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Towards a Human-Centric Industry 5.0 Enabled by the Convergence of Artificial Intelligence, Internet of Things, and Blockchain

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A R T I C L E I N F O

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A B S T R A C T

Industry 5.0 envisions a transformative industrial paradigm that goes beyond mere automation, emphasizing human-centricity, sustainability, and resilience. The convergence of Artificial Intelligence (AI), Internet of Things (IoT), and Blockchain forms a powerful technological foundation to achieve this vision, enabling intelligent, interconnected, and secure industrial operations. In this paper, we propose a comprehensive conceptual architecture for integrating these three technologies, facilitating seamless interaction between humans, machines, and decentralized systems. We conduct a systematic review of the existing literature, examining design patterns, practical use cases, adoption barriers, and key challenges. Additionally, we analyze real-world industrial implementations to extract the insights, lessons, and best practices. Our findings highlight critical technical, governance, and scalability issues, including interoperability, data privacy, regulatory compliance, and infrastructure limitations. To address these challenges, we present a multiphase strategic roadmap for the deployment and adoption of AI–IoT–Blockchain convergence in human-centric industrial environments. Finally, we discuss emerging research directions, such as post-quantum blockchains, federated learning, autonomous economic agents, and resilient cyber-physical systems. Our analysis indicates that while the convergence of these technologies holds transformative potential for Industry 5.0, practical and scalable adoption requires careful system design, iterative prototyping, and robust policy frameworks. This study provides a structured reference for researchers, practitioners, and policymakers seeking to advance human-centric, sustainable, and technologically empowered industrial systems

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1. Introduction

Industry 5.0 represents the next evolutionary step in industrial transformation, moving beyond the core objectives of Industry 4.0, which primarily focused on automation, connectivity, and efficiency. In contrast, Industry 5.0 emphasizes human-centricity, sustainability, collaboration, and system resilience, positioning humans at the center of industrial processes (Sandner et al., 2020). Operationalizing this vision requires the integration of intelligent Internet of Things (IoT) devices with advanced decision-making capabilities powered by Artificial Intelligence (AI), all supported by a trustworthy and decentralized infrastructure enabled by Blockchain (Aravinth, 2025; Atlam et al., 2020).

IoT devices generate vast streams of real-time data from machines, environments, and human interactions. However, these data streams are often siloed, vulnerable, or untrusted unless properly secured and managed. Blockchain addresses these limitations by providing an immutable, distributed ledger, enabling smart contracts, secure data provenance, and decentralized trust (Leng et al., 2022; Rejeb et al., 2025). Simultaneously, AI techniques, ranging from edge-based machine learning to federated learning, extract actionable insights from IoT data, enabling predictive maintenance, real-time anomaly detection, and adaptive decision-making. When combined, these technologies facilitate autonomous economic agents capable of transacting, negotiating, and self-governing through blockchain-mediated contracts while leveraging AI for intelligent behavior.

Although several studies have theorized this paradigm and highlighted its potential for Industry 5.0 systems (Aounzou et al., 2025; Azad et al., 2025; Choi et al., 2024; Rehman et al., 2022; Taherdoost et al., 2022;), the practical realization of AI–IoT–Blockchain convergence in industrial environments remains challenging. IoT devices are often resource-constrained in terms of computation, energy, and memory, blockchain networks may face scalability and latency issues, and AI models frequently lack transparency and governance mechanisms. Moreover, deployment requires robust policy frameworks addressing data ownership, identity management, accountability, and legal compliance.

Despite the growing literature, a clear research gap exists: While numerous systematic reviews and conceptual studies have discussed individual aspects of AI, IoT, and Blockchain in Industry 5.0, there is limited research that simultaneously integrates these three technologies into a structured, actionable framework while linking it to human-centric industrial objectives. To address this gap and guide both researchers and practitioners, this paper explicitly defines its research focus through the following research questions:

RQ1: How can AI, IoT, and Blockchain be seamlessly integrated into human-centric industrial architectures?

RQ2: What are the major technical, governance, and scalability challenges in implementing this tri-technology convergence?

RQ3: Which real-world examples and near-future deployments can provide actionable insights and best practices for Industry 5.0 systems?

RQ4: What emerging research directions and technologies can facilitate the development of next-generation human-centric industrial systems?

By addressing these questions, this study moves beyond existing systematic reviews and conceptual analyses, offering a comprehensive, multi-layered conceptual architecture, a critical evaluation of existing literature, practical deployment examples, a phased roadmap for adoption, and a forward-looking research agenda aligned with the goals of Industry 5.0. This structured approach not only clarifies the scope and contributions of the study but also provides a foundation for future research and industrial implementation.

2. Methodology of Systematic Review (PRISMA-Based)

2.1. Review Design

This study was conducted as a systematic literature review following the PRISMA 2020 guidelines to ensure transparency, replicability, and methodological rigor. The primary objective was to identify, analyze, and synthesize scientific studies examining the convergence of Artificial Intelligence (AI), the Internet of Things (IoT), and Blockchain in the context of Industry 5.0. The review was explicitly aligned with the research questions presented in the introduction to address how AI, IoT, and Blockchain can be seamlessly integrated into human-centric industrial systems (RQ1), major technical, governance, and scalability challenges (RQ2), real-world examples and best practices that can inform practical deployment (RQ3) and emerging research directions for future Industry 5.0 systems (RQ4).

2.2. Data Sources and Search Strategy

A comprehensive search was conducted across four major scientific databases: Scopus, Web of Science, IEEE Xplore, and ScienceDirect, covering publications from January 2015 to January 2025. A structured combination of keywords and Boolean operators was used, including "Industry 5.0," "AI and IoT," "AI and Blockchain," "IoT and Blockchain," "technology convergence," "human-centric industry," and "cyber-physical systems." Only peer-reviewed journal articles and conference papers published in English were included to ensure scientific quality and accessibility.

2.3. Inclusion and Exclusion Criteria

To maintain relevance and methodological rigor, inclusion criteria required direct relevance to Industry 5.0 or human-centric industrial paradigms, the coverage of at least two of the three target technologies (AI, IoT, Blockchain), the availability of full-text articles, peer-reviewed publication status, and publication in English. Exclusion criteria removed studies that focused solely on Industry 4.0, purely conceptual papers lacking technological integration, duplicate publications, and studies not addressing technological convergence.

2.4. Study Selection Process (PRISMA Flow)

The study selection followed the PRISMA four-phase process (Figure 1). In the Identification phase, 265 records were retrieved from the four databases. After removing 61 duplicates, 204 records remained for title and abstract screening. This screening excluded 134 articles, leaving 70 for full-text assessment. Following full-text review, 45 studies were excluded due to insufficient relevance or the lack of multi-technology integration. Ultimately, 25 studies were included in the final synthesis. The PRISMA flow diagram (Figure 1) provides a transparent overview of the selection process and ensures replicability.

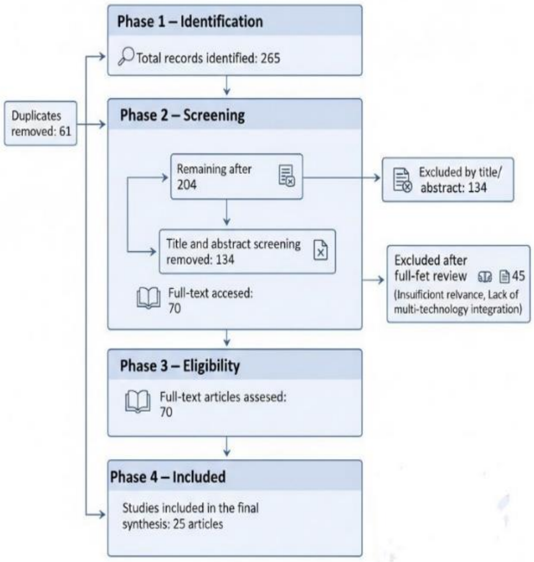

Figure 1

PRISMA Flow Diagram of the Methodology

2.5. The Quality Assessment of Included Studies

To enhance methodological robustness, a descriptive quality assessment was conducted for the 25 included studies. The evaluation considered transparency, methodological rigor, clarity of objectives, technological integration, and alignment with Industry 5.0 principles. Studies were categorized as high, medium, or low in methodological strength, allowing readers to assess the reliability of findings and highlighting areas needing further empirical validation.

2.6. Data Extraction and Analysis

For each of the 25 included studies, key information was systematically extracted, including the application domain, the type and depth of AI–IoT–Blockchain convergence, alignment with Industry 5.0 principles, such as human-centricity, resilience, and sustainability, and the challenges, benefits, models, or frameworks proposed. A qualitative content analysis approach was employed to synthesize major themes, identify knowledge gaps, and highlight opportunities for future research. This approach provides a structured and actionable understanding of the current state of AI–IoT–Blockchain integration in human-centric industrial contexts.

2.7. Research Limitations

While this systematic review provides a comprehensive overview, several limitations should be noted. The use of only four major databases may have limited coverage, and restricting inclusion to English-language publications may have excluded relevant studies in other languages. The timeframe (2015–2025) may have omitted earlier foundational studies. Borderline studies may have been inadvertently excluded during screening. Industry 5.0 remains an emerging field with limited academic maturity, and the heterogeneity of methodologies and application domains across studies further complicates synthesis.

Additionally, the qualitative synthesis introduces potential interpretive bias, and conducting a meta-analysis was not feasible due to methodological and conceptual diversity.

By linking the review methodology to the research questions (RQ1–RQ4) and integrating a detailed PRISMA-based selection process, quality assessment, and data extraction, this study provides a robust and transparent foundation for both theoretical and practical insights into AI–IoT–Blockchain convergence for Industry 5.0.

3. Conceptual Architecture

To guide the design, development, and implementation of converged AI–IoT–Blockchain systems for Industry 5.0, we propose a six-layer conceptual architecture (Figure 2) that integrates sensing, edge processing, trust, intelligence, collaborative learning, governance, and human-centric oversight. This architecture is designed to ensure security, resilience, intelligence, autonomy, and transparency, while enabling human operators to maintain strategic supervision over industrial operations. Each layer has a specific role and contributes to the holistic functioning of a human-centric Industry 5.0 system.

1. Sensing Layer (IoT)

The sensing layer forms the foundation of the architecture. It comprises IoT devices, sensors, actuators, and edge devices deployed across industrial environments to continuously collect real-time operational data. This data includes machine vibration, temperature, pressure, energy consumption, environmental conditions, and operational usage metrics. The sensing layer ensures comprehensive visibility into industrial processes, providing the raw inputs required for advanced analytics and decision-making in higher layers. To maintain data reliability and accuracy, this layer incorporates redundancy, sensor calibration, error detection mechanisms, and adaptive sensing strategies. These features ensure that the collected data accurately reflects system states, enabling downstream AI models and blockchain-based trust mechanisms to function effectively.

2. Edge and Preprocessing Layer

The edge and preprocessing layer perform initial data processing close to the data source, reducing latency, communication costs, and bandwidth usage. Edge nodes are responsible for data filtering, aggregation, normalization, compression, and preliminary anomaly detection, preparing the data for higher-level intelligence processing. This layer ensures that only relevant, high-quality data is transmitted to AI and blockchain layers, minimizing unnecessary load on the network and central servers. Additionally, local feature extraction, encoding, and preliminary analytics are performed at the edge, allowing near-real-time operational insights and enabling rapid automated responses to critical events. Security measures, including local encryption, access control, and anomaly detection, are also implemented at this layer to protect data integrity from the outset.

3. Trust Layer (Blockchain)

The trust layer provides a secure, immutable, and decentralized ledger for recording critical IoT and operational transactions. Depending on requirements, this layer can be implemented as permissioned, public, or hybrid blockchain. It supports smart contracts, which automate operational rules, enforce compliance, and enable verifiable, auditable interactions among devices and stakeholders. By ensuring data integrity, provenance, and traceability, the trust layer mitigates the risks of tampering, fraud, or unauthorized access. Consensus mechanisms allow multiple stakeholders to maintain a shared, reliable system state, which is particularly crucial for multi-organization environments, such as supply chains, collaborative manufacturing, and distributed industrial networks. Therefore, the trust layer forms the backbone for secure, accountable, and transparent operations.

4. Intelligence Layer (AI)

The intelligence layer transforms preprocessed IoT data into actionable insights using AI and machine learning models deployed on edge, fog, or cloud platforms. Key functionalities include predictive maintenance, real-time anomaly detection, process optimization, adaptive decision-making, and operational forecasting. AI models may range from supervised and unsupervised learning to deep learning and reinforcement learning, depending on application requirements. This layer enables both autonomous operational decisions for routine tasks and decision support for human operators in complex scenarios. Integration with the trust layer ensures that all AI outputs are verifiable, auditable, and derived from high-quality, tamper-proof data, which is essential for regulatory compliance and operational accountability.

5. Learning and Collaboration Layer

The learning and collaboration layer supports federated learning, blockchain-mediated collaborative learning, and multi-agent model sharing. Decentralized learning allows AI models to be trained across multiple devices or organizations without sharing raw data, thereby preserving data privacy and compliance with regulations. Collaborative learning enhances model robustness, generalizability, and accuracy by aggregating knowledge from heterogeneous sources. Smart contracts manage training schedules, model aggregation, updates, and incentive mechanisms, ensuring transparent, fair, and auditable collaboration. This layer is critical for industrial ecosystems where multiple stakeholders such as suppliers, manufacturers, and service providers need to collaboratively optimize processes while safeguarding proprietary information.

6. Governance and Agent Layer

The governance and agent layer integrates autonomous agents, smart contracts, and human oversight. Industrial devices and machines act as autonomous or semi-autonomous agents capable of negotiating, transacting, and coordinating actions by smart contracts. Governance policies regulate identity management, permissions, accountability, compliance with ethical and safety standards, as well as operational auditing. Human operators maintain strategic oversight, ensuring that autonomous actions align with organizational objectives, safety requirements, and sustainability goals. This layer ensures a balance between decentralized autonomy and human control, enabling resilient and trustworthy industrial operations while preserving human-centric decision-making.

Integration and Alignment with Industry 5.0 Principles

The proposed architecture aligns with the core principles of Industry 5.0: human-centricity, resilience, sustainability, intelligence, and collaboration. By combining sensing, edge processing, blockchain-based trust, AI intelligence, collaborative learning, and governance, the architecture provides a comprehensive framework for designing resilient, secure, intelligent, and human-centric industrial systems. Each layer supports the others, creating a cohesive ecosystem capable of autonomous yet transparent operations, secure data management, collaborative innovation, and real-time intelligence.

As illustrated in Figure 2, the converged six-layer AI–IoT–Blockchain architecture serves as a blueprint for implementing Industry 5.0 systems, guiding researchers, engineers, and industrial practitioners in developing resilient, secure, intelligent, and human-centric industrial environments. It provides clear pathways for integrating emerging technologies while maintaining trust, oversight, and alignment with human-centric industrial goals.

Figure2

A Converged AI-IoT-Blockchain Architecture for Trust, intelligence, and Autonomy in Industry 5.0

4. Literature Review

4.1. Key Research Contributions

Over the past decade, significant research has explored the convergence of Artificial Intelligence (AI), the Internet of Things (IoT), and Blockchain, particularly within the context of Industry 5.0. Atlam et al. (2020) provided a foundational review demonstrating how blockchain integration with IoT can enhance trust and data security, while AI further addresses scalability challenges and facilitates intelligent decision-making in decentralized industrial environments. Building upon this, Leng et al. (2022) proposed a detailed architecture for secure blockchain middleware in Industrial IoT (IIoT), outlining enablers and challenges specific to Industry 5.0 use cases, thereby providing practical guidance for system designers.

Rejeb et al. (2025) employed co-word and topic modeling analyses to highlight the interplay between blockchain, AI, IoT, and circular economy principles, revealing research gaps and emerging trends in the field. Choi and Kim (2024) further examined the technological convergence of AI and blockchain, identifying critical bottlenecks, such as data reliability and cross-platform compatibility, and proposed a structured research framework to overcome these limitations. Practical applications have also been a focus of recent studies. Taherdoost (2022) critically reviewed AI–blockchain deployments across multiple domains, emphasizing integration risks and obstacles to large-scale implementation. Similarly, Aounzou et al. (2025) conducted a systematic review of blockchain, IoT, and machine learning applications, mapping key opportunities and real-world challenges for industrial systems.

Innovative solutions, such as quantum-resistant blockchain protocols, have been proposed by Azad et al. (2025) to enhance IoT consensus mechanisms, ensuring resilience against potential attacks. Rehman et al. (2022) demonstrated a secure Healthcare 5.0 system that couples federated learning with blockchain to preserve privacy in IoT-enabled medical networks, highlighting the importance of decentralized intelligence and secure data handling. Furthermore, Jahid et al. (2023) explored the convergence of blockchain, IoT, and 6G networks, emphasizing how next-generation connectivity can support scalable, intelligent, and decentralized industrial systems. Conoscenti et al. (2016) systematically reviewed blockchain applications for IoT, providing a taxonomy and identifying architectural patterns that continue to inform contemporary system design.

Recent contributions extend the scope to business and societal applications of AI–IoT–Blockchain convergence. For example, Pezeshgi et al. (2025) investigated how AI-driven mechanisms influence impulsive purchasing behavior, highlighting ethical and decision-making dilemmas. Karizaki et al. (2024) explored automated formative assessment in AI-based education, emphasizing AI's role in providing intelligent feedback and optimizing learning processes. Rivandi (2026) analyzed the global adoption levels of FinTech solutions, revealing technology integration patterns relevant for decentralized industrial systems. Bagherabad et al. (2026) examined machine learning applications for analyzing factors affecting business economics, underscoring AI's utility in operational decision-making. Nikzat (2025) reviewed the AI revolution and its strategic competitive advantage in business and management, connecting insights from organizational intelligence to Industry 5.0 adoption. Nasiri et al. (2026) investigated cybersecurity determinants across individual, social, and organizational levels, demonstrating the importance of secure frameworks in integrated AI–IoT–Blockchain systems. Heidari et al. (2024) proposed standardized regulations for blockchain smart contracts using Delphi and SWARA analyses, addressing governance challenges. Bevilacqua et al. (2025) highlighted multidisciplinary planning for urban ecosystems, emphasizing the role of IoT, AI, and Blockchain in sustainable and resilient city infrastructures.

Taken together, these studies collectively demonstrate that while conceptual foundations and technical prototypes for AI–IoT–Blockchain convergence are well-established, practical deployment in Industry 5.0 remains constrained by challenges such as integration complexity, scalability, governance, and secure collaborative learning. Moreover, gaps in quantum-resistant solutions, cross-platform interoperability, and real-world implementations highlight opportunities for future research, underscoring the critical need for frameworks that bridge theory and practice in designing human-centric, intelligent, and resilient industrial systems. This expanded literature review highlights not only technical contributions but also ethical, regulatory, and business-oriented perspectives, providing a comprehensive understanding of the current state and emerging trends in AI–IoT–Blockchain research.

4.2. The Comparison of Selected studies

To provide a structured overview of the existing research on the convergence of Artificial Intelligence (AI), Internet of Things (IoT), and Blockchain within the context of Industry 5.0, a comparative analysis of selected key studies is presented in Table 1. This synthesis highlights the technologies employed, primary focus or use cases, key contributions, and the identified limitations of each study. The table represents seminal works previously discussed in the literature review (Aounzou et al., 2025; Atlam et al., 2020; Azad et al., 2025; Bagherabad et al., 2026; Bevilacqua et al., 2025; Choi et al., 2024; Conoscenti et al., 2016; Heidari et al., 2024; Jahid et al., 2023; Karizaki et al., 2024; Leng et al., 2022; Nasiri et al., 2026; Nikzat, 2025; Pezeshgi et al., 2025; Rehman et al., 2022; Rejeb et al., 2025; Rivandi, 2026; Taherdoost, 2022) encompassing broader domains, such as consumer behavior, educational AI applications, FinTech, business analytics, cybersecurity, regulatory frameworks, and urban ecosystem planning. This comprehensive comparative review serves as a foundation to identify knowledge gaps, practical deployment challenges, and potential directions for future research.

Table1

Comparative Review of Selected Studies

Ref	Technologies	Focus / Use Case	Key Achievements	Limitations
Atlam et al., 2020	Blockchain + IoT + AI	IoT architectures and trust	Offers a structured survey and identifies future directions	Limited empirical evaluation of combined systems
Leng et al., 2022	Blockchain + IIoT	Middleware for IIoT	Proposes a secure middleware architecture tailored to Industry 5.0	Focused more on blockchain than AI or learning
Rejeb et al., 2025	Blockchain + IoT + AI	Bibliometric / thematic analysis	Reveals trends in sustainability and human-machine collaboration	Little focus on systems implementation
Choi et al., 2024	Blockchain + AI	Convergence challenges	Thorough analysis of technical issues such as scalability and data integrity	Does not deeply address IoT resource constraints
Taherdoost, 2022	Blockchain + AI	Application review	Broad coverage of use cases and risks	High-level; lacks deployment best practices
Aounzou et al., 2025	Blockchain + IoT + ML	Systematic review	Highlights ML-based solutions and integration barriers	Limited focus on runtime performance
Azad et al., 2025	Blockchain (quantum) + IoT	Voting consensus	Proposes quantum-resistant consensus for IoT	Experimental / simulated, not yet deployed at scale
Rehman et al., 2022	Blockchain + Federated Learning + IoT	Healthcare systems	Ensures privacy and trust in distributed medical IoT	Complexity in real-world regulatory compliance
Jahid et al., 2023	Blockchain + IoT + 6G	Network convergence	Vision of future 6G-enabled decentralized systems	6G is still speculative in many regions
Conoscenti et al., 2016	Blockchain + IoT	Taxonomy and applications	Defines architectural patterns and use cases	Does not cover AI integration deeply
Pezeshgi et al., 2025	AI + Behavioral Analytics	Consumer behavior analysis	Demonstrates AI-driven insights for decision-making and moral dilemmas	Focused on retail domain; limited industrial applicability
Karizaki et al., 2024	AI + Educational IoT	Automated formative assessment	Provides structured framework for intelligent feedback and adaptive learning	Limited focus on industrial IoT applications
Rivandi, 2026	FinTech + AI	Adoption and integration analysis	Evaluates adoption patterns and technology integration globally	Not directly applied to Industry 5.0 systems
Bagherabad et al., 2026	AI + ML	Business economics analytics	Demonstrates ML-based decision support for operational optimization	Focused on economic models rather than technical system design

Nikzat, 2025	AI + Strategic Management	Competitive advantage	Reviews AI revolution and strategic advantages in organizations	Limited coverage of IoT and blockchain convergence
Nasiri et al., 2026	Cybersecurity + IoT + AI	Organizational and social determinants	Highlights security considerations and risk mitigation strategies	Mainly focused on cybersecurity, less on integrated deployment
Heidari et al., 2024	Blockchain + Smart Contracts	Regulatory standardization	Proposes standardized frameworks and governance mechanisms	Primarily regulatory focus, rather than technical implementation
Bevilacqua et al., 2025	AI + IoT + Blockchain	Urban ecosystem planning	Multidisciplinary approach for resilient and sustainable urban systems	Focused on city planning; limited industrial system deployment

Table 1 provides a comprehensive comparative review of key studies in the AI–IoT–Blockchain convergence domain, illustrating technological trends, practical applications, and prevailing limitations. It highlights that while significant progress has been made in conceptual frameworks, middleware architectures, and prototype deployments, practical adoption in Industry 5.0 remains constrained by factors such as integration complexity, scalability, governance, cybersecurity, and cross-domain interoperability. This review expands the scope to cover ethical, business, educational, regulatory, and urban ecosystem considerations, providing a holistic perspective that can guide future research and practical implementations toward resilient, human-centric, and intelligent industrial systems.

5. Real-World Deployment Examples

Recent real-world deployments illustrate the practical potential of converged AI–IoT–Blockchain systems in Industry 5.0, highlighting both technical feasibility and operational benefits. Azad et al. (2025) implemented a quantum-resistant blockchain voting protocol within a simulation environment for IoT devices, demonstrating a viable approach toward secure post-quantum consensus in industrial networks. This study underscores the importance of integrating quantum-safe mechanisms to protect decentralized industrial systems against emerging cyber threats and potential post-quantum vulnerabilities.

In the Healthcare 5.0 domain, Rehman et al. (2022) developed a privacy-preserving health monitoring system by combining IoT medical sensors, federated learning, and blockchain technologies. Their deployment exemplifies how decentralized intelligence and secure data management can be effectively implemented in sensitive environments, ensuring both patient privacy and real-time monitoring. Complementing these efforts, Nasiri et al. (2026) highlighted the interplay of individual, social, and organizational determinants in cybersecurity implementation, emphasizing that technical deployment must be paired with organizational policies and awareness to maintain resilient and secure human-centric IoT networks.

Furthermore, Leng et al. (2022) proposed a middleware architecture suitable for industrial deployments that require secure and decentralized Industrial IoT (IIoT). This architecture facilitates predictive maintenance, real-time coordination among heterogeneous devices, and seamless integration of AI analytics and blockchain-based trust mechanisms, illustrating the operational applicability of AI–IoT–Blockchain convergence in complex industrial environments. Nikzat (2025) also stressed the strategic competitive advantage achieved when AI-driven decision-making is effectively integrated with IoT and blockchain in industrial contexts, reinforcing the importance of aligning technology adoption with business objectives.

In addition, recent studies in AI-enhanced business and decision analytics provide complementary insights into deployment strategies. Bagherabad et al. (2026) demonstrated how machine learning can be applied to analyze multifactorial impacts on business economics, which is directly relevant for real-time optimization of industrial IoT processes. Rivandi (2026) explored global adoption patterns of FinTech and Blockchain-based systems, highlighting that practical deployment requires the consideration of regulatory, cultural, and economic factors in different regions. Finally, Karizaki et al. (2024) emphasized the role of automated assessment tools in optimizing system training and knowledge transfer, which is crucial for scaling AI–IoT–Blockchain solutions across human-centric industrial operations. Pezeshgi et al. (2025) additionally raised ethical considerations, such as the potential for AI-driven impulsive decisions in automated systems, underscoring the necessity of governance frameworks that ensure accountability in autonomous operations.

Collectively, these deployments and analyses demonstrate that the successful realization of Industry 5.0 systems depends on carefully designed, secure, and human-centric implementations that integrate emerging technologies into operational environments, while simultaneously addressing governance, ethical, and strategic considerations.

6. Critical Analysis

The integration of Artificial Intelligence (AI), the Internet of Things (IoT), and Blockchain in Industry 5.0, aimed at creating human-centric, transparent, and autonomous systems, faces a complex array of technical, organizational, and regulatory challenges. One of the foremost limitations is scalability and performance, as many blockchain consensus mechanisms require intensive computations that exceed the capabilities of typical IoT devices (Aounzou et al., 2025; Leng et al., 2022). Although middleware solutions can partially mitigate these constraints, further optimization is essential to ensure efficient operation at large scales. Resource limitations, including processing power, memory, and energy, pose another significant barrier, making the design of AI–blockchain integrated systems particularly challenging under constrained conditions (Choi et al., 2024; Khan et al., 2025). This issue becomes critical when machine learning algorithms are applied for real-time decision-making or processing large-scale data, as energy consumption and computational load can quickly deplete IoT resources (Bagherabad et al., 2026; Nikzat, 2025).

From a governance and autonomy perspective, the emergence of autonomous economic agents capable of conducting independent transactions necessitates robust frameworks for identity management, transparency, accountability, and regulatory compliance (Ghaderi et al., 2025; Rejeb et al., 2025; Sandner et al., 2020). The absence of shared standards in this domain can increase legal and ethical risks, particularly when devices make economic decisions without human oversight (Heidari et al., 2024; Pezeshgi et al., 2025). Security and privacy challenges further complicate implementation, as the inherent transparency of blockchain may conflict with the protection of sensitive data, such as in healthcare or financial domains. Federated learning can partially address these privacy concerns; however, governance frameworks for managing access, consent, and accountability remain underdeveloped (Nasiri et al., 2026; Nguyen et al., 2024; Rehman et al., 2022; Singh et al., 2020).

Another critical challenge is future-proofing these systems against emerging threats. Quantum-resistant protocols, such as blockchain-based voting schemes, demonstrate promising potential for securing systems against post-quantum attacks. Nevertheless, practical deployment, cross-system interoperability, and real-world adoption remain nascent, requiring extensive testing and further research (Azad et al., 2025; Rivandi, 2026). Furthermore, integrating AI with IoT and blockchain demands a comprehensive analysis of complex economic and organizational data to understand its effects on business decision-making and strategic competitiveness (Bagherabad et al., 2026; Karizaki et al., 2024; Nikzat, 2025).

In summary, realizing the full potential of AI–IoT–blockchain convergence in Industry 5.0 requires integrated and optimized system design, robust governance models, and precise standardization. Without these measures, human-centric and autonomous systems may fail to achieve the desired scalability, security, and transparency, while legal, ethical, and operational risks could significantly constrain the advancement of this domain (Bevilacqua et al., 2025; Pezeshgi et al., 2025).

7. Deployment Roadmap

The deployment of AI–IoT–Blockchain convergence in Industry 5.0 can be structured into seven sequential phases, each targeting specific technical, governance, and operational objectives. This roadmap integrates insights from prior studies and provides actionable steps for researchers and industrial practitioners (Bhumichai et al., 2024; Fraga-Lamas et al., 2019; Khan et al., 2025; Luo et al., 2024; Mololoth et al., 2023; Rajawat et al., 2022; Sait et al., 2025; Sizan et al., 2025; Tyagi et al., 2024; Zhang et al., 2021).

The first phase, readiness assessment, involves evaluating existing infrastructure, listing IoT devices, edge computing capabilities, and network latency, to identify feasibility gaps and prepare for integration. Phase two, architecture design, focuses on defining the system architecture, selecting the appropriate blockchain type, AI deployment mode (edge or cloud), and smart contract templates, thereby producing a blueprint for integration. In the Proof-of-Concept (PoC) phase, a pilot system is built by integrating IoT sensors, blockchain ledgers, and simple AI models to validate workflows, assess latency, and ensure trustworthiness.

The federated learning phase deploys privacy-preserving collaborative AI models coordinated with blockchain, enabling decentralized intelligence while protecting sensitive data. In parallel, the governance framework phase establishes policies for identity management, access control, accountability via smart contracts, as well as regulatory and ethical compliance. The scale-up involves expanding the system, optimizing consensus mechanisms, refining AI models, and integrating additional devices to achieve production-ready, robust operations. Finally, the continuous monitoring and evolution phase tracks key performance indicators, such as latency, accuracy, and energy consumption, maintaining system efficiency while incorporating new technologies and iterative improvements.

These seven phases collectively provide a structured, actionable roadmap for realizing practical, secure, and scalable AI–IoT–Blockchain deployments in Industry 5.0. The detailed phase-wise summary is presented in Table 2.

Table 2

Roadmap Summary

Phase	Description	Key Actions	Expected Outcome
1. Readiness Assessment	Evaluates existing infrastructure and IoT capabilities	Inventory IoT devices, edge nodes, network latency	Determining feasibility, identifying system gaps
2. Architecture Design	Defines system architecture	Selecting blockchain type, AI deployment mode (edge/cloud), smart contract templates	Blueprint for integration
3. Proof-of-Concept (PoC)	Builds pilot system	Integration of IoT sensors, blockchain ledger, and simple AI models	Validating workflow, assessing latency, ensuring trust

4. Federated Learning	Deploys decentralized collaborative AI	Implementing federated learning with blockchain coordination	Privacy-preserving, collaborative AI models
5. Governance Framework	Establishes rules and compliance	Identity management, access control, accountability via smart contracts	Regulatory and ethical compliance
6. Scale-up	Expands and optimizes system	Optimizing consensus, refining AI, integrating more devices	Production-ready, robust system
7. Continuous Monitoring & Evolution	Maintains and evolves system	Tracking KPIs (latency, accuracy, energy), upgrading blockchain/AI	Maintaining efficiency, incorporating new technologies

Managerial Implications

The deployment of the seven-phase AI–IoT–Blockchain roadmap in Industry 5.0 carries significant managerial implications. Firstly, organizations can optimize the management of technological and human resources, including the allocation of sensors, edge devices, computational capacities, and data analytics teams, thereby enhancing operational efficiency and minimizing resource waste. Secondly, transparency and process auditability, facilitated by smart contracts and governance frameworks, ensure accountability in autonomous decision-making by devices and intelligent systems, which is critical for mitigating legal and ethical risks. Thirdly, continuous monitoring of key performance indicators (KPIs), such as network latency, model accuracy, and energy consumption, enables managers to make data-driven strategic decisions and dynamically optimize operational processes. Moreover, the integration of AI, IoT, and blockchain allows for predictive planning and gradual system improvement, ultimately enhancing operational flexibility, scalability, and resilience. Overall, this roadmap provides a structured, measurable, and controllable framework for managing complex emerging technology projects, equipping managers with the necessary tools to make informed decisions aligned with organizational strategic objectives.

8. Future Research Directions

Recent advances in the convergence of Artificial Intelligence (AI), Internet of Things (IoT), and Blockchain in Industry 5.0 highlight several critical research directions that require further exploration to achieve scalable, secure, and human-centric systems.

Post-Quantum Blockchain: Developing quantum-resistant consensus protocols remains a key challenge and opportunity. Blockchain-based voting schemes and other quantum-safe mechanisms are essential to ensure the security and trustworthiness of industrial IoT networks against emerging post-quantum threats (Azad et al., 2025). Future research should also explore practical deployment, interoperability, and testing of these protocols in real-world industrial environments.

Explainable AI (XAI) and Autonomous Agents: As industrial systems increasingly rely on autonomous agents capable of independent transactions, the need for Explainable AI becomes paramount. AI models must be transparent, auditable, and interpretable to build human trust and support, proper governance, and accountability in autonomous decision-making processes (Nikzat, 2025; Pezeshgi et al., 2025). Additionally, integrating AI with IoT and blockchain under resource-constrained environments remains a critical research area, requiring optimization strategies for computational efficiency and energy management (Bagherabad et al., 2026; Choi et al., 2024; Khan et al., 2025).

Interoperability Standards: Standard protocols for cross-chain and cross-platform communication among blockchain networks, IoT devices, and AI frameworks are urgently needed. Interoperability facilitates multi-platform integration, efficient system management, and seamless operation in complex industrial ecosystems. Research should focus on developing modular, standardized frameworks that can support large-scale Industry 5.0 deployments (Heidari et al., 2024; Leng et al., 2022).

Regulatory and Policy Frameworks: Beyond technical challenges, research into governance, regulation, and policy is essential. Proper legal and policy frameworks are required to ensure accountability, transparency, and compliance of autonomous agents, especially in multi-stakeholder and multi-organizational industrial networks (Heidari et al., 2024; Rejeb et al., 2025; Rivandi, 2026). Ethical considerations, such as mitigating impulsive or biased decisions by AI systems, also demand dedicated study and operational guidelines (Pezeshgi et al., 2025).

Sustainability and Energy Efficiency: Sustainability remains a core objective of Industry 5.0. Future research should focus on energy-efficient consensus mechanisms, lightweight AI models, and eco-friendly IoT architectures that align with environmental goals, reducing energy consumption while maintaining system performance (Alharbi et al., 2022; Bagherabad et al., 2026; Gadekallu et al., 2021; Rejeb et al., 2025). Optimization strategies should consider not only computational efficiency but also the economic and operational impacts on industrial processes (Rivandi, 2026).

Operationalization and Measurement: Translating these research directions into practical solutions requires pilot testing, simulation models, and interdisciplinary collaboration among AI engineers, network specialists, and policy-makers (Bevilacqua et al., 2025; Karizaki et al., 2024). Furthermore, designing measurable tools and metrics to evaluate system performance, energy consumption, security, interoperability, and regulatory compliance is crucial for bridging the gap between research and production-ready Industry 5.0 systems.

Collectively, these research directions emphasize a holistic approach that integrates technical innovation, governance, sustainability, and human-centric design. Addressing these areas will enable the development of robust, scalable, and ethically responsible AI–IoT–Blockchain systems, paving the way for the practical and sustainable deployments of Industry 5.0.

9. Conclusion

The convergence of Artificial Intelligence, the Internet of Things, and Blockchain, as three core pillars of digital transformation, provides an innovative and robust framework for realizing the vision of Industry 5.0 systems, characterized by human-centricity, intelligence, and decentralization. The findings, derived from a systematic review of the scientific literature and the analysis of real-world use cases, indicate that this technological synergy holds substantial potential to enhance productivity, increase flexibility, improve transparency, and strengthen trust within complex industrial environments. Nevertheless, despite notable conceptual advancements and the development of numerous prototypes and pilot implementations, the large-scale and practical deployment of such integrated systems in real industrial settings remains constrained by several technical and operational challenges. These challenges include limitations related to scalability, high computational and energy resource consumption, integration complexity across heterogeneous system layers, as well as issues associated with latency, security, and system reliability.

Beyond technical considerations, organizational, managerial, and governance-related aspects play a decisive role in the successful adoption of these converged architectures. In this context, the design and implementation of effective governance models, the establishment of interoperable standards and protocols, and the development of clear regulatory and policy frameworks to ensure data security, privacy protection, and system interoperability are essential prerequisites. Furthermore, aligning these industrial systems with future-ready technologies, such as quantum-resistant blockchain infrastructures, federated learning approaches for privacy-preserving intelligence, and autonomous economic agents enabling decentralized and intelligent decision-making, can significantly enhance their long-term sustainability and resilience in the face of emerging technological paradigms.

Finally, the adoption of a structured and phased roadmap, beginning with the definition of a conceptual architecture and followed by comprehensive design analysis, performance evaluation, and iterative, incremental system deployment, can effectively bridge the gap between theoretical concepts and real-world industrial applications. When properly implemented, this tri-technology convergence can act as a practical catalyst for the next industrial revolution, fostering the development of intelligent, resilient, reliable, and human-centric industrial systems. Such an approach not only improves operational efficiency and data-driven decision-making but also provides a solid foundation for advancing cutting-edge technologies and formulating science- and industry-informed policy and governance frameworks.

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