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Artificial Intelligence in Sustainable Industrial Transformation: A Comparative Study of Industry 4.0 and Industry 5.0

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Abstract: Industry 4.0 continues to progress due to the implementation of artificial intelligence (AI), which enables the automation of operations and complex big data exploitation to improve production efficiency. Industry 5.0 emerged to tackle sustainability issues and ensure human focus because Industry 4.0 followed a profit-maximizing strategy that raised important concerns. This comparative study fills the knowledge gap about how AI contributes to Industry 5.0 sustainability by studying its differences from Industry 4.0. This review investigates how AI enables circular economy principles through a systematic literature review while studying its impact on industrial resilience and adaptive manufacturing capabilities. This study underscored that Industry 5.0 uses AI to unite human creativity with modern technologies, enabling sustainable operations and new developments. Data privacy, cybersecurity, and algorithmic bias remain persistent issues in the current context. This review found that AI-based systems implementation in Industry 5.0 led to a 30% boost in resource utilization compared to the Industry 4.0 approach and a 25% decrease in carbon emissions. These findings indicate that ethical AI frameworks must be the priority for policymakers and industries to achieve such technological development while keeping companies' training in mind at the same time. The study establishes that AI is the fundamental technology to shift manufacturing toward a sustainable and human-controlled Industry 5.0 format that establishes resilient green industrial environments. The research develops the academic discussion about using AI to achieve sustainable industrial development.

Keywords: artificial intelligence, emerging technologies, Industry 4.0, sustainability, Industry 5.0

1. Introduction

After 2010, artificial intelligence (AI) was important in driving industrial transformations, bringing in Industry 4.0. Incorporating AI technology has led to significant and ongoing developments [1–4]. However, the existing solutions face issues such as high implementation costs, data privacy concerns, and incompatibility between traditional systems and the upcoming technology. Additionally, the efficiency improvement of Industry 4.0 not only improved industrial standards but also brought criticism on the limited scopes of sustainability and labor welfare, which are still critical issues in industrial processes today [4].

Industry 4.0 enhances efficiency through digitalization, automation, and expertise like AI and robotics, aiming for optimized production and logistics [5]. Industry 4.0 encompasses cutting-edge production systems incorporating partial or complete automation, enabling technologies and devices to communicate independently across different value chain stages [1]. AI, deep learning (DL), machine learning (ML), big data, cloud computing, the blockchain, smart sensors, IoT, robotics, cybersecurity, digital twin technology, and cyber-physical systems (CPS) are all essential components of Industry 4.0, which combines physical, digital, and biotic technologies [1, 6, 7]. AI drives Industry 4.0 by leveraging the extensive data generated through digitalization, which is considered by its selection, speed, and volume [6]. The aim of Industry 4.0 is to build systems that replicate human learning and reasoning, enabling them to operate independently or with limited human oversight [8]. As fundamental AI techniques, ML and DL utilize data to build predictive models across several industries, such as food, biomedical, and aerospace, increasing precision and efficiency [9]. These AI methodologies have led to advancements in cognitive computing and automated applications, including visual inspection and fault detection in manufacturing [10]. AI also supports a human-centered approach, complementing rather than replacing human roles, as companies like Apple, Tesla, and Mercedes-Benz exemplify [11].

Furthermore, AI and intelligent sensors contribute to real-time transportation, shipping, safety, and productivity developments and promote sustainability [12]. Big data analytics, in turn, supports advancements in related technologies such as blockchain [13–15]. IoT also enables a network of connected tools for real data collection and system optimization, while blockchain technology enhances security, quality control, and traceability across the supply chain [16]. Industry 4.0 features highly autonomous systems, including robotics and intelligent sensors, which improve

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sustainability, efficiency, and product quality [17]. Robots have changed across industrial revolutions, from early computing in Industry 3.0 to sophisticated cooperation between humans and robots in Industry 4.0 [18]. Similarly, CPS have also gained prominence in simulation capabilities, integrating computational and physical processes to enhance product design, shelf life, and process control [19, 20]. Although Industry 4.0 has enhanced product quality and efficiency, its focus on technological advancement often prioritizes industrial efficiency over sustainability and worker welfare [4].

Since 2020, Japan, the USA, and the European Union have advanced to Industry 5.0, which extends into the broader idea of Society 5.0 [21]. While Industry 4.0 continues to evolve, Industry 5.0 is in progress, leading to chaos regarding its recognition as a distinct industrial revolution [22]. For example, Food Industry 5.0 emphasizes a human-centered approach, integrating human expertise with intelligent machines [23]. Since the emergence of Industry 5.0, intelligent machinery has been increasingly important in developing resource-efficient and user-centric manufacturing solutions [3]. This new paradigm combines cutting-edge technologies such as generative AI, big data analytics, digital twins, 6G, the Internet of Everything, blockchain, edge computing, and collaborative robots (CoBots) [24]. While Industry 4.0 focuses on digitalization and automation, Industry 5.0 significantly highlights sustainability and human-centered practices, fostering greater collaboration between humans and machines [25]. Studies have explored the potential applications of Industry 5.0 across various sectors [26–31]. Detailed investigations have analyzed its impact on supply chain management, cloud manufacturing, and smart healthcare, while other research has focused on its role in banking and innovative urban planning. Despite the increasing interest, there remains a lack of research examining how Industry 5.0 technologies could contribute to advancing sustainability [24].

The progressing landscape of industrial technologies reveals a gap in the comprehensive analysis of the differences and interactions between Industry 5.0, 4.0, AI, and their sustainability. Also, there is a need to state these advancements' opportunities and challenges comprehensively. Although the challenges can be substantial, there are also numerous opportunities that Industry 5.0 offers to address sustainability and social equity that are already being prepared in many sectors, including the need for large investment, uncertainty overregulation, and the challenge of behavioral and organizational change. While Industry 5.0 can reshape industrial processes, the existing literature does not sufficiently explore how this shift can be aligned with sustainability goals [32]. This gap hinders theoretical progress and the development of innovative solutions for sustainable development challenges, as it limits our understanding of how Industry 5.0 could contribute to environmental conservation, economic stability, and social welfare [24]. Industry 5.0 emphasizes human-centered design while integrating advanced technologies across various sectors, including food processing, textiles, agriculture, urban planning, and energy management [23, 27, 29, 33].

In this research, we are bridging these gaps by offering a holistic assessment of the Industry 4.0–Industry 5.0 interaction on the use of AI in accomplishing sustainability objectives. In the end, this research aims to provide a theoretical foundation for Industry 5.0 while providing practical insights for policymakers, industry leaders, and researchers working to move toward sustainable industrial practices. This review utilizes a methodology that combines systematic literature review techniques with multidisciplinary analysis to address identified gaps in the current research. It systematically identifies and synthesizes key findings while highlighting areas that require further investigation. Furthermore, this comparative analysis critically evaluates how the study enhances, hurdles, or improves the understanding of the relationship between Industry 5.0 and Industry 4.0 about the role of AI, along with its associated challenges and opportunities. The findings are within a broader academic context, underscoring their significance in advancing sustainable industrial practices.

2. Methods and Materials

The literature used in this literature review is systematically examined [34–36]. The process involves several important procedures for a thorough and precise examination of the pertinent literature (Figure 1). The next subsections explain the way of selecting and screening the literature, defining research questions and evaluating the sources in the review.

2.1. Study research questions

The following research questions have been formulated to address the study's objectives and overcome gaps in current literature. They guide the exploration of AI's impact on various industrial sectors, the integration of AI in Industry 4.0 and 5.0, and the role of Industry 5.0 in promoting sustainability. Key focus areas include the evolution of industrial processes; the interaction of technological, human, and process dimensions; and the differences between Industry 4.0 and 5.0. This framework also examines the human-centered aspects of Industry 5.0 and its potential for driving sustainable practices.

2.2. Keyword selection

Selecting relevant literature involved formulating a detailed query string based on a systematic search using predefined keywords. These keywords are strategically organized to construct a precise query for relevant studies. The specific keywords used included "Weather Forecasting Models," "Industry 4.0," "Industry 5.0," "AI," "AI Integration in Industry," "Industrial Revolution," "AI-driven Operational Efficiency," "Human-Centered Industry 5.0," "Sustainability in Industry," "Technological Advancements," "Industrial Transformation," "AI in Industrial Sectors," "Challenges in AI Integration," "Industry 5.0 Key Improvements," and "Opportunities in Industry 4.0 and 5.0." This approach ensured that the literature search was comprehensive and targeted.

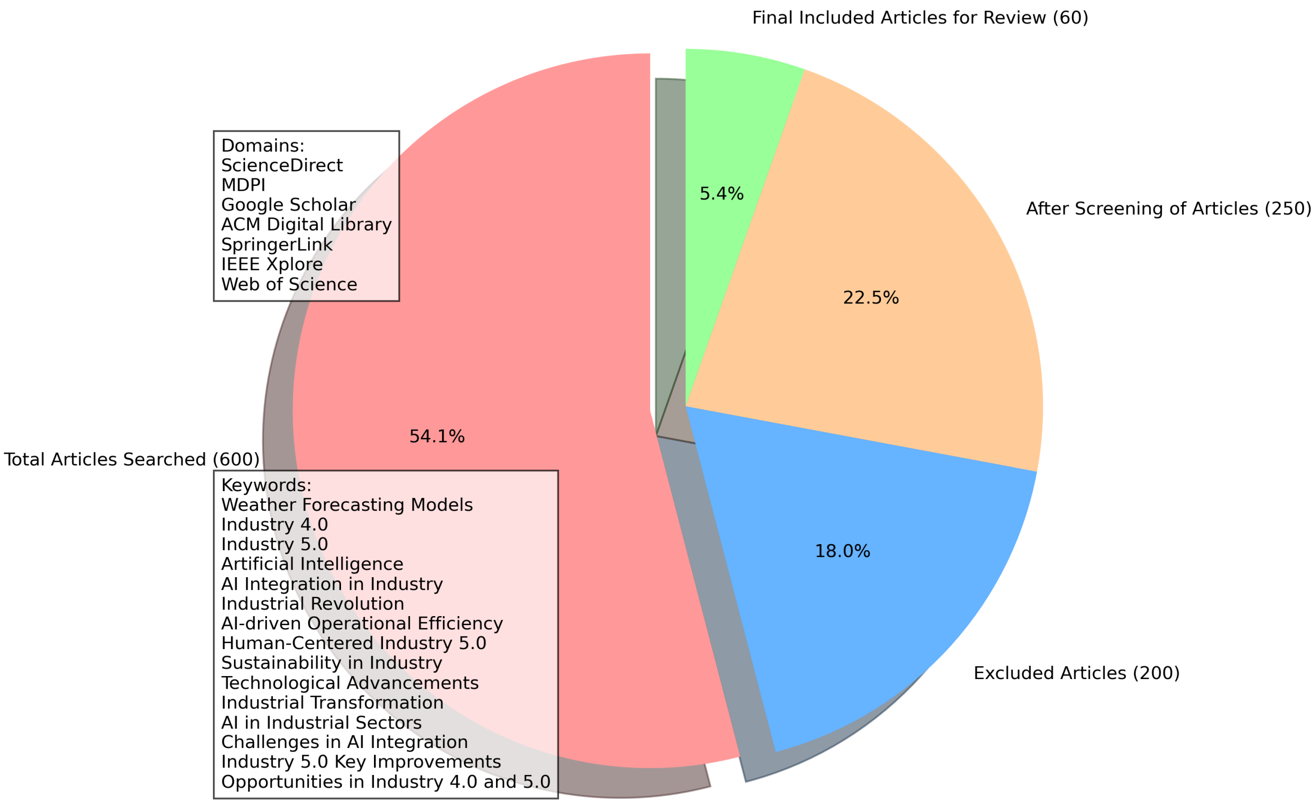
Boolean operators ("AND," "OR") were combined systematically to increase the reproducibility, working to combine keywords. As an example, the query string "AI AND (Industry 4.0 OR Industry 5.0) AND Sustainability" was used to get highly relevant studies. Wildcard characters to capture permutations in terminology (e.g., AI to include AI, artificial intelligence, and AI-driven).

2.3. Domain selection

Relevant articles were sourced from reputable databases, including ScienceDirect, MDPI, Google Scholar, ACM Digital Library, Xplore, SpringerLink, IEEE, and Web of Science. Emphasis was placed on peer-reviewed journal articles to ensure the inclusion of high-quality research contributions.

A multi-stage screening process was implemented to maintain transparency. The predefined query strings were first used to search all identified databases. Reference management software (EndNote) was used to remove duplicate records, and then the remaining articles were screened for titles and abstracts.

Figure 1
Overall literature search and screening process used



2.4. Inclusion criteria

The inclusion criteria focused on relevance and quality, covering publications from 2010 to 2024, including peer-reviewed journal articles, conference papers, and workshop proceedings. Studies on AI advancements in Industry 4.0 and 5.0, AI integration in industrial developments, technological changes, operational efficiency, and sustainability were included. Research comparing AI-driven innovations across sectors and tracing the evolution from Industry 4.0 to 5.0 was also considered.

To ensure consistency, a calibration exercise was performed by two independent reviewers on a random sample of 60 articles and applied the inclusion criteria. These were resolved in discussion, and Cohen's kappa coefficient was calculated to assess interrater reliability ($\kappa = 0.85$ = strong agreement) [37].

2.5. Exclusion criteria

Non-English publications and studies outside the 2010–2024 range were excluded, except for foundational works. Research lacking focus on AI integration, technological advancements, operational efficiency, or sustainability was omitted. Studies were excluded from evaluating AI's impact on industrial transformations or addressing its opportunities and limitations.

2.6. Literature evaluation criteria

Reliability was ensured by sourcing articles from reliable online repositories, prioritizing recent publications for the most current findings. The impartial selection process ensured a comprehensive examination that paid close attention to correctness and detail. Thus, a standardized evaluation rubric was developed to evaluate the quality of included studies. It used this rubric to evaluate factors such as methodological rigor, relevance to research questions, and contribution to the field. Articles with a score below a predefined threshold ($\leq$50%) were excluded.

3. Historical Overview of the Industrial Transformation

The progression of industrial transformation from the 18th century to today underscores a profound shift in production techniques, technological advancements, and societal development [38]—the Industrial Revolution's total collapse. With the advent of steam-powered machinery in the late 18th century, Industry 1.0 signaled a transition from labor-intensive to mechanized production [39]. This period enabled an unprecedented expansion of factories, with machines vastly improving production speed and scale compared to human labor. Key industries such as textiles, coal, iron, and chemicals flourished as production moved from homes to factories, catalyzing rapid industrialization and urbanization and fundamentally altering manufacturing and labor structures [39–41].

Building on this mechanization, Industry 2.0 was categorized by technological revolutions, beginning in the late 19th and early 20th centuries [42]. The internal combustion engine and the machine tool industry saw tremendous growth during this time, which resulted in the automobile industry's rise and a dramatic change in transportation [43]. Conveyor systems significantly enhanced capacity and efficiency, transforming industrial output. The replacement of steam power, along with the introduction of new materials like alloys, lightweight metals, and synthetic polymers, coupled with rising electricity consumption, further boosted mass production across various industries [43, 44].

Industry 3.0, the Digital Revolution, commenced in the mid-20th century and transitioned from analog to digital technologies [45–47]. The introduction of computers and the internet transformed communication and global connectivity, making digital systems essential to industrial production [46]. Automation emerged as a critical factor, enhancing precision and production speed by replacing human labor in numerous processes [47]. The increasing utilization of nuclear energy to meet rising industrial and household demands was also notable during this era [48]. This digital integration transformed industry operations, fostering more complex, data-driven environments [49].

Industry 4.0 combines big data analytics, IoT, AI, ML, DL, and improved automation, connection, and data processing. This convergence makes it simpler for machines, systems, and investors to coordinate and connect in real time [1]. It gave rise to the "smart factory," where advanced algorithms and self-governing machinery optimize production [50, 51]. The advancements of Industry 4.0 have increased productivity and efficiency, enabling greater customization of products, and yet have also introduced challenges such as supply chain disruptions and environmental sustainability concerns [12, 20]. As Industry 4.0 evolves, Industry 5.0 is emerging, emphasizing collaboration between humans and AI [24].

Like Industry 4.0's focus on full automation, Industry 5.0 prioritizes human involvement in decision-making, using AI to augment rather than replace human skills and abilities [25, 27]. The human-in-the-loop model [52] is central to this framework, where AI assists in tasks requiring creativity, common sense, and problem-solving [53]. This strategy emphasizes the necessity of continuing human supervision of automated systems to ensure that technology enhances rather than replaces human labor [26]. Industry 5.0 establishes a balanced environment where humans and AI work together to achieve optimal outcomes [27]. In the cycle of these industrial developments, the rise of AI and ML has been pivotal to the ongoing digital transformation [6]. In large language models and complex algorithms, advances in AI have driven automation and optimization across numerous industries. ML has become a core component of AI systems, enabling data-driven learning, process improvements, and autonomous decision-making [6, 14, 54]. These developments have reshaped industrial production and affected the global economy, driving innovation, improving efficiency, and contributing to sustainability efforts [3].

This history of industrial revolutions illustrates a continuous interplay between technological innovation and societal change. Each phase has introduced transformative technologies that have redefined production, labor, and economic systems. Industry 3.0 signaled the beginning of the digital age; Industry 4.0 embraced enhanced automation and networking, and Industry 1.0 and 2.0 prioritized mass manufacturing and mechanization. Industry 5.0 aims more at communal human–AI interactions, opening up new avenues for innovation while tackling issues of sustainability and the changing role of human labor in technology.

4. Role of AI in the Industrial Revolution

AI has transformed technological paradigms and operational efficiencies across various industries [55]. ML is fundamental to AI, allowing systems to derive insights from data independently and minimizing the need for explicit programming. DL, a subset of ML, including Deep Neural Networks (DNNs) and Convolutional Neural Networks (CNNs), is used to analyze large datasets and tackle complex tasks across various industrial processes (Figure 2) [56]. Furthermore, natural language processing facilitates seamless interactions between machines and human language and develops applications like chatbots and voice recognition systems [57]. These advancements have created intelligent systems capable of performing tasks that require humanlike cognition, including virtual personal assistants and autonomous vehicles [58]. Integrating AI into the industrial sector has introduced substantial benefits alongside notable challenges.

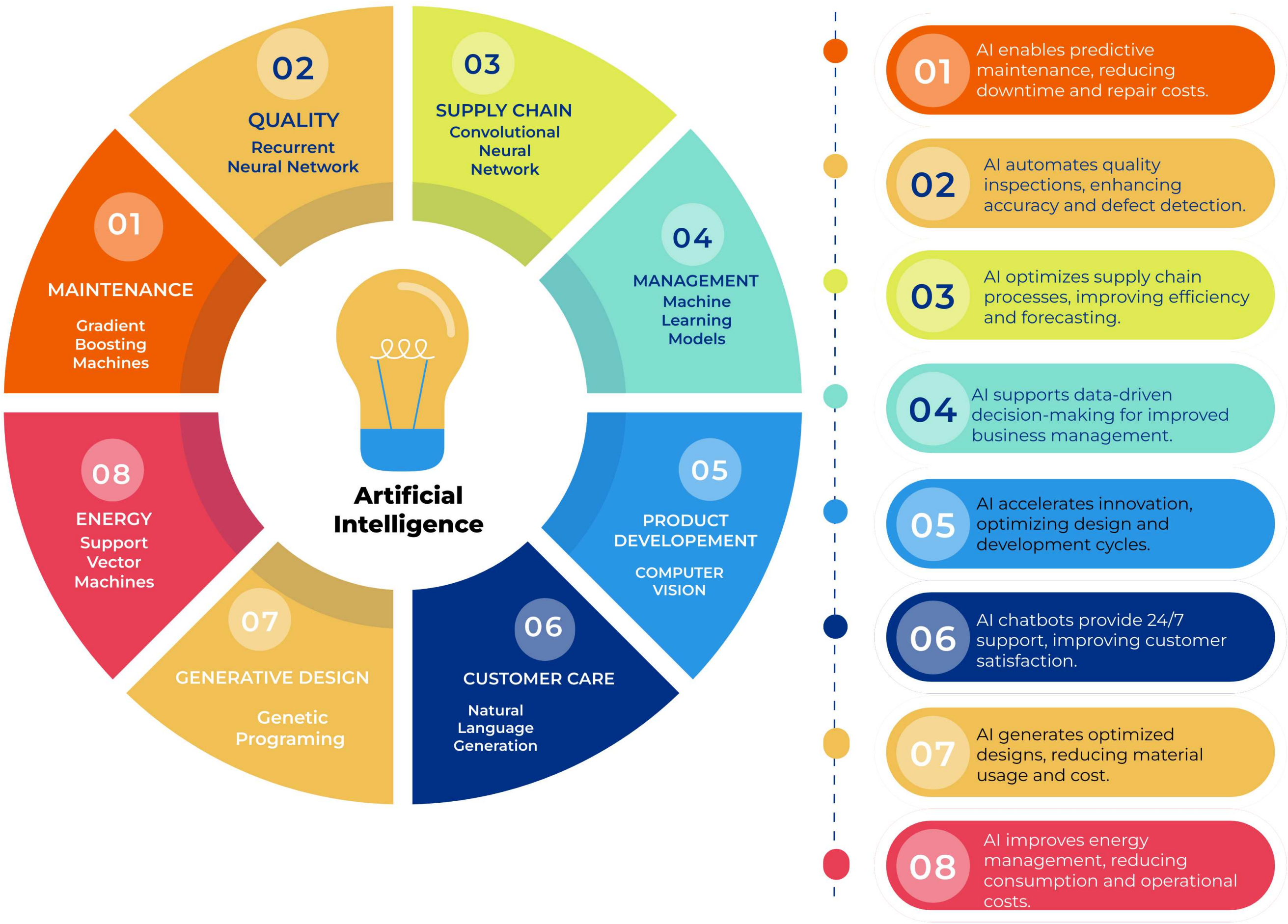
IoT and AI significantly advance intelligent manufacturing [59]. AI improves operational efficiency and lowers costs by enabling automated quality control, maintenance, and data analysis [60]. For example, AI-powered predictive analytics can anticipate equipment failures, allowing for proactive maintenance and reducing operational downtime [61]. Similarly, AI-enhanced computer vision systems conduct quality inspections during manufacturing, identifying defects that human inspectors may overlook [62]. One promising area in AI development is deep reinforcement learning (RL) [63]. Unlike traditional ML techniques that rely on historical data for predictive modeling, RL algorithms learn through iterative interactions with their environment, optimizing performance via trial and error [64]. RL has proven effective in autonomous vehicles, complementing deep learning models to enhance decision-making in complex scenarios [65]. The capacity of RL to refine processes through continuous feedback renders it particularly valuable in dynamic environments where conventional methods may fall short [66]. Emerging research avenues and technologies signify the ongoing progression of AI [67]. Explainable AI aims to effectively solve interpretability issues by making AI decision-making processes more transparent and intelligible [68]. Federated learning solves data privacy challenges by enabling collaborative model training without requiring raw data exchange [69]. RL continues to advance, providing methodologies for optimizing intricate processes [63], while transfer learning facilitates the adaptation of AI models to new tasks with limited data availability [70].

Moreover, advancements in AI for cybersecurity, collaborative robotics, and quantum computing are set to influence the future landscape of industrial AI applications [71]. As AI technologies evolve, their integration across diverse industries will catalyze further innovations and efficiencies [72]. As shown in Figure 3, implementing AI in industries demands a holistic method that tackles technological, workforce, and ethical challenges.

4.1. Advancements, challenges, and opportunities in AI applications

Integrating AI within industrial frameworks offers transformative potential but has significant challenges [3]. Numerous industries face difficulties in the integration of AI into their established structures. It requires a significant financial investment and advanced technical expertise [10]. This challenge is compounded by a shortage of skilled professionals to manage and influence AI technologies in developing states where educational and training means are scarce [60]. Additionally, concerns about privacy and security of surroundings are vital in AI adoption. As industries rely on AI-driven processes, protecting sensitive data against cyber threats is critical [73]. The frequency of cybersecurity incidents demands intelligent strategies to protect data integrity and privacy in sectors such as finance and healthcare, which manage confidential information [73]. Beyond these

Figure 2
Application of artificial intelligence at different stages of industry process



practical considerations, the ethical ramifications of AI introduce further complexity. The propensity for AI systems to, by mistake, perpetuate biases or make autonomous decisions raises questions regarding accountability and fairness [74]. Thus, ensuring transparency, interpretability, and compliance with ethical standards in AI systems is essential for fostering public trust and acceptance [20, 59, 72, 75]. Lastly, the main hurdle lies in assimilating cutting-edge technologies with existing traditional systems. The use of AI is further complicated by ethical concerns about algorithmic bias, accountability, and transparency [76].

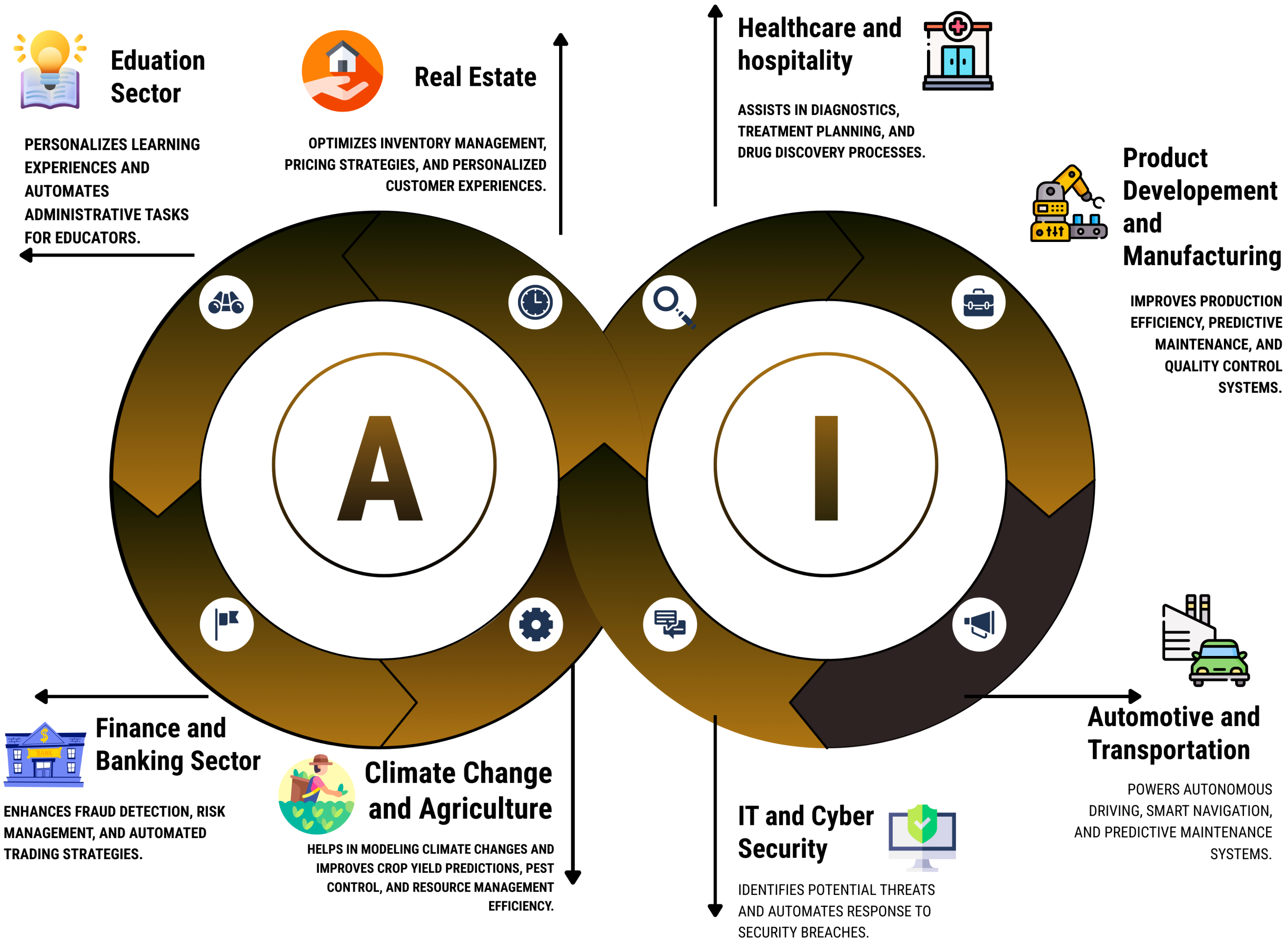
Despite these challenges, the opportunities presented by AI in both industrial revolutions are extensive [3]. AI enables personalized manufacturing, enhancing customer experiences and pushing the boundaries of traditional production methods [77]. Additionally, Industry 5.0's focus on CoBots encourages sustainability, creativity, and the development of new professions centered on AI systems' management, development, and ethical considerations [78]. As shown in Table 1, the incorporation of AI into these industrial revolutions portends a future characterized by ongoing innovation, increased efficiency, and a more human-centered approach to manufacturing.

5. Industry 4.0 Versus Industry 5.0 and Their Sustainability

Industry 4.0 and Industry 5.0 correspond to different paradigms in industrial evolution, each with unique approaches to sustainability, as shown in Table 2. Industry 4.0, instituted in 2011, focuses on automation, digitization, and efficiency through IoT, CPS, and big data analytics [79]. It emphasizes smart manufacturing, predictive maintenance, and energy-efficient systems to optimize resource use and reduce waste [80]. However, its primary focus on productivity often sidelines human-centric design and environmental sustainability, leading to criticisms of insufficient attention to workforce well-being and ecological balance [81]. While Industry 4.0 supports circular economy principles through additive manufacturing and smart supply chains, these efforts are not central to its framework [82]. Challenges such as high implementation costs, skill gaps, and cybersecurity risks further hinder its sustainability potential [83].

In contrast, Industry 5.0 builds on the technological grounds of Industry 4.0 but shifts focus toward human–machine collaboration, creativity, and sustainability [21, 24]. It prioritizes circular

Figure 3
Application of artificial intelligence in different industries



economy models, renewable energy integration, and bio-inspired materials to minimize environmental impact [84, 85]. Advanced collaborative CoBots enhance human capabilities, fostering creativity and problem-solving while reducing job displacement [78, 86]. Industry 5.0 also emphasizes resilience through adaptive systems, enabling industries to navigate global disruptions effectively [87].

By embedding sustainability at its core, Industry 5.0 directs the flaws of Industry 4.0, promoting durable, repairable, and recyclable products aligned with circular economy goals [88]. This paradigm shift underscores a holistic approach to industrial sustainability, balancing technological advancement with human well-being and environmental stewardship.

Table 1
Summary of advancements, challenges, and opportunities in integrating AI in Industry 4.0 and Industry 5.0

Artificial Intelligence	Industry 4.0	Industry 5.0
Advancements	AI-driven automation (smart factories, predictive maintenance).	Human–machine cooperation (CoBots, AI-powered creativity, and adaptable production).
	Real-time decision-making is made possible by cloud computing, IoT, AI, and big data analytics.	AI improves decision-making by utilizing IoT and Big Data to enable real-time flexibility.
	AI in autonomous systems (self-driving cars, robotics).	Personalized products and services through AI-assisted human creativity.
	AI-powered healthcare diagnostics, robotics, and advanced production systems.	Edge computing, blockchain, and 6G for faster, more secure data processing.
	Data privacy, scalability, and computational power requirements.	Ethical issues in human–machine collaboration (privacy, security, bias).

(*Continued*)

Table 1
(*Continued*)

Artificial Intelligence	Industry 4.0	Industry 5.0
Challenges	Difficulty in explainability and interpretability of complex AI models.	AI reliability and the risk of overdependence on machines.
	Legal and regulatory frameworks are lagging behind rapid AI innovation.	Need for trust-building in AI-driven human collaboration and ethical guidelines.
Opportunities	Enhanced efficiency across industries like healthcare, finance, and manufacturing.	Co-creation of value with human creativity and AI capabilities.
	AI in sustainable development (energy efficiency, smart cities).	AI fosters human–AI collaboration to solve complex, non-routine tasks.
	AI's role in addressing global issues, including healthcare and climate change.	Emphasis on permanent learning and development of human skills for Industry 5.0.

Table 2
Comparison of sustainability of Industry 4.0 and Industry 5.0

Aspect	Industry 4.0	Industry 5.0
Core Focus	Focuses on automation, digitization, and efficiency through technologies like IoT, CPS, and big data analytics [79].	It emphasizes human–machine collaboration, creativity, and sustainability, building on Industry 4.0 technologies [21, 24].
Sustainability Goals	It aims to optimize resource use and reduce waste through predictive maintenance, smart manufacturing, and energy-efficient systems [80].	Prioritizes circular economy models, renewable energy integration, and bio-inspired materials to minimize environmental impact [84, 85].
Human-Centricity	Limited focus on human-centric design; automation often displaces human roles [81].	CoBots enhance human creativity and problem-solving while reducing job displacement [78, 86].
Circular Economy	Supports circular economy principles through additive manufacturing and smart supply chains but is not a central focus [82].	Centralizes circular economy practices, emphasizing material reuse, recycling, and sustainable energy management [84].
Energy Efficiency	Improves energy efficiency through IoT-enabled systems and predictive maintenance but prioritizes productivity over sustainability [80].	Actively integrates renewable energy sources and energy-efficient systems to reduce carbon footprints [89].
Resilience	Limited focus on resilience; systems are optimized for efficiency but may struggle with global disruptions [59].	Adaptive systems and flexible production processes build resilience, ensuring operational integrity during crises [87].
Challenges	High implementation costs, skill gaps, cybersecurity risks, and inconsistent regulatory frameworks hinder sustainability efforts [83].	Challenges include integrating human–machine collaboration seamlessly and addressing workforce skill shortages for new roles [78, 86].
Technological Tools	Relies on IoT, CPS, big data analytics, and additive manufacturing to enhance efficiency and reduce waste [25].	Utilizes CoBots, bio-inspired materials, and adaptive systems to promote sustainability and human-centric production [25].
Business Models	Supports product-as-a-service (PaaS) models, enabling better product lifecycle management and resource efficiency [16, 59].	Encourages sustainable business models that prioritize durability, repairability, and recyclability, aligning with circular economy goals [27].

One of the critical technological innovations aiding the sustainability efforts of Industry 5.0 is using bio-inspired materials and intelligent technologies [90]. These materials, embedded with sensors and designed for recyclability, enable real-time resource usage and energy consumption monitoring during production processes. By providing detailed insights into the environmental impact of manufacturing activities, industries can optimize their operations for greater sustainability [25]. Additionally, integrating these smart materials aligns with Industry 5.0's emphasis on ecological balance, encouraging industries to reduce their carbon footprints while maintaining productivity [91].

Another significant advancement under Industry 5.0 is the focus on resilience in the face of global disruptions, such as environmental crises or supply chain breakdowns [92]. Resilience is built into industrial processes through greater flexibility and the ability to respond swiftly to unforeseen challenges [93]. By incorporating adaptive systems that can adjust to changing conditions, Industry 5.0 ensures that production systems can maintain their operational integrity even in times of crisis. This focus on resilience strengthens the industrial sector's capacity to navigate disruptions and enhances its ability to support critical infrastructure and services in the face of global challenges [94, 95].

Despite the many advantages of Industry 5.0, significant challenges must be addressed for successful implementation (Figure 4). One primary challenge is the complexity of integrating human and machine capabilities; as industries shift from

Figure 4
Advantages and disadvantages of Industry 5.0 advancements

Table 3
Comparative summary of Industry 4.0 and Industry 5.0

Aspect	Industry 4.0	Industry 5.0
Progress	Launched in 2011, it focuses on IoT, CPS, and automation. Smart factories, products, and supply chains developed.	Builds on Industry 4.0; emphasizes human–machine collaboration (CoBots), creativity, and circular economy models.
Limitations	Limited human-centric design and environmental focus. High costs, skill gaps, and system complexity.	Challenges in human–machine integration, skill shortages, and potential inefficiencies in flexible production.
Opportunities	Vertical/horizontal integration, predictive maintenance, and smart manufacturing enable customization and efficiency.	Promotes human creativity, adaptive systems, and resilience—shifts from PaaS models to value-added tasks.
Sustainability	Overlooks environmental concerns; efficiency prioritized over sustainability—limited sustainable practices.	Focuses on circular economy, waste reduction, recycling, and renewable energy integration. Enhances energy-efficient systems.

automation to collaboration, advanced cognitive systems are essential for anticipating and responding to human actions. This transition requires substantial AI advancements to enhance their understanding and adaptation to human inputs and environmental conditions [89, 96]. Another significant challenge pertains to the workforce. While Industry 5.0 presents opportunities for increased productivity and creativity, it raises concerns about skill shortages. As technology evolves rapidly, workers must continually update their skills to remain relevant in an increasingly complex industrial environment [97]. Workers and industries face difficulties due to the requirement for continuous upskilling, as educational and training systems must change to satisfy the needs of this new era [77, 96]. The flexibility of production processes under Industry 5.0, while beneficial in many respects, may also lead to inefficiencies and overproduction. Industries must carefully balance the advantages of flexible, responsive systems with the risk of producing more than is necessary, a problem that could undermine the sustainability efforts central to Industry 5.0 [98, 99].

Table 3 compares Industry 4.0 and 5.0, emphasizing advancements, constraints, prospects, and sustainability. Industry 4.0 emphasizes automation and digitization, but it also comes with exorbitant costs and disregard for the environment. With its adaptive systems and circular economy models, Industry 5.0 goes beyond its predecessor and prioritizes sustainability, human–machine collaboration, and creativity.

6. Conclusion

Focusing on sustainability, human-centricity, and resilience, this study examines how AI transforms the shift from Industry 4.0 to Industry 5.0. Industry 4.0 has greatly increased industrial production and efficiency because of automation, the Internet of

Things, and big data analytics. However, its emphasis on technology development frequently ignores human well-being and environmental sustainability, which led to the rise of Industry 5.0. By combining human creativity with cutting-edge AI technologies, encouraging cooperative human–machine ecosystems, and giving circular economy principles priority, Industry 5.0 transforms industrial paradigms. By encouraging sustainable practices, cutting waste, and improving energy efficiency using bio-inspired materials and renewable energy, this change overcomes the drawbacks of Industry 4.0. AI offers operational resilience in the face of global shocks by enabling real-time decision-making, adaptive systems, and predictive maintenance.

This study establishes that AI has a transformative potential to lead us to Industry 5.0, which needs to be a technological development that is in accordance with social and environmental requirements. One must address the systemic challenges of the implementation of Industry 5.0, such as ethical governance, worker upskilling, and equitable AI access. These insights aid academia in identifying the gaps in the literature in the area of AI's practical applications in industrial contexts. These policies also allow policymakers and leaders in the industry to identify the best practices for developing inclusive and sustainable policies. To advance global benefits, future work could focus on AI scalability in low- and middle-income countries to provide a way for the AI business model can be supported as the economies grow away from industrial to high-income economies.

Despite these advancements, the integration of AI into industrial frameworks is hampered by issues like worker skill shortfalls, cybersecurity threats, and data privacy concerns.

This study is based on existing literature, which does not adequately represent implementation issues in the actual world. Furthermore, to stay relevant, AI technologies must be updated frequently due to their rapid evolution.

Future studies should concentrate on creating strong ethical frameworks for the application of AI and solving the lack of skilled workers through focused training initiatives. Policymakers and business executives must work together to create uniform rules that guarantee inclusive and sustainable industrial development.

Ethical Statement

This study does not contain any studies with human or animal subjects performed by any of the authors.

Conflicts of Interest

The authors declare that they have no conflicts of interest to this work.

Data Availability Statement

Data sharing is not applicable to this article as no new data were created or analyzed in this study.

Author Contribution Statement

Muhammad Waqas: Conceptualization, Methodology, Software, Validation, Writing – review & editing, Visualization, Supervision, Project administration, Funding acquisition. **Adila Naseem:** Formal analysis, Investigation, Resources, Data curation, Writing – original draft.

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Appendix

AI	Artificial intelligence
CPS	Cyber-physical systems
IoT	Internet of Things
NLP	Natural language processing
ML	Machine learning
DL	Deep learning
USA	United States of America
CoBots	Collaborative robots
IoE	Internet of Everything
PLCs	Programmable logic controllers
RNNs	Recurrent Neural Networks
CNNs	Convolutional Neural Networks
DNNs	Deep Neural Networks
SVM	Support Vector Machine
GB	Gradient boosting
XAI	Explainable AI
RL	Reinforcement learning
SCADA	Supervisory Control and Data Acquisition
MES	Manufacturing Execution Systems
AR	Augmented reality
VR	Virtual reality
CE	Circular economy
PaaS	Product-as-a-service