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Strategic Maintenance Practices and Sustainability: A Theoretical Framework Integrating TPM, RBV, and the Triple Bottom Line

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Abstract

This study investigates the strategic role of maintenance in advancing sustainability within manufacturing enterprises. While existing literature explores individual sustainability pillars and maintenance strategies, the integration of strategic maintenance with comprehensive sustainability performance remains underdeveloped. Drawing on Total Productive Maintenance (TPM), the Resource-Based View (RBV), and the Triple Bottom Line (TBL) framework, this paper develops a theoretical model linking proactive maintenance practices to economic, environmental, and social outcomes. A bibliometric analysis of 189 publications from 2014 to 2024 reveals an annual growth rate of 52.27%, underscoring the rising global interest in the convergence of maintenance, sustainability, and Industry 4.0 technologies. The analysis identifies dominant research themes—including digital transformation, life cycle assessment (LCA), and institutional influences—that support the conceptualization of maintenance as a strategic enabler of sustainable performance. The proposed framework incorporates digital enablers (e.g., IoT, digital twins), institutional pressures, and maintenance typologies (preventive, predictive, condition-based, TPM). This study offers theoretical and practical insights for aligning maintenance strategies with sustainability goals. Future research should empirically validate the proposed framework using structural models, explore sector-specific applications, and investigate the longitudinal impact of digitalized maintenance strategies on sustainability performance.

Keywords
Strategic Maintenance, Sustainability, Life Cycle Assessment, Industry 4.0, Resource Based View

1. Introduction
Manufacturing enterprises are under increased scrutiny to improve their sustainability performance to remain competitive in today's increasingly environmentally constrained landscape. Regulatory reforms, such as the global Sustainable Development Goals (SDG), are amending organizational strategies to adopt operational practices to achieve the triple bottom line (TBL) of sustainability: economic, social, and environmental performance. Maintenance, traditionally viewed as a support function focused on asset reliability and cost reduction, is emerging as a strategic lever capable of influencing TBL. Evolution from traditional maintenance practices to strategic maintenance paradigms, particularly through frameworks such as Total Productive Maintenance (TPM) and emergence of new technologies (Fourth Industrial Revolution), has earmarked maintenance as a focal point of operational excellence. Existing research often examines the sustainability constructs in isolation, failing to capture the interconnected and systemic nature of sustainability. Furthermore, theoretical foundations such as Resource Based View (RBV) or Life Cyle Assessment (LCA) to explain how maintenance contributes to sustainable performance are lacking. Some studies have attempted to link preventative maintenance to the TBL, however, a comprehensive and holistic framework capturing the multidimensional impact of maintenance on sustainability remains underexplored. As a result, organizations and policy makers are left with inadequate guidance on how to align their maintenance strategies with broader sustainability goals.

1.1 Problem Statement
Maintenance has evolved from a necessary evil to a strategic role within organizations. However, despite the growing recognition of maintenance's strategic role, there remains limited empirical and theoretical integration of maintenance practices with sustainability frameworks. Existing research often examines economic, environmental, or social impacts in isolation, failing to capture the interconnected and systemic nature of sustainability. Moreover, few studies adopt robust theoretical underpinnings—such as the Resource-Based View (RBV) or Life Cycle Assessment (LCA) to explain how maintenance capabilities contribute to long-term competitive advantage and sustainable performance. Furthermore, the advent of Industry 4.0 and digital transformation offers new opportunities to enhance maintenance intelligence and traceability, yet this integration remains underexplored in sustainability-oriented studies. As a result, organizations are left with inadequate guidance on how to align their maintenance strategies with broader sustainability goals.

1.2 Hypotheses and Objectives
Leveraging the extant literature and theoretical frameworks, the key hypotheses tested in this study are:
- H1: Preventive maintenance positively impacts TBL.
- H2: Predictive maintenance positively impacts TBL.
- H3: Condition-based maintenance positively impacts TBL.
- H4: Total Productive Maintenance (TPM) positively impacts TBL
- H5: Institutional pressures moderate the relationship between maintenance practices and sustainability outcomes.

The study aims to advance understanding of how strategic maintenance practices contribute to sustainability across the three sustainability pillars, economic, social and environmental. The specific objectives are to:
- Investigate the relationships between specific maintenance strategies (preventive, predictive, condition-based, and TPM) and their respective sustainability outcomes.
- Develop a comprehensive theoretical framework integrating TPM, RBV, and TBL that elucidates how maintenance capabilities foster sustainable competitive advantages.
- Explore the moderating role of institutional pressures on the relationship between maintenance practices and sustainable outcomes.
- Incorporate emerging Industry 4.0 technologies and LCA into the framework, facilitating traceability and continuous improvement.
- Utilize meta-analytic techniques to synthesize existing evidence, deriving key hypotheses and establish correlations between maintenance practices and sustainability performance.

Overall, the framework aims to guide practical decisions for sustainable maintenance.

1.3 Significance of Study
Advancing the theoretical and practical understanding of maintenance's role in sustainability, we offer valuable insights for researchers, industry practitioners, and policymakers seeking to transform maintenance from reactive function to a strategic force for sustainable value creation. The synthesis of existing theoretical evidence through a

bibliometric analysis, quantifying the impact of maintenance on sustainability pillars is a key contribution to ongoing research in this field. A novel theoretical framework grounded in TPM, RBV, and TBL offers a multidimensional lens for maintenance evolution. The integration of Life Cycle Assessment and Industry 4.0 technologies into maintenance research, addresses the growing need for digital and systematic solutions in sustainable manufacturing.

2. Literature Review (12 font)

2.1 Maintenance Strategy Overview – From Reactive to Strategic

Maintenance strategies have morphed from reactive approaches to more proactive and strategic methodologies. This evolution has been driven by the need to enhance asset reliability, reduce downtime, and optimize operational efficiency. The transition from reactive to strategic maintenance involves several key approaches, including Total Productive Maintenance (TPM), Preventive Maintenance (PM), and Predictive Maintenance (PdM). Each of these strategies have distinct characteristics, advantages, and challenges, and their integration into asset management practices has impacted industrial operations.

2.1.1 Reactive Maintenance: The Traditional Approach

Reactive maintenance, also known as corrective maintenance, is the most basic and traditional form of maintenance which is typified by addressing equipment failures after they occur. This approach is often criticized for its inefficiency, as it leads to unplanned downtime, increased repair costs, and reduced asset lifespan. Despite its drawbacks, reactive maintenance is still widely used in many industries, particularly where the cost of preventive or predictive maintenance is perceived as prohibitive (Afolalu et al., 2024; Poór et al., 2019).

2.1.2 Preventive Maintenance: A Scheduled Approach

Preventive maintenance (PM) represents a step forward from reactive maintenance. PM involves performing maintenance tasks at predetermined intervals, based on time or usage. This approach aims to prevent equipment failures before they occur, thereby reducing downtime and extending asset life. PM is typically more cost-effective than reactive maintenance, as it minimizes the need for costly repairs and reduces the likelihood of unexpected failures (Afolalu et al., 2024; Poór et al., 2019).

2.1.3 Total Productive Maintenance (TPM): A Holistic Strategy

Total Productive Maintenance (TPM) / Autonomous maintenance is a proactive maintenance methodology that emphasizes the involvement of all employees in maintaining equipment effectiveness. TPM integrates maintenance into the overall production process, focusing on maximizing equipment efficiency and productivity. This approach involves regular maintenance activities, such as cleaning, lubrication, and minor repairs, which are often performed by production staff rather than dedicated maintenance personnel. TPM also includes activities aimed at improving equipment design and reducing downtime (Fredriksson & Larsson, 2012; Ruitenburg, 2017).

2.1.4 Predictive Maintenance: Data-Driven Insights

Predictive maintenance (PdM) is the most advanced form of maintenance and represents a significant shift from traditional reactive and preventive approaches. PdM leverages data-driven insights to anticipate equipment failures and facilitate timely interventions. By transitioning from reactive and preventive strategies to a proactive approach, organizations can significantly reduce unplanned downtime and enhance operational performance. PdM relies on advanced technologies such as IoT, AI, and machine learning to analyze real-time data from sensors and predict potential failures (Krishna Menon & Tuladhar, 2024).

Table 1 provides a succinct summary of the key maintenance strategies, their descriptions, and the relevant sources from the provided context.

Table 1: Maintenance Strategy Description

Strategy	Description	Citation
Reactive Maintenance	Involves addressing equipment failures after they occur.	(Afolalu et al., 2024) (Poór et al., 2019)
Preventive Maintenance	Involves performing maintenance tasks at predetermined intervals.	(Afolalu et al., 2024) (Poór et al., 2019)
Total Productive Maintenance (TPM)	Emphasizes the involvement of all employees in maintaining equipment effectiveness.	(Fredriksson & Larsson, 2012) (Ruitenburg, 2017)
Predictive Maintenance	Leverages data-driven insights to anticipate equipment failures.	(Menon & Tuladhar, 2024)

2.2 Sustainability in Manufacturing Overview: The TBL Framework
Sustainable manufacturing has emerged as a critical approach for industries to address environmental, economic, and social challenges while maintaining competitiveness. The Triple Bottom Line (TBL) framework, also known as the three pillars of sustainability, encompasses environmental, economic, and social sustainability, provides a holistic approach for businesses to achieve sustainable development.

2.2.1 Environmental Sustainability
Environmental sustainability is the cornerstone of sustainable manufacturing, focused on reducing the ecological footprint of manufacturing processes, including resource consumption, emissions, and waste management (Çimen et al., 2024). Manufacturing enterprises are facing concerted pressure to reduce their environmental footprint, including greenhouse gas emissions, resource depletion, and pollution (Sherif et al., 2022). Various strategies have been adopted to mitigate these impacts:

- **Sustainable Supply Chain Management (SSCM)**: This involves integrating environmental considerations into supply chain operations, such as sourcing raw materials sustainably, reducing energy consumption, and minimizing waste. Studies have shown that SSCM practices can significantly reduce environmental impacts while improving economic performance (Chen & Wu, 2024; Jum'a et al., 2024).
- **Green Manufacturing Practices**: These practices focus on reducing the environmental impact of production processes. For example, the adoption of lean and green manufacturing tools has been shown to reduce waste and improve resource efficiency (Sundermann, 2022).
- **Circular Economy Principles**: Companies are increasingly adopting circular economy models that emphasize recycling, reuse, and remanufacturing of products. This approach not only reduces waste but also creates new revenue streams (Anwar et al., 2023).

2.2.2 **Economic Sustainability**
Economic sustainability is essential for the long-term viability of manufacturing businesses and involves maintaining economic viability while ensuring long-term profitability and competitiveness (Mbah et al., 2025). Profitability and competitiveness are critical business KPIs driving business performance. Cost reduction, technology adoption and innovation are regarded as key strategies for achieving economic sustainability.

Improving operational efficiency can reduce costs and enhance profitability. For instance, the adoption of Industry 4.0 technologies has been shown to optimize production processes and reduce costs (Machado et al., 2024; Teixeira & Teixeira, 2024). Companies are increasingly investing in sustainable technologies such as renewable energy and energy-efficient equipment. These investments not only reduce environmental impact but also lower operational costs in the long run (Contini & Peruzzini, 2022). Innovation in sustainable manufacturing can create new market opportunities and revenue streams. For example, companies that develop eco-friendly products can differentiate themselves in the market and attract environmentally conscious consumers (Bonfanti et al., 2023).

2.2.3 **Social Sustainability**
Social sustainability addresses the well-being of employees, communities, and other stakeholders, including labor rights, safety, and social equity. It is a critical component of TBL, as it ensures that manufacturing activities contribute to the betterment of society (Riedelsheimer et al., 2020).

Ensuring fair labor practices, safe working conditions, and employee well-being is essential for social sustainability. Studies have shown that companies that prioritize employee well-being tend to have higher levels of employee satisfaction and productivity (Bonfanti et al., 2023; Yip et al., 2023). Manufacturing companies are increasingly engaging with local communities to address social issues such as poverty, education, and healthcare. This not only enhances the company's social license to operate but also contributes to the overall well-being of society (Bonfanti et al., 2022). Ensuring that manufacturing activities do not violate human rights and ethical standards is a key aspect of social sustainability. This includes avoiding child labor, ensuring fair wages, and respecting the rights of indigenous communities (Bonfanti et al., 2022).

Table 2 provides a comparative analysis of TBL implementation across different industries, highlighting their performance in each dimension.

Table 2: Application of TBL Across Industries

Industry	**Environmental Performance**	**Economic Sustainability**	**Social Sustainability**	**Source**
Automotive	High	High	High	(Machado et al., 2024) (Teixeira & Teixeira, 2023)
Pharmaceutical	Moderate	High	Low	(Islam et al., 2024)
Food and Beverage	High	High	High	(Widodo & Vanany, 2023)
Manufacturing (General)	Moderate	Moderate	Moderate	(Khandelwal et al., 2025) (Jia-chen, 2025) (Jum'a et al., 2024)

There is great emphasis for organizations to consider their impact on the environment, society, and the economy. A holistic framework is fundamental in measuring operational impacts on the TBL and achieving SDG.

2.3 Theoretical Underpinnings

2.3.1 Resource Based View (RBV)

The Resource-Based View (RBV) is a strategic management framework that emphasizes the importance of a firm's internal resources in achieving competitive advantage(McGee, 2015; Paauwe, 2024). It suggests that resources must be valuable, rare, inimitable, and non-substitutable to provide a sustained competitive edge (Miller, 2019). This theory has been extended and applied across various domains, including Total Productive Maintenance (TPM), sustainability, and stakeholder theory, to enhance operational excellence and competitive advantage (Madhani, 2009). The Resource-Based View (RBV) theory, Total Productive Maintenance (TPM), and sustainability are interconnected concepts that contribute to operational excellence and competitive advantage (Madhani, 2021; McGee, 2015; Miller, 2019).
The integration of these theories provides a comprehensive understanding of how firms can leverage their resources for superior performance

2.3.2 Life Cycle Assessment (LCA)

Life Cycle Assessment (LCA) is a critical tool in evaluating the environmental impacts of products and services throughout their entire life cycle, from raw material extraction to disposal(Piron et al., 2024). LCA provides a framework for assessing the environmental impacts of maintenance activities, which is crucial for industries like aviation and road infrastructure. For instance, in the aviation industry, LCA helps identify the ecological impacts of aircraft maintenance, enabling the prioritization of sustainability measures (Rahn et al., 2024). In road infrastructure, LCA evaluates the maintenance phase's impact on traffic operations and the environment, offering insights into optimizing maintenance strategies for efficient and low-carbon operations (Liu et al., 2023).

2.3.3 Industry 4.0

Industry 4.0 encompasses technologies like IoT, AI, and automation, which facilitate the development of value chains, resulting in shorter lead times and higher quality products (Harikannan & Vinodh, 2025). The integration of Artificial Intelligence (AI) and related technologies has revolutionized the manufacturing sector from supply chains to quality control, enabling real-time data collection, process optimization, and faster decision-making, leading to cost savings and higher accuracy (Pires et al.; Ramu, 2024). This integration has generated benefits such as reduced errors, streamlined operations and enhanced supply chain traceability (Li et al., 2024). As industry 4.0 advances, it offers significant potential to promote innovative, sustainable manufacturing practices. The adoption of AI and 4IR technologies in manufacturing not only optimizes business models but also fosters innovation and sustainability, paving the way for future advancements in the industry.

2.4.4 Existing Research Gaps

Table 3 elucidates the identified research gaps concerned with the subject of maintenance and sustainability in industrial settings.

Table 3: Existing Research Gaps in Literature

Research Gap	**Description**	**Sources**
Lack of balanced coverage across sustainability pillars	Uneven focus on economic, environmental, and social aspects of sustainability.	(Bredebach, 2022) (Vasic et al., 2024) (Saihi et al., 2022)
Limited practical application of research findings	Gap between theoretical advancements and real-world implementation.	(Bredebach, 2022) (Vasic et al., 2024) (Saihi et al., 2022)
Insufficient comprehensive frameworks for sustainable maintenance	Need for unified approaches that address all three pillars of sustainability.	(Bredebach, 2022) (Vasic et al., 2024) (Saihi et al., 2022)
Need for advanced data-driven models and tools	Lack of reliable and timely data for model development.	(Saihi et al., 2022) (Espinoza-Castro et al., 2024)
Limited stakeholder awareness and engagement	Stakeholders are often unaware of maintenance's impact on sustainability.	(Franciosi et al., 2021) (Bianchi et al., 2021)
Insufficient consideration of cross-industry applications	Most studies focus on specific industries, limiting generalizability.	(Bredebach, 2022) (Vasic et al., 2024)
Need for standardized methodologies and indicators	Lack of standardized KPIs for measuring sustainability in maintenance.	(Saihi et al., 2022) (Franciosi et al., 2021) (Bianchi et al., 2021)
Insufficient attention to global and cultural contexts	Sustainability priorities vary across regions and cultures.	(Vasic et al., 2024) (Espinoza-Castro et al., 2024)
Need for long-term sustainability assessments	Focus on short-term benefits, neglecting long-term consequences.	(Saihi et al., 2022) (Espinoza-Castro et al., 2024)
Insufficient focus on SMEs	Unique challenges faced by SMEs in implementing sustainable practices.	(Vasic et al., 2024) (Franciosi et al., 2021)
Need for policy and regulatory frameworks	The role of policy in promoting sustainable maintenance is underexplored.	(Vasic et al., 2024) (Espinoza-Castro et al., 2024)
Insufficient attention to human factors	Influence of worker behavior and decision-making on sustainability.	(Franciosi et al., 2021) (Bianchi et al., 2021)
Need for LCA integration	Limited application of LCA in understanding environmental impacts of maintenance.	(Saihi et al., 2022) (Espinoza-Castro et al., 2024)
Insufficient focus on supply chain sustainability	Alignment of maintenance practices with broader supply chain goals.	(Vasic et al., 2024) (Espinoza-Castro et al., 2024)
Need for risk assessment and management tools	Tools to identify and mitigate risks associated with sustainable practices.	(Saihi et al., 2022) (Saihi et al., 2022)
Insufficient attention to technological obsolescence	Impact of rapid technological changes on maintenance sustainability.	(Vasic et al., 2024) (Espinoza-Castro et al., 2024)
Need for stakeholder involvement in decision-making	Enhanced engagement of stakeholders in sustainable maintenance decisions.	(Franciosi et al., 2021) (Bianchi et al., 2021)
Insufficient focus on maintenance-sustainability trade-offs	Optimization of maintenance practices to achieve both objectives.	(Saihi et al., 2022) (Saihi et al., 2022)
Need for benchmarking and best practices	Lack of studies providing insights and guidance for adopting sustainable practices.	(Saihi et al., 2022) (Franciosi et al., 2021)
Insufficient attention to leadership and governance	Role of leadership in driving the adoption of sustainable practices.	(Franciosi et al., 2021) (Bianchi et al., 2021)

A multidisciplinary approach that integrates insights from maintenance, engineering, sustainability and organizational management is required to resolve these identified research gaps. Future research should focus on developing practical data-driven tools and frameworks that can be applied across industries for generalizability. Addressing these gaps positions industrial sectors towards achieving the triple bottom line of sustainability – economic prosperity, environmental stewardship, and social equity.

3. Theoretical Frameworks and Hypotheses Development

3.1 Conceptual model

Figure 1 depicts the proposed theoretical model, illustrating the relationships between the maintenance practices and sustainability outcomes within the integrated framework. Central to this model are the four strategic maintenance practices, Preventive Maintenance (PM), Predictive Maintenance (PdM), Condition-Based Maintenance (CBM), and Total Productive Maintenance (TPM), which are dependent variables that influence the three sustainability pillars. External institutional pressures (i.e. regulations, policies, and standards) are posited to moderate relationships, enhancing or mitigating the impact of maintenance practices on sustainability performance. This model aligns with the RBV, emphasizing maintenance capabilities as strategic resources fostering sustainable competitive advantage.

3.2 Integration of TPM, RBV, and TBL

The proposed framework is based on the synthesis of Total Productive Maintenance (TPM), Resource-Based View (RBV), Triple Bottom Line (TBL), and the convergence of Life Cycle Assessment (LCA) and Industry 4.0 technologies, a conceptual framework is proposed to integrate maintenance strategies into sustainability performance. The framework illustrates how maintenance practices serve as internal strategic resources (RBV), which, when optimized using LCA and Industry 4.0 technologies (e.g., Digital Twins, IoT, AI, Blockchain), can significantly contribute to economic, environmental, and social dimensions of sustainability (TBL). TPM acts as the operational foundation for implementation.

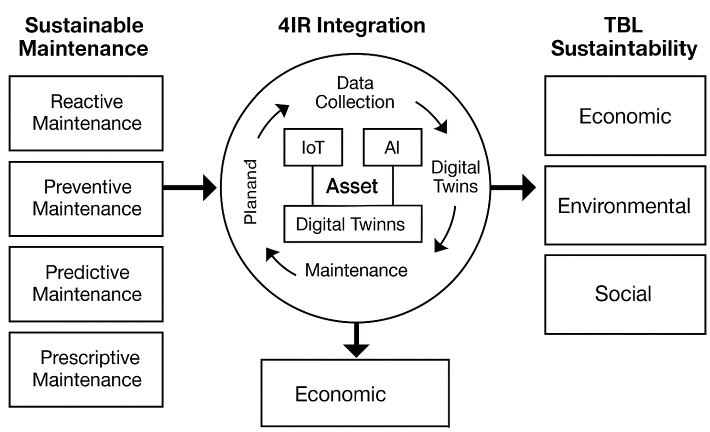

Figure 1: Proposed Theoretical Framework Layout

The proposed theoretical framework illustrates how strategic maintenance practices, organizational resources, digital enablers (Industry 4.0), and life cycle assessment collectively contribute to data-driven maintenance and real-time optimization leading to sustainability outcomes framed by the Triple Bottom Line (economic, environmental, social).

4. Research Methodology

This study employs a bibliometric analysis approach to systematically examine and synthesize existing literature on maintenance practices and sustainability outcomes. Utilizing bibliometric tools such as Vosviewer and Bibliometrix R software, the methodology allows for mapping research trends, identifying key themes, influential publications, and research gaps in the domain of strategic maintenance and sustainability.

4.1 Research Design

The research adopts a descriptive and exploratory bibliometric analysis framework. This approach enables quantifying the scholarly impact, visualizing knowledge networks, and uncovering the evolution of research topics pertinent to maintenance strategies, sustainability pillars, and their interrelations.

4.2 Data Collection

Data for analysis will be collected from Scopus scientific database, the largest abstract and citation peer reviewed literature database (Quatrini, Costantino, Di Gravio, & Patriarca, 2020). A comprehensive search strategy will be employed using the following search string as depicted in Figure 2. The timeframe will cover the last 10 years to capture recent trends. The retrieved metadata-titles, abstracts, keywords, authorship, citations, and reference-will form the basis for the bibliometric analysis.

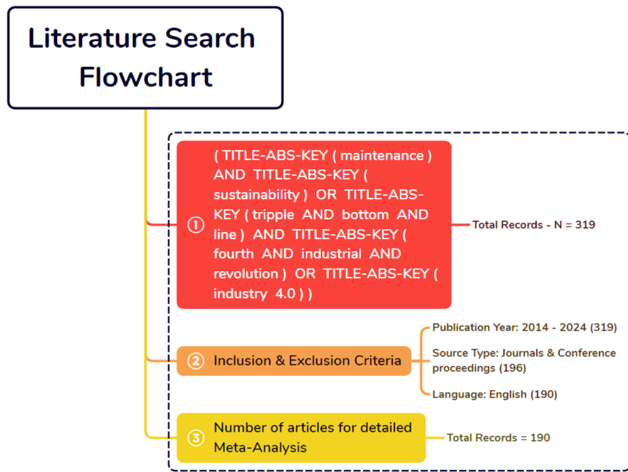

Figure 2: Data Collection Search Flow Chart

4.3 Data Processing and Preparation

The collected bibliometric data will be exported in a compatible format (BibTex and CSV) for analysis in Bibliometrix R and Vosviewer. Data cleaning procedures, such as removing duplicates and standardization author names and keywords, will be conducted to enhance analysis accuracy.

4.4 Bibliometric Analysis Technique

The analysis will include:

- Descriptive analysis: Quantifying publication trends, top authors, institutions, and countries contributing to the field.
- Citation analysis: Identifying highly cited papers and influential research streams.
- Keyword co-occurrence analysis: Mapping the frequency and relationships of keywords to uncover prevalent themes.
- Co-authorship and collaboration networks: Visualizing research collaborations across regions and institutions.
- Thematic evolution: Tracking how research themes are related to maintenance practices and sustainability have developed over time.

Vosviewer will be used to generate visual maps of keyword co-occurrence, co-authorship networks, and citation links. Bibliometrix will facilitate statistical analysis, trend detection and detailed bibliometric metrics.

4.5 Deriving Research Gaps and Hypotheses

The Bibliometric approach will reveal underexplored areas, emerging themes, and the degree of integration between maintenance strategies and sustainability frameworks. Insights gained will guide the formulation of specific research hypotheses (H1-H5) and highlight the significance of innovative practices, such as Industry 4.0 and LCA, within the literature.

5. Results

5.1 Descriptive Bibliometric Analysis

A total of 189 documents spanning the period 2014 to 2024 were analyzed. The dataset showed an annual scientific production growth rate of 52.27%, highlighting increasing research attention on maintenance, sustainability, and Industry 4.0 convergence. The average age of documents was 2.75 years, indicating that the field is both contemporary and rapidly evolving (Figure 3).

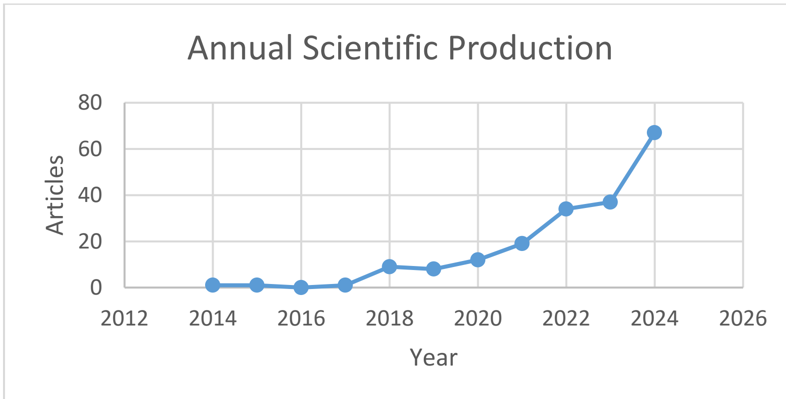

Figure 3. Annual Scientific Production per year (2014 – 2024)

5.2 Publication Outlets and Document Types

The documents were drawn from 135 unique sources, encompassing journals, books, and conference proceedings. The breakdown is as follows:

- Journal articles: 90
- Conference papers: 61
- Reviews: 24
- Others (editorial, short papers): 14

This distribution underscores a balanced mix of rigorous peer-reviewed outputs and rapidly disseminated conference insights, both essential in shaping an emerging yet critical interdisciplinary research area.

5.3 Collaboration and Authorship Patterns

- Total authors involved: 753
- Single-authored publications: 21
- International co-authorship: 33.33%
- Co-authors per paper (average): 4.31

These figures reflect high levels of scholarly collaboration, suggesting that the integration of maintenance and sustainability is being approached across disciplines and globally, supporting the systemic orientation of the study's framework.

5.4 Keywords and Thematic Mapping

The keyword analysis, Figure 4, Figure 5, Figure 6, and Figure 7 showed:
Authors' Keywords: 636 unique terms
Keywords Plus: 1352 terms
Preliminary Vosviewer clustering highlighted five dominant thematic axes:

- Strategic Maintenance Practices – Preventive, Predictive, Condition-Based, TPM
- Sustainability Dimensions – Economic, Environmental, Social
- Digital Transformation – Industry 4.0, IoT, Smart Sensors, Digital Twin
- Theoretical Anchors – RBV, LCA, TBL
- Institutional and Policy Contexts – SDGs, Regulations, Circular Economy

These clusters reflect a strong alignment with the study's hypotheses and theoretical foundations.

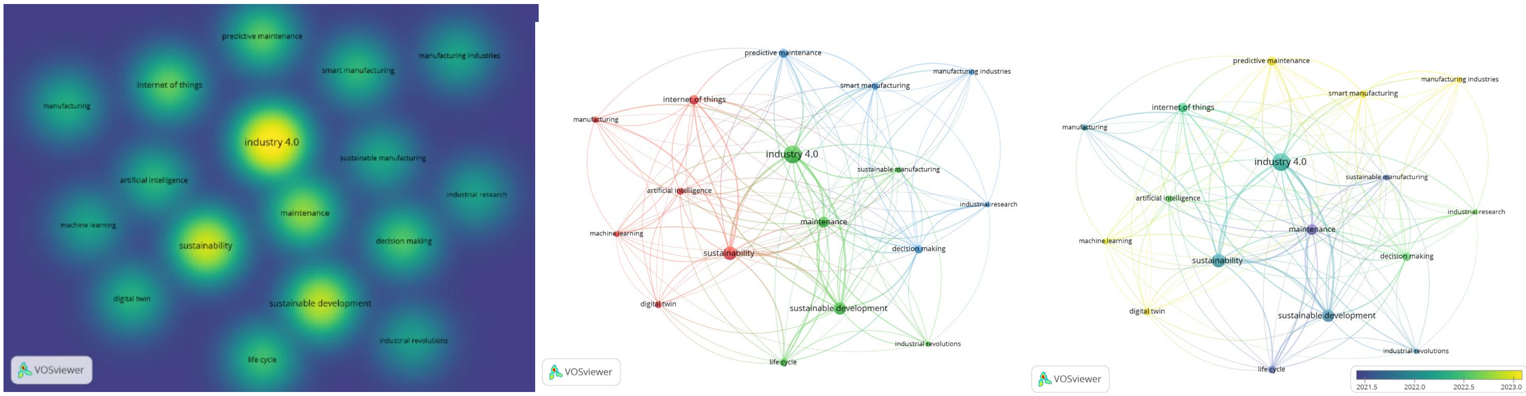

Figure 4. Density Visualization, Network Co-Occurrence Visualization, Overlay Visualization (Vosviewer)

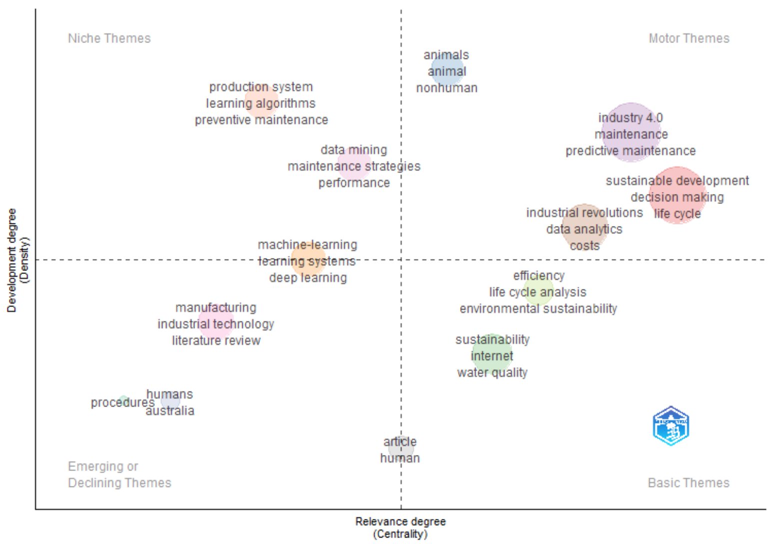

Figure 5. Thematic Mapping (Bibliometrix R)

Figure 6. Word Cloud (Bibliometrix R)

Figure 7. Tree Map (Bibliometrix R)

6. Discussions

The bibliometric evidence confirms that the integration of strategic maintenance and sustainability performance is an emerging research frontier. The sharp growth in literature since 2018 parallels the global shift toward sustainable industrial practices, digitalization, and compliance with frameworks such as the Sustainable Development Goals (SDGs).

6.1 Gaps in Theory and Empirical Evidence

Despite the growing number of publications, the fragmented focus remains evident. Many studies explore only one or two dimensions of the Triple Bottom Line. Very few adopt robust theoretical constructs such as TPM, RBV, or LCA. The moderating role of institutional pressures is underrepresented. Integration of digital tools (IoT, predictive analytics) into maintenance strategies remains conceptually underdeveloped. This study directly addresses these gaps by synthesizing themes into a holistic and testable theoretical framework supported by meta-analytic evidence.

6.2 Contribution to Maintenance and Sustainability Research Domains

Framing maintenance not as a cost center, but as a strategic capability, this work aligns with emerging trends that view proactive maintenance as a driver of sustainable competitive advantage. The bibliometric data reinforces the urgency of formalizing integrated frameworks that link, Maintenance strategy, Organizational resources (RBV), Sustainability outcomes (TBL), Maintenance execution, Digital enablers (I4.0), Traceable performance improvement (LCA). Therefore, positioning this paper as a bridging study, connecting fragmented literatures and offering a comprehensive unifying lens.

7. Conclusion

The bibliometric analysis provided empirical justification for the relevance and timeliness of this study. The results demonstrate the rising global interest in the convergence of strategic maintenance and sustainability. A fragmented research landscape, lacking theoretical cohesion and empirical generalizability. The need for an integrated framework that combines TPM, RBV, TBL, LCA, and Industry 4.0 technologies. This study addresses these gaps by proposing and testing a model that articulates the causal and moderating mechanisms linking maintenance practices to the sustainability pillars. It advances both theory and practice, offering decision-makers a framework for designing maintenance strategies that are simultaneously cost-effective, socially responsible, and environmentally sound.

7.1 **Future Research Directions**

Leveraging on the identified gaps, several future research opportunities emerge. Developing empirical studies using Structural Equation Modelling (SEM) to test the proposed framework poses the potential to significantly improve this current study. Moreover, researchers are encouraged to investigate the role of specific Industry 4.0 technologies (e.g.

Blockchain, AI-based predictive analytics), in enhancing sustainable maintenance practices. Sector specific applications are necessary to contextualize the proposed framework model. Lastly, the examination of longitudinal data to assess the long-term sustainability impact of maintenance strategies as well as the integration of institutional theory and stakeholder theory promises to enhance the understanding of the contextual influences. These directions can significantly expand theoretical insight and guide practice in aligning maintenance strategy with sustainability goals to support organizational decision-makers and policymakers.

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