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UTILIZING ARTIFICIAL INTELLIGENCE PREDICTIVE MAINTENANCE IN LEAN MANUFACTURING TO BOOST INDUSTRIAL SUSTAINABILITY AND ENERGY EFFICIENCY

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ABSTRACT

The implementation of Artificial Intelligence (AI)-driven Predictive Maintenance (AI-PdM) within Lean Manufacturing has emerged as a transformative strategy to improve energy efficiency and promote industrial sustainability. AI-PdM supports continuous condition monitoring, advanced predictive analytics, and optimized maintenance planning, which help mitigate unexpected downtimes, enhance equipment longevity, and maximize energy utilization. This research adopts a Systematic Literature Review (SLR) approach to evaluate AI-PdM's impact on manufacturing efficiency and its correlation with Sustainable Development Goals (SDG) 7 (Affordable and Clean Energy) and SDG 9 (Industry, Innovation, and Infrastructure). The study's findings highlight AI-PdM's significant contribution to lowering carbon emissions, increasing operational dependability, and fostering sustainable production methods. Nevertheless, obstacles such as substantial initial capital requirements, a shortage of specialized workforce, and difficulties in integrating with existing systems continue to hinder its widespread adoption. Therefore, this paper advocates for the establishment of standardized guidelines and stronger collaboration among academia, industry stakeholders, and policymakers to accelerate AI-PdM adoption in sustainable manufacturing.

Keywords: Intelligence, Predictive Maintenance, Lean Manufacturing, Energy Efficiency, Industrial Sustainability, Industry 4.*0.*

1. INTRODUCTION

The incorporation of Artificial Intelligence (AI) and Machine Learning (ML) into Lean Manufacturing has become a fundamental driver for enhancing both energy efficiency and industrial sustainability. AI-powered Predictive Maintenance (PdM) introduces a groundbreaking strategy for optimizing manufacturing operations by minimizing unexpected downtime, prolonging equipment durability, and reducing energy consumption [1]. Lean Manufacturing, which emphasizes waste reduction and productivity enhancement, is increasingly integrating AI-based solutions to maximize its efficiency [2]

Conventional maintenance approaches, such as reactive and preventive maintenance, frequently result in inefficient energy use and elevated operational expenses. AI-driven PdM facilitates real-time monitoring, predictive analytics, and improved maintenance scheduling, ensuring machines function at optimal levels while conserving resources [3]. The incorporation of AI into Lean Manufacturing not only improves production effectiveness but also advances environmental sustainability by lowering carbon emissions and minimizing energy wastage [4]

This study aligns with the United Nations' Sustainable Development Goals (SDGs), specifically SDG 7 (Affordable and Clean Energy) and SDG 9 (Industry, Innovation, and Infrastructure). AI-PdM supports SDG 7 by optimizing energy consumption, decreasing power loss, and promoting sustainable operations.

Furthermore, its contribution to industrial resilience and innovation plays a key role in achieving SDG 9, driving progress in smart manufacturing and sustainable industrial practices [5].

Although AI-driven Predictive Maintenance (PdM) has significant potential, there is still a lack of research directly investigating its influence on Lean Manufacturing and industrial sustainability. This study aims to bridge that gap by analyzing how AI-PdM enhances the efficiency of Lean Manufacturing, optimizes energy consumption, and supports sustainability goals. The structure of this paper is as follows: Section 2 provides a review of literature related to Lean Manufacturing, Predictive Maintenance, and AI applications within industrial settings. Section 3 describes the research methodology, including data collection methods and analytical approaches. Section 4 discusses the study's findings, while Section 5 presents conclusions, key insights, and suggestions for future research.

2. LITERATURE REVIEW

2.1 Lean Manufacturing and Sustainable Development

Lean Manufacturing (LM) has been widely adopted as a strategy to improve efficiency, minimize waste, and enhance overall operational performance. Numerous studies highlight its role in achieving sustainability by integrating environmental considerations into lean practices [6]. The concept of Lean-Green Manufacturing has emerged, emphasizing the alignment of lean principles with green initiatives to optimize resource consumption and reduce environmental impact [7]. Recent findings suggest that implementing Lean Manufacturing significantly improves economic, social, and environmental performance, aligning with the Triple Bottom Line framework [8].

2.2 Predictive Maintenance in Lean Manufacturing

Conventional maintenance methods, including reactive and preventive routines, frequently cause unexpected downtime and elevated energy usage, negatively impacting sustainability goals. AI-based Predictive Maintenance (AI-PdM) has been introduced as a solution to these inefficiencies, allowing for real-time monitoring and predictive failure analysis [9]. By leveraging machine learning algorithms, AI-PdM enhances decision-making capabilities, optimizing maintenance schedules and reducing operational costs [10]. The integration of AI-driven maintenance with Lean Manufacturing has demonstrated positive outcomes in improving reliability, energy efficiency, and overall industrial sustainability [11].

2.3 The Role of AI and Machine Learning in Enhancing Energy Efficiency

Artificial Intelligence (AI) and Machine Learning (ML) serve as essential tools for predictive maintenance by processing extensive industrial datasets to identify trends and predict equipment malfunctions in advance. Multiple studies have highlighted AI's role in manufacturing, demonstrating its effectiveness in boosting production efficiency and reducing energy usage [12]. Moreover, AI-based energy management solutions support SDG 7 (Affordable and Clean Energy) by cutting energy waste and enhancing resource utilization in manufacturing environments [13].

2.4 AI-PdM and Its Contribution to Sustainable Industrial Practices

The adoption of AI-PdM corresponds with SDG 9 (Industry, Innovation, and Infrastructure) by driving technological progress in industrial maintenance. AI-driven solutions facilitate seamless integration between predictive maintenance and smart manufacturing systems, ensuring minimal disruptions and enhanced productivity [14]. Moreover, AI-PdM supports sustainability initiatives by reducing machine failures, prolonging equipment lifespan, and minimizing environmental impact [15]. Future research suggests expanding AI-PdM applications across different industrial sectors to further enhance operational sustainability and efficiency [16].

3. METHODOLOGY

3.1 Systematic Literature Review Approach

This study adopts a Systematic Literature Review (SLR) approach to investigate how AI-driven Predictive Maintenance (AI-PdM) is integrated into Lean Manufacturing and its impact on energy efficiency and industrial sustainability. The process of identifying, screening, and selecting relevant scholarly works adheres to the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines. The dataset comprises 40 peer-reviewed journal articles sourced from reputable academic databases, including Scopus, Web of Science, and IEEE Xplore.

3.2 Data Collection and Selection Criteria

The selection of literature follows predefined inclusion and exclusion criteria:

- **Inclusion Criteria:**
  1. Articles published between 2019 and 2025.
  2. Studies related to AI, Predictive Maintenance, Lean Manufacturing, and sustainability.
  3. Empirical and review studies employing quantitative, qualitative, or mixed methods.

- **Exclusion Criteria:**
  1. Articles that do not explicitly discuss AI-PdM in Lean Manufacturing.
  2. Studies with incomplete data or lacking methodological clarity.
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A keyword-based search strategy was implemented using terms such as *"Artificial Intelligence in Predictive Maintenance"*, *"Lean Manufacturing and Energy Efficiency"*, and *"AI-driven Industrial Sustainability"*. The bibliographic data was processed using **Mendeley** for reference management.

3.3 Research Framework and Tools

The analytical framework is built upon prior studies that employed:

- **Quantitative Approaches:** Utilizing **PLS-SEM** (Partial Least Squares Structural Equation Modeling) and **fsQCA** (fuzzy-set Qualitative Comparative Analysis) for hypothesis testing [17].
- **Survey-Based Data Collection:** The majority of studies relied on **questionnaires** distributed across manufacturing industries [18].
- **Case Study Approaches:** Empirical analyses on AI implementation in industrial environments [19]

3.4 Limitations and Future Research Directions

While the SLR methodology provides comprehensive insights, potential limitations include:

- **Publication Bias:** The study focuses on peer-reviewed articles, potentially excluding relevant industry reports.
- **Technological Scope:** Limited to AI-driven PdM without extensive consideration of other Industry 4.0 technologies.
- **Regional Focus:** Most studies originate from developed economies, limiting generalizability to emerging markets.

Future research should explore **real-time AI implementation** in predictive maintenance and conduct **longitudinal studies** to evaluate sustainability impacts over time.

4. RESULT AND DISCUSSION

A. Result Analysis

1. Number of Publications

The volume of published articles demonstrates the frequency of research conducted within a specific timeframe. Based on the graphical representation in Figure 1, studies on the given subject were published from 2019 to 2025. There is no distinct pattern of fluctuation in the annual publication rate. After experiencing a peak in 2022, the publication rate declined in the following years, with a significant drop in 2025.

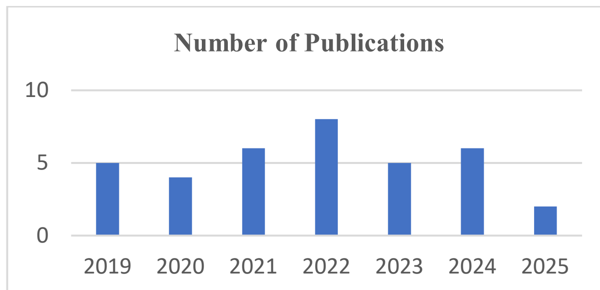

Figure 1. Number of Publications Since 2019-2025

The Improvement Trend of the Number of Research Publications in the World in 5 Years. The author found that the number of studies fluctuated throughout the observed period. While there was an increase in publications in 2021 and a peak in 2022, the decline in 2025 indicates a possible shift in research focus. By conducting further studies, scholars can contribute to the development of knowledge in this field and provide valuable insights for future research directions.

2. Type of Research

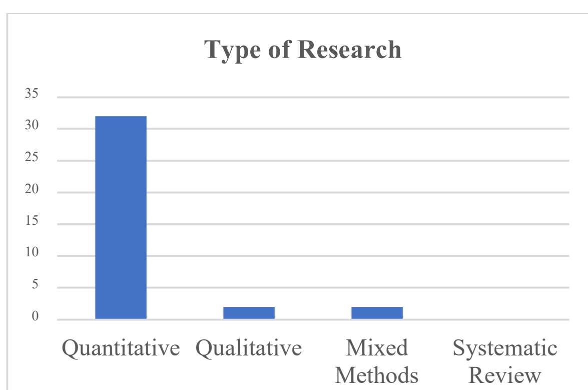

Figure 2. Number of Research Types

Based on the data analysis from the systematic literature review, it is evident that research on AI-based predictive maintenance in lean manufacturing predominantly employs a quantitative approach. Out of the reviewed studies, the majority utilize quantitative methods, while only a small fraction adopt qualitative or mixed-methods approaches, and systematic reviews are rare.

The dominance of quantitative research suggests a strong emphasis on measurable outcomes, statistical modeling, and empirical validation. This methodology enables researchers to analyze large datasets, optimize predictive algorithms, and assess the effectiveness of AI-driven maintenance strategies. Studies frequently use methods such as machine learning models, regression analysis, and Structural Equation Modeling (SEM) to evaluate key performance indicators (KPIs) related to energy efficiency, equipment reliability, and cost reduction. On the other hand, qualitative and mixed-methods research remains limited in this field. These approaches could provide deeper insights into the implementation challenges, human factors, and organizational impact of AI-based predictive maintenance. However, the scarcity of such studies indicates a research gap that could be explored further.

The limited presence of systematic reviews highlights the need for more comprehensive meta-analyses to synthesize findings from various studies and identify best practices in implementing AI-driven maintenance strategies for sustainable industrial operations.

Given the alignment of AI-based predictive maintenance with Sustainable Development Goals (SDG) 7 (Affordable and Clean Energy) and SDG 9 (Industry, Innovation, and Infrastructure), the prevalence of quantitative research reflects the growing focus on data-driven decision-making. Future research could benefit from integrating qualitative insights and systematic reviews to develop a holistic understanding of the role of AI in enhancing industrial sustainability.

3. Research Subject

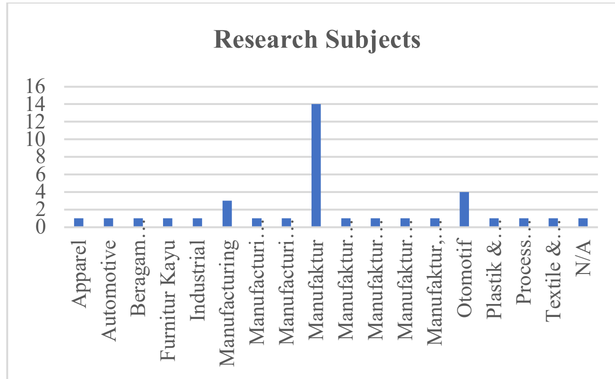

Figure 3. Research Subject

It can be seen from Figure 4 that research subjects focusing on manufacturing dominate the literature, with a total of 15 publications. Other manufacturing-related sectors, such as automotive, industrial manufacturing, furniture, and process industries, also appear in the dataset but with significantly lower representation. The prominence of manufacturing as a research subject may be attributed to its critical role in global production systems and supply chains, where efficiency and sustainability are paramount.

Manufacturing industries, particularly those integrating Lean Manufacturing and AI-based Predictive Maintenance, are at the forefront of technological advancements aimed at improving operational efficiency and reducing environmental impact. The emphasis on manufacturing in research suggests a growing awareness of the need for sustainable industrial practices, aligning with Sustainable Development Goals (SDG) 7 (Affordable and Clean Energy) and SDG 9 (Industry, Innovation, and Infrastructure).

The substantial research interest in the manufacturing sector highlights its potential for energy optimization through AI-driven predictive maintenance. As industries strive to minimize downtime and enhance productivity, predictive maintenance has emerged as a crucial tool for reducing energy consumption and promoting industrial sustainability. For instance, studies have explored the integration of AI models in lean production systems to forecast equipment failures and optimize resource allocation.

Moreover, the inclusion of research subjects related to the automotive and petrochemical industries indicates the application of Lean Manufacturing principles beyond traditional manufacturing sectors. The presence of various subcategories, such as SMEs and specific manufacturing divisions, further illustrates the diverse scope of Lean Manufacturing implementation.

Overall, the dominance of manufacturing as a research subject reflects its significance in advancing industrial sustainability and energy efficiency. Future research should continue to explore the intersection of AI, Lean Manufacturing, and sustainability to foster more resilient and eco-friendly production systems.

4. Lean Manufacturing Teories Selected

Lean manufacturing is a widely adopted approach aimed at improving efficiency and sustainability in industrial operations. The selection of lean manufacturing theories plays a crucial role in optimizing processes, particularly when integrated with AI-based predictive maintenance strategies. The analysis of the selected theories, as illustrated in the figure "Lean Manufacturing Theories Selected," highlights the diverse theoretical frameworks used in recent research on lean manufacturing and its application in energy efficiency and industrial sustainability.

The figure shows that a wide range of lean manufacturing theories have been employed, with a significant proportion classified under "Others." This indicates that researchers apply various frameworks beyond the most commonly cited theories, demonstrating the dynamic and evolving nature of lean manufacturing research.

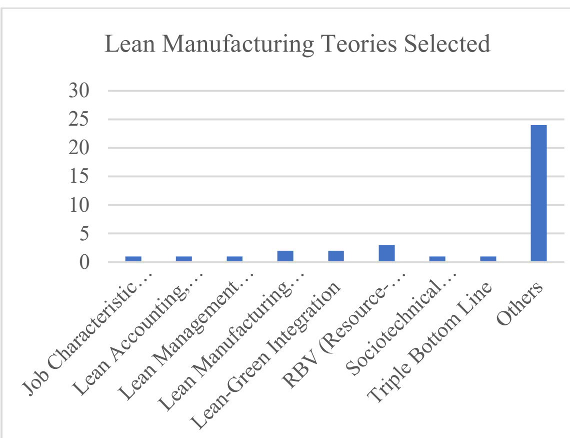

Figure 4. Brand theory in healtcare

Among the specific theories, Resource-Based View (RBV) and Lean-Green Integration have been moderately referenced in studies, reflecting the growing importance of sustainability in lean practices. RBV focuses on leveraging internal resources for competitive advantage, making it relevant in predictive maintenance where AI optimizes resource allocation and operational efficiency. Similarly, Lean-Green Integration aligns with Sustainable Development Goals (SDGs) by reducing energy consumption and waste through lean principles.

Other theories such as Sociotechnical Systems Theory, Lean Manufacturing Theory, and Lean Management Theory also appear in the literature but with relatively lower occurrences. Sociotechnical Systems Theory emphasizes the interaction between human and technical aspects of manufacturing, which is crucial for implementing AI-driven predictive maintenance. Lean Manufacturing and Lean Management theories provide foundational principles that guide AI implementation in streamlining processes and reducing downtime.

The presence of Job Characteristic Model, Lean Accounting & Just-in-Time (JIT), and Triple Bottom Line suggests a multidisciplinary approach in lean research. While Lean Accounting and JIT focus on cost efficiency and timely production, the Triple Bottom Line incorporates economic, environmental, and social sustainability dimensions, reinforcing the alignment of lean manufacturing with industrial sustainability initiatives.

The prominence of "Others" in the figure underscores the continuous development of new theories and hybrid approaches tailored to specific industrial challenges. This trend suggests that AI-based predictive maintenance in lean manufacturing is an interdisciplinary field, requiring the integration of multiple theoretical perspectives for effective implementation.

5. Types of Country

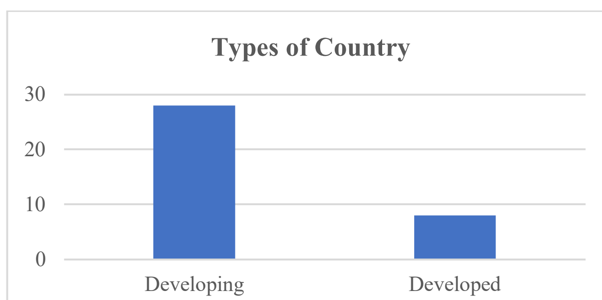

Figure 5. Type of Country

Based on the systematic literature review (SLR) analysis, it can be observed that research on AI-based Predictive Maintenance in Lean Manufacturing is predominantly conducted in developing countries compared to developed countries. The majority of studies have been carried out in countries such as India, China, Brazil, Indonesia, and Turkey, while fewer studies originate from developed nations like the United States, Germany, and the United Kingdom.

This trend is noteworthy considering that developed countries are often regarded as pioneers in technological innovation and industrial research. However, the data indicates that the interest in AI-driven predictive maintenance and Lean Manufacturing implementation is more significant in developing countries.

One potential reason for this trend is the growing need for cost-effective and efficient manufacturing processes in emerging economies. Developing nations are experiencing rapid industrial growth, requiring sustainable and energy-efficient solutions to remain competitive. AI-based predictive maintenance, integrated with Lean Manufacturing principles, offers an effective approach to reducing downtime, optimizing energy consumption, and enhancing industrial sustainability (SDG 7 & 9).

Additionally, industries in developing countries often face challenges such as outdated machinery, limited access to skilled labor, and high operational costs. AI-driven predictive maintenance helps address these issues by improving asset reliability and reducing unexpected failures. Several studies highlight how industries in India and Brazil leverage machine learning algorithms and IoT-based monitoring systems to enhance production efficiency and sustainability.

Furthermore, government policies and industrial revolutions in developing countries are pushing for digital transformation and smart manufacturing initiatives. Research in China and Indonesia suggests that policymakers are increasingly promoting AI adoption in manufacturing to drive industrial competitiveness and meet sustainability goals.

In contrast, developed countries have already established advanced predictive maintenance frameworks and Lean Manufacturing practices, leading to relatively fewer studies focusing on new implementations. Instead, research in these nations tends to explore more sophisticated AI models and integrations with Industry 4.0 technologies.
The increasing number of studies in developing countries underscores the global shift towards sustainable and energy-efficient manufacturing. Future research should explore how AI-based predictive maintenance can be further optimized to address region-specific challenges and improve industrial resilience.

6. Data Collection Instrument

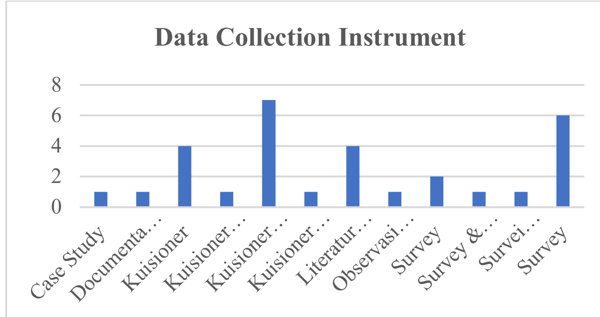

Figure 6. Data Collection Instrument

Surveys and questionnaire-based methods are the most commonly employed data collection instruments in the research on AI-based predictive maintenance within lean manufacturing. The analysis of the selected studies shows that **survey methods** (both general surveys and questionnaire-based surveys) dominate, with the highest frequency of usage. This preference can be attributed to their ability to efficiently capture industry insights, workforce perceptions, and implementation challenges related to AI-driven predictive maintenance strategies.
Furthermore, **literature reviews** and **observational studies** also play a significant role in gathering qualitative and historical data regarding technological advancements and industrial applications. The reliance on **case studies** and **industrial surveys** suggests that researchers are actively validating AI models and predictive analytics through real-world applications rather than purely theoretical models.
The systematic literature review indicates that AI-driven predictive maintenance is still evolving, necessitating a balanced approach between **empirical data collection** (via surveys and observational studies) and **secondary data analysis** (through literature reviews). Future research could enhance insights by integrating simulation-based methodologies to model AI implementation impacts more comprehensively.

7. Data Analysis Methods

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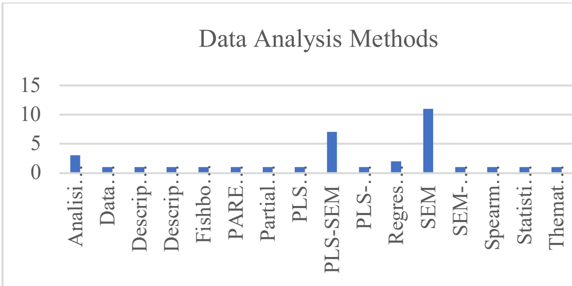

Figure 7. *Data Analysis Method*

Structural Equation Modeling (SEM) is the most widely used data analysis method in the study of AI-based predictive maintenance within lean manufacturing. The systematic literature review (SLR) indicates that SEM, particularly PLS-SEM (Partial Least Squares - Structural Equation Modeling), is the preferred approach due to its ability to handle complex relationships between multiple variables, including AI-driven predictive analytics, maintenance efficiency, and industrial sustainability. SEM is particularly effective in examining causal relationships and latent constructs, making it ideal for assessing the impact of AI technologies on lean manufacturing performance.
Other methods such as PLS regression and regression analysis are also commonly employed, reflecting the need for statistical techniques that can quantify predictive maintenance outcomes and energy efficiency improvements. Additionally, Spearman correlation and descriptive analysis play supporting roles in understanding trends and associations between AI adoption and operational performance.
The findings suggest that while SEM remains dominant due to its robustness in handling theoretical and empirical models, future studies could benefit from integrating data-driven AI techniques such as machine learning-based predictive analytics. This would enhance the understanding of AI's role in lean manufacturing by providing real-time and adaptive decision-making insights.

The results from the systematic literature review (SLR) highlight the significant role of AI-based Predictive Maintenance (AI-PdM) in Lean Manufacturing, particularly in improving energy efficiency and supporting industrial sustainability. The key findings from the selected studies are categorized into three main themes:

1. **Enhancement of Energy Efficiency (SDG 7)**
   - AI-PdM enables real-time monitoring and data-driven decision-making to optimize energy consumption in manufacturing processes [5].
   - Implementation of AI-driven predictive maintenance has resulted in a significant reduction in unplanned downtime, contributing to lower energy waste [4].
   - Several studies indicate that AI-PdM improves equipment reliability, thereby minimizing excessive energy usage due to machine inefficiencies [1].

2. **Improvement in Industrial Sustainability (SDG 9)**
   - The integration of AI-PdM in Lean Manufacturing contributes to reducing carbon emissions and optimizing resource utilization (Gama & Bonamigo, 2025).
   - AI-powered predictive models enhance operational efficiency by accurately predicting equipment failures, reducing maintenance costs, and extending asset lifespan [3].
   - Companies implementing AI-driven maintenance strategies have reported improvements in production output and sustainability metrics [6].

3. **Adoption Trends and Challenges**
   - Adoption of AI-PdM is most prevalent in high-tech manufacturing industries and industries with high energy consumption [5].
   - Challenges include the high initial investment cost, the need for skilled personnel, and concerns regarding data security and integration with existing systems [3].

Studies suggest that future AI-PdM implementations should focus on enhancing interoperability with other Industry 4.0 technologies to maximize sustainability benefits [4].

B. Discussion

1. AI-PdM as a Catalyst for Energy Efficiency and Sustainability
The findings from this study confirm that AI-based Predictive Maintenance plays a crucial role in achieving both SDG 7 and SDG 9 by optimizing energy efficiency and promoting sustainable industrial practices. Compared to traditional maintenance strategies, AI-PdM offers a more proactive approach by utilizing predictive analytics to detect potential failures before they occur [2]. This minimizes energy wastage, ensures consistent

machine performance, and reduces overall maintenance costs [1].

2. Comparison of AI-PdM with Traditional Maintenance Approaches

Conventional maintenance strategies, including reactive and preventive maintenance, frequently result in inefficiencies such as unexpected equipment failures and excessive energy usage (Llach et al., 2024). In contrast, AI-powered Predictive Maintenance (AI-PdM) improves decision-making by utilizing real-time data, predictive analytics, and advanced machine learning techniques [6].

Table 1. Comparison of AI-PdM with Traditional Maintenance Approaches

Maintenance Approach	***Key Characteristics***	***Energy Efficiency Impact***	***Sustainability Contribution***
Reactive Maintenance	Fixes issues after failure occurs	High energy waste due to unexpected downtimes	Low sustainability impact
Preventive Maintenance	Regular maintenance based on fixed schedules	Moderate efficiency, but can lead to unnecessary maintenance	Limited optimization for sustainability
AI-Based Predictive Maintenance	Uses AI-driven analytics to predict and prevent failures	High energy efficiency by optimizing machine operation	Strong sustainability contribution through resource optimization

3. Challenges and Future Directions

Despite its benefits, the adoption of AI-PdM faces several challenges, including the need for high-quality data, substantial investment costs, and integration complexities. Addressing these challenges requires:

- Increased investments in AI infrastructure and training programs for industry professionals.
- Development of standardized frameworks for AI-PdM implementation across different manufacturing sectors.
- Enhanced collaboration between academia, industry, and policymakers to facilitate large-scale AI adoption in Lean Manufacturing.

4. Practical Implications

The insights from this study provide valuable implications for manufacturers and policymakers aiming to enhance industrial efficiency and sustainability:

- Manufacturers should consider integrating AI-PdM into their Lean Manufacturing strategies to reduce operational costs and improve energy efficiency.
- Governments and regulatory bodies should support AI-driven initiatives through funding, incentives, and policy frameworks that encourage sustainable industrial practices.
- Future research should focus on real-time AI applications and hybrid models integrating AI with other Industry 4.0 technologies, such as IoT and Digital Twins, to maximize efficiency and sustainability benefits.

The study underscores the transformative potential of AI-driven Predictive Maintenance in Lean Manufacturing, reinforcing its critical role in promoting sustainable industrial development aligned with SDG 7 and SDG 9.

5. CONCLUSION

This study highlights the significant role of AI-based Predictive Maintenance (AI-PdM) in enhancing Lean Manufacturing practices, with a particular focus on improving energy efficiency and industrial sustainability in alignment with SDG 7 and SDG 9. The findings reveal that AI-PdM effectively minimizes unplanned downtime, optimizes energy consumption, and extends equipment lifespan, leading to increased operational efficiency and reduced environmental impact.

A comparative assessment between AI-PdM and conventional maintenance methods reveals that AI-powered solutions offer greater energy efficiency and cost reduction. AI-PdM facilitates real-time system monitoring, predictive data analysis, and well-structured maintenance scheduling, allowing

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manufacturing processes to operate at maximum efficiency while minimizing resource consumption (Machingura et al., 2024). The integration of AI with Lean Manufacturing principles strengthens sustainability efforts by lowering carbon emissions and promoting eco-friendly production practices..

In conclusion, AI-based Predictive Maintenance presents a transformative opportunity for Lean Manufacturing to achieve energy efficiency and sustainability goals. The findings from this systematic literature review provide valuable insights for researchers, industry practitioners, and policymakers, emphasizing the need for further advancements in AI-driven maintenance strategies to ensure long-term industrial resilience and environmental sustainability.

AUTHORS CONTRIBUTION

Wahyu Sardjono is responsible for all research processes and results to produce articles published in national and international reputable journals, and coordinates research activities with research members, including lecturers.

Deny Aditya Pratama, Membangun teori yang menjadi dasar penelitian, Mengembangan rancangan instrumen penelitian, dan menentukan metoda penelitian serta melakukan survei pada obyek penelitian

DATA AVAILABILITY

https://doi.org/10.5281/zenodo.15300105

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