Assessing the Sustainability Impacts of Industry 4.0 on Maintenance Policies: A Systematic Literature Review and Future Research Directions

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ABSTRACT

Maintenance strategies have traditionally been designed with a primary focus on cost reduction and operational efficiency, often overlooking their broader environmental and social impacts. However, in the current context where industries must align with European carbon neutrality 2050 objectives and the United Nations Sustainable Development Goals (SDGs), maintenance is recognized as a key lever for enhancing the three pillars of sustainability in industries: economic, social, and environmental. In addition, recent studies have shown that the ongoing digital transformation of industry through Industry 4.0 technologies such as artificial intelligence, Internet of Things, digital twins, and big data analytics, offers new opportunities to improve maintenance strategies. These developments have given rise to the concept of Maintenance 4.0, which opens new perspectives for aligning maintenance practices with broader sustainability objectives.

To better understand the impact of these technologies on maintenance sustainability, as well as the existing assessment initiatives in the current state of research, this paper conducts a systematic literature review (SLR). A total of 31 relevant studies were analyzed and classified into literature reviews, conceptual frameworks, and evaluation models. The review reveals that while economic and environmental benefits are increasingly supported by measurable indicators, the social dimension remains underexplored and lacks standardized metrics. In addition, most studies focus on short-term operational gains and do not address life cycle-wide perspective, including manufacturing and end-of-life stages.

Based on these findings, this paper (i) clarifies the current maturity of research and its exploratory nature; (ii) identifies major gaps which is the lack of lifecycle-based assessments and operational social indicators; (iii) highlights the weak operationalization of circular economy principles in maintenance 4.0 strategies; and (iv) proposes future research directions to develop holistic, life cycle-oriented, human-centric, and practically validated frameworks. These contributions aim to support the transition toward more sustainable maintenance practices, in alignment with sustainability goals.

1. INTRODUCTION

In response to the Paris Agreement, which aims to limit global warming to well below 2°C above pre-industrial levels and United Nations Sustainable Development Goals (SDGs), the European Union has set ambitious targets for achieving carbon neutrality by 2050 through comprehensive decarbonization strategies across all sectors (Fetting, 2020). This objective, pursued through the European Green Deal, is designed to guide Europe's transition towards a sustainable, low-emission economy, with specific benchmarks for industries to drastically reduce their carbon footprints (Vela Almeida et al., 2023). Within this context, industrial maintenance has emerged as a key driver in achieving sustainability targets, recognized not only for its traditional role in ensuring operational effi-

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ciency but increasingly for its potential to contribute to environmental and societal sustainability (Franciosi, Voisin, Miranda, Riemma, & Iung, 2020).

In parallel, the rise of Industry 4.0 has introduced a range of advanced technologies including Internet of Things (IoT), artificial intelligence (AI), big data analytics (BDA), and cyber-physical systems (CPS) that are reshaping industrial processes, including maintenance practices (Enyoghasi & Badurdeen, 2021). These technologies offer new opportunities to optimize manufacturing performance and align it with the principles of sustainable development (Enyoghasi & Badurdeen, 2021).

This paper aims to provide a systematic review of the existing academic literature to explore how Industry 4.0 enabling technologies influence sustainable maintenance practices, as well as the current evaluation initiatives, in relation to the three pillars of sustainability. It also seeks to identify critical areas for future research. The objective is to offer insights for industries seeking to adapt their maintenance strategies in line with global sustainability goals and to support the transition toward more resilient, resource-efficient, and environmentally responsible industrial systems.

The remainder of this paper is structured as follows: Section 2 explores the concepts of Industry 4.0 and sustainable maintenance and establishes their connection to introduce the central research question. Section 3 outlines the research methodology used to conduct the systematic review. Section 4 presents the results, while Section 5 discusses the key findings. Section 6 provides directions for future research, and Section 7 concludes the paper.

2. BACKGROUND

2.1. Sustainable maintenance

According to (Franciosi, Voisin, Miranda, Riemma, & Iung, 2020), sustainable maintenance is defined as "a set of interconnected processes that, from one hand, has to sustain assets/equipment during their operation in order to guarantee the compliance of the production process, of the manufactured products and to reduce their industrial impacts on economy, society, and surrounding environment and, on the other hand, itself has to be a sustainable business function in order to limit its own flows and impacts generated during maintenance activities". Building on this definition, sustainable maintenance is an approach that integrates economic, environmental, and social considerations into maintenance activities to ensure the long-term viability of industrial assets while minimizing negative impacts on society and the environment. It aims to balance cost-effectiveness, resource efficiency, safety, and environmental responsibility (Bredebach, 2023; Jasiulewicz-Kaczmarek, 2013).

Economically, sustainable maintenance aims to optimize costs, enhances asset lifecycle management, and improves operational efficiency by adopting predictive and preventive maintenance strategies that reduce downtime and resource wastage (Zhao, Gao, & Tang, 2022). The implementation of circular economy principles, such as remanufacturing and reusing components, further ensures long-term cost-effectiveness and competitiveness (Awan & Sroufe, 2022; Wakiru, Pintelon, Muchiri, & Chemweno, 2021). Environmentally, it aims to reduce energy consumption, minimize waste, and mitigate harmful emissions by adopting green maintenance practices, including energy-efficient processes, and condition-based monitoring techniques to optimize resource usage and minimize ecological footprints (Franciosi et al., 2021; Vasić, Orošnjak, Brkljač, Vrhovac, & Ristić, 2024). Additionally, circular economy strategies, such as refurbishment and responsible disposal of hazardous materials, contribute to the environmental sustainability of maintenance operations (Wakiru et al., 2021). Socially, sustainable maintenance ensures workplace safety, promotes employee well-being, and considers broader societal impacts by implementing rigorous safety protocols, providing continuous training for maintenance personnel, and fostering stakeholder engagement in maintenance decision-making (Franciosi, Voisin, Miranda, Riemma, & Iung, 2020). By reducing occupational hazards and aligning maintenance practices with corporate social responsibility (CSR) initiatives, sustainable maintenance fosters a culture of well-being and enhances organizational sustainability (Franciosi, Voisin, Miranda, Riemma, & Iung, 2020). Overall, sustainable maintenance is a multifaceted concept that aligns maintenance activities with the principles of economic efficiency, environmental stewardship, and social responsibility, ensuring optimized asset performance while minimizing adverse effects on society and the environment.

2.2. Industry 4.0 concept

Emerging in 2011 from an initiative of the German government and industry, Industry 4.0 often associated to the Fourth Industrial Revolution, represents the integration of digital technologies into industrial processes to create smart, autonomous, and highly connected systems (Drath & Horch, 2014). It builds on previous industrial revolutions, each marking a major transformation in the way goods are produced. The first industrial revolution introduced mechanization through steam power, replacing manual labor with machines. The second brought mass production enabled by electricity and assembly lines. The third introduced automation using computers and electronics. The fourth industrial revolution extends these advancements by incorporating cyber-physical systems (CPS), enabling real-time communication between machines, humans, and digital systems to optimize manufacturing and industrial operations (Danjou, Rivest, & Pellerin, 2017; Culot, Nassimbeni, Orzes, & Sartor, 2020; Diop, Durupt, Danjou, Baouch, & Boudaoud, 2025)

A key characteristic of Industry 4.0 is its reliance on a set of enabling technologies that create interconnected, intelligent manufacturing ecosystems. IoT allows real-time data collection through sensor-equipped machinery, facilitating predictive maintenance and optimizing production efficiency (Soori, Arezoo, & Dastres, 2023; Turner, Okorie, Emmanouilidis, & Oyekan, 2022). CPS integrate physical processes with digital systems, ensuring seamless coordination across production lines and supervision for maintenance (Folgado, Calderón, González, & Calderón, 2024). These systems allow for real-time monitoring, analysis, and decision-making, creating a seamless interaction between the physical and digital worlds (Monostori et al., 2016). Artificial Intelligence (AI) and Machine Learning (ML) analyze vast datasets, enabling predictive decision-making, automated quality control, and process optimization (Arredondo-Méndez, Para-González, Mascaraque-Ramírez, & Domínguez, 2021). Big Data Analytics provides real-time insights by processing extensive datasets from industrial operations, enhancing industrial operations management and energy efficiency (Rupp, Schneckenburger, Merkel, Börret, & Harrison, 2021). Cloud Computing supports flexible, scalable storage and computing resources, enabling manufacturers to analyze and share data seamlessly across global operations (Xu, Lu, Vogel-Heuser, & Wang, 2021).

Industry 4.0 also introduces Augmented Reality (AR) and Virtual Reality (VR) to improve training, maintenance, and quality inspections by overlaying digital information onto physical environments (Culot et al., 2020). Digital Twins, virtual replicas of physical assets, facilitate simulations and predictive analysis, reducing downtime and optimizing resource utilization (Folgado et al., 2024). Additive Manufacturing (3D Printing) enhances production flexibility by allowing on-demand, localized manufacturing of components, reducing waste and lead time. Advanced Robotics and Collaborative Robots (Cobots) enable automation of repetitive tasks, improving precision and efficiency while working alongside human operators (Arredondo-Méndez et al., 2021). Horizontal and Vertical System Integration ensures seamless communication across all levels of an enterprise, from factory floors to supply chains, enabling a data-driven, interconnected industrial ecosystem (Rupp et al., 2021).

Subsequently, since 2021, the concept of Industry 5.0, formalized by the European Commission, has gained traction as a paradigm that goes beyond efficiency to emphasize worker well-being, sustainability, and resilience (Xu et al., 2021). It complements Industry 4.0 by fostering innovation as a driver of a human-centric, resilient, and sustainable industry.

2.3. Problem statement

The intersection between Industry 4.0 and sustainable maintenance represents an emerging research area in engineering, driven by the imperative for industries to align maintenance practices with global sustainability goals (Diop et al., 2025). Key practices at the intersection of these domains can include lifecycle optimization, circular economy principles, energy management, resource efficiency, and waste minimization on maintenance (Diop et al., 2025). However, despite these promising advancements, there remains a need to understand precisely how Industry 4.0 enabling technologies influence maintenance policies. Then, the central research question of this paper is to identify what has been documented about the impact of Industry 4.0 technologies on maintenance policies for sustainable management, and the existing evaluation initiatives, in relation to the three pillars of sustainability: economic, environmental, and social. To address this question, a Systematic Literature Review (SLR) was conducted to collect and analyze relevant studies.

3. RESEARCH METHODOLOGY

This study utilizes the SLR approach, which offers a structured method to evaluate and synthesize research on a particular topic, aiming to minimize bias and improve reliability through a transparent, reproducible approach (Page et al., 2021). The SLR methodology follows the PRISMA guidelines, who provide a methodology for conducting and reporting these reviews, including a 27-item checklist and a flow diagram that ensures transparency and completeness in the review process (Page et al., 2021).

3.1. Literature search and keywords

Two databases are used for the SLR: Scopus and Web of Science. Then, the search was organized around 4 main categories of keywords: digital transformation, maintenance, sustainability, and impact assessment, as identified in table 1.[1]

Table 1. Group of keywords.

Category	Keywords
Digital transformation	Industr* 4.0; Industr* 5.0; Smart factory; Digital manufacturing; Smart manufacturing; Industrial Internet; Smart production; Factor* of the future; Advanced Manufacturing; Intelligent Manufacturing; Industr* of the future; High value manufacturing; Smart Industry; Manufacturing 4.0; Integrated Industry; Digital Factory; Manufacturing Renaissance
Maintenance & PHM	Maintenance; Asset management; PHM; Prognostics and Health Management; Health Monitoring; Prognostic*; Diagnostic*
Sustainability	Sustainab*; Circular economy; Lifecycle assessment; LCA; Green; Environmental
Impact assessment	Impact; Evaluation; Quantification; Measurement; Assessment; Metrics

The final list of keywords was generated by combining the

[1]"*" in some words in table 1 is a truncation operator used to search for all variations of a word from a common root, e.g., "industr*" includes industry, industrial, industries, etc.

terms within each category using the operator ”OR”, while the categories themselves were connected with the operator ”AND” to define the relationships between them. The search, conducted on April 1st, 2025, was performed without any publication year limit and focused on papers written in English. Articles containing the search keywords in their title, abstract, or author keywords were screened.

3.2. Papers selection

A filtering process was applied based on three exclusion criteria (EC) to narrow down the selection to the most relevant papers:

- EC1: Conference proceedings, book chapters, or books.
- EC2: Papers that do not establish a clear link between sustainability, industrial maintenance, and Industry 4.0 or 5.0, as they fall outside the scope of this review.
- EC3: Papers in which the sustainable dimension of Industry 4.0 or 5.0 in industrial maintenance is only briefly mentioned or underdeveloped and offers no added value to the research question.

Then, the selection process was performed in two steps. First, the titles, abstracts, and keywords of all articles were screened using EC1 and EC2. Articles for which the full text was unavailable were also excluded at this stage. In the second stage, a full-text review was carried out on the articles retained from the first screening, during which EC2 and EC3 were applied.

4. RESULTS

4.1. SLR flow diagram

Figure 1 presents the SLR process and its application. At the beginning, 343 papers were identified, 255 from Scopus and 88 from Web of Science. After removing 84 duplicates, 259 papers remained for analysis. In the first screening process, 78 articles were retained (29 conference articles, 49 journal papers), while the second screening reduced it to 25 (14 journal papers, 11 conference article). Finally, after reviewing the references of these articles, 6 additional relevant papers were included, resulting in a total of 31 articles retained for the SLR (19 journal papers and 12 conference articles). [2]

4.2. Classification of contribution

Each paper was methodologically classified on three categories and in an iterative way allowing us to more easily discuss the SLR results and identify research gaps. Table 2 presents the classification of the 31 included papers based on their type of contribution. The number of literature reviews (15 papers) suggests that the field is still in an exploratory phase, with researchers focusing more on consolidating existing knowledge than developing new theoretical foundations

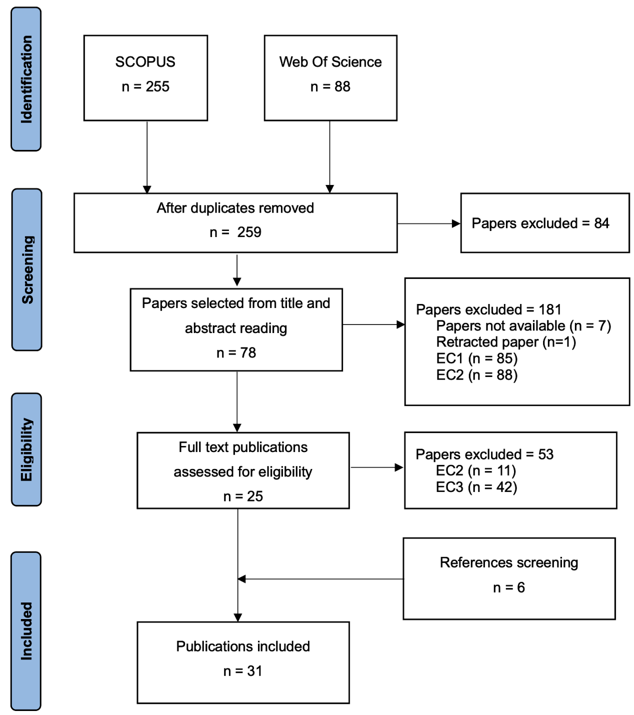

Figure 1. SLR Flow Diagram.

(only 3 papers on theoretical frameworks). While evaluation methodologies and impact assessments (13 papers) indicate a shift toward practical applications, their reliance on case studies (6 papers) and MCDM studies (7 papers) highlights a lack of standardized assessment methods.

4.3. Year wise publications

Figure 2 illustrates the growing academic interest in the intersection of Industry 4.0, maintenance, and sustainability over the past seven years. From 2018 to 2022, the number of publications remained modest and stable, ranging from two to three per year, reflecting an initial phase of exploration. However, a clear upward trend emerges in 2023 and 2024, with a peak of 9 publications in 2024, confirming a strong acceleration of research in this field.

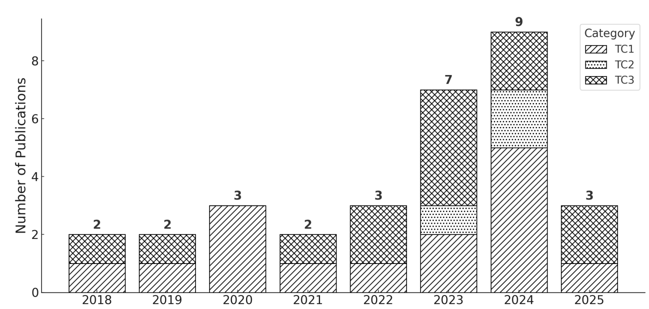

Figure 2. Distribution of the selected papers by their year of publication and type of contribution.

[2]For references whose full text was unavailable, searches via databases and institutional access, as well as author contact attempts, were unsuccessful.

Table 2. Types of contributions (TC) in the reviewed literature.

Category	Sub-category	Description	Number	References
TC1 – Literature Reviews	TC1.1 – Maintenance as the main subject	Reviews primarily focused on sustainable maintenance and its integration with Industry 4.0 or 5.0 technologies.	10	(Cınar et al., 2020); (Franciosi, Iung, Miranda, & Riemma, 2018); (Franciosi, Voisin, Miranda, & Iung, 2020); (Jasiulewicz Kaczmarek & Gola, 2019); (Jasiulewicz-Kaczmarek, Legutko, & Kluk, 2020); (Jasiulewicz-Kaczmarek, 2024); (Madreiter, Trajanoski, Martinetti, & Ansari, 2024); (Orošnjak, Jocanović, Čavić, Karanović, & Penčić, 2021); (Saraswat & Agrawal, 2023); (Vrignat, Kratz, & Avila, 2022)
	TC1.2 – Maintenance as a secondary topic	Industry 4.0 for Sustainable Manufacturing	3	(Khan et al., 2025); (Onu, Pradhan, & Mbohwa, 2023); (Waghanna et al., 2024)
		AI for Sustainable Development Goals	1	(Nedungadi, Surendran, Tang, & Raman, 2024)
		Industry 4.0 and cleaner production	1	(Ma et al., 2024)
TC2 – Theoretical / qualitative frameworks	TC2.1 – Integration frameworks	Conceptual models explore integrating Industry 4.0/5.0 into sustainability of maintenance.	2	(Martinelli, Lopes, & Migliardi, 2024); (Narkhede, Mahajan, Narkhede, & Chaudhari, 2024)
	TC2.2 – Impact oriented frameworks	Frameworks integrate Industry 4.0/5.0 impacts on maintenance sustainability across one or more sustainability pillars.	1	(Chabane, Komljenovic, & Abdul-Nour, 2023)
TC3 – Assessment Studies	TC3.1 – Case based assessments	Concrete impact assessments based on one or more Industry 4.0 technologies on the sustainability of maintenance practices.	6	(El Kihel, El Kihel, & Bouyahrouzi, 2022); (Firat Unal, Albayrak, & Unal, 2023); (Jena, Mishra, & Moharana, 2024); (Lerat & Mahmoudi, 2024); (Munsamy & Telukdarie, 2018); (Sénéchal & Trentesaux, 2019)
	TC3.2 – MCDM or data-driven approaches	Studies use multi-criteria or data analysis methods to assess the adoption and/or maturity of Industry 4.0/5.0 technologies in maintenance sustainability.	7	(Alkhodair & Alkhudhayr, 2025); (Almeida, Ribeiro, & Cardoso, 2023); (Fallahiarezoudar, Ahmadipourroudposht, Bagherian Rafi, & Ngadiman, 2025); (Farsi, Mishra, & Erkoyuncu, 2021); (Ooi, Teh, & Cheang, 2023); (Patalas-Maliszewska & Losyk, 2022); (Samadhiya et al., 2023)

Beyond the quantitative increase, the distribution by type of contribution (TC) provides valuable insights into the evolution of the research landscape. TC1 contributions have been consistently present across the years, with peaks in 2020 (3 papers) and 2024 (5 papers), reflecting both an initial phase of exploration and a continued effort to consolidate existing knowledge. From 2023, TC2 begins to appear, 1 paper in 2023 and 2 papers in 2024, indicating a shift toward the formalization of theoretical models and structured thinking around the integration of Industry 4.0 in sustainable maintenance. TC3 contributions, encompassing both case studies and MCDM-based approaches, shows a dynamic growth. Its expansion, particularly in 2023 and 2024, suggests a transition from theoretical exploration to practical application, with an increasing number of studies aiming to assess the sustainability impacts of digital technologies on maintenance practices.

5. DISCUSSION ON REVIEW RESULTS

The SLR results highlight different topics for discussion depending on the type of contribution. These are examined in detail in the following sub-sections.

5.1. Industry 4.0 for Sustainable Maintenance

The literature classified under TC1 collectively highlights the transformative potential of Industry 4.0 technologies in advancing sustainable manufacturing through more intelligent and efficient maintenance practices. At the core of this transformation are predictive and prescriptive maintenance strategies, driven by Prognostics and Health Management (PHM) systems and enabled by key technologies such as IoT, BDA, AI, and CPS (Vrignat et al., 2022). These technologies contribute to sustainability across its three dimensions, economic, environmental, and social.

From an economic perspective, predictive and prescriptive approaches reduce unplanned downtime, improve production reliability, and extend equipment lifespan, thereby lowering both operational and capital costs (Cınar et al., 2020; Saraswat & Agrawal, 2023). From an environmental standpoint, smarter maintenance enables energy-efficient operations and reduces material waste by avoiding unnecessary replacements and optimizing asset usage (Franciosi et al., 2018; Jasiulewicz Kaczmarek & Gola, 2019). Furthermore, by incorporating lifecycle-based decision-making, these technologies promote circularity and resource conservation (Ma et al., 2024; Onu et al., 2023; Madreiter et al., 2024).

On the social level, maintenance enabling by industry 4.0 technologies can enhance workplace safety, reduce exposure to hazardous failures, and support more humane work environments (Franciosi, Voisin, Miranda, & Iung, 2020). The use of immersive tools such as AR, VR and digital twins also supports operator training and upskilling, contributing to long-term workforce resilience (Jasiulewicz-Kaczmarek et al., 2020; Jasiulewicz-Kaczmarek, 2024; Waghanna et al., 2024).

Studies also emphasize the integrative nature of Industry 4.0 in aligning maintenance strategies with broader sustainability goals. The ability of maintenance 4.0 to simultaneously support economic performance, environmental protection, and social responsibility helps break traditional trade-offs between these dimensions, directly contributing to the achievement of Sustainable Development Goals (SDGs), particularly SDG 7 (clean energy) and SDG 9 (Industry, Innovation, and Infrastructure). Moreover, contributions highlight connections with SDG 12 (responsible consumption and production), as smarter maintenance avoids unnecessary resource use, and SDG 13 (climate action), by improving energy efficiency and reducing emissions from maintenance operations (Khan et al., 2025; Nedungadi et al., 2024; Orošnjak et al., 2021). Socially, enhanced safety and training align with SDG 8 (Decent Work and Economic Growth), by promoting safer work environments and inclusive skill development (Franciosi et al., 2018; Jasiulewicz-Kaczmarek et al., 2020; Jasiulewicz-Kaczmarek, 2024).

However, despite these important contributions, the reviewed literature exhibits notable gaps and limitations. A recurring gap is the systematic measurement of sustainability beyond economic outcomes. Although the environmental and social benefits are discussed, practical and standardized metrics remain underdeveloped.

Another critical shortcoming is the limited consideration of negative externalities. The emphasis is often placed on benefits, with less attention given to potential downsides such as increased energy demand for digital infrastructures (affecting environmental sustainability), technostress and digital overload (impacting social sustainability), cybersecurity vulnerabilities, and the generation of electronic waste.

Moreover, while studies such as (Madreiter et al., 2024) and (Ma et al., 2024) mention the relevance of circular economy principles into sustainable manufacturing, the operational integration of Maintenance 4.0 into circular value chains remains superficial, and the intersection between maintenance 4.0 and circularity is weakly developed in the literature. References to circularity are limited to general statements about asset longevity, resource conservation and efficiency improvements, without engaging in a deeper discussion of how maintenance with industry 4.0 enabling technologies can actively support practices such as reuse, remanufacturing, or component recovery.

A further limitation is the lack of detailed attention given to lifecycle-wide implications, particularly concerning from raw material extraction, manufacturing, distribution and end-of-life phases of these technologies. Addressing trade-offs between operational gains on maintenance and the environmental impacts of design and disposal stages is essential for achieving true sustainability.

Finally, quantitative evaluations of the impacts of Industry 4.0 enabled technologies on maintenance sustainability are largely absent from existing literature reviews. Then, this paper seeks to address these gaps by conducting an in-depth literature review on how the impacts of these technologies on the sustainability of maintenance are assessed. It provides a systematic classification of existing studies according to their treatment of sustainability impacts, and offers a critical analysis of their strengths, limitations, and methodological approaches, as discussed in Sections 5.2 and 5.3.

Overall, these findings demonstrate the pivotal role of Industry 4.0 in advancing sustainable maintenance practices and justify the relevance of conducting this literature review. A summary of the main contributions from the TC1 classified papers is provided in Tables A1 and A2 in the appendix.

5.2. Conceptualizing the integration and impacts of Industry 4.0 on maintenance sustainability

A thorough analysis of the selected literature under TC2 reveals a clear convergence toward rethinking industrial systems through the lens of the Industry 5.0 paradigm, which places sustainability, human-centricity, and resilience at the heart of industrial innovation. The reviewed studies collectively underscore the necessity of moving beyond the machine-centric logic of Industry 4.0, advocating instead for a more inclusive and integrated approach to industrial transformation.

A first point of convergence lies in the call for the integration of advanced digital technologies notably IoT, AI, BDA, and CPS as enablers of more predictive, adaptive, and sustainable industrial systems. These technologies are positioned as key to improving operational efficiency and decision-making, but also as tools to support long-term sustainability by fostering responsiveness to human and environmental needs (Martinelli et al., 2024; Narkhede et al., 2024; Chabane et al., 2023). Also, these studies all advocate for the strategic shift from machine-centric decision-making to more human-centered approaches, addressing the limitations of Industry 4.0's overly techno-centric implementation and its insufficient attention to human and environmental consequences.

(Martinelli et al., 2024) propose a conceptual framework that introduces predictive monitoring systems for human operators, reflecting an evolution from machine-focused maintenance to human-aware industrial environments. Their contribution is significant in that it repositions the human operator as a central node in the predictive architecture, proposing modules for data collection, analytics, and intervention. However, while their framework is robust in structure, it remains conceptual and lacks empirical grounding or practical validation.

Similarly, (Narkhede et al., 2024) contribute a mapping of Industry 4.0 technologies across key operational functions within manufacturing small and medium enterprises (SMEs), such as product development, logistics, supply chain, and maintenance, demonstrating how industry 4.0 enabling technologies support sustainable practices. A key strength of their work lies in the breadth of functions analyzed, the identification of technology-function fit and proposing a roadmap for integrating Industry 4.0 technologies into industrial operations and maintenance for a sustainable industry. Notably, the study introduces the concept of impact assessment but stops short of proposing a concrete evaluation methodology. In addition, the study does not address the socio-organizational barriers that SMEs may encounter when adopting such technologies, such as change resistance, skills gaps, or structural constraints. Furthermore, while sustainability is acknowledged, the analysis remains largely qualitative and focuses primarily on operational efficiency, with limited exploration of measurable environmental or social impacts. As a result, the contribution, though promising, would benefit from a more comprehensive and quantitative assessment framework to fully capture the sustainability potential of these technologies.

(Chabane et al., 2023) move beyond the technical scope of industry 4.0 by proposing an asset management framework that explicitly incorporates the three pillars of Industry 5.0: human-centricity, sustainability, and resilience. Their work is particularly valuable in highlighting how asset management practices must evolve in parallel with industrial transformation, not only to optimize performance but also to manage risks for human, mitigate environmental disruption, and ensure worker well-being. The proposed integration of human and environmental impact assessments into traditional asset management decision-making represents a conceptual advance. However, similar to the work of (Martinelli et al., 2024), their framework remains at a theoretical level, with no practical implementation or standardized quantitative methods to support the evaluation of these impacts. As it stands, the model lacks operational tools and empirical validation, leaving its applicability in real-world industrial contexts to be demonstrated.

Across these studies, a common strength lies in the recognition of the interdependence between digital transformation and sustainability goals. All three articles reinforce the view that industry 4.0 enabling technologies must serve broader societal objectives, rather than purely technical or economic ones. However, a key gap persists: none of the studies proposes a quantitative, lifecycle-based framework capable of assessing both the positive and negative impacts of these digital technologies, from the extraction of raw materials to end-of-life management. This limitation is particularly evident in the context of maintenance, where sustainability assessments view of these works focus on operational gains without accounting for upstream and downstream impacts. Additionally, the concept of "resilience" is often mentioned, especially by (Chabane et al., 2023), but lacks measurable indicators and integration into risk-based asset management tools.

Furthermore, a comparative synthesis of the TC2 contributions shows that only three studies address theoretical or qualitative frameworks, two under TC2.1 (integration frameworks) and one under TC2.2 (impact-oriented framework). This small number indicates that the integration of Industry 4.0/5.0 into maintenance sustainability remains in an early exploratory phase. Current contributions are largely conceptual and lack structured, quantitative methods for evaluating real-world impacts. This reflects both the novelty of the topic and the urgent need to formalize the research through robust frameworks that combine standardized indicators, real case studies, and life cycle thinking. Such formalization is essential to support industrial implementation and to move beyond theoretical vision statements toward concrete, measurable contributions to sustainable maintenance.

To consolidate these findings, Tables A3 and A4 in the appendix present a summary of the main contributions of the TC2 classified papers.

5.3. Evaluation studies on Industry 4.0 impacts on maintenance sustainability

To support the analysis of the papers selected under TC3, Table 3 presents a mapping and classification based on specific criteria. This synthesis aims to facilitate comparison by highlighting, for each paper, the methodological approach employed, the Industry 4.0 technologies addressed, the sustainability dimensions (SD) considered, as well as the types of impacts assessed. Based on the classification under TC3.1 and TC3.2, four categories of methods are considered: Multi-criteria decision making (MCDM), which supports the evaluation of trade-offs among multiple sustainability criteria; data-driven approaches, which rely on empirical data, statistical techniques, or machine learning algorithms; Life cycle assessment (LCA), environmental impacts across the full life cycle of these technologies on maintenance sustainability; and energy & carbon evaluation models, which estimate energy consumption and CO_2 emissions associated with maintenance operations and decision-making processes using industry 4.0 enabling technologies.

In this mapping, two types of impacts are also distinguished: positive impacts, referring to observed or evaluated environmental, economic, or social improvements; negative impacts, associated with potential drawbacks of these technologies on maintenance sustainability. These impact assessments are further complemented by the analysis of life cycle phases considered in the selected papers, covering the different stages of the technology life cycle, from raw material extraction and manufacturing to distribution, use, and end-of-life (e.g., disposal or recycling). This structured overview provides a basis for identifying trends, complementarities, and existing gaps across the selected contributions.

The following subsections present a focused analysis of contributions, first through case studies (subsection 5.3.1), followed by MCDM-based and data-driven approaches (subsection 5.3.2) and subsection 5.3.3 dedicated to sustainability performance measurement in the context of maintenance 4.0. In addition, a summary of the main contributions from the TC3.1 and TC3.2 classified papers is presented in Tables A5 and A6, respectively, in the appendix.

5.3.1. Case-based approaches

Across the reviewed literature under TC3.1, a clear convergence emerges around the sustainability enhancing potential of Industry 4.0 technologies in maintenance practices. For instance, (El Kihel et al., 2022) provide a comprehensive framework by applying maintenance 4.0 to both thermal and compressed air systems within an agri-food company. Their results include a boiler efficiency improvement from 65.3% to 76.9%, plastic waste reduction from 680 kg to 98 kg, and increased production per kWh of energy consumed, showcasing a direct impact on carbon footprint and resource efficiency. These results align with those of (Firat Unal et al., 2023), who also report measurable energy savings through digital twins, although their analysis remains narrower in environmental scope, focusing primarily on energy metrics. (Munsamy & Telukdarie, 2018) also demonstrate that applying IoT and CPS to maintenance functions can reduce energy demand by 46% and CO_2 emissions by 42%. Similarly, (Jena et al., 2024) highlight quantitative gains in their integration of Industry 4.0 with reliability centered maintenance, notably a 9.3% reduction in carbon emissions and 8.7% drop in energy usage. Nevertheless, their analysis remains focused on energy consumption and economic metrics, and would benefit from a more comprehensive life cycle perspective.

(Lerat & Mahmoudi, 2024) evaluate the environmental impact of deep learning for predictive maintenance. Their findings, showing normalized energy consumption of 10.2 to 28.0 kWh depending on the architecture, highlight the relevance of energy-performance trade-offs. However, the scope is mainly computational, and the study does not address the environmental impacts of AI and data centers across the entire life cycle. And, their analysis focused on energy consumption, carbon footprint and economic metrics. Then, as with other works, the analysis remains focused on energy consumption and economic metrics.

Although these studies demonstrate the operational and environmental benefits of smart maintenance strategies, they tend to overlook social sustainability indicators. Moreover, these studies share a common limitation: their sustainability assessments are oriented toward operational gains and short-term benefits, without systematically considering the entire life cycle of the technologies deployed. The material, energy, and environmental costs of producing, maintaining, and disposing of these technologies are not addressed, which restricts the scope of their conclusions.

(Sénéchal & Trentesaux, 2019) partially attempt to address this limitation by proposing a Sustainable Condition-Based Maintenance (SCBM) framework built on Life Cycle Assessment (LCA) principles and introduce the novel Remaining Sustainable Life (RSL) indicator. However, it is important to note that their approach does not conduct an LCA of the enabling Industry 4.0 technologies themselves, and their LCA remains partial. Instead, CPS capabilities are leveraged to enable real-time environmental monitoring and simulation of different maintenance policies. Thus, their work provides an LCA-based comparison of maintenance strategies, not a comprehensive environmental evaluation of the technologies enabling those decisions. Moreover, their analysis is restricted to energy consumption during only three life cycle phases: manufacturing, distribution/transportation, and use phase, based on the ADEME IMPACTS database. Other key phases such as raw material extraction and end-of-life are not considered. This scope limits conclusions about the direct sustainability performance of Industry 4.0 solutions.

The comparative mapping in Table 3 reinforces these observations and gaps. None of the reviewed studies fully implement a global life cycle perspective that spans all relevant phases, from raw material extraction to end-of-life, and integrates both economic, environmental and social impacts. They focus on the use phase of enabling technologies, while the upstream (raw material extraction, manufacturing, and distribution) and downstream (end-of-life) phases are overlooked. Only (Sénéchal & Trentesaux, 2019) make an attempt at LCA-based impact assessment, but even this remains limited in scope. These omissions point to a methodological

Table 3. Mapping and classification based on criteria

References	Methods				I4.0 technologies										SD			Impact		Life cycle phase				
	MCDM	Data-driven	LCA	Energy & carbon evaluation	IoT Sensors	BDA	AI & ML	CPS & Digital Twin	Additive manufacturing	Cloud Computing	Cobot	AR / VR	Simulation	Blockchain	Economic	Social	Environmental	Positive	Negative	Raw material extraction	Manufacturing	Distribution	Use	End-of-life
(Alkhodair & Alkhudhayr, 2025)		X			X		X							X	X		X	X					X	
(Fallahiarezoudar et al., 2025)	X														X	X	X	X					X	
(Jena et al., 2024)				X	X	X									X		X	X					X	
(Lerat & Mahmoudi, 2024)				X			X										X	X					X	
(Almeida et al., 2023)	X				X	X	X								X	X	X	X					X	
(Firat Unal et al., 2023)				X	X	X	X	X							X		X	X					X	
(Samadhiya et al., 2023)		X													X		X	X					X	
(Ooi et al., 2023)		X			X	X	X	X	X	X	X	X	X	X	X	X	X	X					X	
(El Kihel et al., 2022)				X	X	X	X								X		X	X					X	
(Patalas-Maliszewska & Losyk, 2022)	X														X	X	X	X					X	
(Farsi et al., 2021)	X				X		X	X			X	X	X		X	X	X	X					X	
(Sénéchal & Trentesaux, 2019)			X		X										X		X	X			X	X	X	
(Munsamy & Telukdarie, 2018)				X	X	X	X										X	X					X	

imbalance in the current state of the art.

Table 3 also reveals a general neglect of the social dimension and the absence of evaluations of the potential negative externalities associated with the deployment of Industry 4.0 technologies. This narrow approach highlights the need for comprehensive life cycle assessments that capture the full range of economic, environmental and social impacts throughout the life cycle of these technologies.

Nevertheless, these articles collectively validate that maintenance 4.0 can yield tangible sustainability benefits. Still, significant research gaps remain in addressing the social dimension, validating models in industrial contexts, and integrating full life cycle thinking and life cycle impact assessments. Only through such a comprehensive framework can the full sustainability potential of maintenance 4.0 be realized, moving beyond energy and emissions toward inclusive and responsible industries.

5.3.2. MCDM-based approaches

The collective analysis of the reviewed literature under TC3.2 highlights a growing scholarly effort to integrate Industry 4.0 enabling technologies into sustainable maintenance strategies, leveraging both data-driven methods and structured decision-making approaches. Across the studies, a methodological convergence emerges, particularly around multi-criteria decision making (MCDM) frameworks such as Fuzzy AHP, TOPSIS, and hybrid DEMATEL–ANP models. These techniques are prominently featured in works such as (Almeida et al., 2023), (Fallahiarezoudar et al., 2025), (Farsi et al., 2021) and (Patalas-Maliszewska & Losyk, 2022), where they are employed to prioritize sustainability indicators, rank enabling technologies, and weigh their influence on maintenance policies for sustainable maintenance. These methods offer powerful tools for navigating trade-offs between economic, environmental, and social objectives under uncertainty, and are particularly valued for their compatibility with expert-driven decision environments. However, they are overwhelmingly applied at a strategic level, supporting adoption planning and investment prioritization, rather than guiding day-to-day operational execution of maintenance tasks.

In parallel, a significant subset of studies adopts data-driven or machine learning-based methods. (Alkhodair & Alkhudhayr, 2025), for instance, use algorithms such as XGBoost and random forest regression to evaluate sustainability outcomes across 300 SMEs, showing that predictive maintenance enabled by AI and IoT can reduce equipment downtime by up to 30% and cut carbon emissions by 10%. Similarly, (Ooi et al., 2023) employ structural equation modeling (PLS-SEM) to examine how Industry 4.0 technologies moderate the relationship between Lean Production, including total productive maintenance (TPM) on triple bottom line (TBL) outcomes. (Samadhiya et al., 2023) build on this by introducing Circular Economy (CE) as a mediating construct that links digital TPM with improved sustainability performance, highlighting the systemic potential of integrating maintenance and circularity strategies.

Despite their analytical rigor, these contributions remain largely strategic in scope, aiming to inform high-level support decisions about what to adopt, rather than how to implement maintenance approaches in operational environments. The majority of the reviewed studies propose models for ranking sustainability criteria, weighing the contribution of industry 4.0 enablers, or evaluating the strategic relevance of various maintenance levers, but stop short of translating these insights into actionable models for maintenance practices.

Another key limitation is the geographical concentration of the studies, which raises concerns about contextual bias and generalizability. A significant number of empirical contributions are drawn from Indian (e.g., (Samadhiya et al., 2023)), Southeast Asian (e.g., (Ooi et al., 2023)), or Eastern European (e.g., (Patalas-Maliszewska & Losyk, 2022)) manufacturing contexts, often within specific industrial sectors such as textiles, automotive, or electronics. While these domains provide rich testing grounds for digital maintenance strategies for sustainability, the findings may be highly context dependent, shaped by regional infrastructure maturity, regulatory landscapes, or firm sizes and thus not directly transferable to other regions or industries.

Furthermore, while most contributions emphasize the economic and environmental pillars of sustainability, particularly through cost reduction, energy efficiency, or emissions control, the social dimension remains underrepresented. Although studies like (Almeida et al., 2023) and (Farsi et al., 2021) include references to worker safety, organizational culture, or training, these aspects are typically discussed qualitatively, with few attempts to quantify their impacts.

In addition, most studies tend to highlight positive sustainability effects of digital maintenance, while potential negative externalities are not addressed.

Overall, these findings reinforce the pivotal role of Industry 4.0 technologies in shaping sustainable maintenance paradigms and highlight the usefulness of MCDM and data-analytical methods in enabling decision-makers to prioritize, rank, and weigh strategies under conditions of uncertainty. Nonetheless, these papers remains focused on strategic-level guidance and technology adoption, with limited emphasis on operational deployment, real-time integration, and sustainability impacts quantification.

5.3.3. Sustainability performance measurement

To assess the integration of sustainability within maintenance 4.0, a detailed mapping of indicators across the environmental, economic, and social dimensions was conducted based on the final set of contributions retained from the SLR under TC3. Occurrence refers to the number of reviewed papers that mention a given indicator or criterion. The results are synthesized in Table 4, which compiles a broad range of quantitative and qualitative indicators and criterias.

While environmental and economic metrics are relatively well established, particularly the economic indicators, which are already formalized in international standards (*EN 15341: Maintenance - Key Performance Indicators*, 2019), social indicators remain significantly underdeveloped, despite being central to the human-centric principles advocated by Industry 5.0. Moreover, the SLR did not reveal any general classification of sustainability performance indicators specific to maintenance 4.0. Then, studies have to focus on addressing this gap by developing operational, standardized, and context sensitive accepted social metrics to capture the societal implications of digital transformation in maintenance practices. In parallel, they should also establish a dedicated classification of sustainability performance indicators specific to maintenance 4.0.

6. FUTURE RESEARCH DIRECTIONS

Despite the growing academic interest in the intersection of Industry 4.0 technologies and sustainable maintenance, this study reveals gaps that open promising avenues for future research.

6.1. Focus on short-term impacts rather than long-term sustainability

Current studies tend to focus on short-term sustainability outcomes such as reduced costs or energy use, without considering long-term impacts. This short-term view limits the understanding of how maintenance strategies and technologies evolve over time and under different future scenarios. Long-term impacts such as technology obsolescence, resource depletion, rebound effects or workforce changes are not studied.

Table 4. Mapping of indicators and criteria identified from the SLR.

Dimension	Indicators and Criteria	Occurrence
Economic	Maintenance cost	7
	Energy cost	4
	Performance (downtime, OEE, Lead time)	3
	Cost of production	3
	Return on eco-friendly maintenance investment and innovation	2
	Total spare parts used / New spare parts used and raw material purchasing costs	2
	Downtime costs	2
	Scrap costs	1
	Revenue loss	1
Social	Safety / work accidents	5
	Health	2
	Training	2
	Employee satisfaction	2
	Regulatory compliance	1
	Ergonomic	1
	Employee morale	1
	Workers equality and diversity	1
	Dignity at work	1
	Working pressure	1
	Ease of maintenance	1
Environmental	Energy consumption	7
	CO_2 emission	7
	Waste reduction and treatment	7
	Energy efficiency	5
	Climate change	3
	Water use	3
	Resource use	3
	Greenhouse gas emission	2
	Renewable energy consumption	2
	Transportation	2
	Recycling	2
	Eutrophication	1
	Ozone depletion	1
	Acidification	1
	Photochemical ozone	1
	Respiratory effects	1

Future work should adopt long-term modeling approaches to explore how maintenance 4.0 strategies affect sustainability over time. This would help design more resilient, adaptive, and future-proof maintenance policies.

6.2. Lack of clear and measurable social sustainability indicators

While environmental and economic indicators are increasingly formalized, the social dimension remains insufficiently explored. There is a clear need for operational, context-sensitive social metrics that can effectively capture aspects such as human well-being, inclusiveness, skills development, and the quality of human machine collaboration. Future research should focus on defining and validating clear, measurable, and context-specific social indicators tailored to maintenance 4.0. It will help integrate the human factor into sustainability assessments and align maintenance strategies with the human-centered vision of Industry 5.0.

6.3. Absence of a standardized KPI classification for sustainable maintenance 4.0

There is currently no standardized classification of sustainability performance indicators specifically tailored to the context of maintenance 4.0. This gap makes it challenging to compare results across studies, benchmark progress, or guide industrial applications in a coherent and consistent manner. Future research should aim to develop a structured and widely recognized classification of sustainability indicators specific to maintenance 4.0 and covers all three dimensions of sustainability. Such a classification would provide a common reference point for assessment practices, improve cross-sector comparability, and support the effective integration of sustainable approaches within industrial maintenance policies.

6.4. Weak integration of circular economy principles in maintenance 4.0

Although circular economy concepts such as reuse, remanufacturing, and recycling are often mentioned in the context of Industry 4.0, their connection to maintenance 4.0 strategies is still weak. Current research from the SLR rarely explains how maintenance practices, supported by digital technologies, can contribute to circular value creation in a concrete and operational way. Future research should investigate how maintenance 4.0 can support circular economy practices, for example by enabling predictive remanufacturing, reusing and recovering through real-time monitoring of component life cycles, or by fostering design for maintainability (Bocken, De Pauw, Bakker, & Van Der Grinten, 2016; Lieder & Rashid, 2016; Wang, Wang, Yang, Zhu, & Liu, 2020). Technologies like IoT, digital twins, and blockchain could play a key role in tracking assets, optimizing reuse, and closing material loops.

6.5. Limited understanding of life cycle-wide sustainability impacts

There is still a limited understanding of the broader sustainability impacts of Industry 4.0 technologies across their full life cycle. Most existing studies concentrate on the operational benefits and use phase, while often overlooking the environmental and social impacts linked to the manufacturing, deployment, and end-of-life stages. To address this gap, future research should aim to develop integrated assessment methodologies capable of evaluating the entire life cycle of these technologies, from raw material extraction to final disposal. These frameworks should build upon established approaches as Life Cycle Assessment (LCA), Life Cycle Costing (LCC), and Social Life Cycle Assessment (S-LCA), while adapting them to maintenance 4.0. Such methodologies must account for both positive impacts and potential negative externalities, allowing for balanced trade-offs between short-term performance improvements and long-term economic, environmental and social impacts.

6.6. Limited practical validation of proposed frameworks

There is a gap in the practical validation of sustainability-oriented frameworks for maintenance 4.0. Contributions propose theoretical models, but they have not been tested in real industrial environments, making it difficult to assess their practical feasibility, scalability, and real-world impact. In addition, existing evaluations often focus narrowly on a limited set of environmental and economic metrics, mainly related to energy consumption and CO_2 emissions, while broader sustainability aspects remain largely overlooked.

Future research should also aim to develop and validate a sustainability oriented maintenance 4.0 models in real industrial contexts. Such validation is essential to move beyond theoretical frameworks and assess their practical feasibility and impact. It will help to ensure that the proposed methodologies are actionable tools, capable of guiding industries in adopting truly sustainable maintenance practices. Finally, the development of decision-support tools that translate sustainability assessments into operational insights is important to bridging the gap between strategic goals and day-to-day maintenance decisions.

6.7. The need to look beyond digital technologies and assess their supporting infrastructures

There is a gap in current research regarding the broader sustainability implications of the infrastructures that support Industry 4.0 technologies. While the functional benefits of technologies like AI, BDA, and IoT in maintenance sustainability are highlighted, the supporting ecosystem that enables their deployment is neglected, regarding the SLR. These technologies rely on a vast ecosystem of physical and digital infrastructure whose sustainability impacts must be assessed.

For example, the energy consumed during AI model training for predictive maintenance, the carbon footprint of large-scale data centers, and the storage and processing demands of IoT data related to maintenance monitoring and asset management are not sufficiently developed in the current literature, based on the SLR. This omission leads to an overly optimistic view of these technologies on maintenance sustainability, which can lead to them being considered sustainable, while in reality they may contribute to hidden environmental burdens and unseen social impacts across their life cycles.

Future research must adopt a more critical and holistic perspective by moving beyond the direct use of these technologies to assess the entire system that supports them. This includes life cycle evaluations of digital infrastructure and hardware, as well as ethical and social considerations. Without such comprehensive assessments, maintenance 4.0 may unintentionally reproduce the sustainability challenges it aims to mitigate.

6.8. Limited consideration of socio-organizational and contextual diversity in MCDM and data-driven approaches

There is a gap in the consideration of socio-organizational and contextual diversity in studies applying multi-criteria decision making and data-driven approaches to maintenance 4.0. Many of these studies assume a uniform potential for technology implementation, often ignored key organizational constraints, as company size, resistance to change, limited digital competencies, and resource limitations, particularly in SMEs. These elements affect the feasibility and relevance of sustainability maintenance 4.0 strategies and are not integrated into evaluation models or decision-support tools.

Moreover, the empirical foundations of MCDM and data-driven contributions are geographically and sectorally concentrated, based on case studies from specific regions (e.g., India, Southeast Asia, Eastern Europe) or industrial sectors (e.g., automotive, electronics). This raises concerns regarding the generalizability and transferability of results across different socio-economic and regulatory environments.

Future research should aim to make MCDM and data-driven approaches more context-aware and adaptable, by incorporating criterias related to organizational readiness, cultural factors, and local digital infrastructure maturity. It should also seek to diversify empirical applications to better reflect the heterogeneity of industrial sectors, ensuring that proposed strategies for sustainable maintenance are inclusive, scalable, and responsive to real-world constraints.

7. CONCLUSION

This study set out to evaluate how Industry 4.0 technologies impact sustainable maintenance policies and existing impact assessment initiatives across the three pillars of sustainability: economic, environmental, and social. Through a systematic literature review of 31 contributions, the paper offers a comprehensive overview of the current research landscape, classifying works into reviews, conceptual frameworks, and assessment models.

The analysis confirms the growing interest in the topic and highlights several key insights. First, economic and environmental benefits are increasingly quantified through measurable indicators, yet the social dimension remains underdeveloped, with few operational or standardized metrics. Second, although maintenance 4.0 is often presented as a lever for sustainability, most evaluations remain focused on short-term operational performance and do not adopt a full life cycle perspective. Moreover, existing studies seldom account for the negative externalities associated with the implementation of digital technologies.

Based on these observations, this work makes seven main contributions: (i) clarifies the current maturity of research and evaluation initiatives on sustainable maintenance 4.0, (ii) highlights that Industry 4.0 enabling technologies offer concrete opportunities to improve maintenance sustainability by reducing costs, energy consumption, emissions, and promoting workplace safety and employee upskilling, thereby supporting SDGs, (iii) identifies methodological gaps, particularly the lack of full life cycle integration in sustainability assessments and the insufficient evaluation of both positive and negative impacts across all life cycle stages, from raw material extraction to manufacturing, and end-of-life phases,and the limited practical validation of proposed frameworks and models, (iv) reveals the absence of a general and structured classification of sustainability performance indicators tailored to maintenance 4.0, limiting the comparability and benchmarking across studies, (v) shows that while circular economy principles are often mentioned, their operational integration into maintenance 4.0 strategies remains superficial and underdeveloped, (vi) highlights the need to move beyond the assessment of digital technologies alone and consider the economic, environmental and social impacts of their supporting infrastructures for sustainable maintenance, and (vii) underlines that existing MCDM and data-driven approaches mainly focus on strategic prioritization but insufficiently consider socio organizational diversity and contextual factors, affecting their generalization and practical relevance.

Based on these findings, future research should focus on developing global, lifecycle-based, and practically validated frameworks capable of assessing both the benefits and trade-offs of digital technologies in sustainable maintenance. It should also go beyond the evaluation of technologies alone and include the impacts of supporting infrastructures, across their full life cycle. In addition, more efforts are needed to integrate circular economy principles into maintenance 4.0 policies. Finally, there is a need for operational and context-sensitive social indicators, and a structured classification of sustainability KPIs tailored to maintenance 4.0. These advances are essential to support the evolution of maintenance toward more resilient, inclusive, and environmentally responsible practices, in alignment with the principles of Industry 5.0 and sustainability goals.

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APPENDIX

Table A1. Main ideas of the selected papers for TC1.1

References	Main ideas
(Cınar et al., 2020)	• Reviews recent developments in machine learning techniques applied to predictive maintenance (PdM) in the context of Industry 4.0 and sustainable smart manufacturing. • Highlights the importance of selecting appropriate ML algorithms, data types, and feature engineering to ensure effective fault detection and accurate Remaining Useful Life (RUL) prediction. • Emphasizes that effective PdM, supported by PHM systems and AI technologies, contributes to reducing downtime, improving equipment efficiency, and enabling more sustainable maintenance planning.
(Franciosi et al., 2018)	• Investigates how maintenance contributes to sustainability in the Industry 4.0 context through a Scoping Literature Review. • Highlights the increasing relevance of the “maintenance and sustainability” topic and the key role of Industry 4.0 enabling technologies in supporting sustainable practices.
(Franciosi, Voisin, Miranda, & Iung, 2020)	• Explores how integrating I4.0 technologies with maintenance affects sustainable manufacturing. • Shows both positive (efficiency, safety, flexibility) and negative (costs, technostress, environmental impact) effects.
(Jasiulewicz Kaczmarek & Gola, 2019)	• Reviews how emerging digital technologies enable the evolution of maintenance into ”Maintenance 4.0”, supporting sustainable manufacturing. • Highlights that Maintenance 4.0 can break traditional trade-offs by improving equipment lifetime, reducing downtime, and minimizing energy and resource consumption. • Stresses the importance of integrating economic, environmental, and social dimensions throughout the maintenance lifecycle to ensure long-term sustainability.
(Jasiulewicz-Kaczmarek et al., 2020); (Jasiulewicz-Kaczmarek, 2024)	• Examines the evolution from traditional to data-driven maintenance and explores how Maintenance 4.0 technologies (e.g., IoT, AI, digital twins, AR) contribute to sustainability in manufacturing. • Emphasizes that Maintenance 4.0 supports economic, environmental, and social goals by enabling predictive and prescriptive strategies, reducing resource use, and improving safety and working conditions. • Highlights the need to integrate digital tools with lifecycle thinking and sustainability metrics to fully leverage the benefits of smart, sustainable maintenance systems.
(Madreiter et al., 2024)	• Investigates how Industry 4.0 technologies can drive sustainable maintenance practices that align with environmental goals. • Identifies a strong link between technological maturity and the potential to reduce emissions, waste, and resource use.
(Orošnjak et al., 2021)	• SLR reveals limited scientific impact of European Maintenance 4.0 projects, notably in sustainability and energy-based maintenance (EBM). • Identifies a gap in using energy indicators for maintenance decisions and proposes a new EBM paradigm aligned with EU Green Deal targets.
(Saraswat & Agrawal, 2023)	• Reviews the role of Artificial Intelligence as a core enabler of predictive and sustainable maintenance in Industry 4.0. • Highlights benefits such as reduced downtime, increased equipment availability, and lower maintenance costs.
(Vrignat et al., 2022)	• Reviews the evolution of sustainable manufacturing and highlights maintenance as a strategic lever for balancing economic, environmental, and social goals. • Emphasizes the critical role of Prognostics and Health Management (PHM) in enabling proactive, efficient, and resource-conscious maintenance. • Identifies future challenges in integrating data-driven, physics-based, and hybrid prognostics models to support circular economy and resilient systems.

Table A2. Main ideas of the selected papers for TC1.2

References	Main ideas
(Khan et al., 2025)	• Provides a comprehensive review of how Industry 4.0 enabling technologies can enhance sustainability across environmental, economic, and social dimensions. • Highlights both the benefits (e.g. maintenance efficiency, circular economy, job quality) and risks (e.g. job loss, rebound effects) of digitalization.
(Ma et al., 2024)	• Provides a systematic mapping of how Industry 4.0 technologies support cleaner production across all stages of the product life cycle in energy-intensive industries. • Highlights maintenance 4.0 as a key enabler of sustainable practices during the "middle of life" phase of the product life cycle. • Stresses the need to overcome implementation challenges (cost, energy use, e-waste) and calls for integrated frameworks to guide sustainable digital transformation.
(Nedungadi et al., 2024)	• Examines AI and big data's contribution to SDG9, emphasizing predictive maintenance as a key driver of industrial innovation and resilient infrastructure. • Shows how intelligent maintenance enhances defect detection, quality, and efficiency, while advocating for ethical AI for sustainable deployment in smart manufacturing and maintenance systems.
(Onu et al., 2023)	• Highlights how advanced technologies like digital twins, AI, and edge computing enable real-time equipment monitoring and predictive maintenance. • Shows that these technologies improve efficiency, reduce downtime, and support sustainability by lowering energy use and minimizing waste.
(Waghanna et al., 2024)	• Highlights how Industry 4.0 enabling technologies transform manufacturing into smart, data-driven, and adaptive systems. • Emphasizes benefits such as improved efficiency, real-time decision-making, quality control, maintenance management and sustainability through energy and resource optimization.

Table A3. Main ideas of the selected papers for TC2.1

References	Main ideas
(Martinelli et al., 2024)	• Proposes a human-centric predictive maintenance framework in line with Industry 5.0, addressing the lack of technologies focused on operator assessment. • Integrates real-time data, big data analytics, and a closed-loop system using wearables and sensors to monitor and prevent human-related risks. • Utilizes digital twins, machine learning, and immersive tech to enhance decision-making and promote social sustainable and safe working conditions. • Emphasizes a shift from machine-focused to human-focused maintenance strategies, supporting both operator well-being and maintenance sustainability.
(Narkhede et al., 2024)	• Conducts a systematic literature review on the role of Industry 4.0 technologies in supporting sustainability across manufacturing SME functions, including maintenance. • Identifies Big Data Analytics, IoT, and Robotics as key drivers of sustainable performance in areas such as maintenance, production, and logistics. • In the context of maintenance, highlights how IoT and BDA enable predictive maintenance through real-time monitoring, failure prediction, and optimized planning. • The findings emphasize that smart technologies enhance not only operational efficiency and resource optimization but also contribute to reducing environmental impacts and downtime, supporting the triple bottom line of sustainability. • Provides a roadmap for SMEs to adopt Industry 4.0 technologies in line with sustainability goals, emphasizing data-driven maintenance strategies.

Table A4. Main ideas of the selected papers for TC2.2

References	Main ideas
(Chabane et al., 2023)	• Proposes an Industry 5.0 based asset management framework that integrates human-centricity, resilience, and sustainability into industrial strategy. • Argues that Industry 4.0 practices often overlook the impacts on workers and the environment, calling for a shift in approach. • Presents a methodology to evaluate how Industry 5.0 technologies affect human tasks, system performance, and long-term environmental and social impacts, particularly in the context of maintenance. • The framework highlights the need to embed human factors, multidimensional KPIs, and resilience assessments into decision-making, emphasizing that true industrial sustainability and resilience require a human-centric approach where technologies prioritize human and ecological well-being over economic gains.

Table A5. Main ideas of the selected papers for TC3.1

References	Main ideas
(El Kihel et al., 2022)	• The study aims to design and implement a structured Maintenance 4.0 methodology to support sustainable development by reducing energy consumption, waste, and operational risk in an industrial beverage company. • By applying this methodology to thermal and compressed air systems, the company improved boiler efficiency from 65.3% to 76.9%, using AI-driven optimization of fuel flow and combustion temperature, predictive maintenance and IoT sensors. • The implementation reduced plastic waste from 680 kg to 98 kg, and optimized resource use with improved performance indicators: liters of beverage produced per kWh and liters of beverage produced per liter of fuel all increased after 2019; water consumption decreased remarkably after 2019. • The study provides a impact assessment framework combining ISO 50001 energy indicators, AI and IoT, proving the environmental value of Maintenance 4.0.
(Firat Unal et al., 2023)	• The paper investigates the effect of digital twin implementation on sustainability in a real-world steel pipe manufacturing context. • It assesses environmental and economic impacts through an integrated IoT platform combining sensors, artificial intelligence for predictive maintenance. • The case study reports a 10% reduction in energy consumption, leading to a measurable decrease in carbon footprint. • Results demonstrate that digital twins enhance equipment effectiveness (OEE) and failure anticipation, contributing to more sustainable maintenance. • This industrial case serves as a concrete impact assessment of digital twin technologies on sustainability performance, supporting their integration into maintenance strategies.
(Jena et al., 2024)	• The article presents the integration of Industry 4.0 technologies with reliability centered maintenance (RCM) to create a data-driven smart RCM model for sustainable manufacturing. • The approach leverages IoT, cyber-physical systems, cloud computing, and AI to enhance real-time decision-making, predictive maintenance, and system reliability. • A case study in a cement plant demonstrates tangible improvements: production rose by 4.4%, OEE increased by 7.7%, energy use dropped by 8.7%, and carbon footprint decreased by 9.3%. • These results confirm that smart RCM improves both operational and environmental KPIs on maintenance, effectively reducing downtime, material waste, and resource consumption.

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Table A5. (continued)

References	Main ideas
(Lerat & Mahmoudi, 2024)	• The study proposes a scalable and sustainable approach to deep learning in Industry 4.0 by integrating distributed deep learning (DDL) with high-performance computing (HPC) for three key applications: intrusion detection, defect identification, and predictive maintenance. • Experimental results show up to 46 x acceleration in training and improved resource utilization across CPUs and GPUs, while minimizing environmental impact through optimized parallelism and a dedicated energy monitoring tool. • By normalizing energy use by speedup and converting it into carbon emissions (using 0.45 kgCO_2/kWh), the study provides a concrete impact assessment, highlighting the potential of DDL to reduce carbon footprint, supporting responsible deployment of AI in smart manufacturing.
(Munsamy & Telukdarie, 2018)	• The study introduces a Process Centric Energy Model (PCEM) to assess and optimize business-wide energy demand through the application of Industry 4.0 technologies such as IoT, CPS and big data analytics. • In a maintenance process case study, the integration of these technologies resulted in a 46% reduction in energy demand (from 439 kWh to 237 kWh), a 43% decrease in personnel hours, and a reduction of 216 kg CO_2 emissions per week. • These findings provide an impact assessment, confirming that applying Industry 4.0 in an integrated way enhances operational efficiency while supporting measurable progress toward sustainability goals.
(Sénéchal & Trentesaux, 2019)	• The paper introduces a decision-support framework for environmentally aware maintenance in Cyber-Physical Systems (CPS), centered around Sustainable Condition-Based Maintenance (SCBM) and the new indicator Remaining Sustainable Life (RSL). • It integrates Life Cycle Assessment (LCA) methods and environmental efficiency indicators into predictive maintenance decisions, using CPS capabilities for data collection and modeling. • In the application case (compressed air cylinders in an educational CPS platform), the SCBM scenario reduced CO_2-equivalent emissions to 1.7310^{-5} kg, compared to 3.8410^{-3} kg for corrective and 3.8310^{-3} kg for preventive maintenance. • This work provides a quantified impact assessment method using CPS data and LCA offering actionable guidance for sustainable maintenance decisions.

Table A6. Main ideas of the selected papers for TC3.2

References	Main ideas
(Alkhodair & Alkhudhayr, 2025)	• Analyzes how SMEs use Industry 4.0 technologies (AI, IoT, blockchain) to boost sustainability in manufacturing, maintenance, and logistics, based on data from 300 firms and advanced analytics (XGBoost, Random Forest, RFE, quantile regression). • Findings reveal that IoT adoption enhances resource efficiency, AI-driven predictive maintenance reduces downtime by up to 30%, and blockchain improves ethical sourcing and traceability; collectively, these technologies contribute to a 55% average waste management efficiency and a 10% reduction in carbon footprint. • Notes that adoption is hindered by financial and technical barriers, emphasizing the need for supportive policies to scale sustainable maintenance practices.
(Almeida et al., 2023)	• Proposes a human-centric framework using Fuzzy AHP and ELECTRE III to evaluate maintenance factors for sustainable manufacturing, emphasizing PHM's role via Industry 4.0 technologies, based on expert input from multiple industrial stakeholders. • Identifies prognostic performance (e.g., RUL) as a key driver after cross-departmental collaboration, highlighting its influence on reducing unexpected failures and enabling predictive maintenance. • Key sustainability outcomes include a reduction of raw material waste and avoidable energy use, improved equipment lifecycle, and better alignment with environmental objectives such as carbon footprint mitigation and waste management. • The method proved robust under various sensitivity analyses, showing that prognostics significantly affect cost (weight = 0.37), energy consumption (0.34), waste reduction (0.19), and safety (0.09), confirming their multidimensional sustainability impact in maintenance contexts.
(Fallahiarezoudar et al., 2025)	• Proposes a structured method to integrate Industry 4.0 into Total Productive Maintenance (TPM) using DEMATEL-based ANP and ARAS, aiming to optimize sustainability in manufacturing with expert stakeholder input. • Reports a 37.48% improvement in sustainability performance through reduced downtime, energy/material savings, better OEE, and enhanced waste management. • Identifies top management support, structured Industry 4.0 programs, and a culture of continuous improvement as key enablers of sustainable maintenance. • Environmental indicators like energy/materials consumption, waste treatment, and 3Rs culture (reduce, reuse, recycle) emerged as dominant, alongside social metrics (ergonomics, accident rate), positioning Maintenance 4.0 as a lever for carbon footprint reduction, circular economy alignment and human well-being.
(Farsi et al., 2021)	• The study applies Fuzzy TOPSIS to assess the impact of Industry 5.0 technologies on ten sustainability indicators across economic, environmental, and social dimensions in Reliability Centered Maintenance (RCM), using expert input from academia and industry. • Findings show that diagnosis and prognosis activities, enabled by automation, IoT, AI and digital twin, have the highest impact on economic sustainability (e.g. correlation = 0.932 for cost of maintenance), reducing maintenance costs and revenue losses through improved defect prediction and RUL estimation. • Measurement and non-destructive testing (NDT) methods are most influential on environmental sustainability (e.g. correlation = 0.825 for pollution), supporting waste reduction, resource-efficient maintenance, and circular economy strategies. • For social sustainability, operating conditions during monitoring are key (e.g. correlation = 0.914 for workers health and safety), as they affect health, safety, and workplace ergonomics, highlighting the role of smart monitoring in promoting worker well-being and compliance.

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Table A6. (continued)

References	Main ideas
(Ooi et al., 2023)	• The study empirically investigates how Lean Production (LP) dimensions particularly TPM, enhance sustainable organizational performance (economic, social, environmental), using a sample of 252 Malaysian manufacturing firms. • Finds that Industry 4.0 technologies (IoT, AI, Big Data) enhance the sustainability effects of LP, particularly for TPM, by improving reliability and reducing energy use and waste. • Firms with high tech-intensity reported stronger gains in environmental performance, including reductions in energy consumption and CO_2 emissions from optimized inventory and logistics enabled by real-time monitoring. • The integration of I4.0 with lean tools supports a transition toward more resilient, resource-efficient operations, reinforcing the role of smart maintenance in long-term sustainability strategies.
(Patalas-Maliszewska & Losyk, 2022)	• Proposes a decision-support model using Fuzzy-TOPSIS to evaluate maintenance sustainability (MS) with Industry 4.0 technologies, based on data from 125 Polish manufacturers. • Identifies top objectives such as reducing non-renewable energy use, training costs, and downtime, while fostering innovation in sustainable maintenance. • Data from 5 companies shows how Industry 4.0 tools (e.g., for energy tracking, diagnostics) help monitor key MS indicators like energy savings, efficiency, and CO_2 reduction. • Assists managers in prioritizing MS objectives and aligning actions with sustainability goals, with applicability at both strategic and tactical levels.
(Samadhiya et al., 2023)	• The study empirically validates a conceptual framework using PLS-SEM on 304 Indian manufacturing firms to explore how Total Productive Maintenance (TPM) and Industry 4.0 (I4.0) technologies enhance Sustainability Performance (SP) and with Circular Economy (CE). • Finds that I4.0 strongly boosts TPM ($\beta = 0.580$) and CE adoption ($\beta = 0.399$) through real-time monitoring and proactive maintenance, reducing waste, emissions, and energy use. • TPM positively impacts CE ($\beta = 0.285$), supporting waste minimization, carbon footprint reduction, and energy efficiency (e.g. up to 55% emission reduction), thereby facilitating circular production loops. • Then, Industry 4.0 effect TPM and TPM effect CE, reinforcing that digital TPM and CE practices jointly drive sustainable outcomes across economic, environmental, and social dimensions.