RENEWABLE ENGINEERING

Integration of Industry 5.0 Principles in Sustainable Manufacturing Systems: A Literature Review on the Role of Human–Machine Collaboration and Its Impact on Productivity

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ABSTRACT

The transition from Industry 4.0 to Industry 5.0 represents a paradigm shift from technology-driven efficiency toward human-centric, sustainable, and resilient manufacturing systems. Human–machine collaboration is increasingly recognized as a core mechanism for achieving productivity while simultaneously addressing social and environmental objectives. This study aims to systematically review the integration of Industry 5.0 principles in sustainable manufacturing, with particular emphasis on the role of human–machine collaboration and its impact on productivity. A Systematic Literature Review (SLR) was conducted using peer-reviewed journal articles published between 2021 and 2025 from major academic databases. Thematic analysis was applied to synthesize key concepts related to human-centric smart manufacturing, human–robot collaboration, cyber-physical systems, digital twins, and sustainability performance indicators. The findings indicate that collaborative human–machine architectures enhance operational efficiency, quality consistency, adaptability, and resilience, while also supporting worker well-being, skill development, and environmental performance. However, gaps remain regarding long-term empirical validation, standardized sustainability measurement frameworks, and implementation in diverse industrial contexts. In conclusion, Industry 5.0 provides an integrative socio-technical framework in which human–machine collaboration functions as a strategic bridge between productivity enhancement and sustainable manufacturing performance.
Keywords: Human–machine collaboration, Industry 5.0, Sustainable manufacturing, Productivity, Human-centric manufacturing, Digital transformation

INTRODUCTION

The rapid evolution of industrial paradigms has brought manufacturing systems to a new transformative stage marked by the transition from Industry 4.0 to Industry 5.0. While Industry 4.0 was primarily characterized by automation, digitalization, cyber-physical systems, artificial intelligence (AI), and data-driven efficiency, Industry 5.0 introduces a normative shift toward human-centricity, sustainability, and resilience. This transition reflects growing recognition that purely technology-driven optimization, although effective in enhancing economic performance, may generate unintended social and environmental consequences. Recent literature emphasizes that the future of manufacturing must not only pursue productivity gains but also integrate human values and long-term sustainability objectives (Ghobakhloo et al., 2024; Mourtzis et al., 2022;

Grosse et al., 2023; Akundi et al., 2022). In this context, human–machine collaboration emerges as the core mechanism for achieving balanced and sustainable productivity.

Industry 4.0 significantly improved operational efficiency, cost reduction, and flexibility through automation and interconnected digital infrastructures. However, several studies have highlighted its limitations, particularly concerning worker well-being, job quality, and social equity. Ghobakhloo et al. (2024) and Grosse et al. (2023) argue that excessive automation and algorithmic optimization may marginalize human roles, intensify work pressure, and create new forms of digital inequality. Similarly, Mourtzis et al. (2022) emphasize that technological determinism in Industry 4.0 often prioritizes machine performance over human-centered design. Akundi et al. (2022) further note that the lack of integration between social sustainability and technological innovation has created imbalances in manufacturing systems. These challenges have stimulated the emergence of Industry 5.0 as a strategic response aimed at re-centering human values in industrial transformation.

Industry 5.0 redefines manufacturing as a human-centric, sustainable, and resilient system. It promotes concepts such as human-centric smart manufacturing (HCSM), human smart manufacturing (HSM), and human cyber-physical systems (HCPS), where human intelligence and machine capabilities complement each other (Zhang et al., 2023; Mourtzis et al., 2022; Yang et al., 2024; Lou et al., 2025; Rovzanec et al., 2022). Unlike Industry 4.0, which focused on replacing human labor with automated systems, Industry 5.0 emphasizes collaborative integration in which humans remain at the core of decision-making, creativity, and system supervision. This shift reflects a broader normative agenda that integrates social well-being, environmental stewardship, and economic performance.

Human values in Industry 5.0 are articulated through worker participation, skill development, inclusion, safety, and well-being. Zhang et al. (2023) highlight the emergence of the "Operator 5.0" concept, representing a digitally empowered worker who collaborates with intelligent systems rather than being subordinated to them. Peruzzini et al. (2023) argue that explainable AI and transparent decision-support systems are essential for building trust between humans and machines. Rovzanec et al. (2022) further stress that ethical governance frameworks and participatory system design are fundamental to ensuring human dignity in automated environments. Alves et al. (2023) add that workforce upskilling and inclusive design are key drivers of sustainable digital transformation. Together, these studies underscore that Industry 5.0 is not merely a technological upgrade but a socio-technical reorientation.

At the heart of this paradigm lies human–machine collaboration as the principal operational mechanism. Advances in collaborative robotics (cobots), digital twins (DT), machine learning (ML), mixed reality (MR) human–machine interfaces (HMI), and adaptive cyber-physical production systems (CPPS) enable dynamic teamwork between humans and intelligent machines. Langås et al. (2025) and Kaasinen et al. (2022) describe human–robot collaboration (HRC) and human–robot teaming (HRT) as models in which humans and robots share tasks based on complementary strengths. Shabur et al. (2025) and Dhanda et al. (2025) demonstrate that digital twin technologies allow real-time synchronization between physical and virtual systems, enhancing adaptability and predictive maintenance. These innovations expand the potential for co-creative production environments where human judgment and machine precision operate synergistically.

Beyond robotics, human–automation symbiosis and HCPS frameworks further redefine manufacturing ecosystems. Rani et al. (2024) and Lou et al. (2025) propose adaptive systems in which humans are "in the loop," "on the loop," and "in the society

loop," ensuring continuous feedback and ethical oversight. Kadam et al. (2025) emphasize that joint cognitive systems enhance collaborative intelligence, enabling shared situational awareness between operators and AI systems. Peruzzini et al. (2023) advocate for human-centric AI architectures incorporating explainable AI, simulated reality, and user-centered feedback to improve safety and trust. These technological enablers represent the integration of Industry 4.0 tools within Industry 5.0 value frameworks.

Despite this conceptual progress, the relationship between human–machine collaboration, sustainable manufacturing, and productivity remains insufficiently clarified. Sustainable manufacturing in the Industry 5.0 era extends beyond traditional triple bottom line metrics to include resilience, human well-being, and long-term societal value (Shabur et al., 2025; Martín-Gómez et al., 2024; Narkhede et al., 2024). Martín-Gómez et al. (2024) argue that Industry 5.0 aligns manufacturing with circular economy principles, reducing environmental impact while enhancing resource efficiency. Khan and Ansari (2025) suggest that inclusive digital transformation can bridge skill gaps and support vulnerable workers. Amirkhizi et al. (2025) further note that AI-driven optimization integrated with human oversight can simultaneously improve productivity and environmental performance.

However, significant research gaps persist. First, empirical evidence regarding long-term trade-offs between productivity gains and worker well-being remains limited. Zhang et al. (2023) and Ghobakhloo et al. (2024) highlight the need for longitudinal studies assessing whether collaborative systems truly enhance job quality or merely reconfigure labor demands. Grosse et al. (2023) question whether increased digital complexity may inadvertently intensify cognitive workload. Narkhede et al. (2024) also emphasize the scarcity of standardized metrics evaluating both productivity and human-centric performance indicators.

Second, there is a lack of standardized methodologies for measuring sustainability performance within Industry 5.0 frameworks across the entire system lifecycle. Martín-Gómez et al. (2024) and Amirkhizi et al. (2025) call for integrated evaluation models that incorporate environmental impact, social inclusivity, and economic efficiency. Without consistent measurement frameworks, comparative assessment across sectors remains challenging. Third, empirical implementation studies in developing economies and small and medium enterprises (SMEs) are limited. Grosse et al. (2023) and Shabur et al. (2025) argue that most case studies focus on advanced manufacturing contexts, leaving gaps in understanding adoption barriers, ethical governance, and reskilling strategies in emerging economies.

These gaps reveal a critical need for systematic literature synthesis examining how Industry 5.0 principles particularly human–machine collaboration affect sustainable manufacturing and productivity simultaneously. While numerous studies address individual components such as AI, robotics, or sustainability, fewer integrate these dimensions into a unified analytical framework. This fragmentation limits theoretical clarity and policy guidance for manufacturers seeking balanced digital transformation.

The novelty of this study lies in its integrative review of Industry 5.0 literature, synthesizing technological, organizational, and sustainability perspectives to evaluate the role of human–machine collaboration in sustainable productivity. Rather than treating productivity and sustainability as separate objectives, this research conceptualizes them as interdependent outcomes mediated by collaborative socio-technical systems. By mapping dominant themes—human-centric smart manufacturing, collaborative robotics, adaptive HCPS architectures, and sustainability performance metrics this study provides a comprehensive overview of current knowledge and identifies structural research gaps.

Based on the identified phenomenon and literature gaps, the objective of this study is to systematically review and analyze the integration of Industry 5.0 principles in sustainable manufacturing systems, with particular emphasis on the role of human–machine collaboration and its impact on productivity outcomes. Through this objective, the study contributes to advancing theoretical integration and practical understanding of how manufacturing systems can simultaneously achieve technological efficiency, human well-being, and environmental sustainability.

In conclusion, the transition from Industry 4.0 to Industry 5.0 represents a paradigm shift toward human-centered and sustainable industrial development. Human–machine collaboration stands as the core operational mechanism linking advanced digital technologies with social and environmental values. However, empirical validation, standardized measurement approaches, and implementation studies remain limited. Addressing these gaps through systematic literature review is essential for guiding policymakers, practitioners, and researchers toward resilient and inclusive manufacturing ecosystems in the era of Industry 5.0.

METHODS

This study employed a **Systematic Literature Review (SLR)** approach to analyze the integration of Industry 5.0 principles in sustainable manufacturing systems, with a specific focus on human–machine collaboration and its impact on productivity. The review followed a structured protocol adapted from PRISMA guidelines to ensure transparency and methodological rigor. Data were collected from reputable international academic databases, including Scopus, Web of Science, ScienceDirect, and IEEE Xplore. The search strategy combined keywords such as *"Industry 5.0," "human–machine collaboration," "human-centric manufacturing," "sustainable manufacturing," "human–robot collaboration," "digital twin," "HCPS,"* and *"productivity."* Inclusion criteria consisted of peer-reviewed journal articles published between 2021 and 2025, written in English, and directly addressing Industry 5.0, sustainability, or collaborative human–machine systems in manufacturing contexts. Exclusion criteria included conference abstracts without full papers, non-peer-reviewed sources, and studies unrelated to manufacturing applications. After removing duplicates and screening titles, abstracts, and full texts, a final corpus of selected articles was established for qualitative synthesis.

Data analysis was conducted using thematic and content analysis techniques. Each selected article was coded according to predefined analytical dimensions, including (1) conceptualization of Industry 5.0, (2) forms of human–machine collaboration (e.g., HRC, HRT, HCPS), (3) sustainability dimensions (economic, environmental, social), and (4) reported productivity outcomes. Open coding was initially applied to identify recurring themes, followed by axial coding to establish relationships between human-centric principles, technological enablers, and performance indicators. A narrative synthesis approach was then used to integrate findings and map dominant research streams, theoretical frameworks, and empirical evidence. Additionally, gaps in methodology, measurement models, and sectoral implementation were systematically identified. This analytical process enabled the development of an integrative framework explaining how Industry 5.0–based human–machine collaboration contributes to sustainable productivity in manufacturing systems.
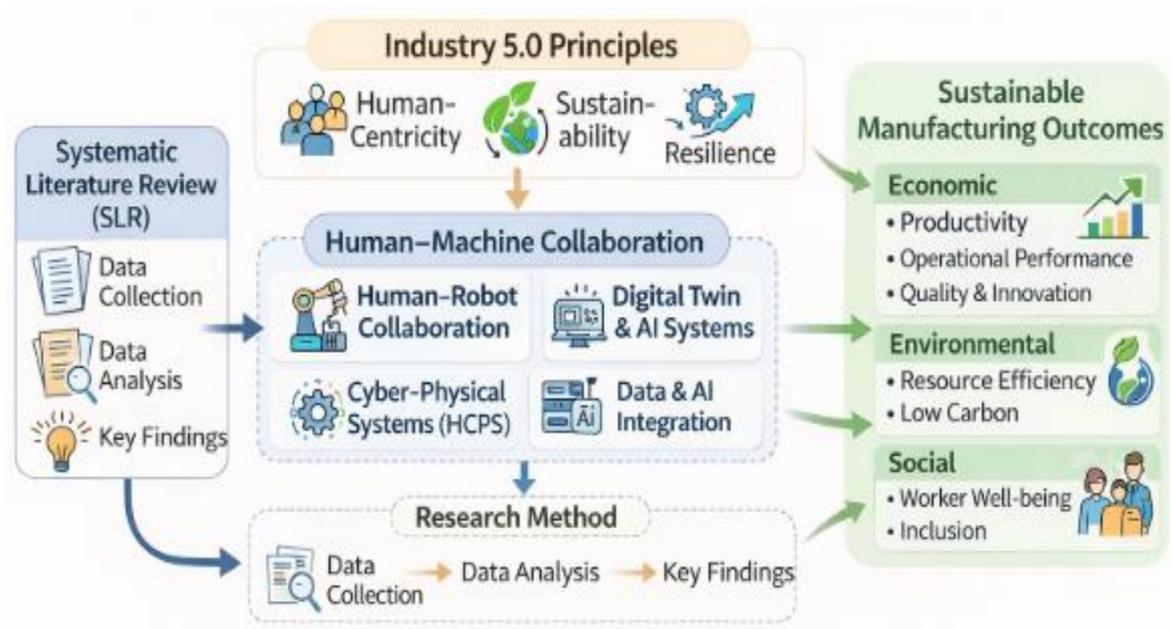
Figure 1. Conceptual Framework This Research

RESULTS AND DISCUSSION

Based on the systematic literature review of peer-reviewed journal articles published between 2021 and 2025, thematic synthesis identified four dominant research clusters linking Industry 5.0 principles, human–machine collaboration, sustainable manufacturing, and productivity outcomes. The reviewed studies consistently demonstrate that the integration of human-centric values with advanced digital technologies reshapes manufacturing performance beyond purely economic indicators. The synthesized findings are summarized in Table 1.

Table 1. Synthesis of Literature Findings on Industry 5.0 Integration and Sustainable Productivity

Thematic Cluster	Key Concepts Identified	Sustainability Dimension Affected	Reported Productivity Impact	Representative Sources
Human-Centric Smart Manufacturing	Operator 5.0, participatory design, worker well-being	Social (skills, inclusion, safety)	Improved adaptability and innovation performance	Zhang et al. (2023); Mourtzis et al. (2022); Alves et al. (2023)
Human–Robot / Automation Collaboration	HRC, HRT, HCPS, adaptive CPPS	Economic & Social	Higher operational efficiency and quality consistency	Langås et al. (2025); Kaasinen et al. (2022); Rani et al. (2024); Peruzzini et al. (2023)
Digital Twin & AI Integration	DT, AI-driven optimization, predictive analytics	Economic & Environmental	Reduced downtime, cost efficiency, lower waste	Shabur et al. (2025); Martín-Gómez et al. (2024); Amirkhizi et al. (2025)
Resilient & Sustainable	Circular economy integration,	Environmental & Social	Stable long-term productivity	Narkhede et al. (2024); Ghobakhloo et al.

| **Manufacturing Systems** | resilience frameworks | and mitigation | risk | (2024); Grosse et al. (2023) |

The findings indicate that Industry 5.0 integration produces multidimensional impacts rather than solely technological gains. First, human-centric smart manufacturing enhances worker empowerment and skill development, which indirectly improves innovation capacity and operational adaptability. Second, human–robot collaboration and HCPS frameworks contribute directly to efficiency, precision, and quality stability while maintaining human oversight. Third, digital twin and AI integration enable predictive optimization, reducing material waste and energy consumption, thereby linking environmental sustainability with productivity improvements. Finally, resilience-oriented frameworks strengthen long-term system stability, mitigating risks associated with supply chain disruptions and technological uncertainty. Overall, the literature confirms that human–machine collaboration under Industry 5.0 principles functions as a strategic bridge between sustainability goals and productivity enhancement. Rather than creating a trade-off, properly designed collaborative systems demonstrate potential synergy between economic performance, environmental responsibility, and social well-being.

Discussion

This study aimed to systematically analyze the integration of Industry 5.0 principles in sustainable manufacturing systems, with particular emphasis on the role of human–machine collaboration and its impact on productivity. Based on the thematic synthesis of the reviewed literature, the findings reveal that Industry 5.0 represents not merely an incremental technological upgrade from Industry 4.0, but a normative and structural transformation that re-centers human values while maintaining productivity and sustainability objectives. The discussion below elaborates how the transition toward Industry 5.0 redefines manufacturing logic, positions human–machine collaboration as a core mechanism, and highlights existing research gaps in sustainable performance measurement and empirical implementation.

The transition from Industry 4.0 to Industry 5.0 marks a fundamental shift from technology-driven efficiency to value-driven manufacturing. Industry 4.0 prioritized automation, cyber-physical systems, AI, and interconnected production networks to maximize productivity and cost efficiency. While this transformation significantly improved economic performance, recent studies emphasize its unintended social consequences. Ghobakhloo et al. (2024) argue that excessive automation and digital optimization may marginalize human labor and intensify digital inequality. Similarly, Grosse et al. (2023) highlight that rapid digital transformation can increase cognitive workload and create psychosocial stress among workers. Mourtzis et al. (2022) and Akundi et al. (2022) further contend that Industry 4.0 frameworks often underemphasize human well-being and social sustainability. These limitations provide the conceptual foundation for Industry 5.0, which seeks to restore human centrality in manufacturing systems.

Industry 5.0 redefines manufacturing as a human-centric, sustainable, and resilient ecosystem. The literature consistently identifies human-centric smart manufacturing (HCSM) and human cyber-physical systems (HCPS) as foundational concepts of this paradigm (Zhang et al., 2023; Mourtzis et al., 2022; Yang et al., 2024; Lou et al., 2025; Rovzanec et al., 2022). Unlike Industry 4.0, which focused on substituting human roles with automated processes, Industry 5.0 promotes complementarity between human intelligence and machine capabilities. Zhang et al. (2023) introduce the

concept of "Operator 5.0," representing a digitally augmented worker who collaborates with intelligent systems rather than being replaced by them. This conceptual shift reflects a broader ethical and socio-technical agenda emphasizing resilience, inclusion, and sustainable development.

Human values within Industry 5.0 are articulated through participation, skill development, safety, and inclusive decision-making. Peruzzini et al. (2023) stress the importance of explainable AI and transparent decision-support systems in building trust between operators and machines. Rovzanec et al. (2022) argue that human-centric AI architectures must integrate user feedback loops and ethical governance mechanisms to ensure accountability. Alves et al. (2023) further emphasize that workforce upskilling and participatory design are essential for enabling meaningful human involvement in digital manufacturing systems. These studies collectively suggest that productivity gains under Industry 5.0 should not be achieved at the expense of worker well-being but rather through collaborative empowerment.

The results of the systematic review confirm that human–machine collaboration functions as the central operational mechanism linking Industry 5.0 principles to sustainable productivity outcomes. Collaborative robotics and human–robot teaming (HRT) models represent the most visible manifestation of this integration. Langås et al. (2025) and Kaasinen et al. (2022) demonstrate that human–robot collaboration (HRC) enhances task precision and safety while allowing humans to focus on cognitive and creative activities. Shabur et al. (2025) and Dhanda et al. (2025) highlight the role of digital twin technologies and machine learning in enabling real-time synchronization between physical and virtual production systems. These technologies support adaptive decision-making and predictive maintenance, directly contributing to efficiency and quality stability.

Beyond robotics, human–automation symbiosis within HCPS frameworks expands collaborative capacity. Rani et al. (2024) conceptualize humans as being "in the loop," "on the loop," and "in the society loop," ensuring continuous oversight and ethical alignment of AI systems. Lou et al. (2025) and Kadam et al. (2025) emphasize adaptive cyber-physical production systems (CPPS) that integrate human cognitive input into automated processes. The integration of explainable AI and simulated reality environments further enhances trust and shared situational awareness (Peruzzini et al., 2023; Rovzanec et al., 2022). These findings indicate that productivity improvements in Industry 5.0 are not solely driven by technological sophistication but by the quality of collaboration between humans and intelligent systems.

Importantly, the literature reveals that sustainable manufacturing under Industry 5.0 extends the traditional triple bottom line to include resilience and human well-being as core dimensions. Shabur et al. (2025) and Martín-Gómez et al. (2024) argue that Industry 5.0 aligns digital transformation with circular economy principles, reducing resource consumption and environmental impact. Narkhede et al. (2024) emphasize resilience as a key indicator of long-term system sustainability, particularly in the context of supply chain disruptions and global crises. Amirkhizi et al. (2025) further demonstrate that AI-driven optimization combined with human oversight can reduce waste and energy consumption while improving cost efficiency. Thus, the integration of Industry 4.0 technologies within Industry 5.0 value frameworks produces synergistic rather than conflicting outcomes between sustainability and productivity.

Nevertheless, despite promising conceptual advancements, significant research gaps remain. First, empirical evidence on long-term trade-offs between productivity and worker well-being is limited. Zhang et al. (2023) and Ghobakhloo et al. (2024) highlight the need for longitudinal studies examining whether collaborative systems truly enhance

job quality or simply redistribute labor intensity. Grosse et al. (2023) caution that digital augmentation may increase cognitive demands, potentially undermining well-being. Narkhede et al. (2024) also note the absence of standardized human-centric performance metrics. The reviewed literature indicates that many studies rely on short-term case analyses rather than comprehensive lifecycle assessments.

Second, standardized methods for measuring sustainability performance within Industry 5.0 frameworks are underdeveloped. Martín-Gómez et al. (2024) call for integrated evaluation models that combine environmental, social, and economic indicators. Amirkhizi et al. (2025) emphasize the importance of lifecycle assessment tools adapted to human-centric manufacturing contexts. Without harmonized metrics, comparative analysis across industries and regions remains challenging. This gap underscores the need for methodological innovation in sustainability assessment aligned with Industry 5.0 principles.

Third, empirical implementation studies in diverse industrial contexts particularly in developing economies and small and medium enterprises (SMEs) are scarce. Grosse et al. (2023) argue that most Industry 5.0 case studies focus on technologically advanced regions, limiting generalizability. Shabur et al. (2025) and Narkhede et al. (2024) emphasize barriers such as high investment costs, digital skill gaps, and governance challenges. Amirkhizi et al. (2025) further highlight the importance of ethical AI governance frameworks in emerging markets. Addressing these contextual variations is essential for ensuring inclusive and globally applicable Industry 5.0 adoption.

In relation to the research objective, the findings demonstrate that human–machine collaboration serves as a strategic bridge between Industry 5.0 principles and sustainable productivity outcomes. Productivity under Industry 5.0 is not narrowly defined as output maximization but as multidimensional performance encompassing quality, flexibility, resilience, and sustainability. Collaborative architectures enable shared decision-making, reduce operational risks, and enhance innovation capacity. However, achieving these benefits requires careful system design, ethical AI governance, participatory workforce development, and standardized sustainability metrics.

The synthesis of literature also suggests that Industry 5.0 integration is inherently systemic. Technological enablers such as AI, IoT, robotics, and digital twins must be embedded within human-centric governance frameworks. This socio-technical alignment distinguishes Industry 5.0 from purely automation-oriented paradigms. By re-centering human values, Industry 5.0 addresses social sustainability concerns while preserving economic competitiveness and environmental responsibility.

In conclusion, the discussion confirms that the transition from Industry 4.0 to Industry 5.0 represents a strategic realignment of manufacturing priorities toward human-centric, resilient, and sustainable development. Human–machine collaboration emerges as the core mechanism enabling productivity enhancement alongside social and environmental performance. However, empirical validation, standardized sustainability measurement frameworks, and inclusive implementation studies remain limited. Future research must therefore advance longitudinal analyses, lifecycle-based evaluation models, and context-sensitive adoption strategies to fully realize the transformative potential of Industry 5.0 in sustainable manufacturing systems.

CONCLUSION

This study concludes that the integration of Industry 5.0 principles into sustainable manufacturing systems fundamentally redefines the relationship between technology, human roles, and productivity. Human–machine collaboration emerges as the central mechanism that enables the alignment of economic performance with social well-being

and environmental sustainability. Unlike the efficiency-driven logic of Industry 4.0, Industry 5.0 promotes a human-centric, resilient, and value-oriented manufacturing paradigm in which collaborative robotics, digital twins, AI systems, and adaptive cyber-physical architectures function synergistically with human intelligence. The literature synthesis confirms that properly designed human–machine collaboration can enhance operational efficiency, quality, flexibility, and long-term resilience while supporting worker empowerment and sustainable resource use. However, significant gaps remain in long-term empirical validation, standardized sustainability measurement, and real-world implementation across diverse industrial contexts. Therefore, achieving sustainable productivity under Industry 5.0 requires not only technological advancement but also integrated socio-technical governance, inclusive workforce development, and robust evaluation frameworks..

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