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| RESEARCH ARTICLE

Blockchain-Enabled Lean Automation and Risk Mitigation in Supply Chain 4.0 A Systematic Review and Future Directions

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| ABSTRACT
Supply Chain 4.0, powered by Industry 4.0 technologies, will turn traditional operations into smart and agile systems that are significantly more efficient, resilient, and sustainable. However, most of the available literature related to blockchain enabled supply chains focuses on individual applications such as fraud prevention or logistics optimization, and very few have considered its holistic potential in lean automation and risk mitigation. Besides, limited integration of complementary technologies like IoT and AI, challenges to scalability, interoperability, and regulatory issues are still considered to be crucial implementation obstacles. This review fills these gaps through a systematic analysis of insights from more than 100 peer-reviewed studies across diverse industries, including healthcare, agriculture, and manufacturing. It synthesizes the potentials of blockchain in lean automation and operational resilience, providing a conceptual framework for integrating Industry 4.0 technology toward enhanced end-to-end performance in supply chains. Further, the review puts forward workable strategies on how to overcome various barriers to the implementation of such technological integration and pinpoints future research avenues toward fostering sustainability and a human-centered approach to supply chains according to Industry 5.0 principles. By addressing critical research challenges, this paper offers actionable insights for researchers, policymakers, and industry practitioners to build resilient and transparent global supply chains.

| KEYWORDS

Lean Automation, Risk Mitigation, Supply chain, Blockchain

| ARTICLE INFORMATION

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1. Introduction
Supply chains form basically the backbone of the entire global economy, which enables the flow of goods, services, information, and funds across connected networks. Traditional supply chain models are linear in nature and siloed in operation, but always have been instrumental in meeting the demands of the marketplace. But as the global marketplace becomes increasingly dynamic and interlinked, these models will prove seriously restrictive. Globalization, customers changing requirements, and the increased speed at which technology is developing make traditional supply chains unable to respond to existing needs in an agile or resilient manner [1].

These challenges find their answer in Supply Chain 4.0, which is considered an evolution in supply chain management. Supply Chain 4.0, conceptualized on Industry 4.0, will use a suite of sophisticated technologies like the IoT, AI, big data analytics, and cloud computing to drive smart, connected, and autonomous operations [2]. Put together, these technologies promise to enhance efficiency, responsiveness, and sustainability in supply chains by overcoming certain inefficiencies and limitations that have traditionally characterized supply chains [3].

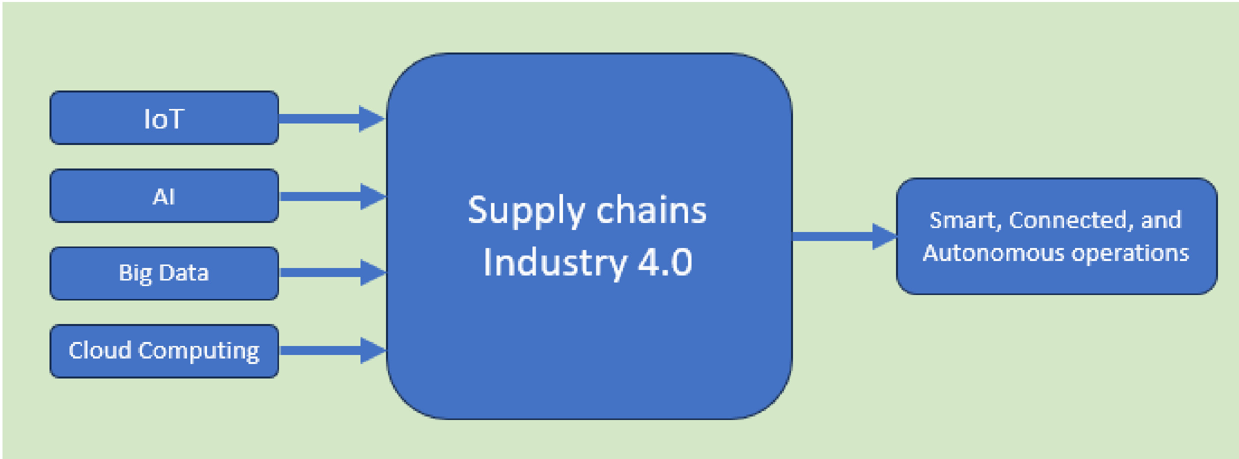

Fig1. Enablers of Supply Chain 4.0: Driving Smart, Connected, and Autonomous Systems

The transition to Supply Chain 4.0 had its challenges. Traditional supply chains have many points of inefficiency: fragmentation in data systems, high levels of lead time, and heavy reliance on manual processing [4]. Poor supply chain transparency across tiers leads to fraud, counterfeiting, and disruption [5]. These vulnerabilities were in stark highlight during the COVID-19 pandemic, which showed and told how fragile global supply chains were, hence requiring more resilient, agile, and transparent systems [6]. Innovating the solution to such challenges calls for ingenious solutions in line with Industry 4.0's spirit.

2. Blockchain as Enabler

2.1 Overview of Blockchain Basics.

From its very first appearance in 2008, serving as the underlying technology for Bitcoin, to today's date, blockchain has been on quite a journey outside of the concept of virtual currencies [7]. On a very general level, blockchain is no more than a distributed means of recording and verifying the occurrence of a transaction over a decentralized network of sorts. Thus, it is very decentralized and, at the same time, void of the need for any sort of intermediaries; such transactions are considerably safer and far more effective, thus making them totally transparent [8]. Each transaction, when verified by the consensus mechanism, is added to an immutable block in a continuous chain of records. This makes data integrity possible because tampering with one block requires consensus within the entire network [9].

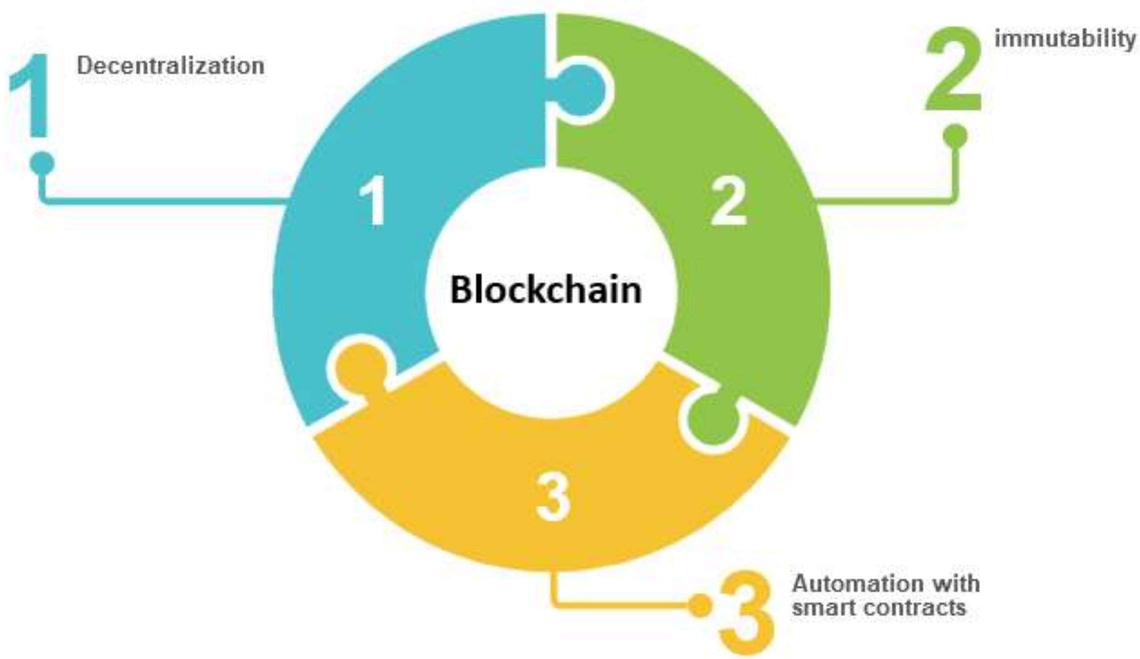

Fig 2. Key attributes of blockchain

The key attributes of blockchain are decentralization, immutability, and automation with smart contracts, and in these ways, blockchain serves as a perfect tool for taming the most advanced features of modern supply chains. Decentralization makes sure that any data access is equally guaranteed by every participant in a supply chain network, thus establishing a line of trust and collaboration among them [10]. The immutability of records creates reliability for audit trails under regulatory compliances and dispute resolution processes [11]. Smart contracts ensure that different conditions of processes, for instance, are automatically concluded by making automatic payments after conditions have been fulfilled, conducting inventory, or complying with legal checks [12].

2.2 Blockchain Value Proposition in Supply Chains

In the context of supply chains, most of the critical challenges related to traditional models have been addressed in blockchain. Its contribution pertains especially to enhancing transparency and improving traceability [13]. The method allows stakeholders to track shipments and verify their origin and authenticity instantly because of an immutable source of truth that it brings into a single lot. This capability is especially important in industries such as healthcare, where counterfeit drugs create very serious risks, and agriculture, where food safety and sustainability are at stake.

This may not be the only significant merit, as the blockchain can provide greater levels of operational efficiency. The use of papers and manual processes is common within the supply chain systems to this day, but when this is done through digitization and automation on blockchains, it could trim the time and cost involved for different activities such as order processing, invoicing, customs clearance amongst others [14]. For example, blockchain implementation in logistics has been proven to reduce administrative costs by up to 20% while improving accuracy and speed [15].

Besides, blockchain improves risk management by providing better visibility in supply chain activities. The potential disruptions arising due to a particular supplier's defaulting or shipment delays or compromised product quality can be completely avoided through better visibility, hence helping the organizations take more proactive action [16]. Moreover, since the nature of blockchain is that records are tamper-proof and secure, it really works well in reducing fraud and assuring compliance with regulations [17].

3. Problems with Traditional Supply Chains

Traditional supply chains are beset by a number of inherent problems that make them poorly suited to satisfy the demands of today's marketplace. Among the most critical of these issues is inefficiency: the supply chains are often typified by long lead times, excessive inventory, and poor demand forecasting, which translate into higher costs and reduced competitiveness [18]. All these inefficiencies are compounded by the lack of real-time data and reliance on manual processes that hamper effective decision-making and responsiveness.

The lack of visibility is another huge challenge. Supply chains involve tiers of suppliers, manufacturers, distributors, and retailers-moving products within independently owned and operated systems. Fragmentation in the supply chain makes end-to-end visibility hardly achievable; hence, resulting in undetected cases like counterfeit goods, unethical labor practices, and environmental violations [19].

Besides being inefficient and non-transparent, traditional supply chains are also eminently vulnerable to risks and disruptions, coming from natural calamities, geopolitical conflicts, cyberattacks, or pandemics. For instance, the COVID-19 pandemic brought supply chains around the world to a grinding halt, thus bringing to the fore the need to make supply chains robust and responsive [20]. Further, the linearity of the traditional supply chain contributes to sustainability issues like depletion of resources, waste, and high carbon emissions [21].

4. Gap in Research

While the uses of blockchain in supply chain management have been widely explored, much of the existing research is focused too narrowly on a particular industry or aspect of logistics optimization or fraud prevention [6][22]. It provides little in the form of a holistic look at how blockchain can fundamentally change Supply Chain 4.0. Further, there are under-explored critical areas such as the integration with other Industry 4.0 technologies, what role blockchain will play in achieving sustainability goals, and the challenges in implementation [23][24][25].

This review aims specifically at filling these gaps comprehensively by distilling insights more than 100 peer-reviewed pieces of evidence from a wide array of sectors' health care, agriculture and manufacturing. The review tries to give a holistic approach within which knowledge on blockchain's actual transformative potential may be evolved and point out avenues for an agenda of future research.

5. Objectives

The main purposes of this review are as follows:

I. The analysis of how blockchain is being integrated into Supply Chain 4.0 and, from there to enable lean automation in risk mitigation.

II. To synthesize insights from case studies across various industries, providing a comprehensive understanding of blockchain's applications.

III. To critically discuss the challenges in adopting blockchain, including scalability, interoperability, and regulatory issues, and propose solutions.

IV. The identification of opportunities opening up for future research, with a special emphasis on sustainability and integration of blockchain with emerging technologies such as IoT and AI.

The aim of the paper is to critically establish the transformation potential of Supply Chain 4.0 by blockchain and to perform an in-depth synthesis considering a wide set of factors that will serve as practical considerations for researchers, practitioners' communities, and policy makers amid ongoing efforts towards creating robust ecosystems. Addressing critical existing challenges with conventional supply systems and emphasizing distinctive opportunities entailed by the adoption, this work serves to upgrade the level of discussion about building robust, sustainable, transparent, and highly efficient supply chains for their prospective application in practice today.

Research Methodology

The approach followed here is SLR (systematic literature review), which is largely followed in the literature to systematically gather existing research into the desired study. The SLR methodology warrants that the review has transparency in its selection of studies, consistency in the presentation, and comprehensiveness in coverage to ensure an effective synthesis of insights and identification of research gaps. The steps that were followed in the current research are detailed next.

1. Systematic Literature Review Approach

1.1 Databases searched

Targets included several high-impact academic databases in order to ensure comprehensiveness, such as IEEE Xplore, ScienceDirect, SpringerLink, Wiley Online Library, and Taylor & Francis Online. These have been selected because they provide access to a large collection of relevant peer-reviewed journal articles, conference proceedings, and book chapters on blockchain, lean automation, and supply chain management. The searching was done by keywords and Boolean operators such as:

* Blockchain AND Supply Chain 4.0

•"Lean Automation AND Blockchain"

•"Risk Mitigation AND Supply Chain"

*"Blockchain Implementation AND Industry 4.0"

Search filters were applied for the results to be written in the English language; the year of publication was searched between 2008 and 2024 to capture fresh developments with a historical context when blockchain applications were used at supply chains.

1.2 Search Process and Refining Results

This first search produced over 2,500 articles. After de-duplication, titles and abstracts of the remaining works were screened. Articles on irrelevant blockchain topics, lean automation, and mitigation strategies of risk in supply chains were also eliminated. Full-text articles were considered in order to check the relevance, leading to 100 core studies which have been deeply analyzed in this review. These studies cover the core foundation of this review, cutting across industries, regions, and research methodologies [14][26].

2. Inclusion and Exclusion Criteria

2.1 Inclusion Criteria

The following criteria were applied to include articles:

I. Relevance to the Research Questions: Explicitly blockchain applications, lean automation, or risk mitigation within supply chain contexts.

II. Peer-Reviewed Sources: Apart from the conference proceedings, only publications in reputable, peer-reviewed journals were included.

III. Thematic Focus: Particular attention was paid to works related to the areas of technological integration, operations efficiency, and risk management.

IV. Empirical and theoretical contributions were considered in a balance of case studies and theoretical frameworks.

2.2 Exclusion Criteria

Studies were excluded based on the following:

I. Not Targeted: Articles that had too general or broad approaches to the topic of blockchain technology and were not precisely aimed at supply chains were omitted.

II. Redundancy: Articles whose findings are already represented in earlier, more comprehensive articles.

III. Obsolete Research: This covers only papers that had been published prior to 2010, since which no fundamentally novel aspects applicable to today's Industry 4.0 technology are expected, if indeed the foundation had originally set this process in motion.

3. Categorizing Studies Framework

Then, a thematic framework was developed in order to analyze the selected studies on a systematic basis. Therefore, research could be differentiated into three dimensions:

3.1 Lean Automation

Various studies from this dimension, assessing the capability of blockchain for automating supply chain processes with the aim of eradicating waste and thus reducing lead times, consequently contributing toward better operational efficiency. To cite an example, blockchain smart contracts were found very useful in the automation of inventory management and supplier payments, both having the least human intervention and hence the minimal occurrence of errors [27][28].

3.2 Risk Mitigation

This dimension is about how blockchain enhances the resilience of supply chains by providing supply chain transparency, traceability, and security. Most of the identified relevant cases are the prevention of counterfeits in pharmaceuticals, fraud detection in finance, and operational risk management in logistics [29][30].

3.3 Blockchain Implementation

It focuses on technical and organizational dimensions in adopting blockchain, including the problems of scalability, integration, and regulatory issues. These case studies, drawn from industries like agriculture and manufacturing, give real insights into the implementation strategies adopted and barriers [31][32].

4. Scope and coverage

4.1 Timeframe of Studies

This related literature review spans from the year 2010 up to 2024. This period encompasses the gradual evolution of blockchain-from the initial days when the innovation was only used in digital cryptocurrency to the present era when the supply chain management domain is already applying the power of blockchain. The decade also coincides with the rise of Industry 4.0, enabling an analysis of blockchain’s synergy with other emerging technologies.

4.2 Distribution Throughout Sectors

Studies were analyzed across the following diverse industrial sectors to gain a comprehensive understanding:

* Health care: Blockchain for drug traceability, patient data security.

Manufacturing: Quality control, just-in-time inventory, and supplier collaboration applications.

* Agriculture: Use cases in farm-to-fork traceability and sustainability initiatives.

Logistics: Integration of IoT for real-time tracking and optimization of delivery.

4.3 Geographic coverage

It also considered the regional point of view: studies have been from developed economies represented by the U.S. and Europe and emerging markets based on Asia and Africa. Such geographical diversity underlined how the adoption of blockchain varies across different regulatory environments, and technological infrastructures.

5. Methods of Analysis

The findings are appropriately synthesized by using a combination of these qualitative and quantitative methods:

I. Thematic Analysis: Themes and key patterns across the studies were identified to point out the different ways in which blockchain makes several contributions to supply chains.

II. Descriptive Statistics: This approach used metrics such as the number of studies by sector and year to illustrate research trends.

III. Comparative Analysis: Comparisons among the selected studies were done concerning methodologies, findings, and implications in order to highlight best practices and gaps in research.

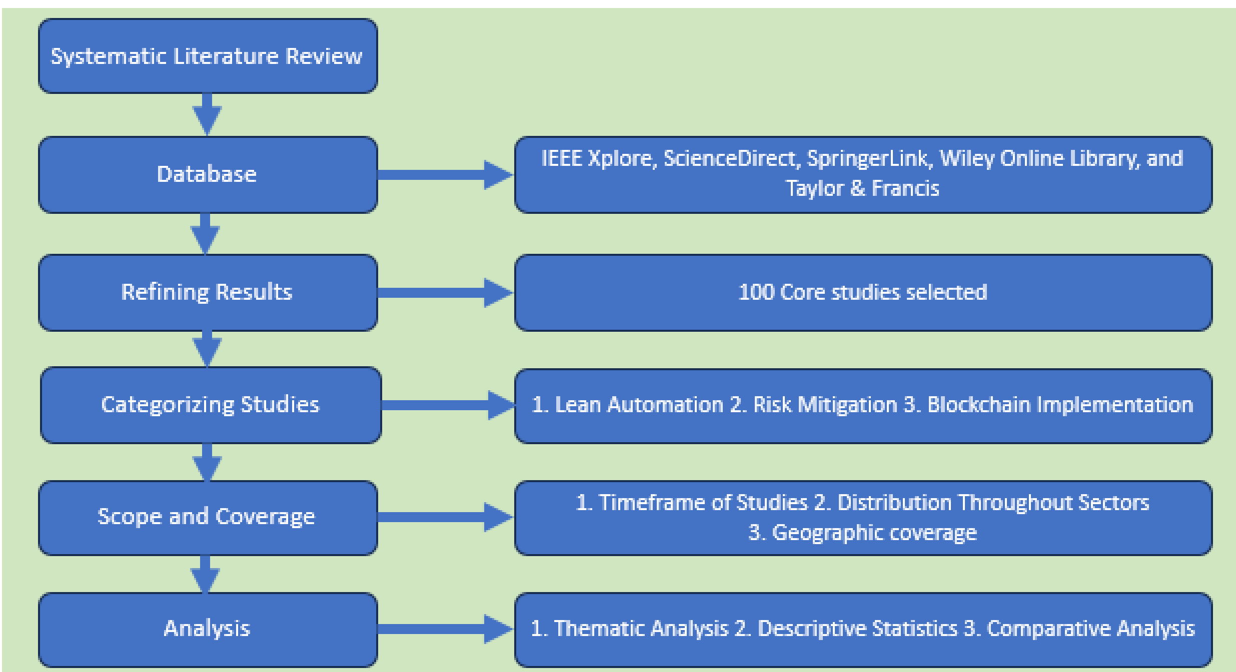

Fig 3. **Research Methodology**

3. Blockchain in Supply Chain 4.0: Literature Review

Blockchain technology has emerged as the cornerstone for reshaping supply chains in ways that greatly improve their transparency, operational efficiency, and risk management capabilities. This section provides a critical review of the literature with respect to the basics of blockchains, applications across industries, contribution of lean automation, strategies for mitigating risks, and comparison of blockchain frameworks.

3.1 Fundamentals of Blockchain

3.1.1 Key Features of Blockchain

Smart Contracts

Smart contracts are a set of programmable agreements introduced along with the blockchain platforms, such as Ethereum. They execute a set of actions automatically when predefined conditions are met. There are no intermediaries in such contracts, thus smoothing the operations and lowering transaction costs. In supply chains, this automation of processes involves everything from clearance of payments to updating inventory levels or compliance checks. Example: For international shipping, smart contracts can be issued to make a payment upon verification of delivery conditions using IoT sensors. The result is reduced disputes, as the technology offers a clear insight into the deal chain, ensuring every transaction happens effectively and transparently. There is evidence to suggest that more than a 30% reduction in administrative delay has been seen alongside improving cross-border trade reliability following the increase in smart contract adaption for logistics research [33][34][35].

Immutability

Immutability by blockchain ensures that once the data goes on-chain, it is irreplaceable and cannot be deleted. It is the tamper-evident attribute of this technology that gives it the most crucial elements in building trust among parties. Immutability in supply chains can be about delivering accurate record-keeping, whether it is related to keeping inventory, shipment records, or transaction records. Records within a pharmaceutical perspective shall forbid the alteration of critical products such as vaccines, since very minute deviances invite risks in public health. Immutability, for example, has been proven as one of the most influencing factors in the adoption of blockchain within highly regulated industries where audit trails and compliance are crucial [36].

Consensus Mechanisms

The consensus mechanism refers to the protocols that validate and secure the transaction occurring on the blockchain network. While mechanisms such as Proof of Work (PoW) provide security but are resource-consuming, newer mechanisms like Proof of Stake (PoS) and Practical Byzantine Fault Tolerance (PBFT) assure scalability and energy efficiency. Supply chain mechanisms ensure data integrity and decentralized decision-making. In decentralized supply chains, for example, the consensus mechanisms enable confirmation of a transaction with no central authority and still be fair and transparent [37].

3.1.2 Intersections with Other Technologies

IoT - Internet of Things

IoT combined with blockchain facilitates tracking of goods at every stage in the supply chain in real time. From temperature and humidity to the location of items, IoT sensors track everything and record this information on a blockchain for secure, transparent tracking. For example, perishable items are shipped under proper conditions of storage in the cold chain, in which temperature-sensitive shipments are traced using blockchain-based IoT systems. The combination will prevent losses and builds confidence among suppliers and buyers, since, at any point in supply, stakeholders can have vital data in real time [38][39].

Artificial Intelligence - AI

AI-powered systems analyze trends, optimize inventory management, and predict potential risks using information from blockchains. For example, machine learning models with access to historical data on a blockchain can forecast demand fluctuations that will make it easier for manufacturers to tune the production schedule in order to meet demand. Additionally, AI detects anomalies in blockchains, such as unusual forms of transaction patterns, and makes early warnings of fraud or the failure of systems. The interaction of this AI and blockchain encompasses especial value for the complex supply chain; it demands adaptive decision making, based on insight or data [40].

Cloud Computing

Integrating blockchain into cloud computing solves scalability issues through secure data storage and processing. The infrastructure for handling the computational requirements of blockchain, while ensuring data availability to stakeholders over large distances is afforded by cloud platforms such as AWS and Microsoft Azure. For example, big conglomerates use cloud blockchain solutions to manage supply chain activities across different international markets. This would also allow the integration of planning and decision-making since blockchain data in real time is available to all authorized stakeholders [41][42].

3.2 Supply Chain Applications

3.2.1 Healthcare

Prevention of Drug Counterfeiting

The major issues are the counterfeit, expensive drugs, sometimes at the cost of lives. Blockchain prevents at least this problem by assuring end-to-end traceability of pharmaceuticals. Each and every transaction within the supply chain of the drug-from the stage of manufacturing to retail-is recorded on an immutable ledger, serving as proof of its authenticity. Thus, MediLedger platforms check the origin of these drugs with the help of blockchain; therefore, the counterfeit ones would never reach the consumer side. Case studies reported on the case of blockchain adoption in the pharmaceutical supply chain, which significantly resulted in decreasing the incidences of counterfeiting by up to 50%, saved billions annually, and improved public health outcomes [29][43][44].

Data Privacy

Besides this, blockchain also addresses such a critical need for data privacy in healthcare. Often, sensitive patient information and pharmaceutical data are exchanged between several stakeholders; as such, they are extremely vulnerable to breaches. Blockchain provides the guarantee that only those parties that are authorized can view the data, maintaining confidentiality while sharing it securely. For example, decentralized blockchain networks may allow hospitals and suppliers to share clinical trial data without revealing any sensitive patient information and, at the same time, adhere to some tough regulations like HIPAA [45][46].

3.2.2 Agriculture

Traceability

Transparency of origin and production methods has become a significant demand for modern consumers. It creates a tamper-proof record of agricultural products on their journey from farm to fork, thus building trust and making one accountable. For example, the blockchain pilot at Walmart shaved tracing the origin of its mangoes from seven days down to just a few seconds. This capability enhances food safety by affording an opportunity for rapid recall in the event of contamination [47][48].

Ecologically Friendly Practices

Blockchain promotes sustainable farming by ensuring that standards of sustainable farming are adhered to. Smart contracts will ensure farmers practicing organic standards and reduced pesticide usage are auto-incentivized. The blockchain projects for coffee farmers have been utilized to authenticate the source of ethics and enable farmers to get fair compensation directly rather than through intermediaries [49].

3.2.3 Manufacturing and Logistics

Real-time tracking

IoT coupled with blockchain offers a very succinct and crystal-clear tracking system for goods across the supply chain. For instance, Maersk, a global leader in logistics, and IBM's TradeLens track shipping containers and can offer real-time statuses of location and condition to supply chain participants. The transparency thus created causes fewer delays and builds trust across the supply chain. Specifically, on-ground studies after the deployment of TradeLens have demonstrated that it actually streamlined customs clearance and reduced processing by up to 20% [14][50].

Efficient Inventory Management

Smart contracts automate inventories based on the quantity in stock and demand forecasting. This is quite advantageous in the JIT manufacturing environment since it prevents overstocking of inventories. For example, using blockchain, some manufacturers reported a 25% reduction in overstock and a massive improvement in supply chain responsiveness [36].

3.3 Blockchain-Enabled Lean Automation

Principles of Leanness in Supply Chain 4.0

Lean principles work on the concept of no waste and more efficiency by aligned production to demand. Blockchain, in fact, does support these by way of automation of processes, enabling correct demand forecasting, and real-time visibility of inventories. In this context, for example, blockchain in the automotive industry synchronizes supplier networks to reduce idle inventory and improve production timelines [51].

Case Studies on Lean Automation

In the retail sector, Walmart employed blockchain to highlight products in their inventories that were nearing expiration dates; this helps reduce food wastage. The system brought down the inventory wastage rate by 30% while improving customer satisfaction. In the same manner, the automotive firms, such as BMW, have instituted blockchain to optimize supplier coordination; this allows them to reduce delays in production and operational costs [52][53].

3.4 Blockchain for Risk Reduction

3.4.1 Categories of Risk

Cybersecurity Threats

More often than not, modern supply chains become increasingly digitalized and, as a consequence, are increasingly exposed to cyber-attacks, data breaches, and ransomware. By decentralizing where the information is stored, blockchain renders any kind of compromise in a system impossible for an attacker to perform, which reduces cybersecurity risks to a minimum. Unlike traditional systems reliant on one point of failure-a single central database-blockchain doesn't have that one node. For example, in a logistics network, the blockchain allows encrypting the shipment data across various nodes such that if one of them gets attacked, the data remains safe and immutable. The application of blockchain in cybersecurity has reduced the incidents of tampering with data considerably in industries like finance and healthcare, where the exchange of data securely is considered paramount [27][54].

Operational Risk

Supply chains are always vulnerable to late shipment, supplier failure, or inventory record inaccuracies. Blockchain solves these risks by offering real-time data and complete transparency across all stakeholder interactions. For example, this is how blockchain technology could be applied in the automotive industries, where manufacturers can have tracked supplier performance and early warnings of potential bottlenecks, thus enabling proactive interventions. Operational disruptions in blockchain-enabled supply chains are resolved faster, by 40% and more, due to better visibility of data [55].

Fraud

Among all concerns, fraud-from the manipulation of invoices to actual distribution of counterfeit products, or unauthorized shipment record changes-has to be considered one of the major threats in an international supply chain. Blockchain immutability means each transaction is tracked and validated for its accuracy, while fraud is less likely. Everledger, for instance, uses this technology in the authentication of high-value items such as diamonds; owing to the traceability of origin and ownership of goods, it reduces fraudulent claims, increasing consumer confidence in luxury markets [56][57].

3.4.2 Risk Mitigation Strategies

Fraud Detection

Because of the transparency and traceability in Blockchain, every stakeholder can see what discrepancies or frauds are occurring at an instance. In the case of pharmaceuticals, everything that involves a transaction, right from raw material procurement to finished goods delivery, is tracked through an immutable ledger by blockchain. Transparency here ensures that in such cases, irregularities-like unauthorized substitution or missing shipments-are easily identified to take quick corrective actions. It has been studied that, in research related to blockchain technology-based drug supply chains, incidents of fraud were reduced by more than 50%, saving millions annually from losses [29].

Decentralized Decision-Making

Supply chain resilience requires a decentralized ability to make decisions. Blockchain allows decentralized systems where all the stakeholders exclusively verify the data and do their business accordingly, without relying upon any authority. For instance, farmers, distributors, and retailers in different supply chains of food can all use the same block-chain data, thereby keeping independent decisions coordinated, which may relate to adjusting supply as per the real-time requirements. The very process of decentralization further decreases the dependence on an intermediary and increases the capabilities of the system to be more resilient in case of either- natural or sudden changes within market conditions [48][58].

3.5 Comparative Analysis of Blockchain Frameworks

3.5.1 Popular Platforms

Hyperledger

Hyperledger is an opensource blockchain framework oriented on enterprise applications. It provides a permissioned network focused on private transactions with value, whereas public blockchains like Bitcoin are driven purely by speculation. For sectors like health and finance that boast strict data privacy, such a framework would be considered hyper-ideal. On a supply chain, it boasts a modular architecture and fosters customized solutions toward given needs, such as tracking perishable goods and management of supplier certifications. For example, Walmart has applied Hyperledger in the traceability of food and reduced the time taken to identify sources of contamination from days to seconds [59][60][61].

Ethereum

Ethereum enables the powerful functionality of smart contracts, enabling decentralized applications (dApps) to create elaborate workflow automation. Ethereum avails the contract execution process smoothly to supply chains, including the automatic release of payments once set preconditions have been met. However, the dependence of Ethereum on Proof of Work has brought criticisms on the grounds of energy consumption and slower transaction speeds, both factors which potentially limit scalability in volume supply chains. Recent developments like Ethereum 2.0 seek to address these issues by moving to the more sustainable Proof of Stake model [62][63].

Corda

Corda is a blockchain platform that was designed with business in mind from day one and therefore brings data privacy and efficiency to the platform. Unlike most blockchains that broadcast all transactions out into the entire network, within Corda, when somebody writes something to the ledger, only those who need it necessarily get it. Hence, confidentiality is ensured within transactions, which is most welcome in supply chains entailing sensitive data, including monetary or financial transactions besides proprietary product designs. Various industrial applications of Corda in aerospace and automotive indicated its capability to manage supply chain systems in a complex process without losing data security [64][65][66].

3.5.2 Evaluation Metrics

Scalability

Scalability is perhaps one of the most vital metrics with which blockchain frameworks can be reviewed, especially large-scale supply chains. Hyperledger stands out for its scalability; its modular design allows networks to process a high volume of transactions without affecting their performance. That makes it ideal for industries such as retail, whose supply chains see thousands of transactions daily. In contrast, Ethereum has struggled with scalability issues, with congestion on the network causing slower transaction speeds when demand is high [67].

Latency

Latency refers to the time required for transaction confirmation and its subsequent recording. Though public blockchains are basically plagued with latency-a function of the consensus algorithm, private blockchains such as Hyperledger and Corda contribute toward reducing latency by lessening nodes. In cases of cold chain logistics or similar supply chains needing real-time update requirements, timely decisions necessitate the absence of high latency among the blockchain solutions [68].

Energy Consumption

The most important challenge in the adoption of blockchain technology is its energy consumption, particularly for those frameworks that are based on the Proof of Work mechanisms, which require a lot of energy. For example, Ethereum was criticized about its environmental effects, so Ethereum 2.0 is being developed with Proof of Stake. Platforms such as Hyperledger and Corda, using permissioned networks, consume much less energy and, therefore, are much more sustainable for large-scale supply chain operations [69].

This in-depth literature review highlights the transformative potential blockchain offers in Supply Chain 4.0. Enabling lean automation, mitigating risk, and solving some very fundamental challenges, blockchain frameworks such as Hyperledger, Ethereum, and Corda have emerged as versatile, industry-applicable platforms for discussion. These will indeed form a strong platform of discussion for future innovations and actual practical implementations of blockchain supply chain management.

4. Challenges and Limitations

Although blockchain technology is touted to have immense potential for changing the supply chains of today, there are some challenges that this technology is likely to face along technical, economic, organizational, and regulatory dimensions. Finding the solution to these limitations holds the key to the realization of the full potential for blockchain in Supply Chain 4.0.

4.1 Technical Challenges

4.1.1 Scalability

One of the most essential technical barriers to blockchain adoption by far is its lack of scalability: public blockchain networks can handle just a few dozen transactions per second, whereas VISA, on the other hand, is capable of processing thousands. This makes it a significant bottleneck for supply chains in retail and e-commerce [70]. This, in turn, can sometimes make the transaction processing and other network delays more expensive during periods of peak demand. Second-order solutions involving sharding or layer-2 protocols-like the Lightning Network-would improve this, but implementation for large-scale supply chains remains resource-intensive and complicated [71].

4.1.2 Interoperability

Most blockchains are a sort of vacuum that allows no seamless integrations from other systems or even across different networks. Lack of allowing interaction puts a lot of pressure on supply chains depending on data across many platforms. For example, blockchains for inventory might be incompatible with the payment systems and logics network used by other players in the same transaction, which would further enhance inefficiency and duplication of processes. Initiatives such as the Interledger Protocol and Blockchain Interoperability Alliance have been launched to bridge these gaps, but standardized interoperability remains a work in progress [72][73].

4.1.3 High Energy Consumption

Most of the blockchain networks with PoW consensus mechanisms go on to consume a great deal of energy, including Bitcoin. This element brings up environmental and economic concerns, especially for those sectors of the industry that want to go green. Researchers estimate that Bitcoin alone already consumes as much energy yearly as some small countries around the world. Whereas more modern consensus mechanisms are in use, like Proof of Stake (PoS) and Proof of Authority (PoA), which consume less energy, their complete migration of already operating systems involves huge investments and technical experience. Agriculture and manufacturing, in this respect, are more sensitive to ecological issues that directly connect with the energy aspect of blockchain use [69][74].

4.2 Economic and Organizational Barriers

4.2.1 High Initial Costs

The implementation of blockchain implies huge upfront investments in infrastructures, development, and integration. Every organization needs to build up or adapt systems to handle blockchain, which most of the time means a new cadre and hardware or software; these costs may be exorbitant for an SME, hence limiting wide diffusion. Moreover, blockchain networks have a cost of ongoing maintenance and upgrades that might strain the financial resources, especially when the margin of profit in an industry is very minimal, such as retail or logistics [57].

4.2.2 Resistance to Adoption

The other major barriers are organizational resistances to any type of change. All those participants in the supply chain may be resistant to adopting blockchain due to conventional systems and required major shifts in workflow or business model reconfigurations. Integrating blockchain, for instance, into the flow of an existing supply chain has been known to retrain employees, rebuild processes, and convince the use of the network by convincing other partners. Additionally, a lack of knowledge concerning the benefits of blockchain instills skepticism and hesitation in the minds of decision-makers, which in turn reduces the speed of adoption [75].

4.3 Regulatory and Legal Issues

4.3.1 Data privacy laws

Such a transparent and indelible nature of Blockchain is contradictory to data privacy laws such as the GDPR of Europe. The GDPR legally gives individuals the "right to be forgotten," whereby one may request their personal data to be erased. In this respect, Blockchain cannot legally permit deletion, once data is recorded in it, which creates a contradiction to such legal tenets.

It therefore means that organizations adopting blockchain shall find ways of complying with these regulations, either by storing sensitive data off-chain or using privacy-preserving techniques such as zero-knowledge proofs [76][77].

4.3.2 Global Trade Regulations

Most international supply chains transcend more than one legal jurisdiction with its corresponding sets of trade regulations and standards. Unfortunately, this means there is no globally consistent legal framework best supporting the blockchain. For example, whereas some countries create supportive policy conditions to help increase blockchain adoption, others impose stringent regulatory limitations or outright prohibitions on specific applications. This creates regulatory inconsistency, adds to uncertainty for businesses, and deters investment and experimentation in blockchain technology. Besides this, a number of additional issues-for example, on intellectual property rights, taxation, and compliance-further complicate blockchain's adoption within global trade networks [78].

4.4 Addressing the Challenges

Nevertheless, behind these challenges, important efforts are being made to surpass the limitations of blockchain and further exploit its full potential in supply chains. From a technical point of view, scalability and interoperability issues are tackled by the development of hybrid blockchain architectures and scalable consensus algorithms. Public-private partnership arrangements, or industry consortia, can also be considered for sharing costs and risks in implementing blockchain as a way to make its adoption by SMEs more affordable. Also, the regulators and heads of the industry go hand in hand in devising standardized guidelines and frameworks regarding blockchain adoptions for the sake of promoting global interoperability and compliance [13][78].

5. Future Direction

Although blockchain technology has already made considerable milestones in supply chain management, most of the potent transformational capabilities have yet to be tapped into. This section presents the future directions of blockchain-integration with emerging technologies, pathways toward sustainable supply chains, its place in human-centric supply chains aligned with Industry 5.0, and some open research questions.

5.1 Blockchain Integration with Emerging Technologies

5.1.1 IoT for Real-time Data Sharing and Tracking

Convergence between blockchain and Internet of Things will create something very powerful: real time sharing of data and across-supply-chain tracking is allowed. IoT devices generate reams of data ranging from location, temperature, and whatever other condition goods may come across while in transit, thus creating an integrated knowledge with blockchain into an immutable record for added value in either transparency or traceability, depending on the use environment [79].

IoT sensors in cold chain logistics monitor temperature-sensitive goods, like pharmaceuticals or perishable food items, and send that information over to a blockchain network. Any deviations from the set conditions are instantly recorded and, therefore, permit real-time corrective actions by the stakeholders. IBM Food Trust is one such blockchain-enabled supply chain solution which has shown this integration and can reduce the time taken to trace the origin of food from days to seconds [47][80]. Future research should go towards the harmonization of protocols in IoT, making the integration with blockchain seamless so as to have maximum data accuracy and interoperability across various supply chains[81].

5.1.2 AI for Predictive Analytics and Decision Making

AI combined with blockchain is a strong enabler of advanced predictive analytics for improved decision-making in supply chain operations. AI algorithms are required to interpret data that may be stored on blockchain in a search for patterns, forecasts of demand, and optimizing inventory levels. As such, AI can look into the history of shipment data stored on the blockchain and make forecasts about seasonal surges in demand, thereby preparing the manufacturer by aligning their production schedule accordingly [82][83].

Also, AI-driven systems may detect anomalies in the record blockchain, such as incorrect data in transactions or unpredicted delays, and therefore indicate a potential chain disruption. That predictive capability supports resilience: supply chain managers can institute corrective actions before small problems scale into full-blown crises. Future studies should be directed at the design of hybrid models which integrate blockchain and AI with a focus on areas where the ability to foresee disruptions and adapt to them with agility is very important, like risk management[40][84].

5.2 Frameworks for Sustainable Supply Chains

5.2.1 Integrating Circular Economy Principles

Blockchain can be set to play a pivotal role in the transition toward models of the circular economy due to the possibility it grants in tracking resource usage and the process of waste management with much more transparency. Within the paradigm of the circular economy, products and materials are reused, recycled, and repurposed at the end of their life in order to cut on waste and environmental impacts. It enables this by presenting an immutable record in safekeeping of a product lifecycle from extraction to the so-called end-of-life disposition [85][86].

Addedly, blockchain technology can contribute to the manufacturing chain; for example, material origin: "Recycled or bio-based raw materials truly exist." Smart contracts promise stakeholders a reward for getting a product back to recyclers by automating cash or credit issuance. Much of the research initiatives proof also on how blockchain technology uses circular supplies in industries from plastics and textiles industries, among others. In fact, future development should aim at blockchain-based systems that easily interface with the current recycling and waste management infrastructure for eventual circular supply chain solutions[85][87].

For instance, blockchain can help with provenance in manufacturing to make sure that inputs are recycled or sustainably sourced. Smart contracts, through automated payment or credit issuance, would incentivize the return of used products to the recycling system. The work being done on research initiatives, such as the Circularise platform, has already been proving the feasibility of blockchain technology for circular supply chains within industries like plastics and textiles. This therefore calls for future development in the creation of blockchain systems that will further integrate into the existing recycling and waste management infrastructure towards scalable, circular supply chain solutions [85][88].

5.2.2 Supply chains with net zero pathways

Besides making processes more efficient, enabling companies to reach their net zero-emission targets is most crucial in the industry-which is, again, feasible through blockchain, enhancing this needed transparency and accountability in current carbon tracking. Blockchain brings complete visibility of the output of emissions throughout the value chain since all the emissions data is transparently recorded and independently checked at each level. Thus, blockchain helps track which products have low carbon and could enable customers to assess goods on how 'carbon friendly' they are in every aspect [89][90].

Additionally, blockchain would be able to support trading in carbon credits by adding a level of transparency in the tracking and verification processes. Energy Web has spearheaded this with its initial application in blockchain for decentralized energy grids and carbon markets, where wider applications in supply chains also seem feasible. Future Research: Integrating blockchain into IoT and AI for actual real-time emissions monitoring. Standardized protocols for maintaining carbon accounting [91].

5.3 Human-Centric Supply Chains

5.3.1 Role of Blockchain in Enabling Industry 5.0

Industry 5.0 will focus on human-centricity, sustainability, and resilience. The few technologies that are apt to directly support such visions include blockchain. In regard to supply chains, control is decentralized, giving an opportunity for transparency across their value chains so as to effectively collaborate with other subjects. For instance, Blockchain allows workers to acquire effective real-time data of various events in the production processes on grounds for better decision-making. These also minimize errors in different aspects [81][92].

Most notably, blockchain does enable higher levels of integrity in enabling better labor practices through full transparency of the records that account for all workers. For example, in industries where the supply chain is very complicated and broadly disseminated across borders, an immutable record of employment relationships and working conditions can confirm if labor standard compliance can be met in place or not. The inclusion of blockchain in the latest Industry 5.0 technologies like cobots and advanced human-machine interface systems should, therefore, be considered as a proposal in further research to gain full development into a more human-centric supply chain [93][94].

5.3.2 Enforcing the development for increased Collaboration Using Decentralized systems.

Decentralized blockchain systems, for instance, offer a single version of reality across any supply chain participant, inducing confidence in and deeper trust between and greater levels of collaboration from participants as a result. So this has some very real monetary value considering many of the quite extensive globally stretched supply chains; after all, there seem to come, innumerable stakeholders, against which priorities get conflicted with each other and/or show varying forms of skepticism. In one context, perhaps a blockchain-enabled decentralized autonomous organization serves as a source for enacting collaborative decision-making or a setting whereby stakeholders are empowered on issues related to the bottom-line supply-chain strategic setting [95][96].

More importantly, blockchain-driven platforms could achieve such better levels of collaboration by facilitating process automation for onboarding suppliers, negotiation of terms of contracts, and dispute resolution. Future research should analyze in detail the possible application of models of decentralized governance for multiagent complex supply chains, especially in industries like aerospace and healthcare, where collaboration is not only required but involves more than one agent [97].

5.4 Open Research Questions

5.4.1 How to Improve Blockchain Scalability While Maintaining Security?

The challenges to blockchain diffusion in supply chains remain scalability. In addition, future research should work on advanced consensus mechanisms such as Proof of History or hybrid models balancing scalability and security between public and private blockchains. Furthermore, exploring the use of sidechains and sharding can also point to methods to scale blockchain networks without giving up their decentralized nature [67][98].

5.4.2 What are the best practices to integrate blockchain with Industry 4.0 technologies?

Most presented with numerous opportunities, blockchain-IoT AI, incorporated with other technologies under one umbrella of Industry 4.0, shows many avenues for seamless integrations, which need a lot to be researched regarding the formation of standardized protocols and framework regarding interoperability, delving deep into the usability of edge and fog computing that might become the very highway to enhance efficiencies in those integrations [99].

5.4.3 How to Determine Standards for Global Blockchain?

Hitherto, blockchain adaption has highly constrained supply chain, simply for want of missing widely accepted globally relevant blockchain frameworks or standards that naturally create bottlenecks at every connection; one potentially highly rewarding investigation in the future can be along issues for laying down International Blockchain Standards, primarily drawn upon principles of Data privacy, Interoperability-related, and Governance-related parameters for blockchain-based systems [100]. Addressing these calls for cooperation involving governments and industrial associations and various accredited bodies such as ISO or IEEE federation to sort the ground.

6. Conclusion

Blockchain technology now contributes to this very supply chain management to deal with the long-known concerns: inefficiency, opaqueness, and fragility of supply chains. On the other hand, inherent decentralization, immutability, and smart contracts place blockchain as a robust enabler to build a supply chain that is much-needed-transparent, efficient, and resilient.

This paper systematically reviewed the potentially transformative role of blockchain in Supply Chain 4.0. We analyzed the depth of its integration with a host of incoming technologies, including IoT and AI, among others, and demonstrated exactly how blockchain enhances real-time data sharing, predictive analytics, and decision-making. Finally, blockchain's pathways towards a circular economy model, together with net-zero contributions, underpin its increasingly key role in the search for sustainable supply chains. It enables human-centric supply chains with decentralized decision-making and collaborative frameworks, which are quite aligned with the principles of Industry 5.0 toward a more equitable and inclusive supply chain ecosystem.

Despite the huge potential, there are several significant barriers to adopting blockchain. The technical challenges are scalability, interoperability, and high energy use, among other pressing issues. High initial costs and organizational resistance are part of the economic barriers. Besides these, regulatory and legal intricacies- especially on aspects like data privacy and the standards of global trade-make the implementation of blockchain all the more complex. How to address these challenges needs serious consideration by researchers, industry practitioners, and policy makers in developing scalable, cost-effective, and regulatory-compliant blockchain solutions.

The paper also identified a few future directions of blockchain research and application. Integrating blockchain with Industry 4.0 technologies, developing sustainable supply chain frameworks, and human-centric supply chain systems are promising avenues to be explored. Answers to the critical research questions on scalability, best integration practices, and global standardization also hold the key to the full potential of blockchain.

This illustrates the paradigm shift in new ways to manage supply chains; with these technologies, great unprecedented opportunities will be derived from the efficiency, sustainability, and resilience of a supply chain. As technologies mature over time, this sector ensures a supporting role through multilevel collaboration among the industrialists, governments, and academia to transcend further than what is possible without limiting and catalyzing the blockchain's transformative powers over global supply chains.

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