Telematics and Informatics Reports 18 (2025) 100204

Contents lists available at ScienceDirect

Telematics and Informatics Reports

journal homepage: www.elsevier.com/locate/teler

Blockchain technology in supply chain management: Innovations, applications, and challenges

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ARTICLE INFO

Keywords:
Blockchain technology
Decentralized systems
Supply chain management
Healthcare
Cybersecurity
Energy efficiency

ABSTRACT

Blockchain technology is emerging as one of the most transformative forces to have ever reshaped supply chain management, with unique transparency, security, and efficiency. This paper reviews the literature on blockchain technology and applications in core industries such as transportation, manufacturing, food and beverages, and healthcare. At its core, blockchain deploys distributed ledger technology to provide tamper-proof, secure record-keeping, enhancing traceability and provenance verification for complex supply chains. Smart contracts, IoT connectivity, and decentralized financial services allow blockchain to address its most critical challenges, including counterfeiting, supplier management, and the enforcement of sustainable and responsible sourcing practices. However, widespread adoption of blockchain in supply chains is inhibited by severe issues like scalability, interoperability, regulatory uncertainty, and lack of standardization. Additionally, the environmental impact of blockchain, i.e., the energy-intensive proof-of-work mechanisms is examined, along with potential strategies for mitigation. As the technology continues to evolve, the integration of artificial intelligence and 5G networks will further reshape supply chain management, unleashing new efficiencies and capabilities.

1. Introduction

A blockchain is a chain of blocks, serving both as a repository of information and as a secured ledger for transactions. Each block keeps a list of recent transactions, and once the block is complete, then it becomes a part of the permanent blockchain. The database updates with each new block that comes along, allows for secure money, property, and contract transfers. In a nutshell, blockchain is a software protocol operating over the Internet. This technology ushers in a new economy whereby blockchain will rule over digital assets, currencies, and smart contracts [1]. The various application of blockchain range from healthcare and banking to the public sector and are therefore an active concern of many studies and implementations. For instance, in the health sector, it has provided a safe foundation for storage and record-keeping of patient information, thus allowing the sharing of confidential data among medical experts. The blockchain safeguards the security of financial products [2]. Many organizations and enterprises are interested in how the use of blockchain fits into their operations in order to improve their performance and gain a competitive edge. Increased breakthroughs in technology will definitely translate to increased usage in more areas of application. Blockchain enables secure and non-repudiable data storage and management; hence, it is regarded as a critical building block in the digital economy. In any case, some of the most revolutionary technologies, such as blockchain, are very likely in the future to turn a number of industries tune to secure, transparent, and decentralized networks [3].

Blockchain disrupted conventional financial systems by enhancement, remittances, smart contracts, among other things through a decentralized ledger system [4]. A new cryptocurrency asset classes have also evolved on blockchains, hence disrupting rather well-established financial systems. In the case of supply chain management, blockchain presents considerable application in enhancements in traceability and transparency in transaction and asset records. Tamper-proof record creation enables the tracking of goods in real time, reducing counterfeiting, as well as improving the efficiency within the supply chain as a whole [5]. In the healthcare sector, blockchain has promised further development in managing patient data, clinical trials, and pharmaceutical supply chains which can help patients to take full

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https://doi.org/10.1016/j.teler.2025.100204
Received 14 December 2024; Received in revised form 13 March 2025; Accepted 13 April 2025
Available online 17 April 2025

control over their medical information, while researchers will benefit from improved data accuracy and integrity through secure interoperable data sharing. It also finds applications in peer-to-peer energy trading, carbon credit systems, and grid management. Energy platforms based on blockchain allow for direct transactions among the producers and consumers of energy. This directly translates to increased utilization of renewable energy, reduced dependence on monopolized power systems, and generally a big cost saver [5]. Fig. 1 shows the decision making and interaction framework involving policymakers, producers, and users. The green and yellow colours represent each player's two scheduling and decision-making agents [6].

Blockchain technology is also explored in other sectors such as real estate, government services and intellectual property rights, adopting higher standards of transparency, minimal fraud, and convenience to the processes. The main barriers to mainstream usage are the constraints of scaling, interoperability, legal frameworks, and energy consumption. Several barriers have to be traversed so as to reach the full utilization of blockchain technology in business operations. Based on type, it could be classified in the four categories i.e., public blockchains, consortium blockchains, private blockchains, and hybrid blockchains as shown in Fig. 2.

The public blockchain is stored decentralized so that it is not under the control of any single entity. This is non-possessive in nature and every participant who owns required hardware along with access to internet can join the network. Every computer in the network keeps an accurate copy of the whole blockchain, and every bit of information is available transparently. In every network block, there is a replica present on each computer to make sure that any dataset is completely distributed, tamper-proof, and transparent across the whole network. Public blockchains form the backbone for cryptocurrencies like Bitcoin and Ethereum because they allow openness in participation and also in the details of transactions [7]. Contrary to public blockchain, private blockchains are restricted in their accessibility. They can be accessed and participated by those persons or entities that are authorized. These types of blockchains are present with a controlled environment to keep sensitive data. Due to limited participation, private blockchain networks provide more privacy and quick transaction processing than public blockchains. These are typically utilized in industries that require a high level of control and privacy, making them well-suited for applications in banking and supply chain management [8].

Hybrid blockchains incorporate aspects of both public and private blockchains. While there may be a central entity in control of the network-perhaps even to ensure that unauthorized changes do not occur, the blockchain can nonetheless be open to the public for transparency. This blockchain model is flexible, hence allowing the organization to take advantage of the strengths between the public and private models. While the public side ensures transparency, the private side should keep in close confidence, with confidentiality over sensitive data guaranteed [9]. The integration of IoT and blockchain in supply chains enhances transparency, security, and efficiency through the capability to trace goods in real-time, enable automated payments, and store safe data. IoT sensors monitor the location and condition of goods, while blockchain ensures data integrity. Smart contract-based automatization of payments and activities reduces delays. RFID and GPS facilitated by IoT enhance inventory management, while predictive analytics optimize logistics. This fusion eradicates fraud, counterfeiting, and regulatory non-compliance, ensuring the authenticity and sustainability of the product. Ultimately, IoT-driven blockchain supply chains create a secure, automated, and efficient ecosystem. Due to the continuous advancements, blockchain technology enhances risk management and supply chain resilience, rendering decentralized data sharing in a more efficient and secure way [10]. In blockchain, there is always trade-off between time, cost, and quality [11]. Blockchain and crypto-based IoT supply chain networks enhance security and efficacy [12]. An open innovation paradigm through blockchain is leveraged in formulating data-led supply chain frameworks that advance transparency as well as defend against fraud [13]. Blockchain is also crucial in the health sector, demonstrating its efficiency in safe waste disposal and ensuring robustness and sustainability in healthcare networks. Applications of this kind make blockchain a reliable, decentralized option for industries that are most critical [13].

The consortium blockchain model, also known as Federated Blockchain, introduces collaboration by allowing multiple entities to jointly hold the reins of control for the blockchain. A consortium blockchain is neither public nor private; it is run by a set of pre-selected group members. It finds the best fit in those use cases that need the

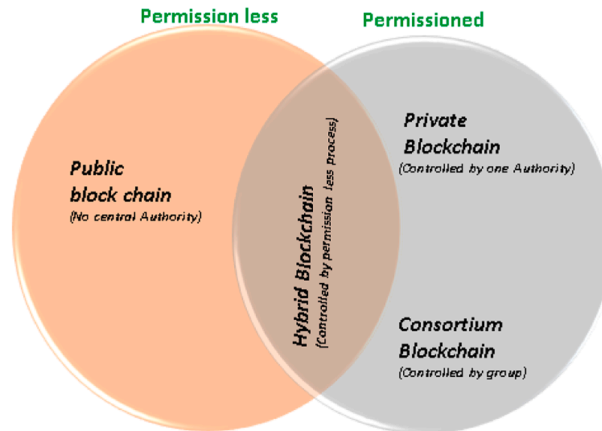

Fig. 2. Types of blockchains.

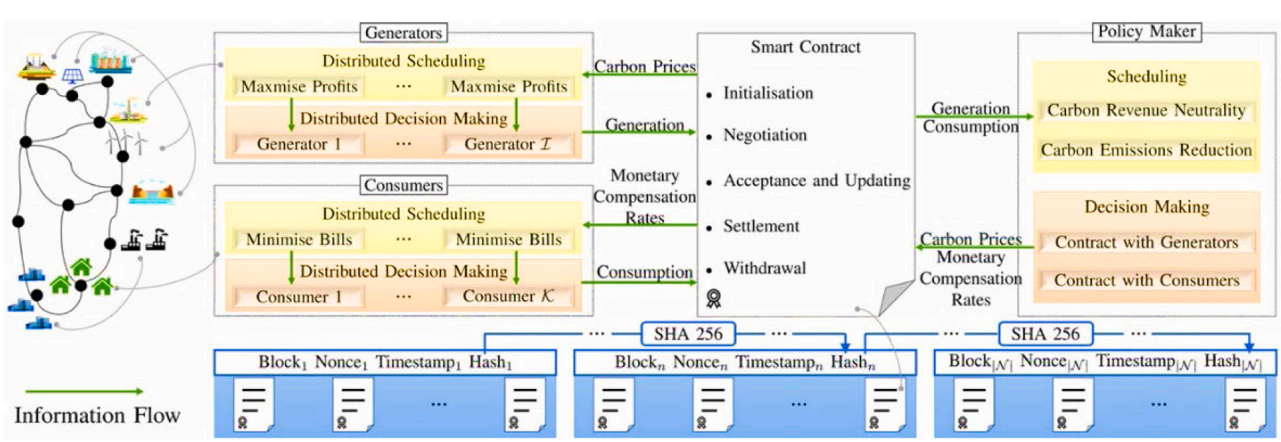

Fig. 1. Decision making and interaction structure.

collaboration of industries, such as supply chain, finance, and healthcare. It allows a trade-off between transparency and control and therefore is a more efficient means of meeting collective needs for a diverse set of stakeholders [14]. A comparison among these blockchain technologies is listed in Table 1.

Blockchain technologies have a compromise between security and transparency, with public blockchain offering transparency but scalability and energy concerns, against efficiency of private and consortium types but lacking decentralization. Hybrid and federated blockchains attempt to balance both but introduce governance complexity. Barriers to adoption are framed in terms of regulatory hurdles, trust in central authority, and multi-party governance complexities.

In order to examine the trend of research, a search on publications related to blockchain was carried out, and the number of publications is shown in Fig. 3. The evidence shows that in the year 2023, 62 publications on blockchain technology were made, reflecting a high number in comparison with the preceding years. As can be seen in Fig. 4, the computer science field has contributed most to the research on blockchain technology. Further, as shown in Fig. 5, research articles make up a larger proportion of blockchain publications compared to other categories, such as news articles, review articles, and book chapters.

This paper describes blockchain use cases across various sectors, its strengths, weaknesses, and future improvements. The key contribution of this paper includes:

(i) Industry Analysis: Explains blockchain usage in supply chain, healthcare, finance, real estate, and IoT.
(ii) Blockchain Typology: Describes blockchain as public, private, hybrid, and consortium types.
(iii) Innovations: Talks about smart contracts, identity management, and AI-integrated blockchain solutions.
(iv) Challenges & Solutions: Addresses scalability, interoperability, regulations, and energy costs and proposes effective algorithms and policies.
(v) Future Directions: Emphasizes pointing out 6 G security, decentralized AI, and sustainable blockchain integration.

The rest of the paper organized in the following sections: Section 2 explains the industry applications of blockchain technologies. Section 3 explains the industry Blockchain methods, Section 4 presents the discussion and analysis part of the paper, and Section 5 presents conclusion and future scope.

2. Application of blockchain techniques in industries

Different sectors have adopted blockchain technology with innovations in both design and applications. It facilitates cross-border payments in finance and banking, helps with the execution of smart contracts in a manner that increases the levels of efficiency and reduces time, supports secure management of electronic health records in

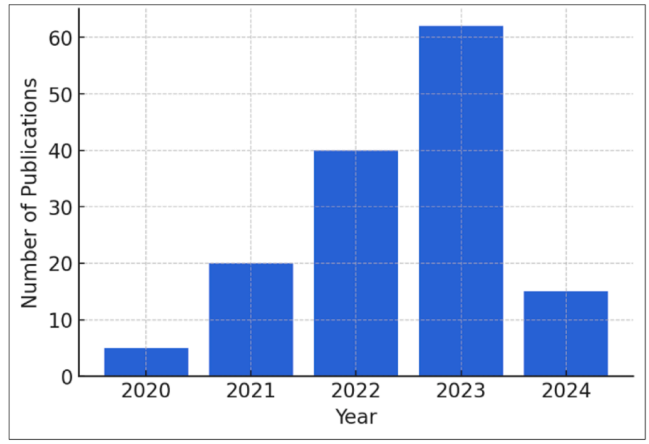

Fig. 3. Year wise publication.

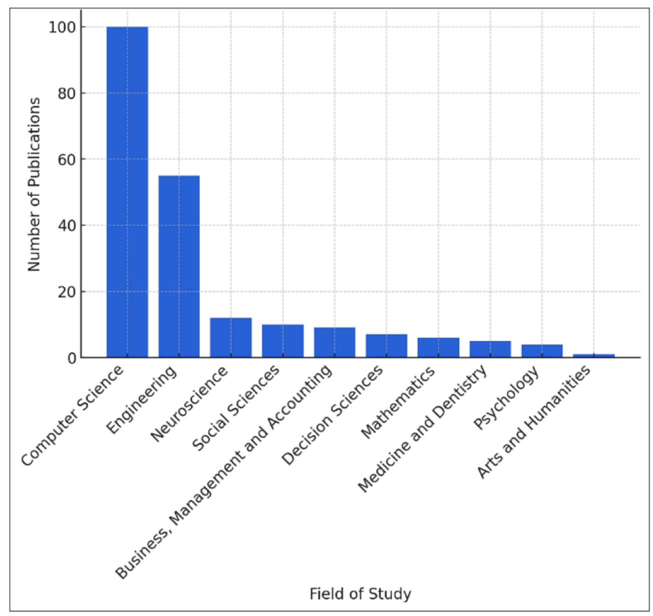

Fig. 4. Number of publications and subject area.

Table 1
Blockchain technologies.

Blockchain type	Advantages	Disadvantages	Use cases	Examples
Public	Reliable and Secure, Decentralized and Anonymity, and Immutable and transparent	Slow transaction, High Energy Consumption, Acceptance Issues	Traditional financial systems, decentralized applications (dApps)	Bitcoin, Ethereum, Litecoin
Private	High Speed, Scalability, Privacy & permissioned access.	Security concerns, Centralized control, Trust issues (Required trust in centre Authority)	Voting Systems, Internal Auditing, Supply Chain Management	Hyperledger, Corda
Hybrid	Ecosystem-driven, Lower Costs, Combined benefits of public and private block chains, Balanced Operations between public and private attributes	Efficiency can be limited, Lack of full transparency, Managing the ecosystem can be complex	Healthcare, government service, real estate, and financial institutions	Ripple network, XRP token
Consortium	High speed transaction, Privacy, Efficient for industry collaboration	Requires approval from consortium members, Transparency concerns, Limited Public Access	Enterprise Solution, and payment processing	Quorum, Multichain

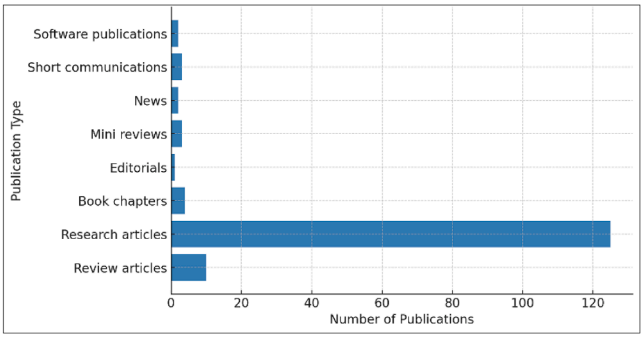

Fig. 5. Number of publications, including various article categories.

healthcare, and enhances the integrity of clinical trials. In real estate, it finds use in property title management and in tokenizing real estate for fractional ownership, enabling easier transactions. Fig. 6 shows the exponential growth in the application of blockchain technology [15]. In the healthcare sector, blockchain improves clinical trials by enhancing reproducibility and transparency through the recording of trial data and verification of results [16]. This ensures transparency and accuracy are maintained in research processes. In intellectual property, blockchain provides a secure mechanism for digital rights management. It ensures fair compensation for creators and protects their intellectual property, hence fostering trust and fairness [17]. The gaming and entertainment industry benefits from blockchain through the use of smart contracts, which guarantee royalty payments and enable fair income sharing. Blockchain also allows players to own and exchange digital assets outside gaming systems, enhancing ownership and flexibility [18]. In the case of voting and governance, blockchain ensures decentralized governance, which opens the decision-making process and ensures more transparency. Additionally, blockchain allows for secure voting with traceability, reducing fraud within a supply chain, as mentioned by [19].

In the energy and sustainability sector, blockchain allows for the creation of an auditable system that tracks carbon emissions to foster sustainability. It also supports decentralized energy grids, allowing peer-to-peer energy trading for renewable energy sources [21]. Identity management is significantly improved with blockchain-based self--sovereign identity systems, which ensure the secure management of personal data. These systems reduce the risk of identity theft and unauthorized access to sensitive information [22]. In government and public services, blockchain secures the issuance of digital identities and cuts bureaucracy. The decentralized nature of the technology promotes trust in administrative procedures [23]. In a similar way, supply chain management benefits from blockchain because it can maintain traceability and transparency, thereby reducing fraud and ensuring the authenticity of merchandise [24]. These applications underpin the transformative potential of blockchain across many domains.

2.1. Blockchain techniques in supply chain management

Supply chain management incorporates various blockchain techniques that can enhance traceability, security, and efficiency. It also allows supply chain finance to provide smooth processes of payment and builds trust in transactions between different parties. This blockchain technology makes it easier for compliance and auditing by recording regulatory data in a secure manner and prevents counterfeiting because

Fig. 6. Applications of Blockchain [20].

the verification of goods' authenticity is obtained. Blockchain further enhances supplier management through the tracking of supplier reputations and allows collaboration by sharing data and enabling interoperability. It also contributes to sustainability and ethical sourcing since it guarantees transparency in material sourcing. By addressing key points, blockchain drives greater efficiency, accountability, and transparency across supply chains. Fig. 7 illustrates some of these blockchain techniques, while Table 2 describes specific applications of these techniques in supply chain management.

Blockchain technology is extensively used in supply chain management to enhance efficiency, traceability, and trust. Distributed ledger technology ensures that events occurring within the supply chain are securely recorded in a tamper-resistant manner [32]. Every participant retains a copy of the transaction record, minimizing data modification risks. Smart contracts automate various supply chain processes, including fulfilment, payment settlement, and compliance inspections. These contracts guarantee the instant execution of predefined actions, which can be releasing payments right after shipment delivery [33].

Blockchain helps to enhance traceability and provenance by recording a product's journey right from raw materials to the end user [34]. This ensures authenticity and thus easy identification of problems or rejections in a very short time. The integration of RFID and IoT with blockchain, as explained by [35], improves visibility through the secure recording of data obtained from tracking devices, which enables the real-time monitoring of goods. Blockchain-based solutions revolutionize supply chain finance by improving transaction visibility and reducing risks related to financing and inventory levels [36]. The solutions make it easier for suppliers to obtain credit and manage cash flow. Blockchain also simplifies compliance and auditing processes by providing a visible, immutable record of regulatory adherence across the supply chain [37]. The significant advantage of counterfeit prevention, since blockchain is immutable, enables consumers to verify product authenticity through QR codes or NFC-enabled devices [38]. The management of suppliers is enhanced by establishing distributed reputation systems for assessing supplier performance and history [39]. It assists in informed decisions about the selection of suppliers. Blockchain enables seamless data sharing and interoperability among supply chain partners fostering collaboration and process efficiency [39]. It also supports sustainability and ethical sourcing by providing transparent data on material sourcing, thus promoting better decision-making for consumers and encouraging adherence to sustainability policies [40].

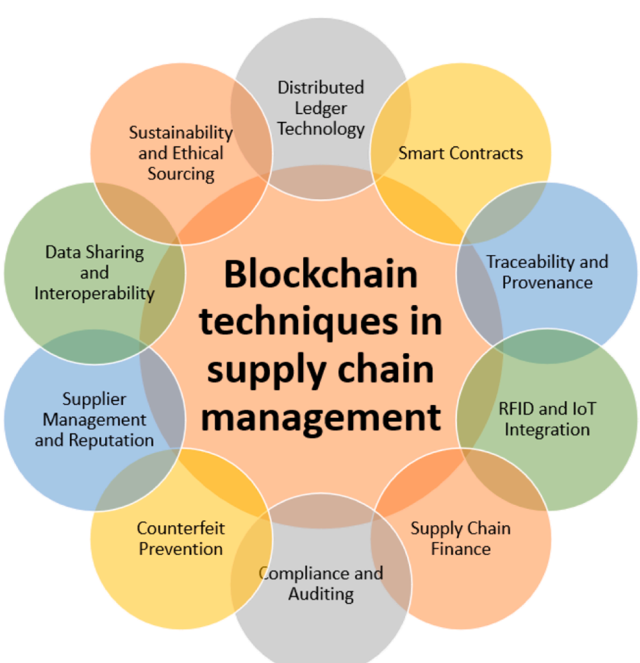

Fig. 7. Blockchain techniques in supply chain management.

While blockchain technologies offer numerous advantages in regard to supply chain management, real success will require stakeholder collaboration, standardization efforts, and the overcoming of a number of key issues related to scalability, interoperability, and data security. Broader dissemination is expected within industries as the technology matures. The ability to handle high volumes of transactions faced by blockchain systems in ever-increasingly complex supply chains ensures performance [38]. The current blockchain technologies are too unscalable to go into high-scale supply chain management applications, such as small-scale construction projects are especially facing challenges in the adoption of blockchain, usually because of a lack of technical resources and expertise [2]. Table 2 presents key research articles that provide insights into the concept, proposed solutions, and the benefits of blockchain technology across various industries.

Existing blockchain implementations are plagued with scalability and energy consumption problems that limit their usefulness for high-frequency supply chain transactions. Interoperability is an issue, because integration among several blockchain platforms as well as with traditional systems remains in infancy. The majority of studies involve transaction recording, not the utilization of real-time data to provide predictive analytics. While IoT is incorporated in a few solutions, the potential for AI-driven predictive analytics in supply chains enabled through blockchain remains underexploited. Also, current applications address common supply chain challenges, but industry-specific customization, particularly in sectors like renewable energy and precision agriculture, requires more research and application.

3. Blockchain in the industries

There has been great attention to blockchain technology across various sectors, with a wide adoption. The distributed database system basically makes the record of data and transactions in a decentralized computer network, securely and transparently. It's a new innovation to an old problem in industries. While all these eventualities are expected of it, the system faces many challenges in terms of regulatory uncertainty and scalability. However, with the help of continuous research and development, such obstacles are likely to be abated. As the technology develops further, we can expect more innovative and practical uses of blockchain throughout various industries. Table 3 provides an overview of blockchain technologies being used in many industries.

Blockchain implementation in the renewable energy sector is still underdeveloped compared to its implementation for supply chain, textile, and pharmaceutical use cases. There appears to be a lack of end-to-end studies of the use of blockchain and AI/ML for predictive analysis in the energy market as well as fault detection. P2P energy trading through blockchain technology is still in its infancy without defined regulations for real-time-based transactions as well as settlements with smart contracts. In addition, regulatory and policy impediments remain obstacles to blockchain implementation in energy markets and need further exploration.

Blockchain technology faces several challenges, each required targeted solutions to enhance its adoption and efficiency. Scalability remains a critical issue, particularly for public blockchain networks like Ethereum and Bitcoin, which struggle with high transaction volumes and real-time demands. Solutions are sidechains, sharing mechanisms, and layer-two systems are being explored, while private or collaborative blockchains offer alternatives for industrial applications [46]. Interoperability is another significant hurdle, as legacy systems often face compatibility issues with blockchain networks. This can be addressed by developing standardized APIs and protocols to enable seamless integration, along with cross-chain solutions like atomic swaps to enhance interoperability [47]. Data privacy and security concerns arise despite blockchain's immutability and inherent security features, especially in sectors handling sensitive information. It would also be important to

Table 2
Blockchain techniques in supply chain management.

Reference	Industry/service provider	Address the problems	Concept	Solution	Benefits
[25]	Transportation	There is a requirement for more information about the provenance of the goods, lack of updated information, and hence, the difficulty of tracking the movement of the goods	Details of the duration of delivery, confirmation of receipt of the product, and status of shipment that was safely stored in a block then went into the blockchain..	Under a blockchain based supply chain, the data is verified and thereafter kept within the blockchain network. The immutability of the blockchain guarantees that the data stays unchangeable and unopposed to falsifying. As so, the recipient of such material might be quite confident in its accuracy and validity. Once the provider has kept data inside the blockchain network, it becomes accessible.	The enhanced credibility and transparency of the supplier chain.
[26]	Industry 3.0 and Industry 4.0 in manufacturing	Capturing and storing substantial data with blockchain technology is a significant endeavour.	Integrated blockchain technology with distributed storage mechanisms to present a blockchain-based solution tailored for the supply chain domain.	The Inter Planetary File System (IPFS) provides an actual, real-world solution. IPFS is distributed file system that tries to connect all computational devices with a unified file system. IPFS allows people to use vast amounts of data and then add the immutable and permanent IPFS links into a transaction in a blockchain.	Blockchain technology together with distributed storage enhances supply chain system appropriate for next-generation industry.
[27]	Food and Beverages, Automotive Sector, Aerospace sector, Textile and Apparel, Shipping and logistics	Traceability	Distributed ledger technology (DLT) based supply chain tracking solutions	Based on the underlying reasons and intended goals of applying traceability measures, a new method founded on empirical data to define the degree of Supply Chain Traceability (SCT).	Enhances transparency, ensures compliance, improves efficiency.
[28]	Cobalt industry	The monitoring of the performance of environmental, social, and governance (ESG) and compliance within sectors characterized by inadequate regulatory and institutional frameworks.	A framework is required to establish a connection between blockchain source data and Environmental, Social, and Governance (ESG) measures.	Constructed blockchain designs that are both interoperable and comprehensible.	Enhances ESG monitoring by ensuring compliance, transparency, and interoperability in sectors with weak regulatory frameworks.
[29]	Agri-based industry	Issues with factory monitoring	The Ethereum blockchain technology is used to monitor and record the activity of shareholders.	IoT play a crucial role in generating and using digital data across the distribution process, intending to achieve enhanced transparency and traceability.	Enhance transparency and traceability in the Agri-based industry
[30]	COVID-19 vaccines	Detection of COVID-19 vaccines and supply chain traceability.	A network based on blockchain technology.	Integration of private and public blockchains helps to boost transaction capacity. Helping to standardize and govern the data flow could depend on blockchain technologies.	Immutable Vacledger is linked to distributed peer-to-peer file systems that record everything that has ever happened and every transaction that has ever been made.
[31]	Agri-food	Traceability	Smart contracts are used in a multi-agent system to streamline supply chain management. To record all transactions of supply chain, use the blockchain technology.	Blockchain-based supply chain model with integrated agent automation.	Enhances COVID-19 vaccine detection and supply chain traceability
[1]	Bunker supply	Successful Resolution of Bunker Quality Concerns	Blockchains can be additionally used to validate electronic bunker delivery notes to improve quality and quantity bunker disputes and the new International Maritime Organization 2020 regulations.	Bunker disputes	Enhances confidence and reputation within the bunker business.

minimize these challenges with the help of permissioned blockchains that have restricted access, methods of encryption, and sophisticated techniques such as homomorphic encryption and zero-knowledge proofs for privacy in public blockchains [48]. The other barrier is regulatory matters. Different industries need to act within the ambit of specific legislation and regulations. Collaboration with regulators and showcasing the potential of blockchain and transparent frameworks will help address these concerns [49].

Energy consumption remains another issue, especially about Proof-of-Work mechanisms, which are seen as very harmful to the environment. Moving toward energy-efficient models like Proof-of-Stake or the utilization of renewable energy sources already decreases these issues, while hybrid or private blockchains further enhance the efficiency of this technology [50]. In addition, the fast evolution of blockchain has entailed a shortage of skilled workers in this field. Addressing this gap involves promoting training programs, partnering with educational institutions, and supporting open-source initiatives to cultivate expertise [51]. Additionally, perception and adoption barriers persist, as some

Table 3
Blockchain scope for industries.

Reference	Industry	Scope
[1]	Coffee Industry	A framework for changing the supply chain business processes of coffee industry with uses of blockchain-capable workflows.
[41]	Railcar industry	Life cycle assessment (LCA) methodology is employed to facilitate tracking components and orders throughout the supply chain (SC) of railcar remanufacturing. The research focused on enhancing Product Lifecycle Management (PLM) by integrating blockchain and Configuration Management (CM) for traceability, using Supply Chain (SC) information systems.
[42]	Textile and clothing industry	Using the mass balancing validation procedure, the operational illustration of a blockchain framework is used to establish traceability for organic cotton.
[3]	Oil industry	Blockchain technology is strongly advised for intricate and interconnected supply chain networks, particularly within the oil sector. The relationship between Blockchain technology attributes and supply chain management methods may help managers and decision-makers understand how to use Blockchain in actual scenarios.
[43]	Textile and clothing	Distributed ledger technology (blockchain) architecture for Internet of Things (IoT) applications facilitate commercial transactions between various entities in the garment industry's supply chain. A blockchain-based distributed ledger and Internet of Things applications collaborating to provide transaction services within a global textile consortium. The IoT is a global network for the sentient in which interconnected objects that communicate with one another through standardized protocols and individual addressing schemes to achieve shared objectives in collaboration with other network nodes and external business partners. Decisions in the apparel industry could be facilitated by the data collected by Internet of Things applications throughout the supply chain.
[44]	Fashion Industry	Researchers proposed that blockchain may provide transparency and trust in the supply chain., therefore protecting consumers and stakeholders against greenwashing. This technology exposes greenwashing, which might backfire for businesses not doing the right thing. Additionally, corporations cannot conceal unsustainable behaviours using blockchain.
[4]	Food	Demonstrate a blockchain-based quality control framework tailored for localized food delivery networks.
[45]	Food	Implementing a blockchain based service system for pharmaceutical with aims to address many issues, including limited efficacy, lack of transparency, and susceptibility to data tampering. The solution encompasses the whole recall process, which contains decision-making, the examination of out-of-specification/out-of-trend (OOS/OOT) occurrences, the actions taken by the working group, the implementation of Corrective and Preventive Actions (CAPA) a recall management system enables the reduction of time, improvement of transparency, and safeguarding of data integrity in the context of pharmaceutical recalls.
L. Guo et al.2022	Supply chain finance	Proposed a new approach using IoT and Blockchain technologies to handle data in Supply Chain Finance (SCF), called BC4Regu, the suggested structure solves information asymmetry. BC4Regu is used in several contexts, and its usefulness is validated by a theoretical study applying the principle-agent model.

sectors hesitate to embrace blockchain due to misunderstandings and scepticism about its benefits. Running pilot projects, sharing best practices, and distributing educational resources can help build trust and foster adoption [52]. The high costs associated with blockchain implementation and the need for clear return on investment (ROI) metrics poses additional challenges. Conducting cost-benefit analyses and emphasizing high-impact use cases can demonstrate value and encourage investment [53].

Blockchain technology is increasingly recognized as a central enabler of security, scalability, and efficiency in 6 G wireless communication networks. Blockchain's decentralized security guarantees prevent unauthorized access and data breaches. Its distributed structure prevents single points of failure, enhancing the integrity and privacy of IoT devices within 6 G networks [46]. Moreover, smart contracts facilitate autonomous resource and network management, which reduces service provision latency by a significant amount [10]. This aspect is particularly beneficial for dynamic spectrum sharing, intelligent network slicing, and secure mobility management in 6 G [12]. Blockchain facilitates open edge computing and decentralized AI-driven decision-making, enabling thrustless peer-to-peer communication for ultra-reliable low-latency communication (URLLC) applications [54].

4. Discussion and analysis

There are regulatory uncertainties and a lack of standardized policies on the widespread adoption of blockchain [55]. The challenges of real-world implementation include the fact that a shift from traditional supply chains to blockchain-based systems is very challenging for any organization. Several challenges are related to training, change management, and technical hurdles. All these require sufficient consideration and planning from business. Another issue that needed more research involved the environmental impact due to blockchain technology. The consensus mechanisms of blockchain networks, especially the proof-of-work-type consensus mechanism, have faced criticism for the high amounts of energy they use.

Other than these technological challenges, scholars have also queried the factors determining the uptake and resistance to adopting blockchain in supply chains. Resistance to change, transparency, and trust were critical factors in deciding whether supply chain stakeholders would take up blockchain technology. It is extremely crucial to know these variables in an effort to enhance broad acceptance and universal adoption. Another significant facet under discussion is the maturity of smart contracts. Smart contracts, despite their huge potential in automating supply chain processes, are still constrained in addressing complicated business logics and real-world scenarios. Researchers have put efforts into enhancing and adjusting smart contracts for improved supply chain management needs. The potential of blockchain to further sustainable supply chains has also drawn a lot of interest. The technology makes it possible to trace and authenticate environmental and ethical credentials to guarantee supply chains align with sustainability goals. Researchers have researched how blockchain can enhance transparency and accountability in sustainability-focused supply chains [55]. Regulatory uncertainties remain a nagging problem. To mitigate against this, there have been calls by some scholars for regulatory sandboxes risk-free places in which blockchain projects may be tested against rising regulatory standards and thereby bridge the gap between innovation and compliance.

Some of the key milestones in blockchain adoption have been documented across various fields. Although cooperation, education, and awareness continue to be important, the development of regulatory standards has also come a long way. Research has also advanced in the areas of scalability solutions, smart contract functionality, data sharing, and interoperability.

The increased influence of blockchain is being seen in terms of higher number of adoptions and pilots. Future trends imply more interconnectedness between sectors with higher interoperability and improved multi-tiered supply chain visibility. Technologies such as digital identity authentication, supply chain financing, and IoT integration will likely make improvements. Moreover, decentralized marketplaces, efforts at sustainability, and ESG tracking will also be among the driving forces in shaping the future of blockchain in supply chains. While the energy needs of blockchain are still a subject of concern, energy-efficient consensus algorithms are already being studied. Hybrid designs combining elements of both public and private blockchain networks are also under development to optimize efficiency and scalability.

Smart contracts can be daunted in complex value chains by costly integration and trust problems. A lack of technical expertise and the complexity of integrating blockchain deter adoption, especially in healthcare organizations [56]. Prohibitive costs, uncertainty of ROI, governance, and industry competition also slow down adoption. Organizational resistance to change and legal challenges, such as liability in decentralized networks, also pose challenges. Ethical concerns of data ownership and consent must be addressed. Improving user experience and enabling collaboration among stakeholders will be key to more pervasive blockchain adoption as the technology evolves.

5. Conclusion

Blockchain technology has drawn a great attention across industries due to its potential to revamp processes, enhance transparency, and build more efficient ecosystems. There remain a variety of challenges, primarily on scalability and performance, interoperability and integration, data privacy and security, regulatory and legal frameworks, cost-benefit analysis, adoption barriers, and environmental sustainability. Industries are becoming more aware of the need for energy-efficient consensus mechanisms and metrics to track blockchain networks' environmental footprint in the pursuit of sustainable computing. Despite these challenges, blockchain uptake is advancing with advances in traceability, transparency, interoperability solutions, IoT integration, digital identity, and smart contracts. The future of blockchain environments across industries is towards regulatory evolution, enhancing interoperability, industry-specific solutions, convergence with sustainability, mass adoption, and novel applications. Future research efforts can look into advanced consensus processes, constructing privacy technologies, and simplifying user experiences in order to speed up broader adoption. Bridging existing research gaps and shattering technology constraints will release the transformative potential of blockchain. As research and practical implementations further evolve, blockchain is an accelerator of a more transparent, efficient, and sustainable digital economy, cementing its central role in technological advancements across sectors.

CRediT authorship contribution statement

Narendra Kumar: Writing – review & editing, Writing – original draft, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Krishna Kumar:** Writing – review & editing, Visualization, Validation, Supervision, Methodology. **Anurag Aeron:** Writing – review & editing, Writing – original draft, Formal analysis, Data curation, Conceptualization. **Filippo Verre:** Visualization, Validation, Supervision, Methodology, Formal analysis, Data curation.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

No data was used for the research described in the article.

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