SSRG International Journal of Computer Science and Engineering
ISSN: 2348–8387 / https://doi.org/10.14445/23488387/IJCSE-V12I10P101

Volume 12 Issue 10, 1-13, October 2025

Review Article

Blockchain for Industry 5.0: Theories, Algorithms, and Possible Outcomes

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Received: 07 August 2025 Revised: 12 September 2025 Accepted: 02 October 2025 Published: 17 October 2025

Abstract - *The review explores the multifaceted role of blockchain technology in the context of Industry 5.0, highlighting its theoretical foundations, algorithmic frameworks, and real-world implications. The paper begins by outlining the core principles and architectural features of blockchain systems, followed by an in-depth examination of consensus algorithms and cryptographic mechanisms that ensure decentralization, transparency, and trust. It then delves into emerging theoretical perspectives that position blockchain as a catalyst for human-centric, resilient, and intelligent industrial ecosystems. A focused analysis is presented on blockchain's application in optimizing supply chain management, emphasizing enhanced traceability, automation, and efficiency. Furthermore, the paper identifies key challenges – such as scalability, interoperability, and regulatory concerns – while forecasting potential developments including integration with quantum-safe cryptographic standards and cross-chain interoperability. The review concludes by synthesizing insights to propose future research directions aimed at harnessing blockchain's full potential in shaping the evolution of Industry 5.0.*

Keywords *- Blockchain, Human Machine Interaction, Industry 5.0, Network Security, Smart Contracts.*

1. Introduction

The conceptualization of Industry 5.0 was brought about by industries in Europe. It was further backed by the European Commission [1]. Basically, Industry 5.0 exhibits the forthcoming evolutionary stage of industrialization. It dwells on the synergistic collaboration between the human factor and the machines in the whole process of production. Broadly, Industry 5.0 extends on and augments Industry 4.0 [2]. However, it differs from Industry 4.0 in various aspects. Industry 4.0 relies primarily on complete automation, digitalization, and the unification of Cyber Physical Systems (CPS). On the other hand, Industry 5.0 advocates for bringing human intelligence and creativity back into the manufacturing loop. Industry 4.0 focuses on combining machine-to-machine and moving towards an automated world. On the other hand, Industry 5.0 focuses on combining machines with humans by using advanced and cutting-edge technologies. These technologies are used to improve the production outcomes. For example, in Industry 4.0, supply chain management and security automation were delivered through a machine network. On the contrary, Industry 5.0 brings advancements in the supply chain through real-time tracking without any human interaction.

The cutting-edge technologies leveraged by Industry 5.0 range from Artificial Intelligence (AI) [3], Blockchain [4], [5], Robotics [6], and the Internet of Things (IoT) [7]. It is done to achieve sustainable and efficient industrial growth. By integrating AI, machines can process a huge chunk of data in a very short duration of time. Machines can learn from patterns and make autonomous decisions to optimize production workflows. The robotics, more specifically collaborative robots (Cobots) [8], are used to enhance productivity in Industry 5.0. These cobots are used in sectors that require high precision, consistency, and efficiency. These cobots are pivotal in the sustainable development of Industry 5.0 by improving working conditions, reducing wastage, and decreasing the harmful environmental impacts. These cobots are nothing but a collaboration of humans with robots. Similarly, IoT is used to gather data from machines in real time using advanced sensor technology. The gathering of real-time data from the machines is helpful in preventing predictive failures and downtimes in Industry 5.0. The fusion of these technologies allows for more personalized, flexible, and efficient manufacturing practices.

In Industry 5.0, human workers and intelligent machines work side by side, each complementing the other's strengths [9]. Humans bring problem-solving abilities, creativity, dexterity, and adaptability to complex or unexpected situations. Machines contribute precision, endurance, and the ability to handle repetitive or hazardous tasks with high efficiency. The purpose of this collaboration is to create a more responsive manufacturing ecosystem that can rapidly and dynamically modify itself according to changes in the market and the customer's needs. The goal of Industry 5.0 is to harness the collective intelligence of humans and machines to create, develop, and design different processes related to manufacturing that are efficient, sustainable, and socially accountable. By combining human ingenuity with advanced technological

capabilities, industries can achieve innovative solutions that drive growth while considering environmental impact and workforce well-being. This human-centric approach corroborates that the technology is used to enhance human work rather than to replace it, leading to a more empowered workforce and a more adaptable production ecosystem.

However, such hyper-connectivity of heterogeneous devices in Industry 5.0 brings with it multifaceted security challenges. The large-scale deployment and integration of IoT sensors, cobots, and other automation devices produce more complex and faster streams of data. Such integration also exposes the network interconnections to exploitation by the attackers. The data streams are thus vulnerable to an integrity breach. The trust between the different devices and nodes can be manipulated by the adversaries. The attacks on confidentiality and integrity may thus affect the overall security and interoperability of the integrated heterogeneous devices. To overcome these security challenges, researchers have suggested centralized security mechanisms. However, these traditional centralized security mechanisms may prove a single point of failure. To enhance security, the digital ecosystem of Industry 5.0 requires some decentralized, distributed, and trustworthy security mechanisms. Such a mechanism can be based on cryptographic hashing, consensus mechanisms, and immutable record keeping. It is a dire demand to protect the said digital ecosystem and make it temper-proof, transparent, and robust against any cyber attacks. If we analyse these requirements, blockchain truly becomes the best option to safeguard the digital ecosystem of Industry 5.0.

In reference to blockchain, Industry 4.0 enhances efficiency through more secure and transparent data without human involvement [10]. On the other hand, Industry 5.0 primarily emphasizes building trust between machines and humans by using blockchain as a medium for secure and immutable transactions [11]. Blockchain forms the backbone of a decentralized architecture by aggregating data from billions of IoT sensors and robotic systems over a network of distributed nodes. Using robust consensus protocols like Proof of Work (PoW), Proof of Stake (PoS) [12], and Byzantine Fault Tolerance [13], it corroborates that each transaction is validated securely and immutably through rigorous cryptographic functions. Besides, the integration of smart contracts automates complex governance and operational processes, facilitating transparent and secure interoperability across the digital ecosystem of Industry 5.0. It not only eliminates the inherent vulnerabilities of a centralized system, such as single points of failure and cyber threats, but also delivers scalability, low-latency, etc, which are essential for real-time industrial applications. Blockchain's role in Industry 5.0 is, therefore, not just about securing data; it is about reshaping the foundational architecture of industrial operations to be more resilient, transparent, and collaborative. It ensures secure, transparent, and tamper-proof transactions and data exchanges, enhancing traceability and integrity of the supply chain [14]. Further, blockchain technology is also widely used in the management of the supply chain [15], healthcare [16], voting systems [17], etc.

The main objective of the current work is to define, describe, and delineate the fundamental attributes of the Blockchain technology from the standpoint of Industry 5.0. It explores the main theories, algorithms, and possible outcomes of blockchain technology for Industry 5.0. It further identifies the key challenges and future improvements. The rest of the paper is organised as follows. Section 2 presents the fundamental concepts of Blockchain, Section 3 presents the core algorithms used in blockchain, Section 4 discusses the main foundational aspects of blockchain theories, Section 5 presents the application domains of blockchain in industry 5.0, Section 6 explores the future perspective of integrating the blockchain technology with industry 5.0, Section 7 presents the challenges and limitations being faced by this technology while getting implemented in Industry 5.0., and finally Section 8 presents the conclusion.

2. Blockchain Technology

Blockchain is a decentralized and distributed ledger of blocks that helps in secure, immutable, and transparent transactions. In other words, it is a system of data sets. These data sets contain the chain of data packets called blocks. Each block has multiple transactions recorded, such as a cryptographic hash, time-stamp, parent block hash, a nonce, block version, etc., for a secure and transparent medium [18]–[20].

The blockchain expands as and when new blocks are added to it, thus forming a whole ledger that records the whole history of the transactions. These blocks are validated using cryptographic methods. A random number called a nonce is used to verify the hash values. The whole structure makes sure that the integrity of the blockchain is maintained. It secures the chain from the initial or beginning block, known as the genesis block, to the last block of the chain. Hash values are unique. If a block changes, the hash value also changes instantly, thus preventing manipulations. A consensus mechanism determines block validity. The major portion of the nodes must agree on the validity of the transactions and the validity of the block itself. Once approved and agreed upon by all, a block can join the chain.

A consensus mechanism is a process where network validators agree on the state of the ledger [21]. It follows rules to maintain a consistent record across all participating nodes. New transactions do not enter the ledger automatically. The consensus process first stores them in a block for some specific duration. For example, in the Bitcoin blockchain, this duration could be about 10 minutes before the transaction is finally added to the chain. Once added to the blockchain, the information becomes permanent. No further changes are possible. Fig. 1 depicts the blockchain and its components. There are several consensus mechanisms to validate a transaction. These consensus mechanisms make sure that all the nodes agree on a transaction. We have three main types of consensus mechanisms. These are: 1. Proof-of-Work(PoW), 2. Proof-of-Stake (PoS), and 3. Practical Byzantine Fault Tolerance (PBFT). A detailed description of these mechanisms is given in Section 3.

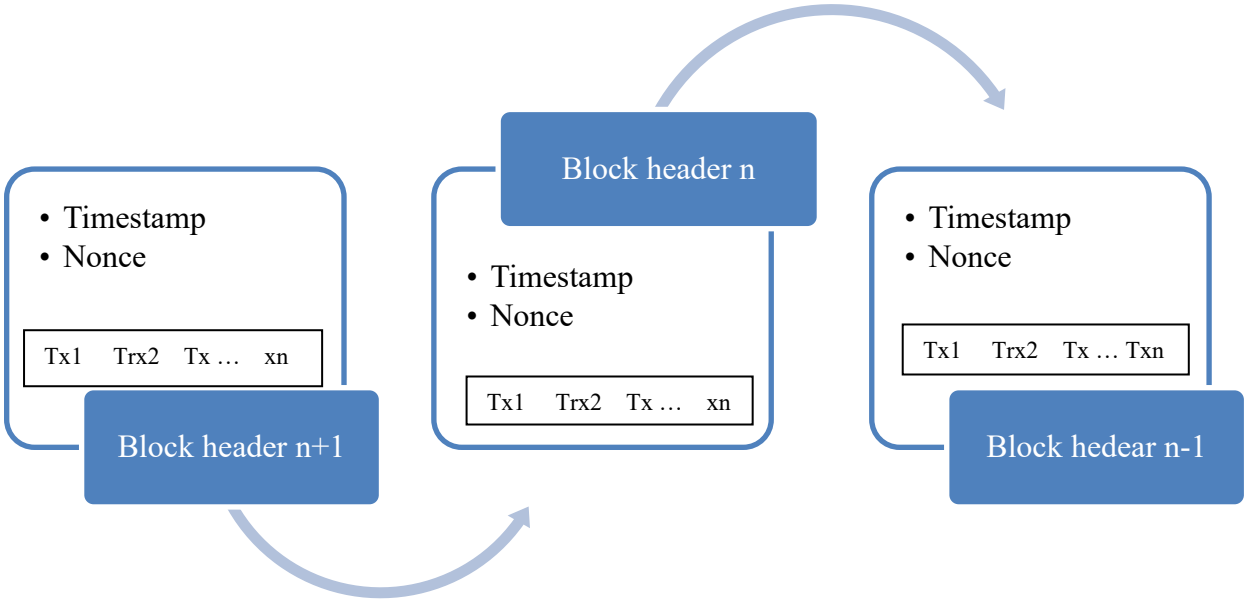

Fig. 1 Blockchain Components

Blockchain Technology has various other key features that can be utilized to ensure the integrity and security of the data in Industry 5.0 [22], [32]. These are decentralization, immutability, transparency, smart contracts, etc. All these are responsible for maintaining security and keeping each node connected in Industry 5.0. Each aspect can be described as follows.

2.1. Decentralization

Blockchain allows a distributed network rather than a centralized one, which reduces tampering of data and allows Peer-to-Peer (P2P) transactions without a central authority. Data is distributed across the whole network, which forms a ledger without storing it in a central location or taking permission from a central authority for validation of transactions.

2.2. Persistence

Blockchain records all data permanently, which means it is nearly impossible to alter data, as it contains a hash of the previous block, which connects blocks with each other, which means any malicious activity can be caught easily.

2.3. Anonymity

With respect to privacy concerns, user can randomly generate addresses through which they can interact with the blockchain without using their personal information.

2.4. Auditability

It records each transaction detail in a block, and each block contains a cryptographic hash, which maintains transparency and simplifies the tracing of transactions.

2.5. Immutability and Transparency

Once data is hashed in a block, it is almost impossible to change it. It is because a change in a block will change its hash. It will further require changing the hash of every block following, because the following block carries the hash of the previous block. Thus, any malicious activity will be caught easily, and modification in any of the blocks is nearly impossible. Further, it is a time-consuming and costly process, which makes the mutation impossible and ineffective. Furthermore, all the data entries in a blockchain are visible to every participant in the network, which builds trust among the participants. It helps in monitoring the data to detect any malicious activity.

3. Blockchain Algorithms and Mechanisms

The core algorithms used in blockchain technology primarily include various consensus mechanisms. These different consensus mechanisms are essential to maintain the integrity and security of the blockchain. The key consensus algorithms are discussed below.

3.1. Proof-of-Work (PoW)

Proof-of-Work (PoW) [12] is the first consensus mechanism. Miners need to solve complex mathematical problems to validate a transaction or create a new block. It takes up to 10 minutes to validate a transaction. It is used by Bitcoin and Ethereum. It is a secure algorithm, but it also consumes high energy. In it, the miners will solve the problem, and then a block will be generated, for which they will get a reward. This process requires high consumption of energy and power, and after performing the numerical calculation, a correct nonce cryptographic hash will be generated. This makes it more difficult and costly for attackers to attack the network.

3.2. Proof-of-Stake (PoS)

Proof-of-Stake (PoS [12] is the second mechanism of discussion. In this mechanism, the creator of a new block is selected based on their wealth because here the miner needs to put up some coins, and if they successfully mine, they get some reward. The coins he put up are known as the stake.

PoS is considered more energy-efficient than PoW. In this algorithm, the validator is chosen based on their wealth and their willingness to hold the coins or to stake the coins. The validator needs to honestly validate the block because they can lose the coins if they attempt to cheat. In this method, less energy is consumed because there is no need to solve complex mathematical problems, and selectors are randomly selected according to their wealth.

3.3. Practical Byzantine Fault Tolerance (PBFT)

Practical Byzantine Fault Tolerance (PBFT) [13] is the third consensus mechanism. This consensus mechanism is designed to work in environments where there is a possibility of failures or malicious nodes. It enables a network to achieve consensus despite the presence of faulty or malicious nodes.

Table 1. Comparative analysis of various blockchain algorithms

Algorithms	Description	Examples	Pros	Cons
Proof of work	In Proof of Work (PoW), miners must solve computationally intensive puzzles to validate and add new blocks to the blockchain, for which they are rewarded.	Bitcoin and Ethereum	Security	High energy consumption
Proof of Stake	In PoS, the selection of the miner for a new block depends on the amount of wealth they possess because here miners need to put up some coins, and if he successfully mines, he gets some reward	Ethereum	Low Energy consumption	Less secure in comparison to PoW
Practical Byzantine Fault Tolerance	In this algorithm, the validator needs a majority of words for the validation of a transaction to add a block	Private blockchain	Fast mechanism	Complexity because of increase in the number of nodes

4. Theories of Blockchain in Industry 5.0

In theory, the main foundational aspects of blockchain are decentralization, immutability, transparency, and security. However, from the Industry 5.0 perspective, smart contracts, interoperability, human-machine interaction, and collaboration are basic theoretical aspects. These are discussed in the following subsections.

4.1. Smart Contracts

Smart Contracts refer to self-executing contracts written into code, which can be used to verify or validate transactions [23]. It enhances security, reduces costs, and handles complex transactions [24], [25]. Smart contracts have gained popularity as blockchain technology has advanced. Thus, a smart contract is an innovative tool that can be operated within a blockchain-based digital ecosystem of Industry 5.0. It automatically negotiates, executes, and enforces a legally binding agreement. Smart contracts offer several advantages. They reduce risk. They lower service costs. They minimize administration expenses. They also improve business process efficiency. Trust is another important key benefit of smart contracts. Smart contracts create confidence between parties. They enable secure agreements even in no-trust environments. This technology will transform traditional business practices. It will redefine how transactions and agreements are handled in Industry 5.0.

4.2. Interoperability

Interoperability enables multiple software components to work together, regardless of differences in language, interface, or execution platforms [26], [27]. Interoperability solves key concerns about blockchain adaptability and reliability. It ensures that services are not limited to a single blockchain, reducing risks related to obsolescence, vulnerabilities, or shutdowns. If user requirements evolve, interoperability allows migration to a more suitable blockchain. This flexibility supports long-term functionality and enhances efficiency in Industry 5.0. For critical services requiring seamless dependability, interoperability guarantees continuous operation without disruptions. It enables cross-chain interactions, maintaining service reliability. Portability is another essential factor. When replicating a use case on another blockchain, interoperability facilitates smooth transitions. It ensures compatibility and minimizes integration challenges in Industry 5.0. For example, integrating AI for the communication of blockchain systems to work together

more efficiently leads to an increase in the number of blockchain applications [28]. It can create interoperability issues. The interoperability issues can be solved by creating interoperable architecture, such as trusted relays, blockchain-agnostic protocols [29], and blockchain migrators. These challenges can also be tackled by using Sidechains and Relays, Notary Schemes, and Hash Time-Lock Contracts [30].

4.3. Human-Machine Interaction

A decentralized system uses Human-Machine Interaction (HMI) for validation. It provides a transparent and secure environment for tracking details of transactions and data exchange. It further enables machines to operate upon and humans to verify these transactions [31]. Human-Machine Interaction (HMI) plays a pivotal role in factory set-ups and industrial settings. Human-Centric Smart Manufacturing (HCSM) combines HMI with advanced technologies. It is expected to define the future of manufacturing. HCSM factories will set new standards for intelligent production. To ensure success, researchers must study technologies that promote HCSM development. These efforts will help industries adapt to Industry 5.0.

4.4. Handling Scalability Issues in Blockchain Algorithms

Blockchain algorithms discussed above may have a scalability issue [33]. These scalability issues can be handled through the following approaches.

On-Chain and Off-Chain Solution [34]: It involves changing the main chain after executing a transaction. It allows for transactions to be handled outside of the main blockchain. Doing so will certainly reduce the load on the main network.

Side Chains Solution [35]: It allows data to be transferred between different blockchains. It helps reduce the burden on the main chain by enabling transactions to occur on separate chains.

Child Chains Solution [36]: It is used to record results back into the parent chain, which creates a structure where the main chain is not overloaded.

Interchain Communication [37]: It allows for communication between different blockchains, enabling a more efficient transaction process.

Lighting Protocols and Sharding [38]: These enhance blockchain to access privacy and improve scalability. Lighting protocols allow for faster transactions. Sharding splits a particular blockchain into smaller, more organised pieces for faster processing.

5. Uses of Blockchain for Improving Supply Chain Management in Industry 5.0

Blockchain technology can be used in manufacturing processes in several phases to enhance efficiency, transparency, traceability, etc. The key application area of Blockchain is in Supply Chain Management (SCM). It can be used significantly to improve the supply chain transparency through several mechanisms. It can improve the tracking and management of products throughout the supply chain. It will allow parties to have real-time access to the data to check the product status. It will enhance traceability, provide detailed records of the product, how it is manufactured and distributed, and maintain quality and standards.

Product authenticity can be done through Blockchain. We can record the entire life-cycle of a product, like manufacturing, delivery, and origin. Each and every detail can be stored and have a digital identity through Blockchain. Further, Blockchain can ensure the tracing of the product and early detection of the product by finding the issue and source through the stored documented and immutable data, which will maintain the quality before delivering.

Big MultiNational Companies (MNCs) have already started using blockchain technology in their Supply Chain Management and logistics. Walmart's food traceability system ensures real-time monitoring, reducing contamination risks. Maersk & IBM's TradeLens automates global shipping documentation, minimizing delays. De Beers utilizes blockchain to track diamonds, preventing fraud and ensuring ethical sourcing. Carrefour verifies food authenticity, allowing consumers to access sourcing details through QR codes.

5.1. Data Integrity for Immutable Recordkeeping

Whenever a transaction occurs in SCM, a cryptographic hash value is generated and recorded in a block. As discussed, every block contains the hash value of its previous block. Thus, any attempt to modify the hash of any of the previous blocks will require the recalculation of the hash values of the following or subsequent blocks in the interconnected chain. Such a recalculation is a computationally infeasible task. Further, admitting the new block in the chain requires validation from the consensus mechanism of the network. If the consensus mechanism finds any modification, it will not admit the block into the chain. This way, Blockchain technology ensures the integrity of transactions within supply chain management by maintaining an immutable and tamper-proof ledger. It operates through a decentralized system where all participants share access to a single source of truth, reducing inconsistencies and disputes. Each transaction is encrypted and linked cryptographically using hashing techniques, preventing unauthorized alterations. Consensus mechanisms like Proof of Work or Proof of Stake validate entries, ensuring data accuracy. Permissioned blockchain models are used to control access selectively. These permissioned blockchain models enhance security by restricting access to authorized participants and safeguarding sensitive information.

5.2. Real-Time Tracking to Increase Efficiency

Blockchain ensures real-time tracking by securely recording and maintaining a complete history of the products from their origin to their final destination. To

maintain transparency in the complete transaction history across the whole supply chain, Blockchain records each transaction in distributed and decentralized ledgers. Each transaction is time-stamped and cryptographically linked to previous records, ensuring an immutable and transparent chain of custody. Such ledgers are secure and immutable. Cryptographic solutions are used to maintain the integrity of such transactions. Consensus mechanisms are used to verify the transactions and every update. All these are monitored and tracked in real time to know the status of a product at a specific time. The automation of the whole process generates alerts if some predefined conditions are reached in the supply chain, thus enhancing accuracy while monitoring the transactions. The decentralized ledger system allows stakeholders to trace the life cycle 7 of a product in real time, facilitating audits, compliance checks, and quality assurance. The real-time tracking prevents fraudulent claims, ensures authenticity, and provides valuable insights for predictive maintenance. By utilizing blockchain's verifiable history, organizations can investigate past performance, optimize asset utilization, and implement preventive measures, ultimately improving efficiency and reliability in Supply Chain Management systems.

Furthermore, it optimizes business revenues, lessens the risk of loss, and enhances coordination between manufacturers, distributors, and retailers. It improves the overall efficiency of the supply chain. From the perspective of inventory management, it provides a real-time view of inventory and the levels of inventory at any moment, and helps the manufacturer to manage it more effectively, reducing excess stock and becoming cost-friendly.

5.3. Smart Contracts in SCM

Smart contracts are basically used to automate the agreement process by fulfilling some terms and conditions before validating or altering the data in the form of code. These self-executing contracts, stored on a blockchain, execute predefined conditions automatically when triggered, ensuring seamless operations. By integrating smart contracts with IoT sensors, organizations can monitor asset conditions in real time and initiate maintenance activities without human oversight.

Cryptographic techniques are used to verify and validate the transactions. In SCM, they can be implemented by using blockchain. It will remove the manual intervention by automatising the workflows, delivery, payment receipts, automated outbound payments, warranty enforcement, scheduled servicing, predicting consumption patterns, generating the demands, etc. Since these contracts are maintained by distributed and decentralized ledgers, they rule out the role of intermediaries in the SCM. On the other hand, the whole automation process will reduce costs, delays, and wastage. Their ability to eliminate intermediaries enhances accuracy, accelerates workflows, improves efficiency, settlement time, and strengthens trust among stakeholders, ultimately optimizing asset life-cycle management in predictive maintenance systems, and finally increasing the reputation of an organisation.

5.4. Enhance Fraud-Proof Collaboration and Quality Control

Blockchain ensures the transparency of data among the different stakeholders through P2P collaborations between suppliers, manufacturers, and distributors. This transparency strengthens the collaboration between the suppliers and the consumers. They can trust the shared information. It leads to improved and efficient communication and brings efficiency and long-term partnerships within the SCM ecosystem. This happens because of cryptographic validation and verification by the underlying consensus mechanisms of blockchain technology. Any malicious manipulations are quickly identified by the peers.

Blockchain enhances quality control and compliance by enabling transparent and secure data sharing across the supply chain. Its decentralized ledger ensures that all participants have access to identical, tamper-proof records, eliminating discrepancies and fostering trust. Cryptographic techniques safeguard data integrity, while consensus mechanisms verify updates, ensuring accuracy and reliability. This transparency allows businesses to track products at each stage, detect anomalies early, and maintain high compliance standards. By reducing trust issues and providing a verifiable single source of truth, blockchain strengthens quality control measures and reinforces regulatory adherence, ultimately improving operational efficiency and stakeholder confidence.

5.5. Other Use Cases of Blockchain Applications in Industry 5.0

The use of blockchain technology is not limited to SCM and logistics. In the context of Industry 5.0, various other sectors are also utilizing blockchain. Some areas of Blockchain applications in Industry 5.0 are as follows.

Energy Sector**:** Blockchain revolutionizes the energy sector by enabling decentralized business models and marketplaces that reduce costs and facilitate Peer-to-Peer (P2P) energy trading. Companies like Power Ledger and WePower leverage blockchain to allow consumers to buy and sell excess renewable energy directly, bypassing traditional utility providers and optimizing energy distribution. Siemens integrates blockchain to enhance automated pay-per-use models, ensuring accurate revenue calculations for electricity sales. Shell utilizes blockchain to validate carbon credit programs, ensuring transparency in sustainable energy initiatives. By eliminating intermediaries, blockchain enhances efficiency, lowers transaction costs, and supports real-time energy trading, fostering a more sustainable and accessible energy ecosystem.

Manufacturing: Blockchain enhances manufacturing by enabling automated processes that streamline ecommerce and optimize supply chain management. Companies like Siemens integrate blockchain to secure digital blueprints for 3D printing, ensuring intellectual property protection and preventing unauthorized modifications. IBM's blockchain

solutions improve supplier collaboration by providing a transparent and tamper-proof ledger for tracking raw materials and finished goods. Foxconn utilizes blockchain-based smart contracts to automate procurement and payments, reducing manual errors and accelerating transactions. By eliminating intermediaries, blockchain enhances efficiency, reduces costs, and ensures real-time visibility into production and distribution networks, fostering a more resilient and agile manufacturing ecosystem.

IOT Integration: Blockchain enhances IoT integration by providing a secure and decentralized framework for data exchange between connected devices. Companies like IBM Watson IoT leverage blockchain to ensure tamper-proof communication between industrial sensors, preventing unauthorized data manipulation. Helium utilizes blockchain to create a decentralized wireless network for IoT devices, enabling secure and cost-effective connectivity. Xage Security integrates blockchain to protect industrial IoT systems from cyber threats, ensuring secure authentication and data integrity. By eliminating centralized vulnerabilities, blockchain enhances security, automates device interactions, and fosters trust in IoT ecosystems, making it a vital component of Industry 5.0.

Collaboration and Data Sharing: Blockchain enhances collaboration and data sharing by providing a decentralized and transparent network where information is securely recorded and accessible to all authorized participants. Companies like IBM's Blockchain for Data Sharing enable businesses to exchange sensitive information without intermediaries, ensuring data integrity and reducing fraud. Estonia's e-Governance system leverages blockchain to securely store and share citizen data across government agencies, improving efficiency and trust. MIT's Open Music Initiative uses blockchain to facilitate transparent royalty distribution among artists and producers, eliminating disputes over payments. By ensuring tamper-proof records and real-time access, blockchain fosters seamless collaboration, enhances security, and builds trust among stakeholders in Industry 5.0.

Healthcare: In healthcare, blockchain is used to securely record patients' data. The blockchain-based records pertaining to the data of the patients are decentralized and immutable, thus improving accessibility and reducing costs, besides being tamper-proof and robust against unauthorized access, alterations, and fraud. Consequently, it brings transparency and efficient emergency response based on critical information retrieval of the patients, and finally, it lowers operational expenses. It can further help in the billing and medical claim process, thus enhancing client satisfaction. For example, MedRec utilizes blockchain to securely store patient records, ensuring data integrity and controlled access. Estonia's e-Governance system utilizes blockchain for citizen data management, preventing unauthorized modifications and improving transparency. Ocean Protocol facilitates decentralized data sharing, allowing businesses to exchange information securely
without intermediaries.

Government Sector: Blockchain technology is abundantly used in various government sector services to increase the transparency, efficiency, and trust of the public. It is used in voting, verification of identity, land record management, etc. Further, the government can utilize blockchain technology to strengthen the accountability of public servants.

6. Possible Outcomes of Integrating Blockchain with Industry 5.0 and Future Perspective

Blockchain technology that can be integrated into Industry 5.0 is:

6.1. Enhancement of Transparency

Blockchain enhances transparency by providing a tamper-proof and unalterable ledger where all transactions are securely recorded and accessible to authorized participants. IBM Food Trust [39] is an example where blockchain is used to track food supply chains, ensuring that data remains immutable and verifiable. Similarly, Maersk's TradeLens [40] leverages blockchain to create a transparent shipping network, reducing fraud and improving efficiency. By eliminating intermediaries and enabling real-time access to verified data, blockchain fosters trust among stakeholders, ensuring accountability and integrity in Industry 5.0 applications.

6.2. Decentralised Data Management

Blockchain enables decentralized data management by distributing information across multiple nodes, eliminating reliance on a central authority and enhancing security and privacy. By ensuring tamper-proof records and encrypted transactions, blockchain strengthens data security, mitigates cyber threats, and fosters trust in various sectors, making it a crucial element of Industry 5.0

6.3. Improved Efficiency

Blockchain enhances efficiency by eliminating intermediaries, reducing transaction costs, and accelerating processes across industries. In finance, JPMorgan's Onyx [41] utilizes blockchain for instant cross-border payments, cutting settlement times from days to seconds. Maersk's TradeLens [40] streamlines global shipping by automating documentation, reducing delays, and operational expenses. Foxconn's Chain Finance [42] employs blockchain to automate supplier payments, minimizing manual errors and improving cash flow. By enabling direct, secure transactions and automating workflows, blockchain optimizes resource utilization, enhances speed, and fosters cost-effective operations, making it a key driver of efficiency in Industry 5.0.

6.4. Smart Contract

Smart contracts automate processes by executing predefined conditions in code, reducing manual intervention

and enhancing efficiency. In finance, JPMorgan's Onyx [41] uses smart contracts for instant cross-border payments, eliminating intermediaries and reducing transaction time. IBM's blockchain-based supply chain solutions leverage smart contracts to automate procurement and inventory management, ensuring seamless operations. Propy utilizes smart contracts in real estate transactions [43], enabling secure and transparent property transfers without third-party involvement. By ensuring accuracy, reducing costs, and enhancing security, smart contracts streamline operations across industries, making them a vital component of Industry 5.0.

6.5. Enhance Security

Blockchain enhances security by leveraging cryptographic hash generation, ensuring data integrity, and protecting sensitive information. Each transaction is encrypted and linked using cryptographic hashing, making unauthorized modifications nearly impossible. Companies like IBM Hyperledger Fabric utilize blockchain to secure enterprise data, preventing cyber threats and unauthorized access. Guardtime employs blockchain-based cybersecurity solutions to safeguard government and healthcare records, ensuring tamper-proof data storage. Xage Security integrates blockchain to protect industrial IoT systems, preventing cyberattacks on connected devices. By decentralizing data storage and employing cryptographic validation, blockchain strengthens security, mitigates risks, and ensures trust in digital transactions across various industries

6.6. Collaboration and Innovation

Blockchain fosters collaboration and innovation by ensuring immutable records and transparent data sharing, building trust among stakeholders. Companies like IBM Hyperledger enable secure and verifiable transactions, allowing businesses to collaborate without concerns over data manipulation. Estonia's e-Governance system leverages blockchain to facilitate seamless inter-agency collaboration, ensuring efficient public services. MIT's Open Music Initiative uses blockchain to transparently distribute royalties among artists, eliminating disputes and enhancing creative partnerships. By providing a tamper-proof and decentralized framework, blockchain strengthens trust, streamlines operations, and accelerates innovation across industries, making it a key enabler of Industry 5.0.

6.7. Sustainable Practices in Agriculture

Sustainable agriculture practices can be implemented by using Blockchain. It includes real-time tracking of agricultural-related activities, beginning with sowing to farm produce and to their distribution. It can be used to record cultivation data, crop patterns and types, storage conditions, inventory management, monitoring surplus produce, and consequently, to estimate demands. Further, Smart contracts can be undertaken to automate the processes related to fair trade and reduce losses due to mismanagement. Furthermore, tracing and tracking in real time would help minimize food waste, check expiration dates, and optimize supplies. This data-driven approach based on blockchain technology would ensure that the produce reaches consumers with minimal spoilage. Finally, it would result in a reduced environmental impact and thus foster sustainable agriculture aligned with Industry 5.0 principles.

7. Challenges, Limitations, and Anticipated Future Trends of Industry 5.0 in Adopting Blockchain Technology

The blockchain is promisingly used in Industry 5.0, but it still has some challenges and limitations, as discussed in the following subsections.

7.1. Scalability

The capacity, throughput, and speed of the transactions that are carried out in blockchain are limited. Due to such limitations, the implementation of blockchain can not be scaled up. Conventional and centralized systems are capable of processing a higher volume of Transactions Per Second (TPS) than blockchain-based systems. It happens due to the fixed size of the blocks. For example, the block size in Bitcoin is generally limited to 1 MB, which only causes restricted transactions in a given duration. It further increases the per-transaction fees during demand inflation.

Additionally, the block creation time further impacts scalability. For instance, Bitcoin adds a new block every 10 minutes, leading to slow confirmation times. The consensus mechanism, especially Proof-of-Work (PoW), adds another layer of complexity, requiring significant computational resources to validate transactions, which further slows processing. Compared to systems like Visa that process tens of thousands of TPS, Bitcoin only manages around 7 TPS. To address these issues, various scalability solutions have been proposed. Layer 2 protocols, such as the Lightning Network for Bitcoin [44] and Plasma for Ethereum [45], enable off-chain transaction processing, reducing congestion on the main blockchain. Sharding [46], another approach, partitions the network into smaller units (shards) to process parallel transactions, significantly increasing throughput. Moreover, shifting from PoW to Proof-of-Stake (PoS) and other more efficient consensus mechanisms can reduce computational requirements and accelerate transaction processing. While these improvements aim to enhance blockchain scalability, achieving high throughput without compromising security and decentralization remains an ongoing challenge for industries integrating blockchain technology.

7.2. Interoperability

Interoperability stands as a key hurdle in blockchain adoption, especially as networks expand and the number of nodes increases. As blockchain ecosystems grow, different platforms operate with unique protocols, consensus mechanisms, and governance models, making seamless interaction between them increasingly difficult. One major issue is the verification time – as the number of nodes increases, more computational resources are required to validate transactions, leading to delays in finalization. Since

blockchain networks function as distributed ledgers, every transaction must be verified by multiple nodes, and this process can become sluggish in large networks, affecting overall efficiency. Additionally, most blockchains operate in isolation, meaning assets, data, and transactions on one blockchain cannot easily interact with another, creating fragmented ecosystems where industries struggle to integrate and exchange data across different blockchain solutions. The lack of cross-chain communication further limits blockchain adoption, as businesses may find it impractical to maintain multiple independent blockchain networks without efficient interoperability. Challenges such as differing protocols, security vulnerabilities in bridging solutions, and the inability to perform cross-chain transactions hinder blockchain scalability and usability. To overcome these limitations, various solutions are being explored. Interoperability protocols like Polkadot and Cosmos provide frameworks that allow different blockchains to interact and share data efficiently, while cross-chain smart contracts enable decentralized applications (dApps) to function across multiple chains. Additionally, blockchain bridges create reliable mechanisms for seamless asset and data transfer between blockchain networks. Addressing interoperability challenges is crucial for widespread blockchain adoption, ensuring smooth communication between different blockchain platforms, reducing inefficiencies, and enabling businesses to operate in a unified decentralized ecosystem.

7.3. System Security and User Privacy Issues

System security and user privacy are two of the most crucial issues in blockchain adoption, despite the technology's inherent cryptographic security. While blockchain ensures tamper-resistant and decentralized recordkeeping, the permanent storage of transactions and their distribution across all participating nodes introduces potential privacy risks. Since blockchain operates as a public or semi-public ledger, each transaction is recorded immutably and is exposed to all entities within the network. Although personal data and information may not be explicitly stored, transaction metadata can still reveal patterns that may be exploited for tracking users or analyzing financial activities. The transparency of public blockchains such as Bitcoin and Ethereum, where transaction details are visible to all, can lead to concerns regarding financial privacy, regulatory compliance, and data exposure.

Additionally, smart contracts, which automate transactions on blockchains, can contain sensitive business logic that might be visible to competitors or malicious actors. Another privacy risk arises from linkability, where multiple transactions associated with the same user can be traced, potentially leading to identity exposure, even if direct identification is not recorded. Addressing these security and privacy concerns requires implementing advanced solutions, such as zero-knowledge proofs, such as ZK-SNARKs [47], which allow transactions to be verified without revealing their actual details, and privacy-focused blockchains like Monero and Zcash [48], utilizing cryptographic protocols to enhance anonymity. Industries are developing their private blockchains to enhance confidentiality as well.

7.4. Selfish Mining

It is a strategic attack in which the miners manipulate blockchain protocols to maximize their rewards unfairly. In fair mining, the miners broadcast the blocks to the entire network after validating them. It ensures transparency and stability in the systems. On the other hand, selfish miners have superior computational power. After mining or validating a block, the selfish miners do not broadcast it immediately in the network. These miners strategically withhold these blocks, making them private. In doing so, they create a private chain that is longer than the public chain of a given blockchain system. Once their private chain turns longer than the public chain, they reveal it, invalidate the already accepted blocks, and ask for higher rewards. This strategic attack badly affects the fair rewarding mechanism and causes loss to the honest miners of the blockchain system. It further involves the risk of centralization of the whole system, leading to the autonomy of selfish miners. Such autonomy reduces the trust of honest miners in the decentralized consensus mechanism. Further, the invalidation of previously accepted blocks causes a double-spending vulnerability, resulting in loss and financial instability for honest miners.

Bitcoin and other PoW-based blockchains have been developed to restrict these manipulations, but dynamic mining strategies, large economic interest, and the availability of exceptional computational power etc., can still motivate large-scale selfish mining. To address this issue, a dynamic reward mechanism can be placed in the system, which penalizes the withholding of the blocks. The underlying consensus protocol can also be modified accordingly. Further, chain selection rules can be implemented to penalize selfish mining.

Some proposals, like the Bitcoin GHOST protocol [49], aim to ensure fair block propagation by recognizing multiple chains instead of favouring the longest one exclusively. While selfish mining does not make blockchains outright insecure, it highlights the ongoing need for improved fairness, decentralization, and incentive structures in mining operations.

7.5. Quantum Resilience

Quantum resilience is becoming a serious concern for blockchain security as emerging quantum capabilities threaten existing cryptographic algorithms. Conventional blockchain security relies on cryptographic techniques such as public-key encryption and hash functions. These cryptographic techniques are currently resistant to conventional computing attacks. However, quantum computers, based on Shor's algorithm [50], can efficiently break widely used encryption methods, such as Elliptic Curve Cryptography (ECC) and RSA encryption. Such a break can potentially compromise blockchain integrity. If quantum computers reach sufficient computational power,

they could decrypt private keys, allowing attackers to manipulate transactions, steal assets, or disrupt decentralized networks. To address such vulnerability, researchers and developers are working on post-quantum cryptography, designing quantum-resistant algorithms such as lattice-based cryptography [51], multivariate cryptography [52], and hash-based signatures. Blockchain protocols are exploring upgrades to integrate quantum-safe encryption to ensure long-term security. While quantum computing is still in its early stages, industries implementing blockchain must proactively prepare for future resilience by adopting quantum-resistant cryptographic methods to safeguard decentralized systems against potential quantum threats.

7.6. Lack of Government Regulation

Conventional financial institutions are regulated by the laws of a country. The legal framework is defined and strictly complied with. In the case of a public blockchain, the nodes of the network are decentralized and geographically dispersed. No universal laws or intergovernmental policies exist. Some countries support it, while others impose stringent restrictions. In the absence of a universal and standardised regulatory framework, the blockchain technology can not be harvested to its full potential. It is so because such absence creates uncertainty, risk, operational insecurity, fraud, breach of privacy, and misuse of the technology itself for illegal activities.

7.8. Implementation Cost

The implementation cost of blockchain technology is a significant barrier to widespread adoption, despite its security, transparency, and decentralization advantages. Deploying blockchain solutions requires substantial computational power, infrastructure, and expertise, making it financially challenging for many organizations, chiefly affecting small and medium enterprises.

The starting set-up involves hardware investments, such as high-performance nodes and secure storage systems, along with the need for skilled professionals to develop and maintain blockchain networks. Additionally, the cost of executing transactions on blockchain platforms can be high, notably across networks like Ethereum, where gas prices shift in response to demand.

The operational expenses further add to the financial burden, as maintaining a decentralized ledger requires continuous network participation, energy consumption (especially for Proof-of-Work systems), and regulatory compliance costs.

Enterprises considering blockchain adoption must also account for integration challenges, as transitioning from legacy systems to blockchain requires custom development, smart contract audits, and security enhancements. Furthermore, scaling blockchain infrastructure to support high transaction volumes demands additional investment in advanced consensus mechanisms, such as Proof-of-Stake or Layer 2 solutions, to optimize cost efficiency.

To overcome financial barriers, organizations explore cost-effective alternatives such as private blockchains. Private Blockchain offers controlled access and lower operational expenses than public blockchain networks. Microsoft and Amazon have started offering platforms with Blockchain-as-a-Service (BaaS). The BaaS provides full features of blockchain to an organization without requiring the organization to develop and invest in full-fledged blockchain infrastructures. While blockchain remains a powerful solution for security and efficiency, addressing cost challenges through technological advancements and optimized deployment strategies is essential for broader industry adoption.

7.9. Current Research Trends

Blockchain research has evolved significantly from its initial focus on cryptocurrencies like Bitcoin to broader applications across industries. Since 2017, the surge in academic publications and citations reflects an increasing interest in exploring blockchain beyond financial transactions. Emerging research covers decentralized identity management, smart contracts, secure data sharing, and enterprise solutions, highlighting blockchain's versatility in transforming digital ecosystems.

Blockchain technology is expanding into multiple sectors beyond finance, including healthcare, supply chain management, IoT, and legal frameworks. In healthcare, blockchain ensures secure patient data management, while in finance, it enhances fraud prevention and transaction transparency. The integration of blockchain with IoT enables device authentication and secure communication, reducing cyber risks in smart industries. Stakeholders must focus on these emerging domains and leverage blockchain's capabilities to enhance efficiency, security, and automation.

Multi-sector research collaboration, government funding, and industry-academia partnership are essential for developing an effective, scalable, and real-world blockchain-based ecosystem. Research to develop quantum-resistant, AI-driven, energy-efficient, and hybrid blockchain frameworks should be undertaken to address the issues of scalability, interoperability, and cost-effectiveness.

8. Conclusion

Industry 5.0 can be transformed through the synergy of blockchain and human-robot collaboration, ensuring enhanced trust, automation, security, and efficiency. Blockchain's immutable and transparent ledger plays a pivotal role in fostering trust among stakeholders, allowing industries to maintain verifiable records of transactions, machine operations, and human inputs. By leveraging blockchain-based auditing and traceability, industries can reduce fraud, eliminate data manipulation, and ensure secure communication between autonomous systems and human decision-makers. Smart contracts further streamline industrial processes by automating agreements and execution, eliminating intermediaries, and enabling seamless human-robot interactions. As each transaction or operational task gets validated across decentralized nodes,

the integrity of machine-driven processes remains intact, marking the human role in oversight and validation.

Additionally, data security and privacy are strengthened through cryptographic encryption, ensuring the protected transmission and storage of sensitive industrial data. Blockchain technology allows industries to implement secure, automated data processing, preventing unauthorized access while accelerating analytical workflows. The integration of collaborative intelligence, where humans and AI-powered robotic systems share data, enables real-time tracking, predictive analysis, and optimized resource allocation. This enhances efficiency in manufacturing, logistics, and decision-making. In supply chain and asset management, human-robot collaboration backed by blockchain enables real-time monitoring of goods, optimizes production scheduling, and reduces losses through accurate tracking mechanisms. By implementing decentralized, AI-integrated frameworks, industries can ensure higher productivity, enhanced security, and seamless automation, paving the way for a more intelligent, resilient, and efficient industrial future.

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