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The Effect of Additive Manufacturing Adoption, Process Optimization Tools, and Energy Management Systems on Sustainability Performance in Indonesian Industrial Plants

Indrani Dharmayanti[1], Aster Aryati Rakhmasari[2]
[1,2] Politeknik APP Jakarta

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ABSTRACT

This study investigates the effect of Additive Manufacturing (AM), Process Optimization Tools (POT), and Energy Management Systems (EMS) on Sustainability Performance (SP) in Indonesian industrial plants. A total of 85 industrial plants were surveyed, and data was analyzed using Structural Equation Modeling - Partial Least Squares (SEM-PLS 3). The results reveal that AM has the most significant impact on sustainability performance, with process optimization tools and energy management systems also contributing positively. Specifically, AM was found to have the strongest influence on resource efficiency and waste reduction, while POT and EMS helped optimize production processes and energy use, respectively. These findings suggest that the combined adoption of these technologies can substantially improve sustainability outcomes in Indonesian industrial plants. The study highlights the importance of embracing advanced manufacturing technologies, process optimization, and energy management strategies to achieve sustainable industrial development in Indonesia.

Corresponding Author:
Name: Indrani Dharmayanti
Institution: Politeknik APP Jakarta
Email: iindh522@gmail.com

1. INTRODUCTION

Sustainability has emerged as a crucial focus in industrial operations, particularly in the face of global environmental challenges, resource scarcity, and evolving regulatory frameworks. Industrial plants worldwide are under increasing pressure to adopt practices that balance economic performance with environmental and social responsibilities. In Indonesia, this shift is particularly significant as the country strives to enhance its industrial competitiveness while aligning with global sustainability goals. The integration of advanced technologies and systems has been identified as a key enabler of this transformation, offering pathways to improve resource efficiency, minimize environmental impact, and promote sustainable development. Advanced technologies are crucial for improving energy efficiency and optimizing resource use in industrial operations [1], and in Indonesia, sustainable practices have been shown to increase efficiency and reduce environmental impacts while delivering broader social benefits [2].

Implementing such practices can enhance competitiveness, cost savings, and long-term value creation for industries [3], as exemplified by the pulp and paper industry in Indonesia, which has experienced positive outcomes on the triple bottom line despite challenges such as high initial investments [4]. However, the adoption of sustainable practices also faces obstacles, including high investment costs and organizational resistance to change [5], which necessitate robust government support through regulations, fiscal incentives, and capacity-building initiatives [2]. Additionally, the roles of Green Intellectual Capital (GIC) and Environmental Management Accounting (EMA) are increasingly recognized for their contributions to economic sustainability and improved business performance, even though the costs of environmental protection remain substantial [3].

Additive manufacturing (AM), commonly referred to as 3D printing, represents one of the most transformative technologies in contemporary industrial processes, significantly contributing to sustainable manufacturing by enabling localized production, reducing material waste, and allowing for complex geometries and customization [6]–[8]. AM builds objects layer-by-layer, contrasting with traditional subtractive methods that often result in significant material loss, and its flexibility in design and on-demand production reduces the need for large inventories, further enhancing sustainability [9].

This technology is further supported by process optimization tools, which utilize data-driven insights and analytics to streamline production workflows, enhance efficiency, and minimize resource wastage [10]. These tools also enable manufacturers to optimize the use of materials and energy, reinforcing sustainable practices. Complementing these advancements are energy management systems (EMS), which play a crucial role in reducing energy consumption and greenhouse gas emissions during AM processes (Suresh et al., 2024). By integrating EMS with AM, industries can achieve substantial energy savings, thus supporting broader environmental sustainability goals.

Despite the recognized potential of advanced technologies such as additive manufacturing (AM), process optimization tools, and energy management systems (EMS), their collective impact on sustainability performance within Indonesian industrial plants remains underexplored. Existing research has predominantly focused on individual technologies or specific industrial sectors, resulting in a fragmented understanding of how the integration of these technologies can drive holistic sustainability improvements. As industrial operations are significant contributors to energy consumption and waste generation, understanding the combined effects of AM, process optimization, and EMS is crucial. This study addresses this gap by empirically investigating the influence of these technologies on the sustainability performance of industrial plants in Indonesia, offering new insights into how technological synergies can support national sustainability objectives.

Sustainability in industrial operations is no longer optional but a critical imperative in the modern global economy. Environmental concerns, increasingly stringent regulatory requirements, and growing societal expectations have pushed industries toward innovative solutions to mitigate their ecological footprint. In Indonesia, this urgency is further intensified by the country's ambitious sustainability agenda aimed at combating environmental degradation and reducing greenhouse gas emissions while fostering economic development. Technological integration, particularly through AM and process optimization tools, has been shown to enhance energy efficiency and resource utilization in industrial settings [5], while EMS contributes to emissions reduction through systematic energy monitoring [11]. Government efforts, including fiscal incentives and ESG regulations, support this transition by encouraging transparency and accountability [2], [12]. Moreover, sustainable practices offer economic and social benefits by boosting efficiency, competitiveness, and CSR initiatives that address income inequality [11],

[13]. Nevertheless, challenges such as limited awareness, high implementation costs, and insufficient empirical data continue to hinder widespread adoption. Thus, this study seeks to provide a comprehensive evaluation of the combined impacts of AM, optimization tools, and EMS on sustainability performance in the Indonesian industrial sector.

2. LITERATURE REVIEW

2.1 *Sustainability Performance in Industrial Operations*

Sustainability performance in industrial operations involves balancing economic, environmental, and social dimensions—an imperative especially in developing countries like Indonesia, where manufacturing is a major economic pillar. The drive toward sustainable practices aims to reduce environmental impact while maintaining competitiveness, focusing on energy efficiency, waste reduction, and compliance with environmental standards, often measured through metrics like carbon footprint and material optimization. Indonesian industries are increasingly aligning with global sustainability benchmarks to meet regulations and enhance competitiveness. Technological integration improves energy efficiency and reduces waste [5], while resource optimization contributes to cost savings and long-term value [3]. Although the shift to sustainable practices requires high initial investment, it offers long-term financial and risk management benefits [14]. Key strategies such as digital transformation, renewable energy, and circular economy approaches support both environmental and economic goals [14], [15]. Moreover, CSR and stakeholder engagement play a vital role in securing legitimacy and aligning with global goals, with evidence from West Java showing that employee awareness and CSR practices significantly enhance sustainability performance [14], [16].

2.2 *Additive Manufacturing and Sustainability*

Additive manufacturing (AM), or 3D printing, is a transformative technology that builds objects layer by layer from digital designs, offering major advantages over traditional methods by reducing material waste, energy use, and transportation emissions, while enabling innovative and customizable designs. Although AM adoption in Indonesia's industrial sectors is still limited and research on its sustainability impacts remains scarce, its potential is considerable. AM significantly improves material efficiency by using only the required material, unlike subtractive methods that produce substantial waste [6], [17], and it consumes less energy, promoting more sustainable manufacturing [7]. Its ability to produce complex, customized products without assembly adds to its design flexibility [6], [18], and integrated production further enhances sustainability by eliminating steps like welding [7]. Already used in aerospace, automotive, consumer, and biomedical sectors, AM holds strong growth potential in Indonesia, especially by enabling localized production that reduces transport-related emissions—a crucial benefit for the country's archipelagic geography [6], [10], [19].

2.3 *Process Optimization Tools*

Process optimization tools are essential for enhancing manufacturing efficiency and productivity by minimizing waste, reducing production time, and maximizing resource utilization. Techniques such as lean manufacturing, Six Sigma, and the industrial Internet of Things (IIoT) are widely adopted to support these goals. Lean manufacturing emphasizes the elimination of non-value-adding processes, thereby increasing customer value with fewer resources [20], and its integration with Industry 4.0 technologies—termed Lean 4.0—marks a significant advancement in operational excellence [21]. IIoT further enhances manufacturing by enabling automation, real-time monitoring, anticipatory maintenance, and streamlined supply chains, leading to better energy management, cost savings, and environmental sustainability [22]. Case studies, such as those from Japanese automotive industries, highlight substantial improvements in productivity and quality through lean strategies [21], [23]. However, Indonesian industries face notable challenges in adopting these tools, including gaps in technical expertise and infrastructure limitations, which require strong leadership, employee training, and effective technology integration to overcome.

2.4 *Energy Management Systems*

Energy management systems (EMS) play a pivotal role in enhancing energy efficiency and reducing consumption in industrial settings by utilizing real-time data and predictive analytics to optimize energy use, thereby achieving substantial cost savings and minimizing environmental impact. Implementation of EMS, especially those aligned with ISO 50001 standards, has been proven to significantly improve energy performance and reduce CO_2 emissions and energy costs [24]. In Indonesia, the adoption of EMS is gradually increasing, supported by government incentives and energy efficiency policies [24]. EMS enables cost reductions through expert engines and numerical solvers that determine optimal energy strategies [25], while also contributing to lower greenhouse gas emissions and improved sustainability outcomes [26]. Furthermore, EMS enhances operational efficiency by integrating diverse energy data and optimizing distribution to prevent unnecessary usage [27]. Despite these benefits, challenges such as high initial investment costs [26] and limited awareness and expertise [24] continue to hinder widespread adoption, underscoring the need for broader education and capacity building in energy management.

2.5 *Theoretical Framework*

The study integrates the Resource-Based View (RBV) and Dynamic Capability Theory to understand the impact of AM, process optimization tools, and EMS on sustainability performance. The RBV suggests that technological assets such as AM and EMS provide firms with competitive advantages by enabling them to utilize resources efficiently [28]. Dynamic Capability Theory further emphasizes the role of adaptive capabilities in responding to changing environmental demands, highlighting the importance of process optimization tools in driving continuous improvement and innovation [29].

While prior studies have explored the individual impacts of AM, process optimization tools, and EMS on industrial efficiency, limited research has examined their collective influence on sustainability performance, particularly in the context of Indonesian industrial plants. This study addresses this gap by investigating the synergistic effects of these technologies. Based on the literature, the following hypotheses are developed:

H1: Additive manufacturing adoption positively affects sustainability performance.

H2: Process optimization tools positively affect sustainability performance.

H3: Energy management systems positively affect sustainability performance.

3. RESEARCH METHODS

This study employs a quantitative research design to examine the effects of additive manufacturing (AM), process optimization tools, and energy management systems (EMS) on sustainability performance in Indonesian industrial plants. The research framework tests hypothesized relationships between the independent variables (AM, process optimization tools, EMS) and the dependent variable (sustainability performance) using the Structural Equation Modeling–Partial Least Squares (SEM-PLS) approach, which is well-suited for predictive modeling and analyzing complex relationships among latent variables. The study population comprises industrial plants across diverse sectors in Indonesia, selected through purposive sampling to target those actively implementing or considering advanced technologies. A total of 85 plants were included, ensuring adequate statistical power for SEM-PLS analysis. Respondents, including plant managers, process engineers, and sustainability officers, provided data through a structured questionnaire based on validated scales to ensure reliability and validity.

The questionnaire consisted of five sections: demographics, additive manufacturing (assessing adoption and application levels), process optimization tools (measuring process efficiency strategies), energy management systems (evaluating EMS implementation and impact), and sustainability performance (covering environmental, economic, and social dimensions). A five-point Likert scale (1 = Strongly Disagree to 5 = Strongly Agree) was used. AM was measured by indicators such as material efficiency, production flexibility, and design innovation; process optimization tools by process efficiency, waste reduction, and resource use; EMS by energy monitoring, consumption reduction, and cost savings; and sustainability performance by emissions reduction, cost efficiency, and employee well-being. Data analysis was performed using SEM-PLS 3 software, following a two-step process: (1) measurement model evaluation—checking construct reliability, validity, and consistency via Cronbach's alpha, composite reliability (CR), and average variance extracted (AVE); and (2) structural model evaluation—testing the hypothesized relationships using path coefficients, t-statistics, and p-values, with bootstrapping (5,000 subsamples) employed to assess the significance of each path.

4. RESULTS AND DISCUSSION

4.1 Descriptive Statistics

The study involved 85 industrial plants from various sectors in Indonesia, with the sample comprising 50% medium-sized, 40% large, and 10% small enterprises. Industry representation included manufacturing (45%), energy (25%), electronics (20%), and others (10%), while respondents' roles consisted of plant managers (40%), process engineers (35%), and sustainability officers (25%). Descriptive statistics summarize the responses related to the main variables—additive manufacturing (AM), process optimization tools (POT), energy management systems (EMS), and sustainability performance (SP)—with details on the mean, standard deviation, minimum, and maximum values for each construct presented in the following table.

Table 1. Descriptive Statistics

Variable	Mean	Standard Deviation	Minimum	Maximum
Additive Manufacturing (AM)	4.12	0.73	2.80	5.00
Process Optimization Tools (POT)	4.05	0.68	2.90	5.00
Energy Management Systems (EMS)	4.25	0.65	3.00	5.00
Sustainability Performance (SP)	4.15	0.70	2.75	5.00

Key observations from the descriptive analysis reveal that additive manufacturing (AM) received a mean score of 4.12, indicating general agreement on its positive impact, with a standard deviation of 0.73 reflecting moderate variability in adoption. Process optimization tools (POT) had a mean score of 4.05, suggesting strong agreement on their effectiveness in enhancing efficiency, and a relatively low standard deviation of 0.68, indicating consistent responses. Energy management systems (EMS) achieved the highest mean score at 4.25, showing widespread recognition of their role in reducing energy consumption and emissions, with a low standard deviation of 0.65, pointing to a strong consensus. Sustainability performance (SP) showed a mean of 4.15, reflecting positive outcomes across environmental, economic, and social dimensions, with a standard deviation of 0.70 indicating moderate variability in perceived performance.

4.2 Measurement Model Evaluation (Outer Model)

The outer model evaluates the reliability and validity of the measurement constructs to ensure they adequately represent the underlying variables. The criteria include indicator reliability (loading factors), internal consistency (Cronbach's alpha, composite reliability), and validity (convergent and discriminant validity).

a. Indicator Reliability (Loading Factors)

Indicator reliability is assessed through the factor loadings of observed variables on their latent constructs. A loading factor of ≥0.7 indicates acceptable reliability. The loading factors for all items are presented below:

Table 2. Loading Factors

Construct	Indicator	Loading Factor
Additive Manufacturing (AM)	AM1	0.82
	AM2	0.88
	AM3	0.85
Process Optimization Tools (POT)	POT1	0.84
	POT2	0.87
	POT3	0.83
Energy Management Systems (EMS)	EMS1	0.86
	EMS2	0.89
	EMS3	0.88
Sustainability Performance (SP)	SP1	0.85
	SP2	0.87
	SP3	0.84

All loading factors exceed the threshold of 0.7, confirming indicator reliability.

b. Internal Consistency

Internal consistency was assessed using Cronbach's alpha and Composite Reliability (CR), with values of 0.70 or higher considered acceptable for construct reliability. The results show that all constructs meet this threshold: Additive Manufacturing (AM) had a Cronbach's alpha of 0.812 and CR of 0.891; Process Optimization Tools (POT) recorded 0.826 and 0.906, respectively; Energy Management Systems (EMS) scored 0.833 and 0.913; and Sustainability Performance (SP) achieved 0.826 and 0.893. These findings confirm high internal consistency across all constructs.

c. Convergent Validity

Convergent validity was evaluated using the Average Variance Extracted (AVE), where a value of 0.50 or higher indicates that a construct explains more than half of the variance in its indicators. The results show that all constructs meet this criterion: Additive Manufacturing (AM) has an AVE of 0.721, Process Optimization Tools (POT) 0.755, Energy Management Systems (EMS) 0.772, and Sustainability Performance (SP) 0.737, thereby confirming satisfactory convergent validity across all constructs.

d. Discriminant Validity

Discriminant validity ensures that constructs are distinct from one another. The Fornell-Larcker criterion and cross-loadings are used for this assessment. According to the Fornell-Larcker criterion, the square root of AVE for each construct should be higher than its correlation with any other construct.

Table 3. Discriminant Validity

Construct	AM	POT	EMS	SP
Additive Manufacturing (AM)	0.857			
Process Optimization Tools (POT)	0.581	0.876		
Energy Management Systems (EMS)	0.613	0.591	0.882	
Sustainability Performance (SP)	0.636	0.622	0.676	0.861

The diagonal values (square roots of AVE) are higher than the off-diagonal correlations, confirming discriminant validity. Cross-loading analysis also verified that each indicator loads higher on its respective construct than on any other construct.

4.3 Structural Model Evaluation (Inner Model)

The inner model evaluates the relationships between latent variables to test the proposed hypotheses. The analysis includes path coefficients, R^2 values, effect size (f^2), and predictive relevance (Q^2). Hypotheses were tested for significance using bootstrapping in SEM-PLS 3.

a. Path Coefficients and Hypothesis Testing

The path coefficients indicate the strength and direction of relationships between constructs. A t-statistic >1.96 at a 95% confidence level ($p < 0.05$) indicates statistical significance.

Table 4. Hypothesis Testing

Hypothesis	Path Coefficient (β)	t-statistic	p-value	Conclusion
H1: AM → SP	0.351	4.207	0.000	Supported
H2: POT → SP	0.306	3.805	0.000	Supported
H3: EMS → SP	0.282	3.451	0.001	Supported

All hypotheses (H1, H2, and H3) are supported, demonstrating positive and significant relationships between the independent variables—additive manufacturing (AM), process optimization tools (POT), and energy management systems (EMS)—and the dependent variable, sustainability performance (SP). Among the three, additive manufacturing exhibits the strongest influence on sustainability performance ($\beta = 0.351$), followed by process optimization tools ($\beta = 0.306$) and energy management systems ($\beta = 0.282$).

b. Coefficient of Determination (R^2)

The coefficient of determination (R^2) measures the proportion of variance in the dependent variable explained by the independent variables, with a value of 0.26 or higher considered substantial in exploratory research. In this study, the R^2 value for Sustainability Performance (SP) is 0.62, indicating that 62% of the variance in SP is explained by additive manufacturing (AM), process optimization tools (POT), and energy management systems (EMS), reflecting a strong explanatory power of the model.

c. Effect Size (f^2)

Effect size assesses the individual contribution of each predictor to the R^2 of the dependent variable.

Table 5. Effect Sizes

Predictor	f^2	Effect Size Interpretation
Additive Manufacturing (AM)	0.181	Medium
Process Optimization Tools (POT)	0.123	Small
Energy Management Systems (EMS)	0.106	Small

Effect size (f^2) evaluates the individual contribution of each predictor to the R^2 value of the dependent variable, providing insight into the relative impact of each factor. In this study, additive manufacturing (AM) shows a medium effect size with $f^2 = 0.181$, indicating a notable contribution to sustainability performance. In contrast, process optimization tools (POT) and energy management systems (EMS) have smaller effect sizes, with f^2 values of 0.123 and 0.106 respectively, suggesting more modest but still meaningful contributions.

d. Predictive Relevance (Q^2)

Q^2 is calculated using the blindfolding procedure to assess the model's predictive relevance, where a value greater than 0 indicates that the model can effectively predict the endogenous construct. In this study, the Q^2 value for Sustainability Performance (SP) is 0.41, confirming that the model exhibits strong predictive relevance for the dependent variable.

4.4 *Discussion*

The findings of this study provide valuable insights into the impact of Additive Manufacturing (AM), Process Optimization Tools (POT), and Energy Management Systems (EMS) on Sustainability Performance (SP) in Indonesian industrial plants.

a. Impact of Additive Manufacturing (AM) on Sustainability Performance

The positive and significant path coefficient for Additive Manufacturing (AM) indicates its crucial role in enhancing sustainability performance in industrial plants, particularly in Indonesia. This finding is consistent with previous studies that highlight AM's contribution to resource efficiency, waste reduction, and energy savings [30], [31]. AM's capability to produce complex and lightweight parts with minimal material usage directly supports sustainability goals, making it especially relevant in Indonesia where resource optimization is vital due to economic limitations and environmental challenges. Processes such as fused deposition modeling (FDM) and selective laser sintering (SLS) are noted for their efficient material usage [32], and AM's support for make-to-order production helps minimize excess inventory and waste. Although some AM processes are energy-intensive, their ability to facilitate localized production significantly reduces transportation-related emissions, contributing to a lower overall carbon footprint [32].

The strategic importance of AM in Indonesian industrial contexts is further reinforced by its role in advancing both operational efficiency and environmental sustainability. Integrating AM enables the production of lightweight components, which lowers material costs and enhances product performance [33]. Additionally, the adoption of AM aligns with recommendations to incorporate energy-efficient technologies and advancements in material science to further improve its environmental performance [32]. These advantages underscore AM's potential as a transformative technology that not only reduces carbon footprints through minimal waste and localized production but also offers competitive and sustainable solutions for industries in Indonesia [30], [31], [34].

b. Effect of Process Optimization Tools (POT) on Sustainability Performance

Process Optimization Tools (POT) demonstrated a significant positive relationship with sustainability performance, emphasizing their critical role in enhancing efficiency, reducing waste, and supporting environmental sustainability in industrial operations. The adoption of methodologies such as Lean, Six Sigma, and Total Quality Management (TQM) leads to improved process efficiency, lower energy consumption, and waste minimization—factors that are central to achieving sustainability goals. In the context of Indonesian industrial plants, the integration of these tools is likely to yield notable sustainability benefits, as they align with broader efforts to reduce operational costs and enhance resource utilization. The positive correlation between POT and sustainability performance reflects the value of continuous improvement methodologies in fostering sustainable industrial practices.

Specifically, Lean manufacturing tools such as Six Sigma, Kaizen, 5S, Value Stream Mapping (VSM), and Single Minute Exchange of Die (SMED) have shown significant impacts on manufacturing sustainability by improving process efficiency and reducing costs and waste [35], [36]. When integrated with sustainability frameworks, Lean Six Sigma (LSS) methodologies help optimize resource use and operational performance, leading to reductions in carbon footprints and material waste [37]. The incorporation of advanced technologies like IoT and AI further enhances the effectiveness of LSS by enabling real-time monitoring and predictive analytics. Moreover, Lean tools contribute across the economic, social, and environmental dimensions of sustainability and align with the seven sustainability principles outlined in ISO 26000 [38], enabling companies to initiate sustainability strategies from early production stages without requiring complex management systems. These findings suggest that Indonesian industrial plants utilizing POT can achieve measurable improvements in sustainability performance through structured and technology-enhanced process optimization.

c. Role of Energy Management Systems (EMS) in Enhancing Sustainability

Energy Management Systems (EMS) demonstrated the smallest yet still statistically significant positive effect on sustainability performance, confirming their role in promoting energy efficiency within industrial operations. EMS are specifically designed to optimize energy usage, reduce overall consumption, and lower greenhouse gas emissions, which is especially beneficial in energy-intensive sectors such as manufacturing and production. This aligns with prior studies that emphasize the effectiveness of EMS in driving energy efficiency improvements. In the Indonesian industrial context, the adoption of EMS has shown measurable advantages in terms of both cost savings and environmental impact, supporting the country's efforts to meet energy efficiency and emission reduction targets.

EMS achieve these outcomes through various mechanisms. They use expert engines and numerical solvers to manage energy production and consumption, optimize usage, and reduce costs by storing excess energy or feeding it back to the grid [39]. EMS also support energy curtailment by transmitting signals to prevent overconsumption and ensuring devices operate within sustainable limits [25]. Some systems enable targeted or self-regulated energy use, enhancing overall efficiency. Moreover, advanced EMS incorporate in situ monitoring units that detect operational events—such as appliances turning on or off—allowing for real-time energy tracking and the identification of optimization opportunities [27]. Although the effect size of EMS on sustainability performance was smaller compared to additive manufacturing and process optimization tools, its long-term benefits in reducing operational energy costs and supporting Indonesia's environmental objectives make EMS a vital component of sustainable industrial development.

d. Implications for Practice

For Indonesian industrial plants seeking to enhance their sustainability performance, the findings emphasize the importance of adopting a combined approach involving Additive Manufacturing (AM), Process Optimization Tools (POT), and Energy Management Systems (EMS). AM should be prioritized as a primary driver of sustainable manufacturing due to its ability to minimize waste, reduce energy usage, and improve efficiency. Nevertheless, POT remains essential for streamlining production processes and fostering operational excellence through systematic improvements. EMS, while contributing a smaller effect, plays a critical role in managing and optimizing energy consumption and emissions as part of a comprehensive sustainability strategy. Overall, this study highlights the urgent need for Indonesian manufacturers to invest in sustainable technologies and practices—not only to comply with local regulations but also to maintain competitiveness in a global market that increasingly prioritizes environmental responsibility.

e. Limitations and Future Research Directions

While this study offers valuable insights, it is important to recognize its limitations. The sample size of 85 industrial plants may not fully represent the diversity of Indonesian industries, especially those located in rural or less-developed areas. Future research could expand the scope by examining the impact of Additive Manufacturing (AM), Process Optimization Tools (POT), and Energy Management Systems (EMS) on sustainability performance across different sectors and regions. Longitudinal studies are also recommended to capture the long-term effects of these technologies on sustainability outcomes. Additionally, as this study primarily focused on technological factors, future research should consider integrating organizational elements such as culture, leadership, and employee engagement to provide a more holistic understanding of the enablers of sustainability in Indonesian industrial settings.

5. CONCLUSION

This study concludes that the adoption of Additive Manufacturing (AM), Process Optimization Tools (POT), and Energy Management Systems (EMS) significantly enhances the Sustainability Performance (SP) of Indonesian industrial plants, with AM emerging as the most influential factor due to its ability to improve resource efficiency, reduce waste, and promote sustainable manufacturing. POT and EMS also play critical roles by enhancing operational processes and optimizing energy usage, respectively. These findings highlight the strategic importance of integrating advanced technologies into industrial practices to meet global sustainability standards and gain competitive advantages. Given the urgent need for industries to minimize environmental impacts while maintaining efficiency, this study offers a practical roadmap for Indonesian industrial plants aiming to adopt more sustainable operations. Future research could examine the long-term effects of these technologies across diverse sectors and regions, while also considering additional factors such as organizational culture and employee engagement to deepen the understanding of sustainability in industrial contexts.

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