R^2 value indicates the extent to which the independent variables explain the variance of the dependent variables in the research model. The results of the R^2 assessment are presented in Table 7.

Table 7 Coefficient of Determination (R^2) Results

Dependent variable	R-square
Environmental Performance	0.609
Operational Performance	0.399

Source: Research data

Based on Table 7, the coefficient of determination (R^2) for operational performance was 0.399, indicating that green manufacturing explained 39.9% of the variance in operational performance. Meanwhile, the R^2 value for environmental performance was 0.609, suggesting that green manufacturing and operational performance jointly explained 60.9% of the variance in environmental performance. These results indicate that the model has a moderate explanatory power for operational performance and a relatively strong explanatory power for environmental performance. In addition to the coefficient of determination, the overall model fit was evaluated to assess the adequacy of the proposed structural model. The results of the model fit assessment are presented in Table 8.

Table 8 Model Fit Assessment

Fit Index	Value	Recommended Threshold	Interpretation
SRMR	0.097	< 0.10	Acceptable
NFI	0.728	> 0.70	Moderate

Source: Research data

As presented in Table 8, the SRMR value was 0.097, which is below the recommended threshold of 0.10, indicating an acceptable model fit. Furthermore, the NFI value was 0.728, exceeding the minimum acceptable value of 0.70, suggesting a moderate level of model fit. Overall, these results indicate that the structural model is adequate and suitable for further hypothesis testing. Subsequently, hypothesis testing was conducted to evaluate the significance of the relationships among the constructs in the research model. The results of the hypothesis testing, including the path coefficients, t-statistics, and p-values, are presented in Table 9.

Table 9 Hypothesis Testing Results

Hypothesis	Variable	Path Coefficient (β)	T-Statistic	P-Value	Decision
H1	*Green Manufacturing* → Operational Performance	0.498	7.739	0.000	Supported
H2	*Green Manufacturing* → Environmental Performance	0.484	6.629	0.000	Supported
H3	Firm Size x *Green Manufacturing* → Operational Performance	-0.200	2.082	0.037	Supported
H4	Firm Size x *Green Manufacturing* → Environmental Performance	0.046	0.616	0.538	Not Supported
H5	Operational Performance → Environmental Performance	0.338	3.647	0	Supported

Source: Research data

The hypothesis testing results presented in Table 9 indicate that green manufacturing has a positive and significant effect on both operational performance ($\beta = 0.498$, $p < 0.001$) and environmental performance ($\beta = 0.484$, $p < 0.001$). Therefore, H1 and H2 were supported. In addition, operational performance was found to have a positive and significant effect on environmental performance ($\beta = 0.338$, $p < 0.001$), supporting H5. Regarding the moderating effects, firm size significantly moderated the relationship between green manufacturing and operational performance ($\beta = -0.200$, $p = 0.037$), supporting H3. However, the moderating effect of firm size on the relationship between green manufacturing and environmental performance was not significant ($\beta = 0.046$, $p = 0.538$). Therefore, H4 was not supported.

Discussion

Green Manufacturing and Operational Performance (H1)

The results indicate that green manufacturing has a positive and significant effect on operational performance, supporting H1. This finding suggests that a higher level of green manufacturing implementation can improve the efficiency and effectiveness of operational processes in the pharmaceutical industry. Practices such as the use of environmentally friendly raw materials, waste reduction initiatives, sustainable supplier selection, and routine environmental monitoring can help companies optimize resource utilization and minimize waste throughout the production process.

In the pharmaceutical industry, operational efficiency is particularly important because manufacturing activities must comply with strict quality standards and regulatory requirements. Therefore, the implementation of green manufacturing not only generates environmental benefits but also contributes to higher productivity, improved process quality, and better control of operational costs. Companies that successfully integrate sustainability principles into their production activities are more likely to develop efficient and well-structured operational systems.

These findings are consistent with the study of Paul et al. (2014), which reported that green manufacturing practices enhance organizational performance through more efficient

resource utilization and waste reduction. The results also support the findings of Eshikumo & Odock (2017), who found that green manufacturing implementation positively influences operational performance. Furthermore, Sun et al. (2025) identified green manufacturing as an important driver of operational efficiency in manufacturing industries facing increasing sustainability demands. This complex relationship is further clarified in industrial operations literature, which suggests that the operational benefits of eco-friendly practices are achieved indirectly through the prior improvement of environmental performance metrics rather than as a direct mechanical outcome (Inman & Green, 2018). Indeed, adopting eco-friendly operational methods has been shown to establish a vital baseline for lowering operational expenses while consistently maintaining high product standards (Khan et al., 2022). This operational baseline is strongly reinforced by empirical data from Asian manufacturing firms, which confirms that higher adaptation of green supply practices directly correlates with optimized capacity utilization, decreased inventory levels, and enhanced product quality (Priyashani et al., 2021). Furthermore, contemporary evidence from consumer goods manufacturing setups substantiates that the simultaneous execution of green manufacturing and eco-design initiatives actively drives overall corporate efficacy, enabling firms to achieve robust environmental footprint reductions while expanding cost-saving capabilities (Saqib, 2024).

In terms of practical implications, these results show that managers should focus on optimizing production line automation to minimize raw material waste. Reducing material losses at the source directly helps pharmaceutical plants lower their long-term manufacturing costs and improve overall process efficiency. This proves that green manufacturing is a helpful cost-saving strategy rather than a financial burden.

Green Manufacturing and Environmental Performance (H2)

The results indicate that green manufacturing has a positive and significant effect on environmental performance, supporting H2. This finding suggests that a higher level of green manufacturing implementation enhances a company's ability to reduce the environmental impacts generated by its operational activities. Green manufacturing practices, including waste reduction, the use of environmentally friendly raw materials, energy efficiency initiatives, and regular environmental monitoring, enable companies to reduce resource consumption and minimize environmental pollution. In the pharmaceutical industry, the implementation of these practices is particularly important because pharmaceutical manufacturing processes may generate chemical waste that requires strict management and regulatory compliance.

These findings are consistent with the study of Sezen & Çankaya (2013), which reported that green manufacturing practices improve environmental performance through waste reduction and more efficient resource utilization. The results also support the findings of Afum et al. (2020). Similarly, manufacturing sector data underscores that green management initiatives serve as critical antecedents that are explicitly designed to yield positive advancements in overall environmental performance parameters (Inman & Green, 2018).

For practical applications, these results suggest that adopting eco-design and clean production methods is essential for legal compliance. This proactive approach helps pharmaceutical companies establish standard waste filtration and monitoring systems early. Consequently, firms can smoothly meet strict government rules, manage chemical waste safely, and avoid heavy environmental penalties.

Moderating Effect of Firm Size (H3 dan H4)

The results indicate that firm size moderates the relationship between green manufacturing and operational performance, supporting H3, but does not moderate the relationship between green manufacturing and environmental performance, leading to the rejection of H4. These findings suggest that firm size influences how green manufacturing

affects operational performance, although the moderating effect is negative. The negative moderation coefficient indicates that the positive impact of green manufacturing on operational performance is stronger in smaller pharmaceutical companies than in larger ones. This finding aligns with the empirical evidence provided by Gupta & Nagpal (2020), which confirms that firm size acts as a critical moderator determining how environmental dimensions translate into operational efficiency. In the pharmaceutical industry, smaller firms generally have simpler organizational structures, allowing operational improvements and decision-making processes to be implemented more quickly. As a result, green manufacturing practices, such as reducing Active Pharmaceutical Ingredient (API) losses, minimizing batch rejects, and improving energy efficiency in production facilities, can be translated into operational improvements more rapidly.

In contrast, larger pharmaceutical companies often face greater complexity when implementing green manufacturing initiatives. These organizations typically operate multiple production facilities and must comply with strict quality management systems, validation procedures, and documentation requirements under Good Manufacturing Practice (GMP) standards. Furthermore, optimizing production utilities such as Heating, Ventilation, and Air Conditioning (HVAC), Air Handling Units (AHU), Purified Water (PW), and Water for Injection (WFI) systems requires substantial investment and cross-functional coordination. Consequently, the operational benefits of green manufacturing may not be realized as quickly as in smaller firms.

This negative moderation offers a clear practical lesson for decision-makers. Large firms must plan their green initiatives early alongside corporate change-control loops and GMP validation protocols to prevent operational delays. On the other hand, smaller drug companies should use their fast decision-making tracks to quickly turn low-waste practices into immediate cost and efficiency advantages.

However, firm size was not found to moderate the relationship between green manufacturing and environmental performance, indicating that improvements in environmental performance are not primarily determined by the amount of resources available to a company. This independence from organizational scale aligns with empirical evidence from Jabbour et al. (2016), which demonstrates that firm size does not significantly dictate green performance outcomes. Instead, environmental performance appears to be more strongly influenced by compliance with environmental regulations, the implementation of environmental management systems, and the consistent management of waste and emissions. Regardless of their size, pharmaceutical companies are required to comply with environmental regulations, including the management of hazardous waste, wastewater treatment through wastewater treatment facilities, and the control of emissions generated by production activities.

Operational Performance and Environmental Performance (H5)

The results indicate that operational performance has a positive and significant effect on environmental performance, supporting H5. This finding suggests that better operational performance leads to improved environmental performance in pharmaceutical companies. In the pharmaceutical industry, operational efficiency can be reflected in lower batch reject rates, higher production yields, and more efficient utilization of Active Pharmaceutical Ingredients (APIs). When production processes operate more efficiently, the amount of wasted materials, production waste, and the consumption of resources such as water and energy can be significantly reduced. As a result, companies are able to improve both operational outcomes and environmental performance simultaneously.

Furthermore, the efficient management of production utilities, including Heating, Ventilation, and Air Conditioning (HVAC) systems, Air Handling Units (AHU), Purified Water (PW), and Water for Injection (WFI) systems, can reduce energy and water consumption

throughout the manufacturing process. These improvements contribute to lower levels of wastewater generation, hazardous waste, and emissions, thereby enhancing the overall environmental performance of pharmaceutical companies.

Therefore, achieving high operational standards acts as a natural driver for environmental protection. From a managerial standpoint, this implies that instead of viewing green upgrades and operational speed as separate goals, plant managers should integrate them. By focusing on daily operational efficiency metrics like reducing machine downtime and cutting down raw ingredient waste, pharmaceutical firms can automatically minimize their hazardous waste and total carbon footprint without incurring separate, heavy environmental costs.

CONCLUSION

This study aimed to examine the effects of green manufacturing on operational performance and environmental performance in the pharmaceutical industry in the Jabodetabek region, as well as to evaluate the moderating role of Firm Size in these relationships. The findings reveal that green manufacturing has a positive and significant effect on both operational performance and environmental performance. Furthermore, firm size moderates the relationship between green manufacturing and operational performance, where the positive impact is stronger in smaller pharmaceutical companies than in larger ones. However, firm size was not found to moderate the relationship between green manufacturing and environmental performance.

1. Theoretical Contributions
   From a theoretical perspective, this study contributes to the green manufacturing literature by providing empirical evidence from the pharmaceutical industry that sustainability-oriented practices can generate both operational and environmental benefits. It enriches the literature on operational agility by demonstrating that smaller organizational structures allow green production metrics to translate into cost-savings and efficiency more rapidly than in complex, larger firms.
2. Practical Implications
   From a practical perspective, the findings suggest that pharmaceutical companies can strengthen green manufacturing implementation by reducing batch rejects, increasing production yields, and optimizing production utilities such as Heating, Ventilation, and Air Conditioning (HVAC) systems, Air Handling Units (AHU), Purified Water (PW), and Water for Injection (WFI) systems, as well as improving hazardous waste and wastewater management. These initiatives are expected to enhance organizational competitiveness while supporting environmental sustainability and compliance with pharmaceutical industry standards.
3. Research Limitations and Future Directions
   However, this study is limited to pharmaceutical companies located in the Jabodetabek region and employs a cross-sectional research design. Future studies may expand the geographical scope to a national or multinational level and adopt longitudinal approaches to provide a more comprehensive understanding of the long-term effects of green manufacturing implementation.

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