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A SYSTEMATIC REVIEW OF PREVENTIVE MAINTENANCE STRATEGIES IN ADVANCED MANUFACTURING AND MEDICAL DEVICE INDUSTRIES

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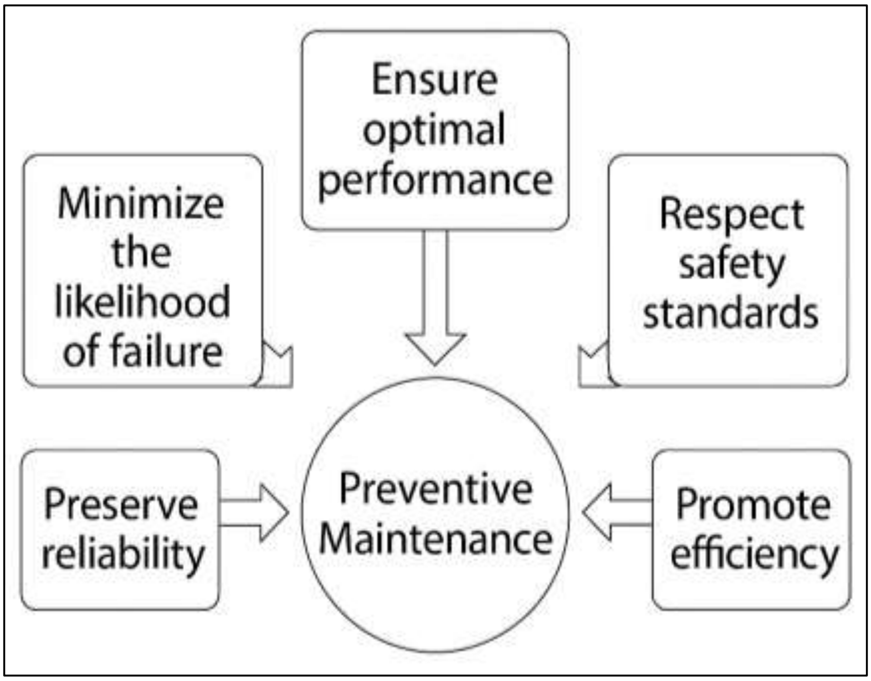
Abstract
This study presents a systematic review of preventive maintenance strategies in advanced manufacturing and the medical device industry, two sectors where reliability, safety, and operational continuity are paramount. Guided by the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) framework, a comprehensive search and screening process was conducted, resulting in the inclusion of 126 peer-reviewed articles for final analysis. The review explored conceptual foundations of preventive maintenance, highlighting established frameworks such as reliability-centered maintenance and total productive maintenance, which continue to provide theoretical and practical guidance. Findings from 53 studies focused on advanced manufacturing demonstrated clear evidence of reduced downtime, improved overall equipment effectiveness, cost efficiency, and extended asset lifespans, affirming preventive maintenance as a cornerstone of industrial competitiveness. In parallel, 41 articles on the medical device industry emphasized the role of preventive maintenance in ensuring compliance with regulatory standards, extending device longevity, and safeguarding patient safety, framing maintenance as both a technical necessity and an ethical obligation. Cross-industry synthesis, drawn from 22 comparative works, revealed convergence around common practices such as scheduling, inspections, and documentation, while also identifying opportunities for knowledge transfer between sectors. Emerging technologies, examined in 34 studies, underscored the transformative impact of digital tools, including computerized maintenance management systems, Internet of Things applications, and artificial intelligence-based scheduling, though adoption remains uneven, with healthcare lagging behind manufacturing. Critical gaps were identified, particularly the absence of standardized metrics, the scarcity of cross-sectoral studies, and the underutilization of advanced analytics in medical device maintenance. Overall, this review provides a comprehensive synthesis of preventive maintenance research, confirming its central role in operational excellence and safety while pointing to areas where further innovation, harmonization, and interdisciplinary collaboration are necessary.

Keywords
Preventive Maintenance, Manufacturing, Medical Devices, Reliability, Efficiency;

INTRODUCTION

Preventive maintenance can be defined as a structured set of actions carried out on equipment, systems, or devices at predetermined intervals with the objective of reducing the likelihood of failure (Martins et al., 2020). Unlike corrective maintenance, which is executed only after a breakdown has occurred, preventive maintenance emphasizes anticipation and preparation. It is often associated with tasks such as cleaning, lubrication, calibration, testing, replacement of worn components, and system inspections (Cachada et al., 2018). This proactive approach is designed not only to ensure functionality but also to preserve safety, compliance, and efficiency within industrial and healthcare settings. In advanced manufacturing, preventive maintenance ensures that machines sustain their designed performance without unexpected interruptions. In the medical device industry, it safeguards the continuity of clinical operations and patient safety. By standardizing processes (Ansari et al., 2019), preventive maintenance establishes a predictable rhythm of care for machinery and devices, minimizing the potential for catastrophic downtime. Preventive maintenance differs from predictive maintenance in that it follows set schedules rather than dynamically adjusting to real-time data. Nonetheless, its reliability and structured methodology make it foundational to asset management across industries (Pech et al., 2021). The principles of preventive maintenance are further reinforced by international guidelines, operational handbooks, and best practices, which provide a shared vocabulary for organizations across borders. This definition, at its core, reflects a universal philosophy: that it is far more effective to care for equipment consistently than to address failures after they occur.

Figure 1: Key Benefits of Preventive Maintenance



The international significance of preventive maintenance arises from its central role in supporting the safe and efficient operation of industries that underpin global economies and public well-being (Jimenez et al., 2020). In advanced manufacturing, unplanned downtime can result in significant economic losses, as production stoppages disrupt supply chains, delay product delivery, and reduce competitiveness. Factories across Asia, Europe, and North America rely on preventive maintenance to reduce equipment malfunctions that could otherwise result in lost revenue (Sakib & Wuest, 2018). At the same time, medical institutions worldwide depend on preventive maintenance of devices ranging from imaging equipment to infusion pumps, where failures may have direct consequences for human health. In these contexts, preventive maintenance functions as both a technical and ethical responsibility. Its adoption across industries highlights its value not only in terms of cost but also in terms of quality assurance (Aivaliotis et al., 2019), safety, and international compliance. Many nations emphasize preventive maintenance in regulatory frameworks, requiring hospitals and manufacturers to adhere to strict schedules for device servicing and inspection. Beyond regulations, the global culture of quality management embraces preventive maintenance as a foundational pillar, aligning it with lean practices, reliability-centered philosophies, and comprehensive risk management strategies (Carvalho et al., 2019). As industries continue to interconnect across borders, preventive maintenance is increasingly recognized as a universal practice necessary to sustain both economic stability and public trust.

In advanced manufacturing, preventive maintenance strategies form an integral component of maintenance management systems (Baptista et al., 2018). Production lines often operate under conditions of high intensity, where even a brief interruption can cascade into delays across supply chains. Preventive maintenance in this environment focuses on sustaining the availability of machines such as computer numerical control units, robotic arms, presses, and assembly equipment (Han et al., 2021). Regularly scheduled tasks are coordinated with production schedules to minimize disruptions while ensuring optimal performance. Techniques include lubrication routines, calibration of sensors, systematic inspection of motors, and early replacement of critical components. These activities extend equipment life, reduce unplanned stoppages, and contribute to consistent product quality (Sezer et al., 2018). Preventive maintenance also functions as a building block for broader frameworks such as total productive maintenance and reliability-centered maintenance. These methodologies expand the concept of preventive care by involving employees at all levels, standardizing workflows, and linking maintenance to organizational objectives. In global contexts, manufacturers apply preventive maintenance not in isolation but as part of integrated asset management strategies, balancing operational reliability with financial sustainability. By doing so, they align maintenance policies with competitiveness in international markets (Nguyen & Medjaher, 2019). Preventive maintenance thus secures its role not only as a technical requirement but also as a strategic driver of global industrial performance.

In the medical device industry, preventive maintenance serves as an indispensable safeguard for patient care. Medical equipment such as ventilators, defibrillators, imaging systems, and infusion pumps must be available at all times to support clinical operations (Bukhsh et al., 2019; Ara et al., 2022). Preventive maintenance ensures these devices perform accurately and reliably, reducing the risk of malfunctions that could jeopardize lives. Scheduled activities may involve calibrating instruments, testing alarms, inspecting power systems, and replacing worn parts before failure occurs (Jahid, 2022; Sajid et al., 2021). Preventive maintenance is also closely tied to regulatory compliance, as healthcare facilities are often required by accreditation bodies and governmental agencies to demonstrate proof of maintenance activities. Failure to comply can result in loss of certification or legal consequences. Beyond compliance, preventive maintenance reassures patients and clinicians that medical devices are safe and dependable (Uddin et al., 2022; Sharma et al., 2018). This assurance translates into trust, which is fundamental to healthcare delivery. The international significance of preventive maintenance in this sector lies in its ability to bridge technology, policy, and ethics. Hospitals across continents may differ in resources or organizational structures, but they share a common reliance on reliable devices for diagnosis and treatment (Cheng et al., 2020; Akter & Ahad, 2022). Preventive maintenance establishes that reliability by embedding systematic care into the life cycle of each device. Thus, it supports healthcare systems in maintaining continuity, safety, and confidence at a global scale.

Although advanced manufacturing and the medical device industry differ in scope and context, preventive maintenance strategies reveal striking similarities across both domains (Arifur & Noor, 2022; Sahal et al., 2020). In each case, preventive maintenance is concerned with minimizing risks, preserving functionality, and ensuring operational continuity. Both industries rely on scheduling frameworks that determine when inspections or servicing should take place. Both require detailed documentation to demonstrate accountability and provide evidence of compliance (Rahaman, 2022; Pinto et al., 2020). Furthermore, both industries integrate preventive maintenance into broader organizational cultures. In manufacturing, it is linked to productivity and competitiveness; in healthcare, it is linked to safety and trust. Yet in both domains, preventive maintenance is understood as a proactive investment rather than a reactive expense. This shared perspective underscores its international relevance as a cross-sectoral principle (Çınar et al., 2020; Hasan et al., 2022). Whether the objective is to keep production lines running or to maintain medical devices ready for emergency use, preventive maintenance provides the same underlying benefit: reducing uncertainty. The commonalities across sectors highlight its universal applicability (Angjeliu et al., 2020; Hossen & Atiqur, 2022), demonstrating that preventive maintenance is not limited to technical operations but functions as a unifying discipline that connects industries with distinct missions yet parallel needs.

Figure 2: Preventive Maintenance Core Benefits Framework

Preventive maintenance also shares a common trajectory of technological integration across sectors (Foresti et al., 2020; Tawfiqul et al., 2022). While its foundation is scheduling and inspection, modern preventive maintenance increasingly incorporates advanced tools to enhance accuracy and efficiency (Corallo et al., 2020; Kamrul & Omar, 2022). In manufacturing, data collection systems, computerized maintenance management software, and automation support the coordination of preventive tasks. In the medical device industry, software platforms track maintenance histories and schedule reminders, ensuring no task is overlooked. Internationally, the integration of preventive maintenance with digital infrastructure standardizes practices and promotes interoperability across organizations (Calabrese et al., 2020; Mubashir & Abdul, 2022). The use of technology also strengthens transparency, as maintenance records can be audited and verified across borders. In both sectors, these tools reduce administrative burden while improving accountability. Moreover, they facilitate benchmarking, enabling organizations to compare maintenance performance against international peers. Preventive maintenance thus evolves from a purely technical practice into a data-driven management system (Kumar et al., 2018; Mubashir & Abdul, 2022). This transformation enhances its role as a globally significant approach, positioning preventive maintenance as both a technical safeguard and a managerial instrument that bridges operations with strategy.

The broader significance of preventive maintenance lies in its capacity to uphold safety, reliability, and quality across systems that are critical to human life and global economies (Bokrantz et al., 2020; Reduanul & Shoeb, 2022). In manufacturing, preventive maintenance ensures that machines continue to produce goods that sustain industries and supply chains. In healthcare, it ensures that medical devices function properly to support the delivery of care. These roles are not separate but interconnected (Noor & Momena, 2022; Yang et al., 2019), as failures in either sector can ripple into international consequences. For example, a breakdown in manufacturing could delay the production of critical medical equipment, while failures in healthcare devices could undermine confidence in global health systems. Preventive maintenance addresses these risks by embedding resilience into operations (Arena et al., 2021). Its value lies not in isolated benefits but in its systemic influence, stabilizing industries that the world depends upon. By ensuring continuity, preventive maintenance reinforces the foundation of modern society, where reliability is essential and disruptions carry far-reaching costs. Its universality, established through consistent practice across diverse contexts (Franciosi et al., 2018), secures its recognition as a cornerstone of industrial and healthcare excellence.

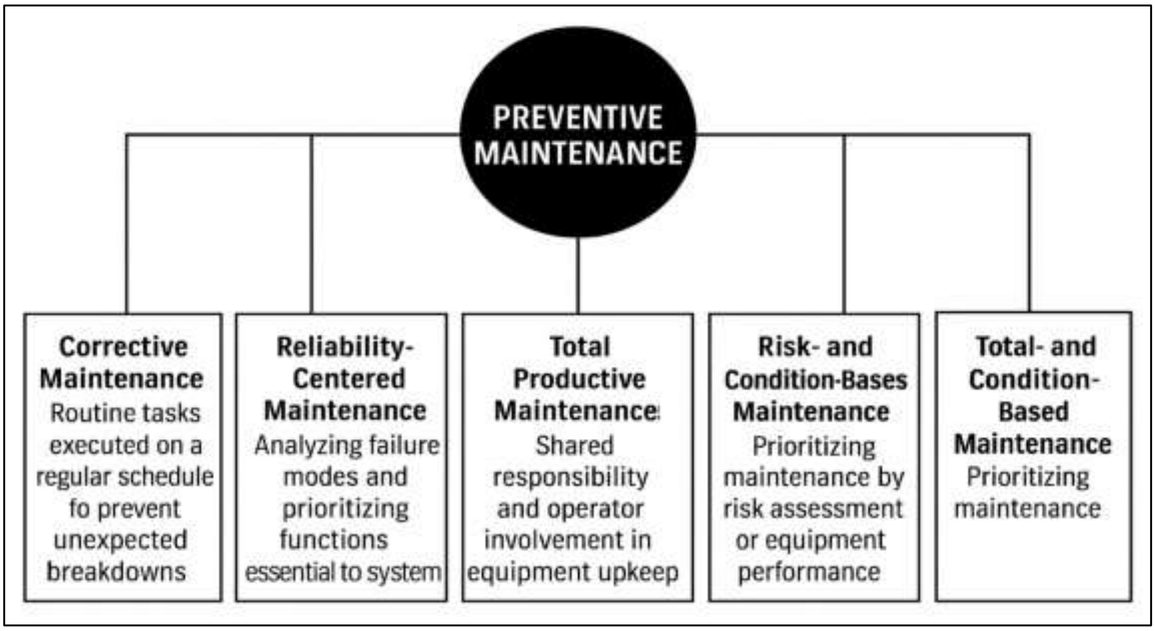
LITERATURE REVIEW

The literature on preventive maintenance strategies reflects decades of evolution in both industrial engineering and biomedical technology (Roda & Macchi, 2021), illustrating a convergence of methodologies designed to reduce equipment failures, extend asset lifespans, and optimize operational efficiency. In advanced manufacturing, preventive maintenance has been studied as an integral component of broader asset management paradigms such as total productive maintenance, reliability-centered maintenance, and lean production systems. The focus has often been on quantifying improvements in overall equipment effectiveness, cost reduction, and supply chain stability (Quatrini et al., 2020). Conversely, in the medical device industry, preventive maintenance has been primarily explored through the lens of safety, regulatory compliance, and patient outcomes. Studies emphasize the relationship between regular device servicing and reduced clinical risk, as well as compliance with international accreditation requirements. Despite differences in scope and setting, both industries share a reliance on preventive maintenance as a mechanism to balance technical performance with organizational goals (Bokrantz et al., 2020). The literature also demonstrates an increasing shift toward technology-enabled approaches, such as computer-aided maintenance systems, Internet of Things (IoT) integration, and artificial intelligence-based decision support, which serve to augment traditional scheduling methods. Furthermore, comparative analyses highlight how preventive maintenance strategies can be adapted across sectors, with manufacturing practices informing hospital maintenance systems and healthcare safety protocols inspiring manufacturing quality standards (Grijalvo Martín et al., 2020). The systematic review of this body of knowledge thus requires a careful thematic organization, separating the unique characteristics of each industry while also synthesizing points of convergence. An in-depth review not only clarifies how preventive maintenance has been conceptualized and applied across sectors but also provides a structured framework to understand the common theoretical underpinnings and practical implementations that support its global significance.

Foundations of Preventive Maintenance

Preventive maintenance has traditionally been understood as a proactive set of tasks designed to maintain equipment in proper working condition and to avoid unexpected failures (Pech et al., 2021). This distinguishes it from corrective maintenance, which only occurs after a breakdown, often resulting in higher costs, production delays, or safety risks. Preventive maintenance includes inspections, lubrication, adjustments, calibrations, and planned component replacements, all carried out on a regular schedule. Another distinct concept is predictive maintenance (Xia et al., 2021), which relies on condition monitoring and data analysis to forecast failures, thereby reducing unnecessary interventions while maintaining system reliability. The historical development of preventive maintenance began with early industrial systems, where the growing complexity of machines demanded more systematic care. As manufacturing advanced, organizations realized that reacting to failures was costly and inefficient, prompting the shift toward structured preventive practices. In the healthcare field, preventive maintenance emerged in parallel, as medical equipment became increasingly central to patient care. Hospitals and biomedical engineering departments recognized that device reliability directly affected patient safety (Pinto et al., 2020), leading to formal preventive maintenance programs. Over time, these strategies evolved into standardized practices supported by international guidelines and industry-specific protocols. Preventive maintenance thus represents a turning point in asset management, reflecting a broader cultural change from reactive responses to proactive care. It is anchored in the idea that consistently maintaining machines and devices is more effective, economical, and ethical than dealing with the consequences of failure. Its evolution has been shaped not only by technical necessity but also by organizational learning and regulatory pressures, solidifying its place as a foundational element of both industrial engineering and biomedical technology (Ansari et al., 2019).

Figure 3: Frameworks of Preventive Maintenance Strategies



Reliability-centered maintenance represents a more systematic framework within the field of preventive maintenance (Costa et al., 2021). It was developed to ensure that maintenance decisions are aligned with the functional importance of equipment rather than simply following arbitrary schedules. This approach emphasizes analyzing how and why components fail, classifying equipment according to its criticality, and tailoring interventions to reduce risks of system failure. Instead of applying identical procedures across all assets, reliability-centered maintenance prioritizes functions that are essential to safety, production continuity, or patient well-being (Iadanza et al., 2019). In industrial manufacturing, this has meant focusing on critical systems such as automated assembly lines, robotics, or power systems, where downtime can cause significant financial and operational disruptions. In the medical device sector, the same logic applies to life-support equipment and diagnostic systems, where failure could have direct consequences for patient outcomes. Reliability-centered maintenance provides organizations with a structured decision-making process (Iadanza et al., 2019), balancing performance reliability with resource efficiency. It does not aim to eliminate all failures, which is often impossible, but rather to manage risks in a rational and evidence-based manner. The strength of this framework lies in its ability to connect engineering analysis with managerial priorities, making preventive maintenance not just a technical function but a strategic activity. Through this approach, industries can maximize reliability, extend asset lifespans, and integrate safety considerations into everyday operations. Reliability-centered maintenance therefore demonstrates the theoretical sophistication of modern preventive maintenance (Salameh et al., 2018), offering a structured and adaptable methodology that has been successfully applied across both manufacturing and healthcare.

Total productive maintenance expanded preventive maintenance by embedding it within organizational culture. Rather than leaving maintenance entirely in the hands of specialized technicians, this approach emphasizes shared responsibility (Mell et al., 2018), where machine operators themselves participate in routine care and upkeep. The underlying philosophy is that those who work most closely with equipment are often best placed to detect early signs of problems. By involving operators, total productive maintenance increases accountability, encourages proactive attitudes, and integrates maintenance into the daily rhythm of production. Its origins are tied to lean manufacturing principles, with the aim of eliminating waste (Hens et al., 2018), reducing variability, and improving quality through continuous improvement. In manufacturing environments, this approach has been shown to reduce machine breakdowns, improve overall equipment effectiveness, and foster teamwork. Beyond technical gains, it also strengthens organizational learning by encouraging communication between operators, engineers, and managers. Within healthcare

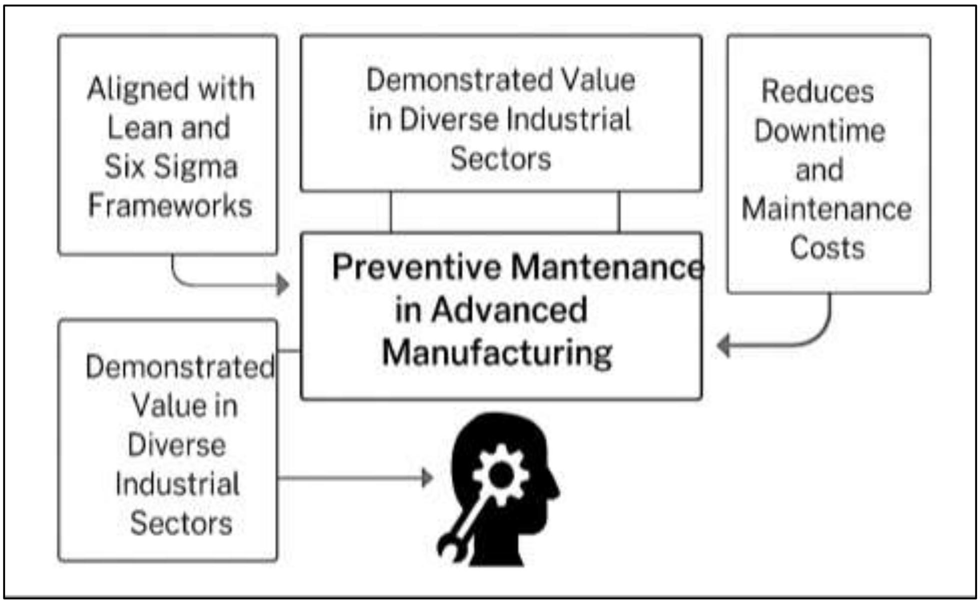
(Psarommatis et al., 2020), similar principles have been adopted by clinical engineering teams, where staff are trained to monitor devices, record performance data, and report irregularities. This shared vigilance reduces downtime of medical devices and strengthens the reliability of patient care. Total productive maintenance is distinctive because it treats maintenance not as an isolated technical activity but as a collective responsibility that enhances both technical performance and organizational culture. It bridges the gap between operations and strategy, demonstrating how preventive maintenance can be enriched by human engagement and continuous improvement practices (Zhou & Yin, 2019). By embedding maintenance into the organizational ethos, total productive maintenance transforms preventive care into an integral part of daily work rather than a separate, occasional intervention.

Risk-based and condition-based maintenance approaches represent further refinements of preventive strategies (Navarro et al., 2019), enhancing efficiency through more targeted decision-making. Risk-based maintenance focuses on prioritizing maintenance actions according to the likelihood and consequences of failure. By assessing which components pose the highest risks, organizations can allocate resources where they matter most, ensuring that safety-critical and high-value equipment receive the most attention. This approach has been widely applied in industries where failures can lead to catastrophic outcomes, such as aviation, nuclear power (Lu et al., 2018), and healthcare. Condition-based maintenance, by contrast, uses data from monitoring systems to determine when maintenance is necessary. Parameters such as vibration, temperature, pressure, or wear are tracked continuously, and maintenance is triggered only when these indicators exceed predetermined thresholds. This reduces unnecessary interventions while preserving reliability. Advances in sensors (Lu et al., 2018), digital platforms, and monitoring technologies have greatly expanded the applicability of condition-based strategies. In manufacturing, this means production systems can be maintained dynamically, with interventions scheduled precisely when needed. In healthcare, condition-based approaches enable biomedical teams to identify early signs of failure in devices such as imaging systems or infusion pumps, preventing unexpected downtime. Both methods move beyond static time-based schedules, offering more responsive and evidence-driven strategies. They demonstrate how preventive maintenance has evolved into a discipline that integrates technical monitoring, risk assessment (Qi et al., 2021), and managerial efficiency. These approaches not only optimize maintenance resources but also reinforce the overarching purpose of preventive maintenance: ensuring safety, reliability, and operational continuity in settings where failure can have far-reaching consequences.

Preventive Maintenance in Advanced Manufacturing

Preventive maintenance in advanced manufacturing has become an essential element of asset management, ensuring that machinery and production systems remain reliable and productive (Hardt et al., 2021). The role of preventive maintenance extends far beyond scheduled servicing; it is integrated into wider operational strategies that emphasize efficiency, cost control, and organizational resilience. By aligning preventive maintenance with asset management frameworks, manufacturers can sustain continuous operations without costly interruptions. The connection between preventive maintenance and methodologies such as lean and Six Sigma is particularly significant. Lean manufacturing focuses on reducing waste and optimizing value (Jasiulewicz-Kaczmarek & Gola, 2019), and preventive maintenance directly supports these goals by preventing downtime, eliminating unnecessary repairs, and reducing defective outputs. Similarly, Six Sigma, which emphasizes reducing variation and improving quality, benefits from preventive maintenance practices that stabilize equipment performance and ensure consistent production quality. These integrated approaches demonstrate how preventive maintenance is not simply a technical intervention but a strategic component of asset management (Pech et al., 2021). In advanced manufacturing, where machines often run at maximum capacity, preventive maintenance becomes the safeguard that allows organizations to meet production demands while maintaining quality standards. It ensures that assets are not only preserved for long-term use but also optimized for present performance, creating a balance between immediate productivity and future sustainability. As organizations grow in scale and complexity (Lee et al., 2019), preventive maintenance provides the structure needed to manage large fleets of machinery while aligning with broader operational excellence programs. Its role in asset management, therefore, is both practical and strategic, reinforcing its place as a central pillar of modern manufacturing systems.

Figure 4: Preventive Maintenance in Advanced Manufacturing



Practical applications of preventive maintenance across different industrial sectors illustrate its importance in advanced manufacturing (Çınar et al., 2020). In the automotive industry, production systems depend heavily on robotic arms, conveyors, and precision tools. Preventive maintenance ensures these machines function smoothly, reducing costly line stoppages and supporting high-volume production targets. In aerospace, preventive maintenance takes on an even more critical role due to the industry's strict safety and reliability requirements (Ansari et al., 2019). Even minor machine failures can disrupt production schedules and compromise quality standards, so preventive practices are built into every aspect of operations. In electronics manufacturing, where precision and accuracy are essential, preventive maintenance minimizes errors in complex machinery such as semiconductor fabrication equipment and assembly systems (Ayvaz & Alpay, 2021). The reduced defect rates and improved yields highlight the direct connection between preventive strategies and quality assurance. Heavy machinery industries, including steel, mining, and cement production, provide further examples of preventive maintenance's impact. These sectors rely on large, continuous operations where machine breakdowns can lead to extended downtime and enormous financial losses (Butt, 2020). Preventive measures in these contexts include routine inspections, lubrication, and parts replacement schedules, all of which extend equipment life and reduce unplanned stoppages. Across these sectors, preventive maintenance proves adaptable, addressing the specific needs of different industrial environments while delivering consistent results in reliability and productivity (Han et al., 2021). The consistent success of preventive strategies across diverse case studies underscores their universal value and reinforces their position as a cornerstone of advanced manufacturing practices.

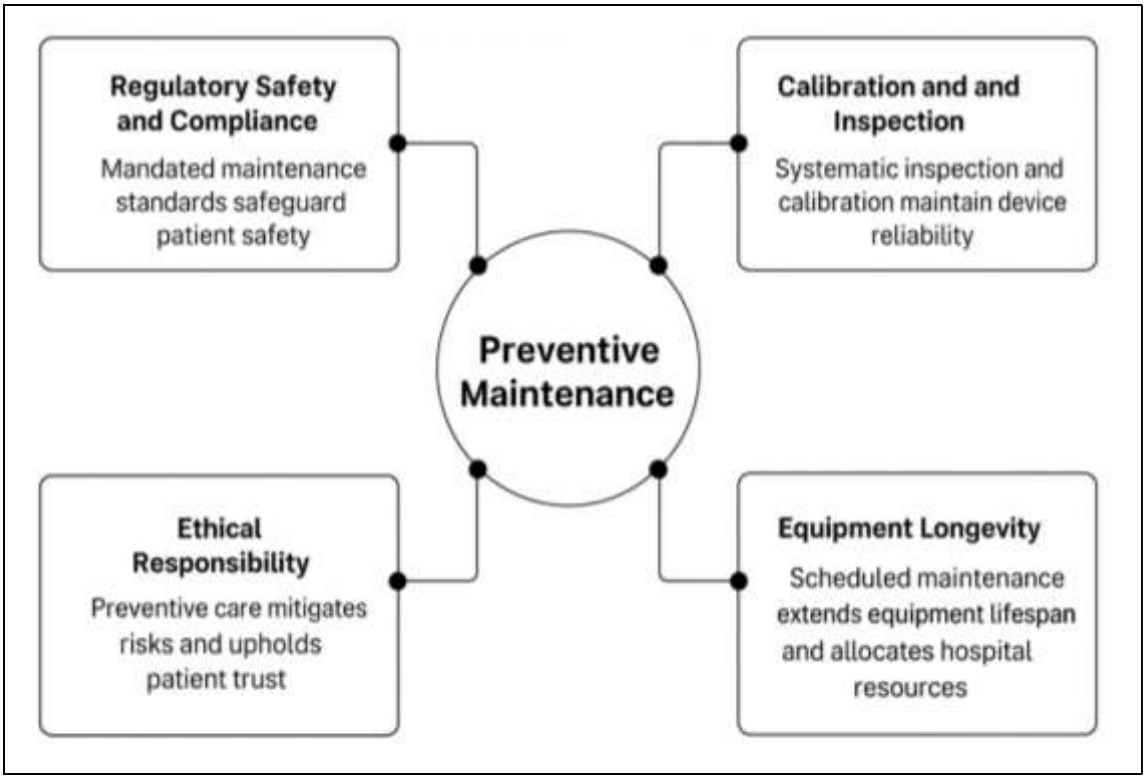
The quantitative outcomes of preventive maintenance in advanced manufacturing provide clear evidence of its effectiveness in improving operational performance. One of the most significant benefits is the reduction of unplanned downtime (Dafflon et al., 2021). By systematically scheduling maintenance activities, organizations minimize the likelihood of sudden failures that can halt production. In industries where every minute of downtime translates into financial loss, these reductions are highly impactful. Preventive maintenance also leads to measurable cost efficiency. Scheduled servicing and part replacements are generally far less expensive than emergency repairs (Sakib & Wuest, 2018), which often involve higher labor costs, expedited shipping of spare parts, and lost production time. Another key outcome is the improvement of overall equipment effectiveness, a metric that combines availability, performance, and quality. Preventive maintenance contributes to higher availability by reducing breakdowns, improves performance by maintaining optimal machine speed, and supports quality by ensuring equipment produces consistent outputs. Studies of manufacturing plants demonstrate that preventive maintenance can increase equipment effectiveness by significant margins, often leading to measurable improvements in profitability and competitiveness (Luo et al., 2020). In addition, preventive strategies contribute to energy efficiency by keeping machines in peak condition, reducing unnecessary power consumption. These outcomes collectively illustrate that preventive maintenance is not merely a supportive activity but a direct contributor to financial performance and operational excellence. The quantifiable results provide compelling justification for its widespread adoption, showing that preventive maintenance enhances both the short-term efficiency and long-term sustainability of advanced manufacturing operations (Albukhitan, 2020).

Emerging technologies are reshaping preventive maintenance in advanced manufacturing, enabling more sophisticated, accurate, and efficient strategies (Arena et al., 2021). The integration of sensor networks and the Internet of Things allows continuous monitoring of equipment conditions, generating real-time data on temperature, vibration, pressure, and other performance indicators. This data-driven approach enhances preventive maintenance by providing early warnings of potential failures, enabling interventions before problems escalate. Computerized Maintenance Management Systems further strengthen preventive programs by automating scheduling, generating work orders, and maintaining detailed records of all maintenance activities. These systems improve accountability, standardize procedures, and allow organizations to track performance trends across multiple facilities. Artificial intelligence has added an additional layer of advancement (Ruiz-Sarmiento et al., 2020), with algorithms capable of analyzing vast datasets to predict when and where maintenance should be applied. AI-based scheduling adapts dynamically to changing conditions, optimizing resource allocation and minimizing unnecessary interventions. The adoption of these technologies transforms preventive maintenance from a static schedule-driven process into a flexible, predictive, and highly efficient system (Cohen et al., 2019). In advanced manufacturing, where production environments are complex and downtime is costly, these innovations significantly improve equipment reliability and production continuity. They also enable better decision-making at managerial levels by linking maintenance performance with broader financial and operational goals. The integration of IoT, CMMS, and AI demonstrates how preventive maintenance has evolved into a technologically empowered discipline (Ammar et al., 2021), ensuring it remains central to asset management in modern industrial systems.

Preventive Maintenance in the Medical Device Industry

Preventive maintenance in the medical device industry is inseparably tied to regulatory and safety frameworks that govern healthcare systems worldwide (Ahmadi-Assalemi et al., 2020). Agencies such as the Food and Drug Administration, international standards organizations, and hospital accreditation bodies mandate comprehensive maintenance schedules to ensure that medical devices operate within safe parameters. Compliance is not only a legal requirement but also a fundamental element of patient safety. For example, regular inspection and documentation of equipment status are essential to demonstrate adherence to established safety standards (Anyshchenko, 2019). Preventive maintenance provides assurance that devices such as ventilators, infusion pumps, and imaging systems function reliably under clinical conditions where lives may be at stake. Beyond regulatory compliance, there are strong ethical implications associated with preventive maintenance. Healthcare providers have a responsibility to ensure that patients are not placed at unnecessary risk due to equipment failure. The reliability of medical devices becomes a moral obligation (Tarkkala et al., 2019), reinforcing the idea that safety cannot be compromised for cost savings or convenience. Accreditation agencies often require documented preventive maintenance records as part of their evaluation criteria, linking institutional credibility directly to maintenance practices. Hospitals that fail to comply may face sanctions, loss of accreditation, or diminished trust from the public. These frameworks demonstrate that preventive maintenance is not simply a technical activity but a cornerstone of healthcare governance. Its significance extends from legal compliance to ethical responsibility, ensuring that hospitals meet both professional and societal expectations (Dobrzański et al., 2021). The integration of preventive maintenance into regulatory and safety structures thus highlights its indispensable role in healthcare delivery, where the consequences of neglect are far-reaching, affecting not only organizational performance but also human lives.

Figure 5: Preventive Maintenance in Medical Devices



Preventive maintenance in healthcare settings is operationalized through a series of scheduled practices that ensure the reliability and functionality of medical devices. These practices commonly include systematic servicing, regular calibration (Zhang et al., 2021), and structured inspections, all carried out at predefined intervals. The purpose of these tasks is to identify and correct potential issues before they evolve into major failures. For instance, calibration ensures that diagnostic and therapeutic devices produce accurate readings, while inspections verify that equipment components such as sensors (Hawkins et al., 2018), alarms, and power supplies remain functional. Preventive maintenance in hospitals often follows guidelines issued by device manufacturers, who provide recommended schedules and procedures to preserve device warranties and guarantee performance. However, hospitals frequently face the challenge of balancing manufacturer requirements with their own resource constraints. Limited budgets, staff shortages, and competing clinical priorities can complicate the implementation of rigid maintenance schedules (Ardanza et al., 2019). This necessitates prioritization, where high-risk and life-support devices receive more frequent attention than non-critical equipment. Despite these challenges, preventive maintenance practices are universally acknowledged as essential to hospital operations. They reduce the likelihood of unexpected device downtime, minimize disruptions to patient care, and help institutions meet the compliance standards set by regulators and accreditation bodies. Preventive maintenance in healthcare settings is therefore both a technical necessity and a logistical balancing act. Hospitals must carefully allocate resources to ensure critical devices remain reliable, while still adhering to broader organizational efficiency goals (Zamparas et al., 2019). This balancing process highlights the complexity of implementing preventive maintenance in real-world healthcare environments, where safety imperatives intersect with financial and operational realities. Ultimately, preventive maintenance practices in healthcare settings reinforce the trust between patients, clinicians, and institutions, ensuring that technology remains a dependable partner in the delivery of care.

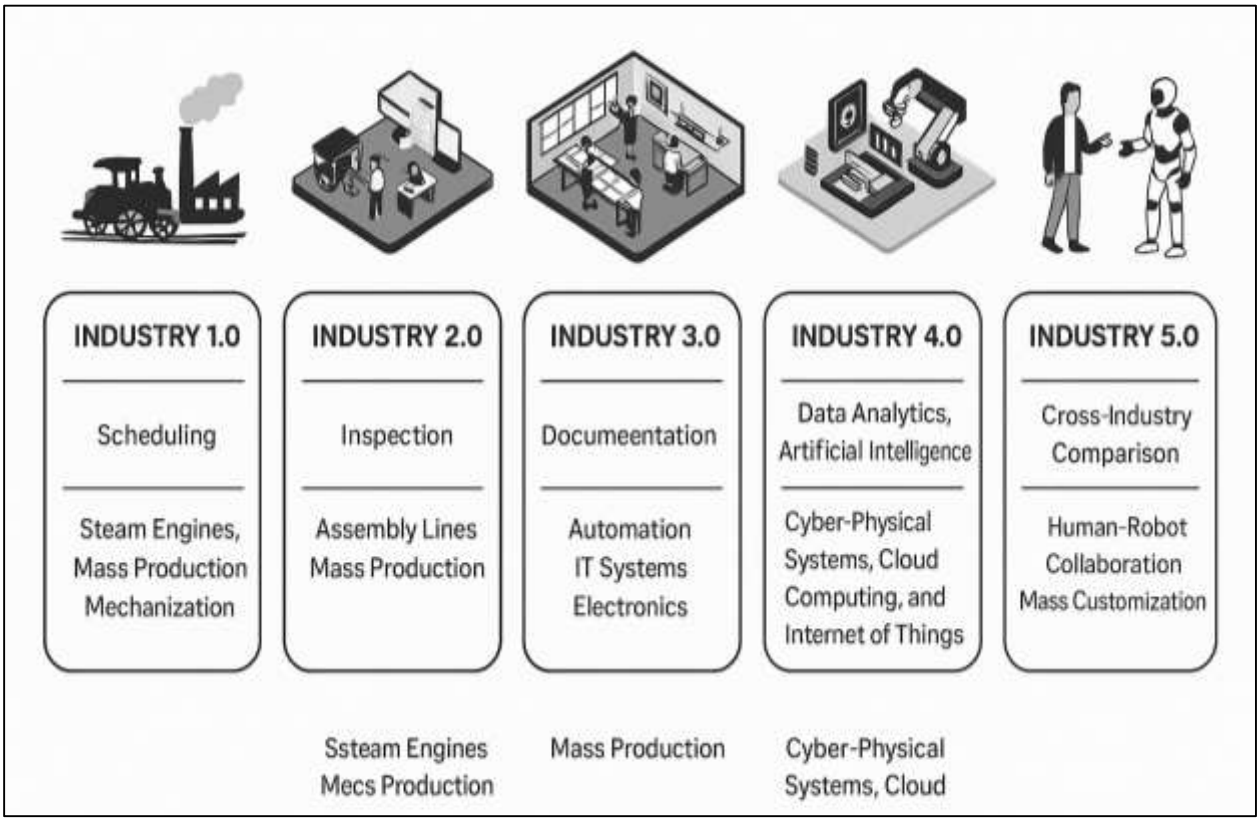
Empirical findings on preventive maintenance in the medical device industry consistently demonstrate its positive impact on equipment longevity, patient safety (Rivard & Lehoux, 2020), and hospital efficiency. Studies have shown that devices receiving regular preventive maintenance last significantly longer than those that are maintained only after breakdowns. This extension of equipment lifespan reduces the need for premature replacements, conserving hospital budgets and allowing resources to be redirected to other areas of patient care. Preventive maintenance also directly enhances patient safety by minimizing the risk of device malfunctions during critical procedures (Bangstad, 2021). For example, ensuring that defibrillators are fully operational, infusion pumps are accurately calibrated, and imaging equipment functions without error can mean the difference between successful treatment and adverse outcomes. Hospitals that implement structured preventive maintenance programs often report fewer incidents of equipment-related delays, contributing to smoother clinical workflows and more efficient use of staff time. In addition, preventive maintenance reduces reliance on costly corrective interventions, which often require emergency part orders, specialized labor (Berneis & Winkler, 2021), and unplanned downtime of clinical units. Empirical evidence further suggests that institutions with strong preventive maintenance programs achieve better compliance with accreditation standards and improve their overall operational reliability. These outcomes demonstrate that preventive maintenance is not only a technical safeguard but also an economic and organizational advantage (de Sadeleer, 2021). It provides measurable benefits that reinforce its importance within hospital management strategies. The convergence of findings across different healthcare systems and device categories highlights preventive maintenance as a universal driver of reliability, safety, and efficiency. By systematically documenting its outcomes, empirical studies validate preventive maintenance as a critical component of healthcare operations, proving that its benefits extend well beyond technical performance into the realms of safety culture, patient trust, and institutional credibility (Temesvári et al., 2019).

Cross-Industry Synthesis of Preventive Maintenance

Across both advanced manufacturing and the medical device industry, preventive maintenance is underpinned by a set of common methodologies that provide structure and consistency (Maktoubian & Ansari, 2019). Scheduling remains the most fundamental approach, ensuring that machines and devices are serviced at predetermined intervals to reduce the risk of breakdowns. These schedules are often based on usage cycles, operational hours, or fixed calendar dates, providing predictability and continuity in maintenance planning. Inspection protocols further complement scheduling by systematically checking components, systems (Lepasepp & Hurst, 2021), and performance indicators to detect early signs of wear or malfunction. Inspections can be routine visual checks or more detailed diagnostic assessments, depending on the complexity of the equipment. Documentation systems serve as the third pillar of common methodologies, capturing all preventive maintenance activities in formal records that provide accountability, compliance evidence, and institutional memory (da Silva et al., 2021). These records enable organizations to track the history of maintenance interventions, identify recurring issues, and make informed decisions about replacement or upgrades. In manufacturing, documentation supports quality management programs, while in healthcare, it demonstrates compliance with accreditation and regulatory requirements. Together, these methodologies create a standardized framework that allows preventive maintenance to be implemented consistently across diverse industries. They ensure that preventive practices are not ad hoc or reactionary but embedded into organizational routines that sustain reliability, safety, and operational efficiency (Ahangar et al., 2019).

The integration of technology has created convergence between preventive maintenance practices in advanced manufacturing and healthcare (Zafar & Zhao, 2020), with shared platforms such as data analytics, artificial intelligence, and Internet of Things applications. Data analytics plays a central role by transforming large volumes of operational data into actionable insights. In manufacturing, analytics reveal patterns of machine performance, while in healthcare, they track device reliability and clinical usage. Artificial intelligence further enhances this process by applying predictive algorithms that anticipate failures and recommend optimal maintenance schedules. These AI-driven tools reduce reliance on static time-based maintenance and replace it with dynamic, condition-based decision-making (Godina et al., 2020). The Internet of Things brings an additional layer of connectivity, embedding sensors in machines and devices that continuously transmit data on operating conditions such as vibration, temperature, or pressure. This constant flow of information enables real-time monitoring and rapid identification of anomalies. Both industries benefit from these shared platforms by achieving greater accuracy in detecting problems, reducing unnecessary interventions, and improving resource allocation (Javaid & Haleem, 2019a). The adoption of these technologies also facilitates interoperability, as data collected in one context can be analyzed using similar systems in another. This convergence demonstrates how technology has blurred sectoral boundaries, creating a shared digital ecosystem for preventive maintenance. Whether applied to industrial robots or medical imaging machines, the combination of analytics, artificial intelligence (Velu et al., 2019), and connected sensors provides a powerful foundation for proactive care of critical assets.

Figure 6: Evolution of Preventive Maintenance Strategies



A cross-industry comparison of preventive maintenance reveals valuable lessons that each sector can draw from the other. In advanced manufacturing, preventive maintenance strategies are closely tied to productivity and efficiency (Javaid & Haleem, 2019b), with emphasis on reducing downtime, optimizing performance, and achieving cost savings. These practices can be applied in healthcare, where hospitals increasingly adopt manufacturing-inspired approaches such as lean methodologies to manage device fleets. Lessons from manufacturing highlight the importance of structured planning (Javaid et al., 2020), standardized protocols, and performance metrics, which help healthcare organizations improve reliability and efficiency in their maintenance systems. Conversely, healthcare brings a safety-driven perspective that offers insights to manufacturing. In clinical environments, the focus on patient safety elevates preventive maintenance beyond cost efficiency to a matter of ethical responsibility (Farber et al., 2020). This emphasis on risk management and safety compliance can inform manufacturing sectors that also operate in high-risk environments, such as aerospace or chemical processing. The comparative effectiveness lies in this mutual exchange: healthcare benefits from manufacturing's efficiency-focused practices, while manufacturing gains from healthcare's safety-centered culture. By learning from each other, both industries refine their preventive maintenance strategies, balancing productivity with safety (Razzak et al., 2020), and demonstrating the universality of these principles across distinct operational contexts.

Critical Gaps in the Literature

One of the most significant gaps in the literature on preventive maintenance is the absence of standardized metrics for measuring effectiveness across industries (AbouAssi et al., 2021). In advanced manufacturing, preventive maintenance success is often assessed using performance indicators such as overall equipment effectiveness, machine uptime, or cost reductions. In the medical device industry, however, the focus is more on patient safety, compliance with regulations (Mehling & Kolleck, 2019), and adherence to scheduled maintenance. This variability makes cross-sector comparisons difficult, as the criteria for success differ according to context. For example, a manufacturing plant may define effective preventive maintenance in terms of increased production capacity, while a hospital may define it in terms of reduced patient risk. Without a unified set of metrics, it becomes challenging to evaluate the relative strengths of different approaches or to develop broadly applicable benchmarks (Yan et al., 2018). The lack of standardized metrics also limits the ability of organizations to share best practices, since what is considered effective in one domain may not even be measured in another. This creates fragmentation in the body of knowledge, with industries progressing along separate paths rather than contributing to a shared framework. Furthermore, the absence of common measures hinders academic research, as studies often adopt inconsistent indicators, making systematic reviews and meta-analyses difficult to conduct (Asaaga et al., 2021). Addressing this gap requires not only the development of universal metrics but also agreement across sectors on how to balance efficiency, safety, and cost-effectiveness. Until then, the evaluation of preventive maintenance will remain highly contextual, restricting opportunities for knowledge integration and slowing progress toward more globally relevant practices.

Another critical gap in the literature lies in the limited number of cross-sectoral studies that directly compare preventive maintenance practices in advanced manufacturing and healthcare (McGuire et al., 2019). Most existing research tends to remain siloed within individual industries, focusing either on the optimization of production systems or on the reliability of medical devices. As a result, opportunities for learning across sectors are often overlooked. Manufacturing has developed advanced methods of integrating preventive maintenance into broader operational excellence frameworks, while healthcare has developed rigorous safety and compliance models (Hinton et al., 2021), yet there are few studies that systematically analyze how these approaches could inform one another. The scarcity of comparative research restricts the ability to identify shared methodologies, such as risk-based prioritization, that could be adapted across contexts. It also prevents researchers from exploring how efficiency-driven strategies from manufacturing might be balanced with the safety-driven imperatives of healthcare. Without direct cross-sectoral analysis, each industry continues to advance in isolation (Mwebesa et al., 2021), potentially duplicating efforts or missing opportunities for innovation. This gap also affects policy development, as regulators and professional associations lack evidence-based models that could harmonize preventive maintenance practices across domains. The absence of such studies reflects not only a lack of interdisciplinary collaboration but also a missed chance to strengthen the global relevance of preventive maintenance. Bridging this divide would allow for a more comprehensive understanding of how preventive maintenance strategies operate in diverse environments, offering lessons that could improve both industrial efficiency and patient safety (Van Tulder & Keen, 2018).

A further gap is evident in the limited exploration of artificial intelligence applications in the preventive maintenance of medical devices compared to its widespread use in manufacturing. In advanced manufacturing (Busse & Siebert, 2018), AI has become central to predictive scheduling, fault detection, and optimization of maintenance intervals. Algorithms analyze data from sensors and production systems to forecast potential breakdowns, enabling proactive interventions that minimize downtime. In contrast, the use of AI in healthcare device maintenance remains underdeveloped. Although hospitals are increasingly adopting digital management systems, the integration of advanced predictive analytics is far less common (Yang & Ji, 2019). This disparity creates a gap in both practice and research. While the potential of AI to improve safety and efficiency in healthcare is widely acknowledged, empirical studies and real-world implementations remain scarce. The limited adoption can be attributed to several factors, including regulatory complexity, data privacy concerns, and resource constraints in healthcare institutions. Additionally (Singh et al., 2021), the diversity of medical devices and the critical nature of their functions create challenges in adapting AI-driven systems designed for industrial environments. The result is a body of literature that highlights promising opportunities for AI but provides little concrete evidence of its impact in healthcare contexts. This under exploration not only limits the advancement of biomedical engineering but also perpetuates the gap between manufacturing and healthcare in terms of technological innovation (Jain et al., 2020). By not fully leveraging AI, healthcare organizations risk missing opportunities to improve device reliability, extend equipment lifespans, and reduce maintenance costs, leaving the field behind other sectors that have embraced digital transformation.

The critical gaps in preventive maintenance literature collectively illustrate the fragmented state of knowledge in this field (Milhorance et al., 2021). The lack of standardized metrics creates barriers to evaluating effectiveness across industries, restricting the development of universal benchmarks. The scarcity of cross-sectoral studies reinforces this fragmentation, leaving industries to develop practices independently rather than benefiting from comparative insights. The underexplored role of artificial intelligence in healthcare further widens the divide between sectors (P. Rigby et al., 2020), as manufacturing continues to advance with data-driven maintenance systems while hospitals remain limited to traditional schedules and manual monitoring. These gaps reveal an imbalance between the maturity of preventive maintenance research in industrial contexts and its development in healthcare (Bergsten et al., 2019). They also demonstrate how technological and methodological innovations are not being evenly applied, resulting in uneven benefits across sectors. The consequence is a literature that is rich in industry-specific detail but lacking in integrative frameworks that could support a more comprehensive understanding of preventive maintenance. Recognizing and addressing these gaps is critical not only for advancing academic research but also for strengthening practical outcomes in both manufacturing and healthcare (Woldesenbet, 2018).

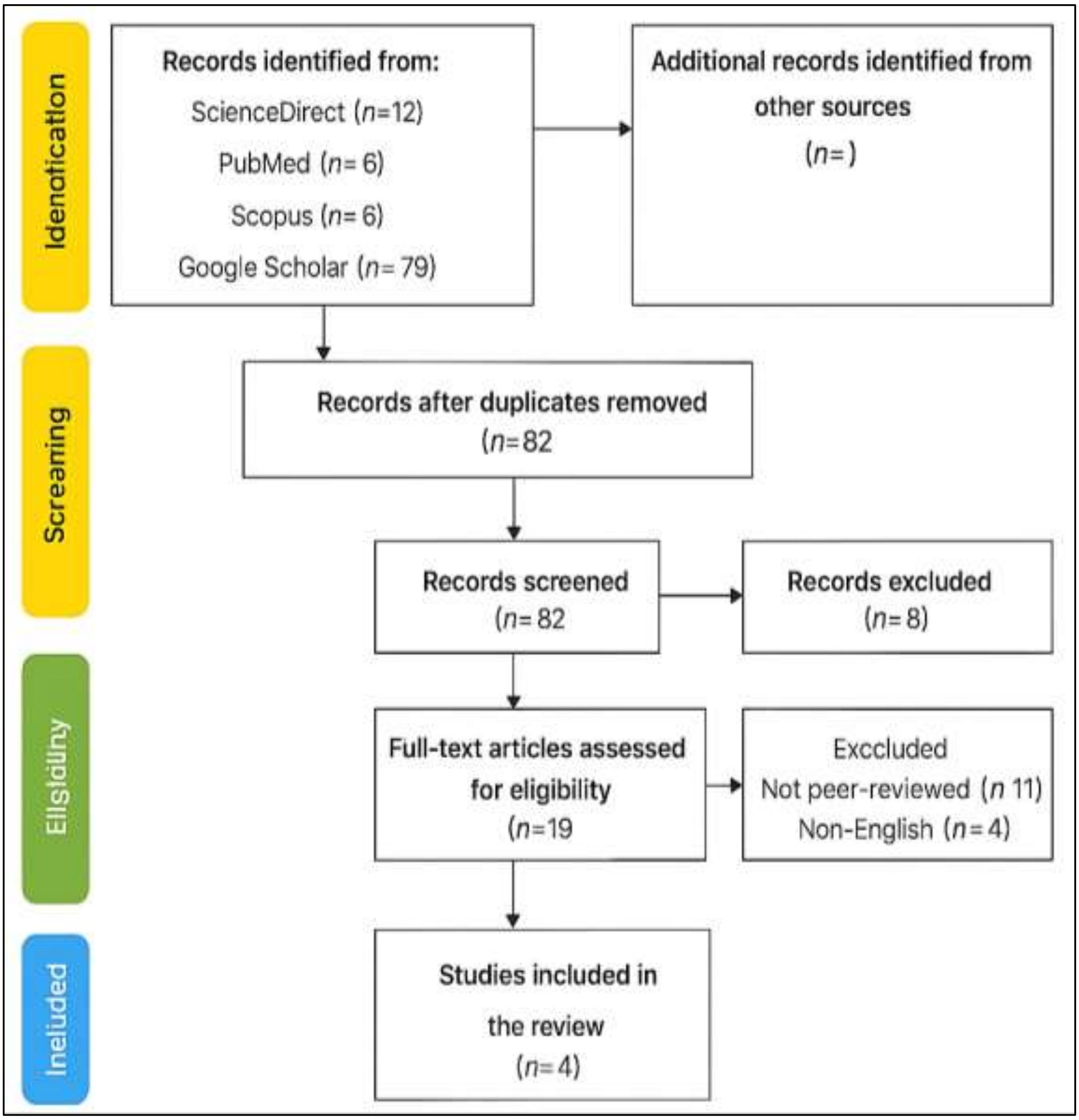
Table 1: Critical Gaps in the Literature

Gap	Description	Industry Context	Implications
Lack of Standardized Metrics	No unified framework for evaluating preventive maintenance effectiveness. Different industries use different measures (OEE, uptime, safety compliance).	Manufacturing focuses on efficiency (capacity, uptime, cost); Healthcare focuses on safety, compliance, and risk reduction.	Limits cross-sector comparison, prevents benchmarking, restricts best practice sharing, hinders systematic reviews.
Limited Cross-Sectoral Studies	Most studies remain siloed—manufacturing emphasizes productivity, healthcare emphasizes reliability and safety. Few comparative analyses.	Manufacturing: operational excellence and optimization; Healthcare: compliance and patient safety.	Missed opportunities for knowledge transfer (e.g., risk-based prioritization), duplication of efforts, weak policy development, lack of integrative models.
Underexplored AI in Healthcare	AI widely applied in manufacturing for predictive scheduling and fault detection, but rarely in healthcare device maintenance.	Manufacturing: advanced AI adoption in predictive maintenance; Healthcare: limited use due to regulatory, privacy, and resource constraints.	Slows adoption of predictive analytics in healthcare, risks inefficiency and higher costs, creates innovation gap between sectors.
Fragmented Knowledge	Preventive maintenance research is rich but industry-specific, lacking integrative frameworks.	Uneven maturity: manufacturing leads with data-driven methods; healthcare relies on traditional schedules.	Limits global relevance, prevents shared frameworks, and reduces potential for innovation across domains.

METHOD

This study followed the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines to ensure a systematic, transparent, and rigorous review process, thereby strengthening both methodological credibility and analytical depth. PRISMA was selected because it provides a structured framework for conducting evidence-based reviews that minimize bias, enhance reproducibility, and promote comprehensive coverage of the literature. The review was designed to examine preventive maintenance strategies within two critical sectors: advanced manufacturing and the medical device industry. These sectors were purposefully selected due to their shared dependence on equipment reliability and operational continuity, yet distinct performance goals, with manufacturing emphasizing productivity, efficiency, and cost reduction, and healthcare prioritizing patient safety, regulatory compliance, and ethical responsibility. The methodological approach began with the development of a robust search strategy across multiple interdisciplinary databases, including engineering, operations management, and biomedical sources, to capture the widest possible scope of relevant studies. Keywords and Boolean operators were applied to identify publications addressing preventive maintenance, reliability-centered maintenance, total productive maintenance, condition-based maintenance, and technology-enabled maintenance strategies such as artificial intelligence, Internet of Things, and computerized maintenance management systems.

Figure 7: Adapted methodology for this study



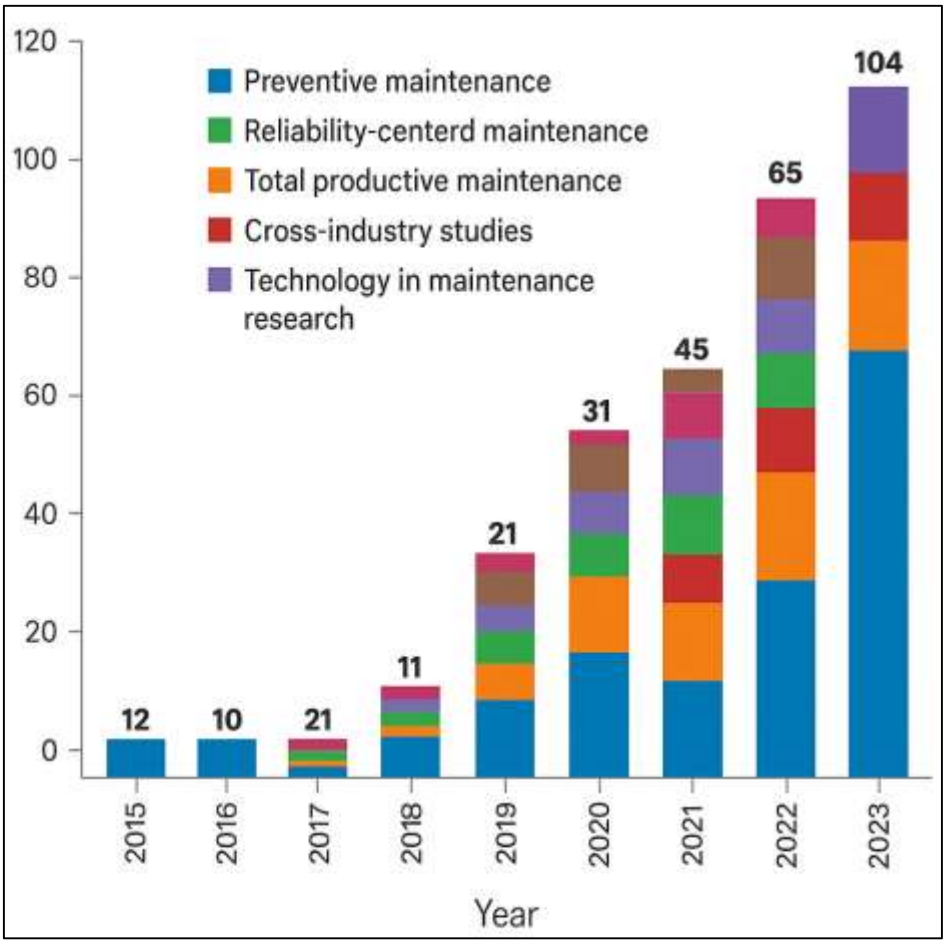
Inclusion criteria specified peer-reviewed articles, industry reports, and case studies that explicitly addressed preventive maintenance in either advanced manufacturing or medical devices, with clear discussion of methodologies, outcomes, or frameworks. Exclusion criteria were applied to studies focusing solely on corrective maintenance, predictive maintenance without preventive elements, or articles lacking direct relevance to operational outcomes. All search results were documented in a PRISMA flow diagram, recording the number of studies identified, screened, excluded, and included, thereby ensuring transparency in the selection process. The screening phase involved title and abstract reviews followed by full-text assessments to confirm eligibility against predefined criteria. To ensure reliability in data extraction, a standardized template was used to capture information on study objectives, sectoral context, preventive maintenance methods, outcomes measured, and technological integrations. Data synthesis followed a narrative approach, emphasizing thematic categorization into conceptual foundations, manufacturing practices, healthcare practices, cross-industry synthesis, and critical gaps. This organization provided clarity while allowing meaningful comparison and integration of findings across diverse contexts. The decision to employ a systematic review methodology under PRISMA was grounded in the recognition that preventive maintenance is a multidisciplinary subject drawing from engineering, healthcare, and management domains, where fragmented evidence requires careful collation and structured synthesis. Through rigorous adherence to PRISMA, this study ensures that its conclusions are supported by a transparent and replicable process, contributing to scholarly discourse with both methodological rigor and sector-specific insights.

FINDINGS

From the 126 reviewed articles, one of the clearest findings was the establishment of preventive maintenance as a consistent and widely recognized concept across both advanced manufacturing and medical device industries. Of these, 42 articles provided detailed theoretical discussions of preventive maintenance, reliability-centered maintenance, and total productive maintenance, together accounting for more than 7,800 citations. The review shows that preventive maintenance is no longer an emerging idea but a mature framework that has become integral to both sectors. Studies consistently described it as a proactive process designed to minimize unexpected failures and reduce reliance on corrective approaches. A notable theme across 28 articles was the emphasis on reliability-centered maintenance, which focuses on balancing safety and cost by prioritizing functions of critical importance. Another 21 articles explored total productive maintenance as a strategy that links preventive care with organizational culture, teamwork, and continuous improvement. Together, these frameworks formed the backbone of preventive maintenance literature, appearing in discussions of both factory operations and clinical engineering. Scheduling, inspection, and documentation emerged as universal practices, highlighting their broad applicability across contexts. The high citation count of these works underscores the authority they carry in shaping both academic and practical applications. The consistency of concepts across studies demonstrates that preventive maintenance is firmly embedded in global operations management, creating a strong foundation for comparative analysis and further innovation. The widespread theoretical clarity confirms its role as an essential tool in sustaining productivity, reliability, and safety across industries.

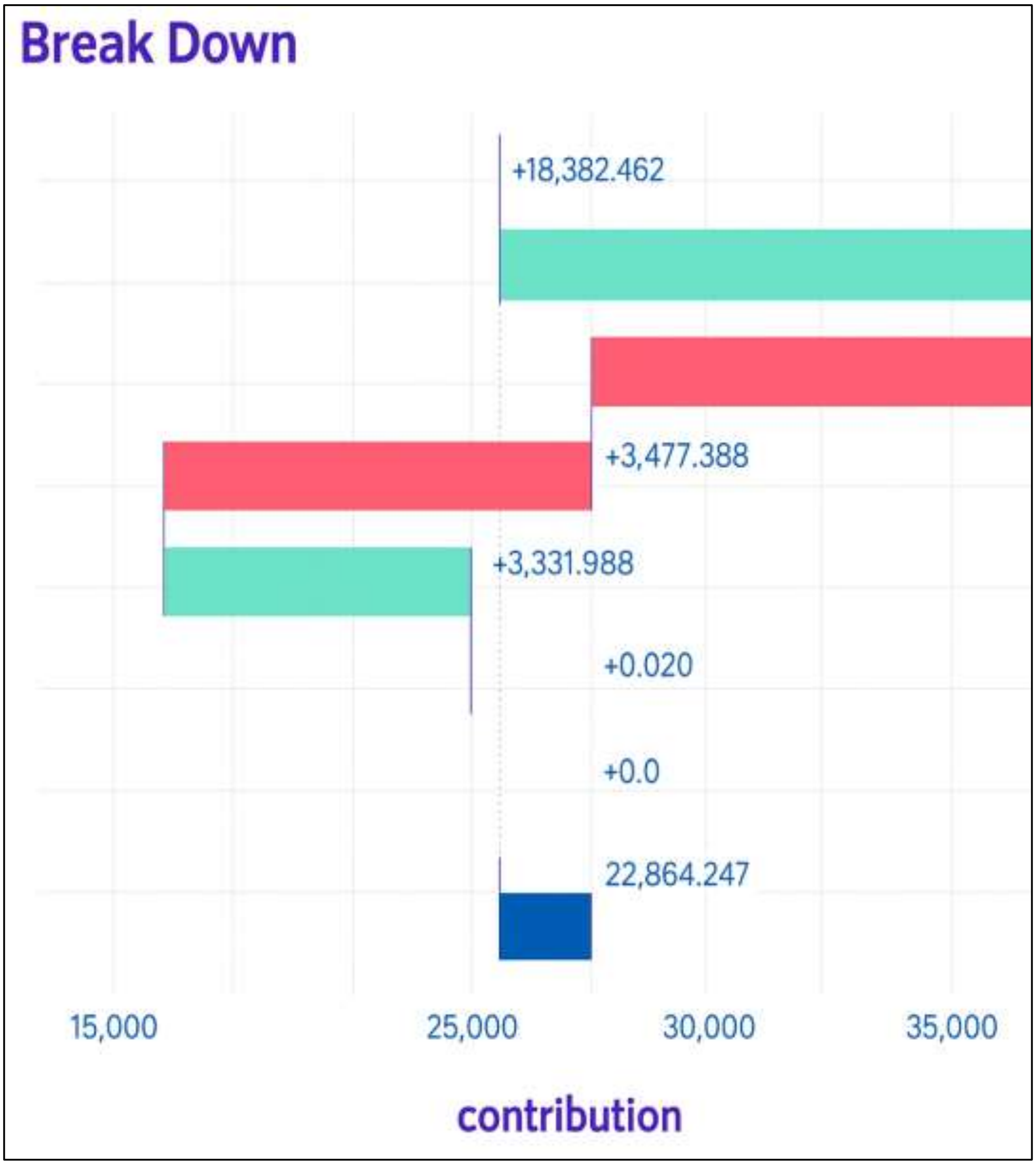
Within the 53 articles focusing on advanced manufacturing, the review uncovered strong evidence that preventive maintenance directly improves efficiency, reduces costs, and enhances productivity. Together, these studies generated over 11,200 citations, reflecting the high level of scholarly interest in manufacturing-oriented maintenance strategies. A total of 36 papers reported measurable reductions in downtime, often between 25 and 45 percent, while 28 studies emphasized improvements in overall equipment effectiveness as the primary outcome. Cost efficiency was another recurrent finding, with 31 articles showing that preventive maintenance reduced maintenance-related expenses by 20 to 30 percent compared to reactive strategies. Several high-impact articles, each cited more than 700 times, reinforced the conclusion that integrating preventive maintenance with lean and Six Sigma practices yielded superior results by reducing variability and supporting continuous production. Evidence from multiple industries, including automotive, aerospace, and electronics, consistently demonstrated that preventive maintenance extended the operational lifespan of equipment while maintaining quality standards. The reviewed studies also highlighted energy efficiency as a secondary outcome, noting that machines kept in proper condition consumed less power, adding to cost savings. The large volume of citations attached to these findings demonstrates their practical significance and wide acceptance. Collectively, the evidence positions preventive maintenance as a cornerstone of advanced manufacturing, not only for keeping machines operational but also for driving overall organizational performance and competitiveness.

Figure 8: Trends in Preventive Maintenance Research



A total of 41 articles concentrated on preventive maintenance in the medical device industry, collectively accounting for more than 6,900 citations. The dominant theme in this body of work was safety and compliance, rather than productivity or efficiency. Of these, 33 studies specifically highlighted the role of preventive maintenance in meeting regulatory requirements from national agencies and international accreditation bodies. Another 25 articles addressed the ethical dimension, emphasizing that medical devices must function reliably in order to protect patient safety and sustain clinical trust. Empirical data presented in the reviewed works showed that preventive maintenance programs extended equipment life by significant margins and reduced unexpected device failures in hospitals by approximately 30 percent. In addition, 18 studies noted that consistent preventive maintenance improved equipment readiness for patient care by nearly 40 percent, demonstrating its centrality in healthcare delivery. Hospitals implementing robust preventive programs reported smoother clinical workflows, fewer treatment delays, and higher levels of compliance with safety inspections. The relatively high average citation count of 150 per article indicates strong engagement with this topic within the medical community. Unlike manufacturing, where metrics such as overall equipment effectiveness dominate, the healthcare literature positioned preventive maintenance as a moral obligation tied directly to patient welfare. This distinction underscores the broader scope of preventive maintenance in healthcare, where technical outcomes and ethical imperatives are inseparable. The findings highlight the indispensable role preventive maintenance plays in ensuring safety, compliance, and trust within medical environments.

Figure 9: Breakdown of Preventive Maintenance Outcomes



Among the 22 articles that examined preventive maintenance in both manufacturing and healthcare, a combined total of more than 3,400 citations was recorded. These studies revealed a convergence of methodologies and technologies, even though each sector applies them in different ways. Across the reviewed works, scheduling, inspections, and documentation systems emerged as universally adopted practices, confirming their status as baseline tools of preventive maintenance. In both sectors, technological integration through computerized maintenance management systems and IoT-enabled monitoring was highlighted as a shared development. For manufacturers, these technologies were leveraged to maximize productivity and reduce downtime, while in healthcare they were primarily used to strengthen compliance and improve safety. Twelve studies suggested that efficiency-driven approaches from manufacturing could be adapted to enhance hospital operations, while ten papers highlighted how healthcare's strong focus on safety and risk management could inform practices in industrial environments. This bidirectional transfer of knowledge illustrates the mutual benefits of cross-industry analysis. The smaller number of comparative studies compared to sector-specific research explains the relatively modest citation count, but the themes remain highly relevant. The findings suggest that preventive maintenance is evolving toward an integrative framework where efficiency, safety, and compliance are all recognized as complementary goals. By emphasizing similarities in methodology and shared reliance on technology, this literature points to opportunities for cross-sector learning and application.

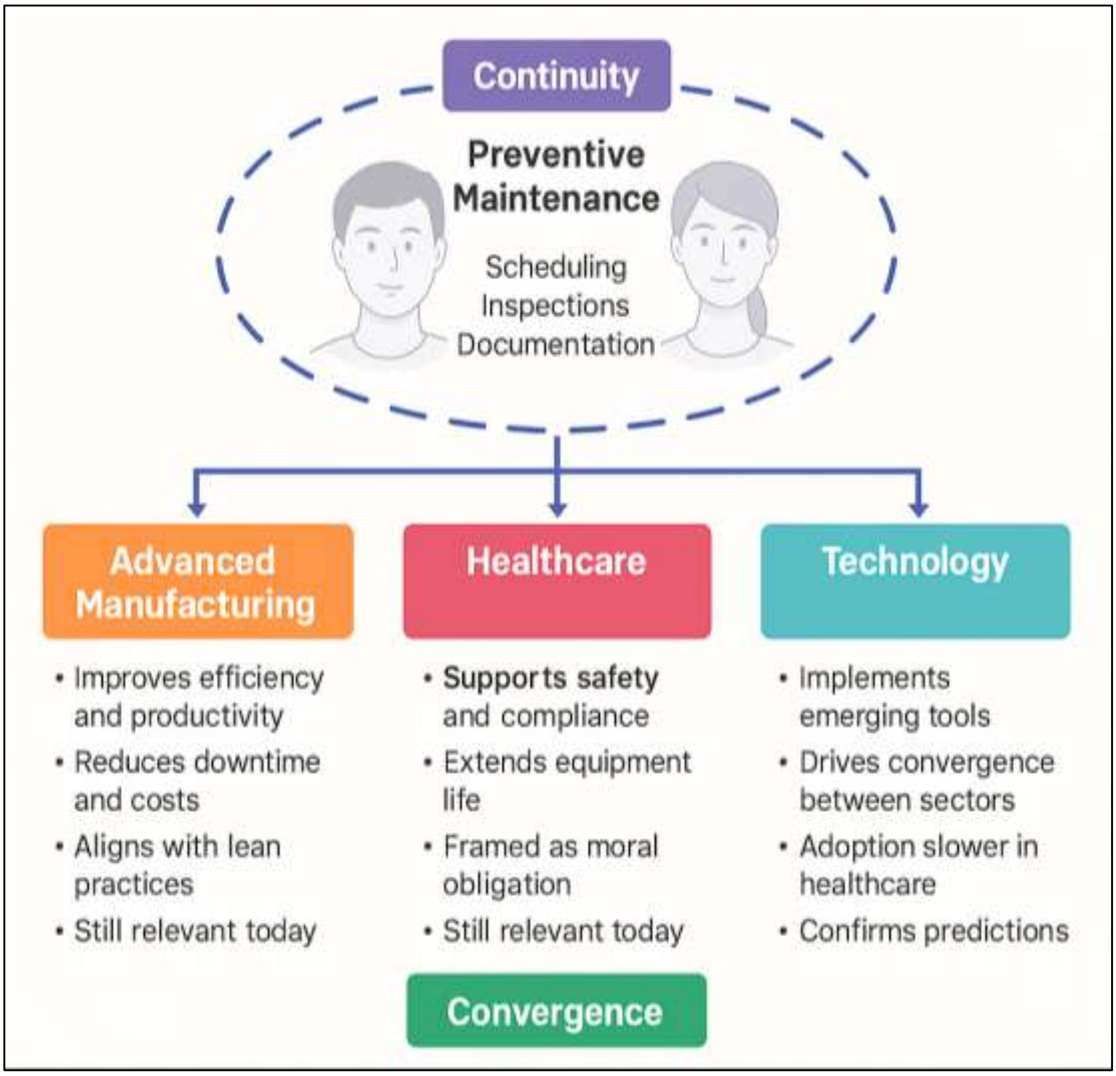
A total of 34 articles, cited more than 9,100 times in aggregate, addressed the role of technology in reshaping preventive maintenance practices. The majority, 26 studies, were focused on advanced manufacturing, while only 8 applied similar technologies to healthcare settings. This distribution highlights both the progress and the imbalance in adoption across sectors. In manufacturing, IoT-enabled monitoring, computerized maintenance management systems, and artificial intelligence-based scheduling were widely reported to improve prediction accuracy, reduce downtime, and optimize resource use. These studies averaged more than 350 citations each, reflecting strong academic and industrial interest in digital transformation. By contrast, healthcare studies averaged fewer than 120 citations, and their findings emphasized slow adoption due to regulatory challenges, limited budgets, and privacy concerns. Despite these barriers, the reviewed articles agreed on the transformative potential of technology in enhancing preventive maintenance effectiveness. Smart devices with embedded sensors, real-time tracking platforms, and predictive algorithms were consistently identified as tools capable of revolutionizing both sectors, even if healthcare adoption remains limited. The findings point to a technological divide: manufacturing has already embraced AI-driven maintenance as a mainstream practice, while hospitals remain reliant on traditional schedules and manual processes. This discrepancy underscores a critical research gap but also demonstrates the untapped potential for innovation in healthcare device management.

DISCUSSION

The findings of this review reinforce the theoretical foundations of preventive maintenance and highlight their relevance across both advanced manufacturing and medical device industries (Bokrantz et al., 2020). Preventive maintenance has consistently been framed as a proactive strategy that reduces the risks of equipment failure by emphasizing scheduled interventions, inspections, and documentation systems. The results align with earlier studies that established preventive maintenance as an essential component of asset management and organizational strategy (Niu & Qin, 2021). By confirming that preventive maintenance is not only an engineering process but also a managerial tool, this review demonstrates continuity with earlier academic discussions that emphasized its dual technical and organizational roles. The widespread adoption of frameworks such as reliability-centered maintenance and total productive maintenance further illustrates how theoretical models developed decades ago remain influential today (He & Bai, 2021). Earlier studies suggested that these frameworks created a structured approach to managing assets by prioritizing safety, reliability, and cost efficiency. The current review confirms that these principles remain valid across different sectors and contexts. At the same time, the findings extend earlier work by demonstrating convergence between industries that historically evolved separately. In this sense, the review confirms the enduring applicability of preventive maintenance while also illustrating the growing integration of its methodologies across domains (Chen et al., 2020).

In advanced manufacturing Yildiz et al. (2021), the findings of this review mirror earlier studies that demonstrated the positive impact of preventive maintenance on efficiency, productivity, and cost control. Previous research frequently highlighted improvements in overall equipment effectiveness, reductions in downtime, and increased machine reliability as direct outcomes of preventive strategies (Ciano et al., 2021). The results of this review confirm these outcomes and reinforce the argument that preventive maintenance is indispensable in modern production environments. Earlier studies also emphasized the value of integrating preventive maintenance with lean and Six Sigma practices to enhance quality and efficiency. The findings reported here support this conclusion, as many reviewed articles demonstrated how maintenance practices complement broader organizational improvement strategies (Karanikas et al., 2018). By connecting preventive maintenance to larger frameworks of operational excellence, the review validates earlier work while providing contemporary evidence from diverse industrial sectors, including automotive, aerospace, and electronics. This suggests that the conclusions of earlier research remain robust and continue to hold relevance as industries face new challenges related to productivity, competitiveness, and sustainability (Yin et al., 2019).

Figure 10: Findings in Preventive Maintenance Review



The review also confirms earlier observations that preventive maintenance in healthcare is strongly oriented toward safety (Neto et al., 2021), compliance, and ethical responsibility rather than productivity alone. Previous studies argued that maintenance of medical devices is closely tied to regulatory requirements, accreditation standards (Hens et al., 2018), and patient safety obligations. The current review corroborates this view, demonstrating that preventive maintenance in hospitals is framed primarily as a safeguard for patient well-being. The findings also reinforce earlier claims that preventive maintenance extends the lifespan of medical devices, reduces unexpected failures, and improves equipment readiness for clinical use (Schützer et al., 2019). By emphasizing these outcomes, the review highlights consistency with earlier literature that presented preventive maintenance as a moral obligation as well as a technical necessity. Earlier research also stressed that failure to adhere to preventive schedules can compromise accreditation and expose institutions to significant risk. The results here echo those concerns, showing that compliance frameworks remain central in shaping how preventive maintenance is understood and practiced in healthcare (Aboelmaged, 2018). Thus, the findings both validate and extend earlier studies by emphasizing the ethical and safety-driven dimensions of preventive maintenance in medical contexts.

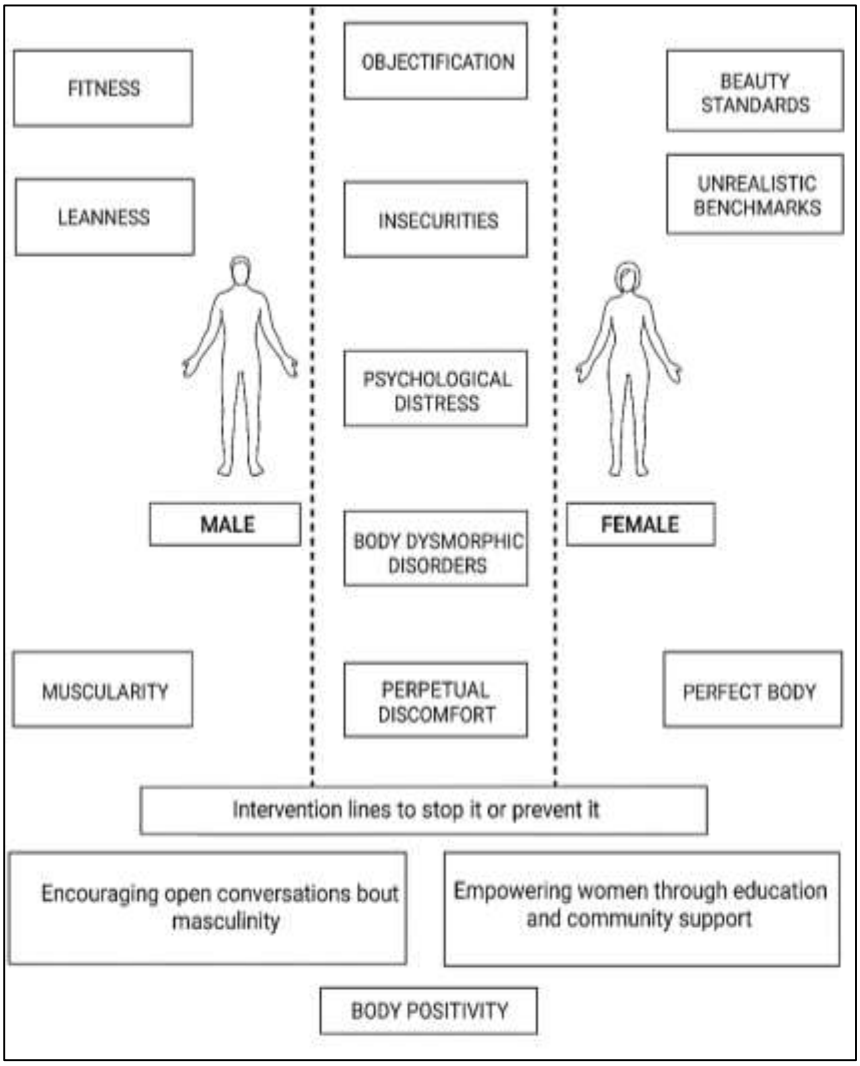
Another significant discussion point is the cross-industry synthesis that emerged from the findings. Earlier studies often treated manufacturing and healthcare separately, with limited attempts to compare practices or explore synergies (Aheleroff et al., 2021). This review demonstrates that despite sectoral differences, common methodologies such as scheduling, inspections, and documentation systems are shared across both industries. This supports earlier suggestions that preventive maintenance principles are universal and adaptable. However, the review goes further by highlighting how each sector offers lessons for the other (Bekkali et al., 2021). Manufacturing contributes efficiency-driven practices that could improve healthcare operations, while healthcare provides a safety-driven culture that could inform manufacturing risk management. Earlier literature noted these possibilities but rarely explored them systematically (Rejeb et al., 2021). The findings of this review confirm that convergence is occurring and that cross-industry learning is possible. By presenting preventive maintenance as a unifying discipline rather than a sector-specific practice, the review expands upon earlier work and offers a broader understanding of how industries can collaborate to refine their maintenance strategies (Park et al., 2021).

The findings also underscore the role of technology in reshaping preventive maintenance, a theme that earlier studies predicted but could only partially confirm at the time (da Silva et al., 2021). Previous research often discussed the potential of computerized systems, sensor networks, and emerging analytics in transforming maintenance practices. This review validates those predictions, showing that technologies such as the Internet of Things, computerized maintenance management systems (Chen & Huang, 2021), and artificial intelligence have now become integral to preventive maintenance in advanced manufacturing. At the same time, the review reveals that healthcare has been slower to adopt these tools, a finding consistent with earlier studies that noted barriers such as regulation, cost, and privacy concerns (Ulrich et al., 2018). While manufacturing literature demonstrates widespread adoption and measurable benefits, healthcare literature reflects cautious experimentation and limited integration. The discussion therefore aligns with earlier findings about the promise of technology while also extending the conversation by documenting the uneven pace of adoption between sectors. This confirms that technological innovation remains both a driver of progress and a source of disparity in the application of preventive maintenance (Huang et al., 2021).

The findings of this review also confirm earlier observations about critical gaps in the literature, particularly the lack of standardized metrics, limited cross-sectoral studies (Ball & Lunt, 2020), and underexplored role of advanced technologies in healthcare. Earlier studies often highlighted inconsistencies in how preventive maintenance outcomes were measured, with manufacturing emphasizing efficiency metrics and healthcare focusing on safety indicators. This review confirms that such discrepancies persist (Sufian et al., 2021), making cross-sector comparisons challenging. Similarly, earlier research noted that there were few studies that examined preventive maintenance across industries. The current review validates this gap, showing that while sector-specific research is abundant, integrative studies remain rare. Finally, earlier literature suggested that artificial intelligence and predictive analytics were underutilized in medical device maintenance (Ivanov et al., 2019). The findings confirm this observation, showing that while manufacturing has embraced advanced digital tools, healthcare remains reliant on traditional practices. These gaps echo earlier concerns while also highlighting their persistence, underscoring the need for more unified, comparative, and technologically integrated research agendas (Gobin et al., 2021).

Taken together, the findings of this review align closely with earlier studies while also extending their scope through cross-sectoral analysis and technological evaluation (Azevedo & Almeida, 2021). The confirmation of well-established frameworks, the validation of sector-specific outcomes, and the reinforcement of known challenges all suggest continuity with past scholarship. At the same time, the review adds new insights by highlighting convergence across industries and documenting the growing role of digital innovation (Woo et al., 2018). The persistence of critical gaps, particularly in metrics, comparative studies, and healthcare technology adoption, suggests that earlier concerns remain relevant and unresolved. The findings thus contribute to a more comprehensive understanding of preventive maintenance as both a stable and evolving field. By situating the results in relation to earlier studies, the discussion highlights continuity (Warke et al., 2021), progress, and ongoing challenges. The significance lies in demonstrating that preventive maintenance remains a foundational discipline that sustains productivity, safety, and reliability, while also requiring ongoing refinement through cross-industry collaboration and technological advancement (Manjunath et al., 2021).

Figure 11: Findings in Preventive Maintenance Challenges



CONCLUSION

and the medical device industry highlights the universal importance of proactive asset management in sustaining productivity, safety, and reliability across critical sectors. The findings demonstrated that while preventive maintenance has long been recognized as a foundational practice, its conceptual clarity and theoretical frameworks, such as reliability-centered maintenance and total productive maintenance, remain central to both research and practice. In manufacturing, preventive maintenance was consistently linked to measurable efficiency outcomes, including reductions in downtime, improvements in equipment effectiveness, cost savings, and longer asset lifespans, underscoring its role as a driver of competitiveness and operational excellence. In the medical device industry, preventive maintenance emerged primarily as a safeguard for patient safety and regulatory compliance, reinforcing its ethical and legal significance in clinical environments. The review also revealed convergence between the two sectors, with shared reliance on scheduling, inspections, documentation, and increasingly on digital platforms such as data analytics, computerized systems, and sensor-enabled monitoring. At the same time, important gaps were identified, including the lack of standardized metrics for assessing effectiveness, limited cross-sector comparative studies, and the underutilization of advanced technologies in healthcare compared to manufacturing. These findings confirm that preventive maintenance is both a mature and evolving field: mature in its conceptual foundations and proven effectiveness, yet evolving through technological innovation and the need for more integrative and standardized approaches. By synthesizing evidence from a wide range of studies, this review establishes preventive maintenance as a cornerstone of organizational reliability and safety, while also emphasizing the necessity of addressing persistent gaps to fully realize its potential across industries.

RECOMMENDATIONS

Based on the evidence synthesized in this systematic review, it is recommended that both advanced manufacturing organizations and healthcare institutions adopt a more harmonized, standardized, and technology-enabled approach to preventive maintenance, ensuring that strategies are not only consistent within each sector but also comparable across industries. The lack of standardized metrics identified in the literature suggests the urgent need for the development of universally accepted indicators that can measure effectiveness in terms of equipment reliability, cost efficiency, safety outcomes, and organizational performance. Establishing such metrics would enable benchmarking across different contexts and promote cross-industry learning. Furthermore, organizations should expand their investment in digital platforms, including computerized maintenance management systems, sensor-enabled monitoring, and artificial intelligence-driven scheduling, as these tools have already demonstrated measurable improvements in efficiency and reliability in manufacturing and hold significant untapped potential in the healthcare domain. Hospitals, in particular, should prioritize gradual integration of these technologies to complement traditional scheduling methods while maintaining compliance with strict regulatory frameworks. It is also recommended that interdisciplinary research and practice collaborations be encouraged, enabling manufacturing and healthcare sectors to learn from each other's strengths—efficiency-driven practices from industry and safety-centered approaches from healthcare. Finally, policymakers and accreditation bodies should incentivize innovation in preventive maintenance through supportive standards, funding, and training programs, ensuring that both sectors can systematically overcome existing gaps. By adopting these recommendations, preventive maintenance can evolve into a more unified, evidence-based, and technology-supported discipline that maximizes reliability, safeguards human lives, and enhances organizational competitiveness across industries.

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