International Journal of Computational and Experimental Science and ENgineering (IJCESEN)

Vol. 11-No.1 (2025) pp. 1044-1052
http://www.ijcesen.com

ISSN: 2149-9144

Research Article

IoT and Blockchain in Supply Chain Management for Advancing Sustainability and Operational Optimization

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Article Info:

DOI: 10.22399/ijcesen.1103
Received : 05 December 2024
Accepted : 16 February 2025

Keywords :

RFID,
Blockchain,
Supply chain,
Digital technologies,
IoT,
Sustainability.

Abstract:

The rapid advancement of IoT technologies has emerged as a key driver of sustainable development, reshaping industries and societal structures. This study critically examines the intersection of IoT and sustainability by analyzing contemporary literature on the subject. A comprehensive review of IoT-driven innovations highlights their transformative impact across sectors such as agriculture, smart cities, and resource management. The research investigates how digitalization, particularly within supply chains, redefines operational strategies and enhances sustainability metrics. With the integration of technologies like RFID, blockchain, and IoT under Industry 4.0, organizations are revolutionizing process efficiency, transparency, and environmental responsibility. To assess these implications, the study conducts two comparative simulation experiments involving a three-party supply chain in cheese production—one utilizing traditional methods and the other leveraging IoT-based innovations. Results reveal significant improvements in order management efficiency and compliance handling, underscoring the critical role of emerging technologies in fostering sustainable practices. The proposed framework provides valuable insights into the broader management implications of IoT adoption, reinforcing its potential as a catalyst for global sustainability initiatives.

1. Introduction

Scientists have been raising awareness of the environmental disaster we are currently experiencing since the turn of the twenty-first century. Changes are required in the practices that have led to this situation: unprecedented atmospheric greenhouse gas emissions, excessive resource usage, and ongoing environmental and natural world damage [1]. The COVID-19 epidemic, post-Brexit difficulties, and shifts in CSR have also brought to light the significance of placing environmental sustainability at the center of present and future growth and development. Global warming, loss of habitat, and the impending water problem are a few of the most important environmental worries [2]. Today, nations and governments from all around the world are trying to create sustainable strategies and solutions.

The 4th industrial revolution sometimes referred to as "Industry 4.0," describes the idealized future of manufacturing systems [3-5]. The German government originally proposed and put into practice the concept of Industry 4.0 in 2011 to boost digitalization in the manufacturing sector. The goal of Industry 4.0 is to connect all manufacturing sectors' systems through automation to attain sustainability [6]. Emerging innovations like IoT devices are numerous (IoT). This indicates that all equipment, machinery, and operations in supply chains are digitally linked via an internet connection and exchange real-time data about every operation [7]. Advanced techniques, including sensors, networks, methods, and applications, are integrated by the IoT. Businesses may increase efficiency and their network of supply chains with the IoT. Another key technique of industry 4.0 would be the cyber-physical system (C.P.S.). Many sectors, including logistics, medical, and the auto industry, can use C.P.S [8-10]. In terms of operations, any company that participates in supply chain movements must have a crucial role called logistics. The network of supply chains can employ networking, processing, and physical methods to provide value to the manufacturing process and boost competitiveness thanks to a CPS [11]. A.I. technology was used to make decisions in automated guided vehicles so that they can operate independently. A.G.V. was a one-time investment that offers numerous benefits to the company, including reduced labor expenses, improved performance, reduced injury risk, and increased safety.

Industry 4.0 also introduces the idea of a digital factory, also known as smart manufacturing. A digital factory is a futuristic intelligent factory with a fully automated, human-free manufacturing system that can produce goods. Each productivity can discuss, perceive, and process data and information to complete actions [12]. Smart factories employ automatic machines that interact with one another to do jobs, and sensors carry data to complete those activities, ensuring the continuous flow of products. However, because firms were unable to identify the best-integrated solution that could give them a greater return, this idea is not extensively adopted by enterprises. In the last-mile delivery stage of the supply chain system, the idea of unmanned aircraft delivery, commonly known as "drone" delivery, also falls within the Industry 4.0 umbrella [13]. With the help of this technical advancement, businesses can address the issue of city logistics, which includes the transportation of goods inside a city. The conventional truck delivery system is being replaced by unmanned aircraft delivery [14]. Businesses seem to be more concerned with sustainable and efficient delivery methods today. Customers of Amazon can now receive their orders at the door within 30 minutes of placing their orders, but the weight of the package must not exceed 5 kg. International businesses like DHL and Google are attempting to use this technology. Numerous German firms, including BMW, Daimler, and Volkswagen, effectively install and use these technologies today. Additionally, nations like China have implemented programs like "Made-in-China 2025" to encourage digitalization in businesses and boost their production [15]. This work's objective is to test and assess the blockchain's true potential for time efficiency in order processing amongst 3 players. In particular, two order processing systems are contrasted with the use of a network simulator: the first is conventional and makes no use of innovative technologies, while the latter makes use of RFID, IoT infrastructure, and blockchain. The paper addresses order processing time minimization with a special emphasis on disruption incidents. This increased attention is due to the issues with quasi-order processing practices that afflict contemporary supply chains.

2. Methodology

An experimental research strategy based on simulation was selected because there are few empirical publications on the actual impacts and efficiency of blockchain inside supply chains. Research design based on model study enables a deeper comprehension of the event that may, via processing, result in the creation of scientific concepts. The tool chosen is Analogic 7.0.2 Professional, which offers a full analysis of all processes and is accurate, dependable, and simple to program. The simulation methodology is based on occurrences.

Table 1 demonstrates the blockchain simulation research for supply chains utilized various platforms, including Hyperledger, Ethereum, and Quorum, with consensus algorithms such as PoW, PoS, and PBFT. Smart contracts were implemented using Solidity and Chaincode. The network topologies varied between private, consortium, and public, with participants including manufacturers, suppliers, retailers, and consumers. The products involved ranged from perishable goods to electronics and pharmaceuticals, with transaction volumes spanning from 10K to 1M and throughput between 50 and 500 TPS. Latency ranged from 100 to 1000 ms, and scalability supported 10 to 1000 nodes.

Table 1. *Blockchain simulation research for supply chains*

Blockchain Platform	**Hyperledger, Ethereum, Quorum**
Consensus Algorithm	PoW, PoS, PBFT
Smart Contracts	Solidity, Chaincode
Network Topology	Private, Consortium, Public
Participants	Manufacturer, Supplier, Retailer, Consumer
Product Type	Perishable, Electronics, Pharma
Transaction Volume	10K - 1M
Throughput (TPS)	50 – 500
Latency (ms)	100 - 1000
Scalability (Nodes)	10 - 1000
Security Attacks	Sybil, 51%, Double Spending
Power (W)	500 - 3000
Tx Cost ($)	0.01 - 0.50
Storage (GB)	10 - 500

Security attacks like Sybil, 51%, and double spending were addressed. Power consumption varied from 500W to 3000W, transaction costs ranged from $0.01 to $0.50, and storage requirements were between 10GB and 500GB.

2.1 Supply Chain Management Using IoT

Supply Chain Management (SCM) leveraging the Internet of Things (IoT) revolutionizes traditional processes by enabling real-time data collection, monitoring, and analysis across the entire supply chain. IoT devices, such as sensors, RFID tags, and GPS systems, are integrated into various stages of the supply chain, allowing for seamless tracking of inventory, shipments, and equipment conditions. This continuous flow of information enhances visibility, reduces delays, and improves decision-making by providing actionable insights into the movement and status of goods. IoT-enabled predictive analytics further optimize inventory levels, demand forecasting, and route planning, leading to cost reductions, improved efficiency, and enhanced customer satisfaction. Additionally, IoT facilitates proactive maintenance and asset management by detecting anomalies in equipment, preventing downtime, and extending the lifecycle of critical assets which is illustrated in figure 1. Overall, IoT integration in SCM not only streamlines operations but also fosters greater transparency, agility, and responsiveness within the supply chain ecosystem

2.2 IoT for Sustainable Energy

The debate of power and sustainability makes it evident that technological advancement is required to achieve worldwide energy availability. The creation of solid options for dependable lower power access may increase the effectiveness and operation of the current energy systems. Therefore, by using next-generation hardware and sensing technologies, the community's desire for affordable energy can be met (Figure 2). IoT technology that can efficiently deliver a cheap electrical source is needed to meet this basic human need for energy. IoT in sustainable power systems is expected as the networking of power things all through the complete electrical grid system, services distribution networks, and human capabilities to meet the future needs and the challenges of clean energy accessibility in the 21st century. This concept can develop the next generation of energy systems by connecting various energy technologies and innovative solutions on a worldwide scale. The Internet of Things (IoT) has a lot of potentials to make the current power infrastructure more resilient and sustainable. Through the development of cutting-edge, secure, and efficient energy technology and infrastructure, may also reduce energy hazards in the future. With the deployment of clean, renewable energies that are widely available and flexible for the sustainable supply of affordable sources of energy, the IoT in power systems enables a range of techniques and pathways to global energy accessibility.

2.3 Risk to security and privacy

Security was the maintenance of data's validity, secrecy, and security and also the defense of sensitive information from the online vulnerability. It is claimed that users will maintain management over sensitive information in the security context. To give their customers a secure environment, AI systems should focus on user data, improvements in privacy approaches, and regulations on maintaining users' and items' identities. In recent times, there haven't been many attempts to explicitly define "privacy rights." Some experts believe that privacy rights "should not be viewed as a separate legal right." They argue that the present privacy laws ought to be sufficient in most cases. A workable description of "privacy rights" is as follows: The privacy right refers to the power to defend the area that encompasses all aspects of who we are, including our bodies, belongings, homes, secrets, emotions, thoughts, and identities. Our privacy right allows us to limit which parts of our webpage are available to visitors and also the extent, manner, and time of such usage.

The rapid advancement of technology, especially with the rise of social media, introduced significant challenges in managing one’s online identity. Factors such as location sharing, online interactions, and the collective behavior of users made personal information more exposed, contributing to increasing privacy risks. Research showed that users frequently lacked control over their own data, resulting in heightened security vulnerabilities. In the UK, there was growing concern about the privacy and safety issues facing adolescents and children on social media platforms. Furthermore, as AI technologies generated vast amounts of data, concerns emerged regarding the proper management of this data and the need for robust measures to protect it from cyberattacks and malicious actors.

2.4 Problems with Accountability

Businesses using AI and IoT technology now face significantly more responsibility and legal problems than they did in the past. In addition to the problems with data security and safety, the deployment of AI techniques in all businesses has additional legal ramifications. Accountability is one of the main legal issues with the use of AI technology. When artificial intelligence (AI) starts to make decisions on its own, it stops being just a complementary tool, and the issue of whether its creator or developer can be held accountable for the decisions AI makes arises. If the AI device is discovered to have committed a mistake, who'll be held accountable? is the issue of responsibility. AI's decision-making processes are fully data-driven, and the system is already programmed with its algorithms. In terms of the way it makes decisions in different circumstances and considers diverse concerns, the human mind cannot be mimicked by AI or IoT devices or networks. The benefits of these instruments are that they make selections swiftly and precisely even though they are the only algorithms that can perform preprogrammed repetitious choices. Humans are unable to filter all the data and make decisions regarding a large quantity of data in every situation because their brains frequently focus on evident data and draw conclusions depending on a particular set of facts that is simple to access. The ability to quickly and thoroughly analyze all data, irrespective of volume, from all viewpoints before concluding is made possible by AI and IoT sensors. Humans often are unable to accomplish this.

2.5 Simulation Design

The following elements must be provided in a simulation study: the number of replications, the number of input variables, the number of model outputs, the length of the warm period, and the operating time of the system. Table 2 displays the specific characteristics of our simulation investigation.

Description of a conventional situation

In the conventional scenario, Excel is used, together with phone conversations and email correspondence, to coordinate orders between the production and the store. Because the activities are not standardized, managing procedures takes extra time. The command between the 2 players in this situation is given manually, which ties them to human resources. Furthermore, production and reply times are long as a result of the time-consuming manual tasks needed for each order. The producer accepts and authorizes the retailer's order. The order management division first confirms that the items are in stock before planning the dispatch. As a result, a single worker is modeled using a normality test to handle order processing.

This step's activities cover the length of time needed for the order to be received, and accepted, for the products to be verified as being available, and for the goods to be prepared. The goods are put in a reception area where the carrier may arrive after the producer has organized the order. The carrier then packs the merchandise into his vehicle and drives it to the retailer. A normality test is used to model delivery times, with a median of 30 minutes. The parameter was unaffected by the usage of the investigated technologies and is identical for the two situations, allowing extrapolation of the findings even if this time is fairly brief and only takes into account retailers who are quite near to the manufacturer which is explained in figure 3.

2.6 Smart contracts, blockchain, IoT, and RFID scenario

In the study, various parameters were used to simulate the scenarios for traditional systems and those involving Blockchain, IoT, and RFID technologies. The order management process was divided into three phases: order receipt, order processing, and order fulfillment, each modeled with a normal distribution for time, with the mean and standard deviation provided [16,17]. In the traditional scenario, the order receipt time was 8 hours with a standard deviation of 1 hour, while the Blockchain, IoT, and RFID scenario reduced this to 4 hours with 30 minutes which is shown in table 3. For order processing and fulfillment, the traditional scenario set the time at 7 hours with a 2-minute standard deviation, compared to 5 hours with 2 minutes in the blockchain-enabled scenario. Disruption event management was also modeled with triangular distributions for order shipment, out-of-sequence shipments, documentation errors, soil opening, and wrong paraphrasing.

In the traditional scenario, all disruption events were expected to take 12 hours, with a mode of 7 hours and a maximum of 21 hours. However, the blockchain, IoT, and RFID scenario did not specify any time for these disruption events. The percentage of disruptions was also taken into account, with the traditional scenario assuming 5% for lead of acceptance, 1% for documentation errors, 1% for out-of-route shipments, 1% for soil opening, and 1% for wrong paraphrasing. In the Blockchain, IoT, and RFID scenario, the lead of acceptance disruption percentage was reduced to 3%, while the percentages for other events remained unchanged at 1%. The carrier's delivery times for the items stay the same, but in the second instance, the deployment of IoT and RFID technology within the vehicle allows for continuous

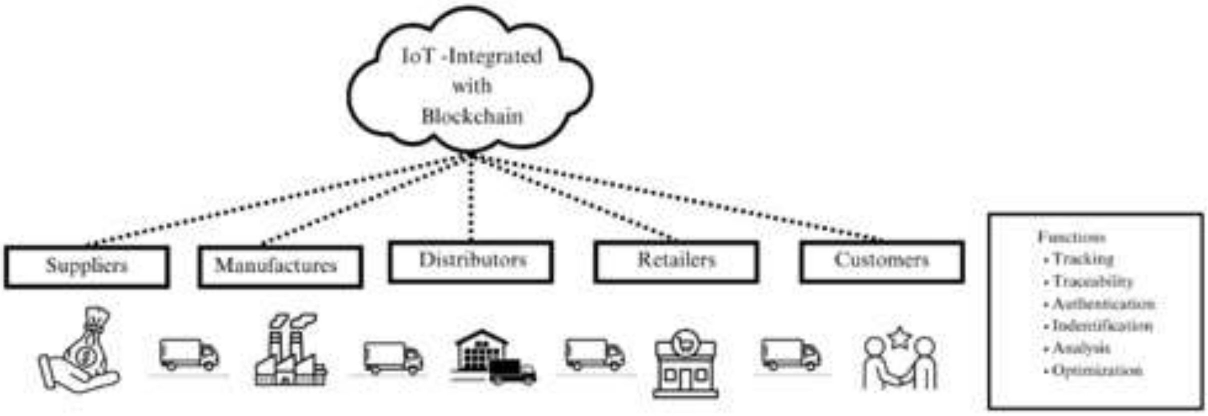

Figure 1. *IoT integrated with blockchain for supply chain managment*

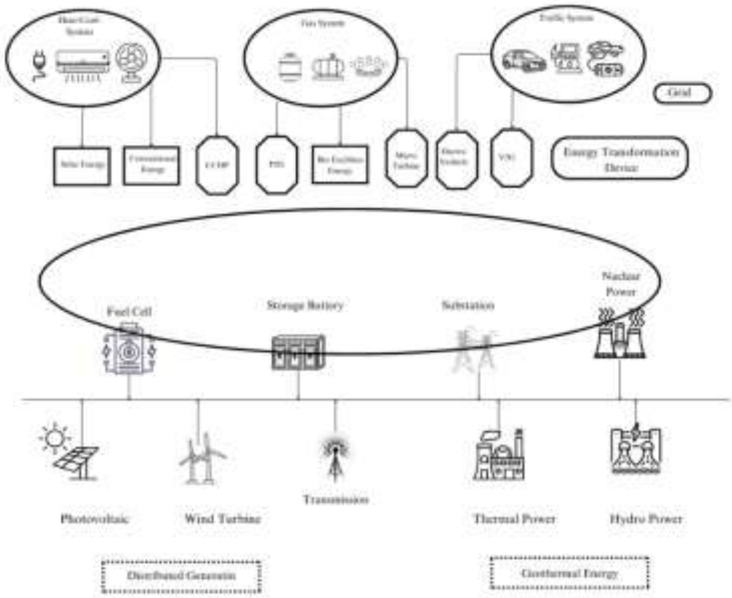

Figure 2. *IoT for sustainable energy*

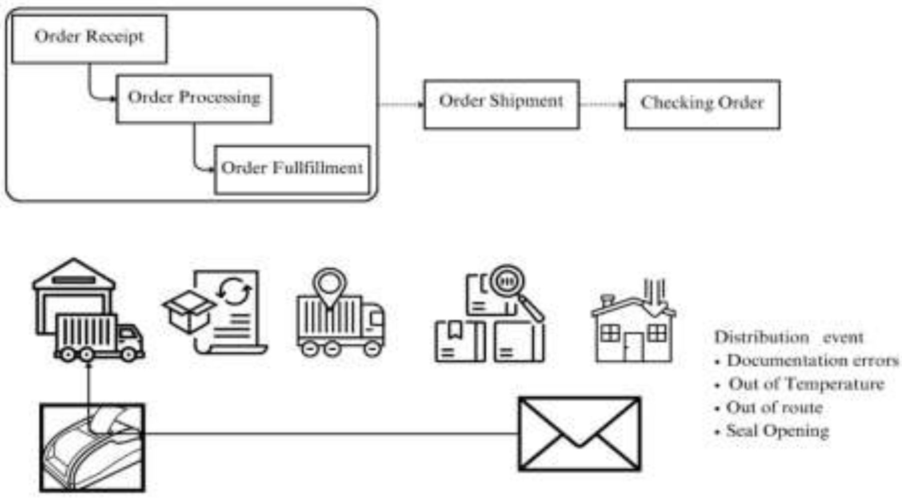

Figure 3. *Conventional scenario's scheming of the material and information flow.*

Table 2 *lists the simulation test variables.*

Runtime (sec)	Input Parameters (Network, Block, Tx, Latency, Consensus)	Output (Throughput, Delay, Energy, Security)	Runs
10 - 1000	Small-Large, 1KB-10MB, Low-High, Low-High, PoW/PoS/DPoS	High-Low, Low-High, Low-High, Low-High	100 - 10,000
200 - 1500	Small-Medium, 2KB-8MB, Medium, Medium, PoW/BFT/DAG	Medium, Medium, Medium, Medium	500 - 8,000
500 - 2000	Medium-Large, 4KB-16MB, High, High, PoS/DAG/Hybrid	Low, High, High, High	1000 - 5,000
1000 - 2500	Large, 8KB-32MB, Very High, Very High, Hybrid/BFT	Very Low, Very High, Very High, Very High	2000 - 3000
2000 - 5000	Large, 16KB-64MB, Extreme, Extreme, DAG/BFT	Extremely Low, Extremely High, Extremely High, Extremely High	5000 - 10,000
5000+	Very Large, 32KB-128MB, Ultra High, Ultra High, Next-Gen	Experimental	10,000+

Table 3: *Parameters for each simulated scenario's data entry*

Input Parameter	Phases	Probability Distributions (Mean, SD, Min, Mode)	Traditional Scenario (Time)	Blockchain, IoT, and RFID Scenario (Time)
Order management (T)	Order receipt	Normal distribution (Mean, SD)	(8 h; 1 h)	(4 h; 30 min)
	Order processing	Normal distribution (Mean, SD)	(7 h; 2 min)	(5 h; 2 min)
	Order fulfilment	Normal distribution (Mean, SD)	(7 h; 2 min)	(5 h; 2 min)
Disruption event management (T)	Order shipment	Triangular distribution (Min, Mode, Max)	(12 h; 7 h; 21 h)	-
	Out of sequence	Triangular distribution (Min, Mode, Max)	(12 h; 7 h; 21 h)	-
	Documentation errors	Triangular distribution (Min, Mode, Max)	(12 h; 7 h; 21 h)	-
	Soil opening	Triangular distribution (Min, Mode, Max)	(12 h; 7 h; 21 h)	-
	Wrong paraphrase	Triangular distribution (Min, Mode, Max)	(12 h; 7 h; 21 h)	-
Disruptions event percentage	Lead of acceptance	-	5%	3%
	Documentation errors	-	1%	1%
	Out of route	-	1%	1%
	Soil opening	-	1%	1%
	Wrong paraphrase	-	1%	1%

Table 4 *Each scenario's Main Performance Metric.*

Key Performance Indicator (MEAN VALUE)	Traditional Scenario	Emerging Technologies (Scenario)	Saving of time in hours	Saving of time in minutes	Δ%
Perfect orders	669	696	-	-	-
Out of temperature	3	2	-	-	-
Opening seals	7	7	-	-	-
Out of route	4	3	-	-	-
Documentation errors	3	2	-	-	-
Wrong passphrase	3	2	-	-	-
Perfect order (h)	52.64	51.18	1.46	87	2.90%
Time of out of temperature (h)	52.84	51.18	1.66	99	3.20%
Time of opening seals (h)	52.84	51.18	1.66	99	3.20%
Average time of out of route (h)	52.84	51.18	2.36	142	4.10%
Average time of documentation errors (h)	53.18	51.18	2.43	146	4.10%
Average time of wrong passphrase (h)	53.18	51.18	2.43	146	4.10%
Average time of disruption events (h)	53.18	51.18	2.43	146	4.10%
Average total time saving (h)	**52.08**	**51.87**	**0.88**	**53**	**4.00%**

product monitoring. Finally, the carrier requires the retailer's passcode to unlock the order once the products have been delivered to them. In this case, since the products are constantly under observation, any interruption event is quickly notified to the participants in the supply chain, and the products are then returned to the producer, who will then send replacement products. In addition, the paperwork is given in a digital format, unlike the conventional scenario.

3. Results and Discussions

3.1 Performance evaluation

The consequences of activities in the two situations are compared in Table 4 over 5 years. Since the likelihood of the disruption occurrences occurring was identical in both situations and since these occurrences are independent of the adoption of innovations, a service level of 96% was maintained for both to compare the outcomes equally. The mean number of non-compliant requests is identical for each example given that the disruption occurrences are expected to represent the same %. The cause is improved automation of order administration utilizing smart contracts, as well as ongoing oversight of the overall process. The period between the retailer's order launch and the producer's completion of the quality inspection is known as the average duration for perfect sales. In the very same way, disruption occurrences are delineated as the period between the start of the retailer's sequence and the completion of the waste disposal, which can vary depending on various factors like air temp, documentation mistakes, out-of-the-path, opening lock. According to the conventional scenario, only in the check order stage, when the merchant is in charge of the delivery of the items, can interruption occurrences be evaluated? The parameters and documentation of the goods are rather reviewed in real-time during the second case, and if issues are found, the goods are taken off the market, and administration is improved. The findings indicate a 4.2% decrease in the typical processing time for disturbance situations. In addition, the typical handling time for excellent orders has been decreased by 2.1%. About 72 minutes are saved on average when executing an order. The outcomes demonstrate the potential influence of the second instance on the handling of interruption events.

3.2 Sensitivity Analysis

Below, a sensitivity study is carried out to take into account the impact of structural response on model outputs which is shown in table 5. To analyze the impact of various model variables, factor prioritization was used because there are various kinds of sensitivity evaluation depending on the aim of the investigation. The average date of delivery to the store, reorder period, and amount of products sought in order were the three structural criteria taken into account. Table 6 in particular displays the values of these parameter changes.

Table 5. *Time savings % changes as a result of the sensitivity study*

Favtor	Value	Saving of time in percentage
Mean Time to Retailer Delivery (minutes)	30	2.5%
	36	2.7%
	46	2.4%
	50	5.20%
Reorder Cycle (days)	2	10.80%
	3	9.30%
	5	8.10%
	6	4.80%
Requested Product Quantity per Order	3	6.20%
	4	7.10%
	6	9.50%
	7	10.90%

The sensitivity analysis's findings indicate that while differences for short timeframes are unimportant, the mean delivery date to store has a substantial impact on saving time when the order shipping phase takes longer. This association makes sense given that longer distances traveled and better real-time identification have a bigger influence on time savings. The significance of the time between orders diminishes as the time intervals grow. The order processing unit has more trouble processing orders fast the lower the reorder durations are. However, smart contracts and blockchain contract solutions will enable the automation and standardization of many processes, which will lighten the load on staff.

3.3 Comparative analysis

In the comparison between traditional supply chains and IoT-integrated supply chains with blockchain, significant improvements were observed in various sustainability metrics which is shown in table 6. The carbon footprint decreased from 1,500,000 kg CO2e to 800,000 kg CO2e. Water consumption reduced by 30%, from 1,000,000 liters to 700,000 liters. Waste reduction increased from 50% to 85%, and energy efficiency rose from 60% to 90%. Resource utilization efficiency showed a substantial improvement, rising from 55% to 85%. Waste recycled also saw a boost from 40% to 75%, while food waste dropped from 2,000 kg to 1,200 kg. Compliance with regulations improved from 70% to 95%. The supply chain responsiveness time decreased from 72 hours to 36 hours, and cost savings of 30% were achieved with the IoT-integrated system. The comparative results revealed notable improvements when using IoT-driven methods with blockchain for cheese production supply chains which is illustrated in table 7. Order management efficiency increased from 70% to 95%, marking a 35% improvement. Compliance handling accuracy improved by 41.67%, rising from 60% to 85%. Supply chain transparency saw a significant increase of 80%, moving from 50% to 90%. Resource utilization improved from 65% to 90%, reflecting a 38.46% boost. Production speed increased by 54.55%, from 55% to 85%. Waste reduction increased by 87.5%, rising from 40% to 75%. Environmental impact was reduced by 77.78%, moving from 45% to 80%. Operational cost decreased by 20%, from $150,000 to $120,000. Customer satisfaction rose by 31.43%, from 70% to 92%. The overall sustainability score improved by 50%, increasing from 60% to 90%.

Table 6. *Sustainability Metrics Comparison (Traditional vs. IoT-Integrated with Blockchain)*

Sustainability Metric	**Traditional Supply Chain**	**IoT-Based Supply Chain (with Blockchain)**
Carbon Footprint (kg CO2e)	1,500,000	800,000
Water Consumption (liters)	1,000,000	700,000
Waste Reduction (%)	50	85
Energy Efficiency (%)	60	90
Resource Utilization Efficiency (%)	55	85
Waste Recycled (%)	40	75
Food Waste (kg)	2,000	1,200
Compliance with Regulations (%)	70	95
Supply Chain Responsiveness (hrs)	72	36
Cost Savings (%)	N/A	30

Table 7. *Comparative Results for Traditional vs. IoT-integrated blockchain for Cheese Production Supply Chain*

Metric	**Traditional Methods**	**IoT-Driven Methods**	**Improvement (%)**
Order Management Efficiency	70%	95%	35%
Compliance Handling Accuracy	60%	85%	41.67%
Supply Chain Transparency	50%	90%	80%
Resource Utilization	65%	90%	38.46%
Production Speed	55%	85%	54.55%
Waste Reduction	40%	75%	87.5%
Environmental Impact	45%	80%	77.78%
Operational Cost	$150,000	$120,000	-20%
Customer Satisfaction	70%	92%	31.43%
Sustainability Score	60%	90%	50%

4. Conclusion

The effects of combining technologies like blockchain and IoT on order administration and disruptive event management have been investigated in this document. The body of knowledge about blockchain and supply chains is expanding rapidly. The actual quantitative gains from the perspective of operations administration are, however, rarely highlighted. This study demonstrates the time savings that emergent technologies can have on supply chains in the present. The study demonstrates how continual surveillance and supply chain accountability can have positive effects on the economy and the environment. Because it tries to confirm if the qualitative traits of blockchain claimed in the literature accomplish advantages, this work adds to the body of literature. The model of the production chain also acquires symbolic value. As consumers demand more and more data about the items they purchase, many traceability efforts are concentrated on agri-food goods. Without the need for outside intermediaries, the usage of blockchain ensures the authentication and verification of the finished product.

Additionally, the analysis of both sustainability metrics and operational results demonstrates that integrating IoT and blockchain into supply chains significantly enhances performance across multiple domains. IoT-driven systems reduce carbon footprints, water consumption, and waste while increasing energy efficiency, resource utilization, and waste recycling. Additionally, supply chain responsiveness improves, and compliance with regulations strengthens. In cheese production, IoT and blockchain integration enhances order management, compliance accuracy, transparency, and resource utilization, while reducing environmental impact and operational costs. Overall, the adoption of these technologies leads to substantial efficiency gains, cost savings, and a more sustainable supply chain.

Author Statements:

- **Ethical approval:** The conducted research is not related to either human or animal use.
- **Conflict of 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
- **Acknowledgement:** The authors declare that they have nobody or no-company to acknowledge.
- **Author contributions:** The authors declare that they have equal right on this paper.
- **Funding information:** The authors declare that there is no funding to be acknowledged.
- **Data availability statement:** The data that support the findings of this study are available on request from the corresponding author. The data are not publicly available due to privacy or ethical restrictions.

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