

An ICT-Integrated Data-Driven Framework for Optimizing the Tobacco Supply Chain Using Blockchain and Cloud Computing

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Abstract

INTRODUCTION: Tobacco supply chain is a complicated multi-level structure that presents cultivation, processing, packaging, logistics, and distribution, which are often limited by inefficiencies, absence of transparency and data integration.

OBJECTIVES: To address them, this paper introduces an ICT-Integrated Data-Driven Optimization Framework (IDDOF) that would combine blockchain technology, cloud computing, and machine learning to design an intelligent and transparent supply chain ecosystem. The framework also uses ICT and IoT-driven sensors to collect real-time information on the quality of tobacco leaves, the environment, and the performance of logistics, which are safely transferred to a cloud-based system that allows the accommodation of a large amount of data and its rapid processing.

METHODS: Smart contracts based on the Ethereum platform are blockchain-based, which provide secure, tamper-resistant, and transparent data and transactions that encourage trust and accountability among stakeholders. The performance of the proposed framework is assessed using key ICT metrics—latency, throughput, scalability, security index, and energy efficiency.

RESULTS: Random Forest enables precise predictive analytics for demand forecasting, quality assessment, and anomaly detection with low latency and optimal energy use, while Particle Swarm Optimization (PSO) enhances logistics scheduling, routing, and resource allocation to improve throughput and scalability.

CONCLUSION: The integration of ICT, blockchain, and cloud computing ensures high security, interoperability, and operational efficiency across the tobacco supply network. Moreover, the modular and scalable design of the proposed framework makes it generalizable and adaptable to other agro-industrial supply chains, enabling similar gains in transparency, sustainability, and operational intelligence across diverse agricultural sectors.

Keywords: Blockchain technology; Cloud computing; Random Forest; Particle Swarm Optimization (PSO); Tobacco supply chain management.

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1. Introduction

The world tobacco supply chain is regarded as one

of the most intricate and closely controlled agro-industrial systems involving several interrelated steps,

including cultivation, curing and processing to packaging, distribution and retailing [1]. All the stages will have a variety of stakeholders, among which are farmers, processing companies, distributors, exporters, and governmental agencies [2]. Although the tobacco industry is an important source of economic support to most developing areas, its supply chain is usually full of inefficiencies, information silos, and end-to-end transparency [3]. Problems in the mismatch of inventory, reduction of quality, and loss of traceability are emanated by manual documentation, data fragments, and lack of consistency between stakeholders [4]. Beyond structural complexity, the tobacco supply chain is significantly affected by operational inefficiencies, including information delays, demand uncertainty, poor coordination, inventory mismatches, and limited visibility across stakeholders. These challenges increase costs, reduce responsiveness, and weaken decision-making effectiveness. The absence of integrated digital infrastructure further amplifies these inefficiencies. ICT integration improves supply chain efficiency by enabling real-time data acquisition, automated information exchange, and enhanced process coordination. However, issues related to data integrity, trust, and secure multi-stakeholder interaction often remain. Blockchain technology addresses these limitations by providing a decentralized, tamper-resistant ledger that ensures transparency, traceability, and data reliability, thereby strengthening coordination and reducing information asymmetry. Cloud computing further complements this architecture by enabling scalable storage, high-speed processing, and efficient management of large IoT-generated datasets. Together, ICT, blockchain, and cloud computing create an integrated ecosystem that enhances operational efficiency, reduces latency, and improves overall supply chain performance.

These information and communication challenges are not unique to tobacco but are common across many agro-industrial supply chains, where the absence of integrated ICT infrastructure and real-time data visibility hampers coordination, sustainability, and regulatory compliance [5]. Therefore, developing data-driven, ICT-enabled frameworks is crucial for enhancing transparency, interoperability, and operational efficiency across agricultural value networks.

ICT has become a key enabler in transforming traditional supply chain systems into intelligent, interconnected networks [6]. ICT-based systems enhance decision-making by enabling automated, real-time

visibility, seamless information flows, and data-driven coordination across the value chain through the integration of technologies such as the Internet of Things (IoT), cloud computing, and data analytics [7]. IoT sensors deployed across farms, processing units, and logistics nodes continuously monitor environmental parameters, crop quality, and transport conditions, while communication protocols such as MQTT, LoRaWAN, and 5G ensure reliable and low-latency data transmission between devices and enterprise systems. Cloud platforms (e.g., AWS, Azure, or Alibaba Cloud) provide scalable storage and processing for these high-volume data streams, supporting integration with Enterprise Resource Planning (ERP) and Supply Chain Management (SCM) systems for end-to-end operational control [8]. Furthermore, big data analytics combined with machine learning enable organizations to forecast demand, detect anomalies, and optimize production and distribution processes in real time [9]. However, the lack of trust, data security, and transparency remains a major limitation of ICT-based supply chains, particularly where information is exchanged among multiple independent entities [10]. These challenges can be mitigated through blockchain integration, which provides a decentralized, tamper-proof, and verifiable ledger of transactions, ensuring data integrity and secure communication between all participants in the network [11].

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While numerous studies have explored individual digital technologies for supply chain enhancement, there remains a notable gap in their system-level integration within a unified ICT architecture. Prior research has focused on blockchain-based traceability systems that enhance data integrity and transaction transparency [12], IoT and cloud-based monitoring frameworks that enable real-time sensing and scalable data processing [8], and machine learning models for demand forecasting, quality prediction, and anomaly detection [13]. Likewise, optimization algorithms such as Particle Swarm Optimization (PSO) and other metaheuristics have been applied to logistics scheduling and resource allocation [14]. However, these solutions are typically developed in isolation, focusing on specific functions or stages of the supply chain without ensuring end-to-end interoperability, real-time communication, or seamless information flow between heterogeneous ICT components. Consequently, there is a pressing need for an integrated, data-driven ICT framework that combines blockchain, cloud computing, IoT, and AI-based analytics to provide a secure, intelligent, and scalable digital ecosystem for comprehensive supply chain management. This integration aligns with Industry 4.0 principles, emphasizing automation, cyber-physical connectivity, and intelligent decision-making across the value network [15].

To address these challenges and opportunities, this paper presents an IDDOF, which combines blockchain technology, cloud computing and machine learning to streamline and secure the tobacco supply chain. The system uses ICT and IoT sensors to gather real-time data regarding the quality, environmental factors, and logistic performances of tobacco leaves. Such data are sent safely to a cloud-based system and it allows storage which can be scaled, fast processing, and cross stakeholder integration. In such an ecosystem, smart contracts implemented on blockchain (on the Ethereum network) guarantee data integrity, transparency and reliability among the participants of the supply chain. Random Forest algorithm helps with predictive analytics applied to demand forecasting, quality assessment and

anomaly detection, whereas PSO can optimize transportation routes, resources distribution, and logistics organization. The combination of these smart elements enables the making of adaptive and data-driven decisions throughout the supply chain. The proposed framework improves transparency, decreases costs of operations, and makes supply chain management sustainable by combining the transparency of blockchain, the computational power of cloud computing, and the analytical power of AI. The result is a powerful digital base of this holistic strategy of turning the classic tobacco supply chain into a smart, secure, and efficient ecosystem, which are aligned with the objectives of global digital transformation and Industry 4.0.

2. Literature Review

A number of research works within the last several years have been devoted to the implementation of digital technologies, including blockchain, cloud computing, and artificial intelligence, to improve the supply chains in agriculture and industry in terms of transparency, efficiency, and sustainability. The conventional supply chain models usually make use of central databases which can easily be manipulated, lost, and interoperable. In bid to circumvent these problems, there have been studies by researchers into blockchain-based traceability systems that provide records of transactions and product provenance that are immutable and thus dependable across all stakeholders. Likewise, scalable data storage and analytics have been substantially embraced using cloud computing structures that allow a smooth flow of the IoT-generated data at the cultivation, processing, and logistics streams. Simultaneously, predictive analysis, quality monitoring, and optimization of logistics have been performed using machine learning and optimization algorithms, including the Random Forest, Support Vector Machines (SVM), Genetic Algorithms (GA), and PSO. Although these methods have proved to have profound data visibility, process automation, and decision-making accuracy, they are usually characterized by the fact that they are not easy to scale, are expensive, lack security, and have data fragmentation across various digital platforms. The combination of these technologies, especially combining blockchain, cloud computing, and AI has become a promising way to eliminate these disadvantages and have a single, secure, and flexible digital ecosystem. A comparative overview of key techniques undertaken in existing works is summarized in table 1 below outlining

their major limitations and benefits as applied to the context intelligent supply chain management.

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Table 1. Summary of Existing Techniques, Advantages, and Disadvantages in Blockchain and Cloud-Based Supply Chain Research

S. No.	Title / Author(s)	Techniques / Technologies Involved	Advantages	Disadvantages / Limitations
1	Blockchain-Based Architecture for a Sustainable Supply Chain in Cloud Architecture [16]	Blockchain integration with cloud computing for decentralized and sustainable supply chain management	Enhanced data integrity, sustainability tracking, interoperability among stakeholders	High energy consumption of blockchain operations; limited scalability under heavy data load
2	Blockchain-Based Smart Tracking and Tracing Platform for Drug Supply Chain [17]	Blockchain-enabled IoT system with smart contracts for end-to-end drug traceability	Real-time tracking, counterfeit prevention, improved transparency and compliance	Implementation cost, complex synchronization between blockchain nodes and IoT gateways
3	Supply Chain Traceability: A Case of Blockchain Modelling Application to Agro-Business Product in India [18]	Hyperledger Fabric blockchain model applied to agricultural product traceability	Secure and tamper-proof product lifecycle management, improved accountability	Limited automation, absence of integrated predictive analytics or optimization components
4	Secure and Efficient Drug Supply Chain Management System: Leveraging Polymorphic Encryption, Blockchain, and Cloud Storage Integration [19]	Blockchain with cloud computing and polymorphic encryption for secure data sharing	Strong security and privacy, efficient decentralized storage, reduced data tampering	High computational cost for encryption and decryption, latency in multi-node communication
5	Blockchain-Based Cannabis Traceability in Supply Chain Management [19]	Blockchain and IoT framework for product traceability and regulatory compliance	Enhanced visibility, regulatory adherence, and consumer trust	Lack of machine learning or optimization layer; scalability and interoperability concerns

In the paper, [16] suggest a Blockchain-Based Architecture of a Sustainable Supply Chain in Cloud Architecture, in which blockchain is combined with cloud computing to improve the sustainability and transparency of operations in industries. They focus on the architecture that is characterized by decentralized data storage and real-time cooperation of the parties to enhance traceability and environmental responsibility. Blockchain and cloud secure the data integrity and promote the sustainability of practices through the monitoring of carbon emissions and material sourcing. The framework has however encountered some challenges like high power consumption which is due to blockchain validation processes and the problem of scalability when handling large scale datasets. In spite of such limitations, this paper forms a solid base of implementing blockchain-cloud synergy in the intricate supply chains.

A smart tracking and tracing platform for the drug supply chain was designed using a blockchain-based system that integrates IoT-collected data with smart contracts [17]. Their platform allows tracking pharmaceutical logistics in real-time, which guarantees the authenticity of products and eliminates counterfeit. The blockchain layer has the benefits of securing transactions records and increasing the level of data transparency and stakeholder trust. The system is effective to facilitate the compliance and visibility throughout the pharmaceutical network but it is expensive and complex to implement and align the blockchain nodes with the IoT devices. However, the model proves the feasibility of blockchain and IoT convergence to enhance the traceability and reliability in supply chain management.

A traceability model for the agro-business supply chain in India was developed using blockchain technology based on the Hyperledger Fabric framework [18]. Their strategy will provide tamper proof records and safe information transfer in the agricultural value chain distribution to production. The paper notes how blockchain can contribute to the improvement of transparency, accountability, or the connection between farmers and the market. But it also finds a deficiency in automation and predictive elements of analysis, which restricts the capability of the system to actively optimize logistics or quality management. The article offers useful information regarding the flexibility of blockchain to an agricultural environment and discloses the necessity of the intelligent analytics adoption.

A secure and efficient drug supply chain management system was proposed that employs polymorphic encryption, blockchain, and cloud computing to enhance data security and transaction efficiency [19]. The paper is aimed at the protection of sensitive pharmaceutical information by encryption and decentralized management of trust with the use of blockchain. Cloud computing is used as the support of the scalable data storage and computational processing. Although this integration enhances the security of data and minimizes the chances of tampering, the model has weaknesses of high computing and latency time when handling complex encryption and decryption actions. The approach emphasizes the role of integrating blockchain and cloud computing towards achieving security but points out the need to optimize on computational efficiency.

A blockchain-based cannabis traceability framework was developed to enhance regulatory compliance and strengthen consumer confidence within the cannabis industry [19]. The system uses blockchain and IoT solutions to have the records of cultivation, processing, and distribution phases be immutable and to allow transparency and accountability in a highly controlled setting. The system is effective in creating product authenticity and facilitating effective auditing. Nonetheless, it is not integrated with machine learning or optimization algorithms able to boost predictive abilities and adaptability of the process. The study, even though limited, helps broaden the field of blockchain application beyond the traditional industries, demonstrating the applicability of the technology to the agricultural and pharmaceutical traceability systems.[20] demonstrated that hybrid AI models and sustainable machine learning techniques can significantly enhance logistics efficiency and resource utilization in supply chain systems. These findings conceptually inform the proposed framework by reinforcing the importance of intelligent optimization strategies for improving operational efficiency, system scalability, and overall supply chain performance.[21]

Although existing studies have demonstrated significant advances in applying blockchain, cloud computing, IoT, and machine learning to enhance transparency, traceability, and decision-making in supply chains, a critical ICT integration gap remains. Current approaches typically address isolated aspects—such as blockchain-based data integrity, IoT-enabled monitoring, or machine learning-driven forecasting—without achieving a fully unified architecture that combines

IoT/ICT-based data acquisition, cloud analytics for scalable processing, a blockchain trust layer for data integrity, and intelligent optimization within a single ecosystem. Moreover, most frameworks do not explicitly address the information and communication properties essential for next-generation supply chains: distributed ledgers that ensure data immutability and auditability; smart contracts that enable automated, secure, and real-time communication between stakeholders; and cloud-edge interoperability that sustains low-latency information flow across decentralized networks. Consequently, existing models fall short of delivering an end-to-end intelligent, transparent, and adaptive ICT ecosystem capable of simultaneously ensuring data integrity, operational efficiency, and real-time decision support. To overcome these limitations, the proposed ICT-Integrated Data-Driven Optimization Framework (IDDOF) combines blockchain, cloud computing, IoT, and machine learning with optimization algorithms into a single, secure, and scalable architecture for supply chain management—bridging the gap between transparency, intelligence, and communication efficiency in accordance with Industry 4.0 principles.

3. Comprehensive Flow of the Proposed ICT-Integrated Data-Driven Optimization Framework

The proposed IDDOF represents an integrated and intelligent architecture that digitalizes and streamlines the tobacco supply chain on the basis of the harmonious interaction of IoT, cloud computing, blockchain, machine learning, and optimization technologies. In the first stage, IoT and ICT systems deploy networks of smart sensors, RFID tags, and communication units through cultivation fields, curing plants, and logistics facilities to constantly monitor the operation and environmental conditions, including soil moisture, temperature, humidity, and color of the leaves. These tools, which are facilitated by a wireless ICT infrastructure, provide a stream of time-stamped, georeferenced data, which is the digital base of the system. Having been collected, the data is safely transferred to the cloud through encrypted protocols. The cloud layer is the data hub, which cleans, normalizes and aggregates to convert various raw data into structured analytics-ready data. This interoperable environment will enable joint data access to all stakeholders: farmers, processors, distributors, and policymakers, and these include interoperability, reliability, and efficient data sharing through the whole value chain. The information

flow within the proposed framework progresses seamlessly from the IoT layer to the cloud environment, then to the blockchain network, and finally to the decision-making layer, ensuring secure data transmission, transparent record-keeping, and intelligent, data-driven decision support across the entire tobacco supply chain.

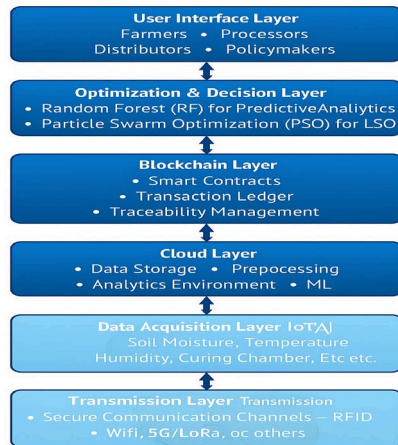


Figure 1. Proposed Architecture

Figure 1 illustrates the layered communication structure of the proposed framework. Data generated by IoT devices is transmitted continuously to the cloud layer using lightweight streaming protocols. However, interactions between the cloud and blockchain layers are governed by an event-driven synchronization mechanism. Rather than recording every sensor update, blockchain transactions are selectively triggered by significant operational events, including quality certification updates, logistics state transitions, ownership transfers, anomaly detection, and smart contract execution conditions. This hierarchical data flow strategy combining continuous sensing with event-triggered ledger registration prevents excessive blockchain overhead while enhancing latency, throughput, scalability, and energy efficiency.

The data that has been processed in the cloud are preserved and authenticated with a blockchain based trust layer in successive stages where every transaction or operation record is permanently stored in cryptographic hashing and consensus verification in order to maintain transparency and resistance to tampering. This verified information is then run through the machine learning layer of intelligence where the random forest algorithm will identify predictive clues like the yield estimate, demand prediction and quality classification. The PSO module also uses these insights to find the best operational modes, including the production scheduling

and transport routes, as well as resource allocation. The framework is dynamically versatile to changing market environments and resource limitations through the optimization of collection intelligence. Together these combined stages create a closed loop digital ecosystem that is able to learn continuously, make decisions independently and coordinate transparently. Therefore, the IDDOF will make the previous tobacco supply chain Industry 4.0-compatible and the system that is sustainable, efficient, and accountable.

3.1 Integrated Data Acquisition and Cloud-Based Data Processing

The first step of the suggested framework is to create the basis of a data-focused and digitally connected supply chain of tobacco by implementing Information and Communication Technology (ICT) and the Internet of Things (IoT). It will be conducted by installing a network of interdependent devices and intelligent sensors on different tiers of operation, such as farm fields, processing stations, warehouses, and transportation systems, in order to track and capture significant variables in real-time [21]. At the cultivation stage, parameters such as soil moisture, ambient temperature, humidity, intensity of light, and color of tobacco leaves are captured to assess crop health and estimate yield quality. Similarly, during processing and packaging, sensors monitor curing temperature, storage humidity, and machine execution to ensure quality consistency. During the logistics phase, GPS devices and environmental sensors mounted in transport vehicles track position, vibrations, and temperature variations to prevent product damage. These devices operate efficiently through well-developed ICT infrastructures, including wireless communication modules, cloud gateways, and mobile interfaces, ensuring uninterrupted data flow between field nodes and central repositories [22].

Parallel to this, RFID tags, barcodes, and mobile-based applications play a crucial role in maintaining traceability and identification of tobacco batches across the supply chain. Each batch is assigned an individual digital identity, allowing stakeholders to track its movement from farm to factory and through distribution channels. Within the proposed framework, physical identifiers such as RFID tags and barcodes are directly synchronized with blockchain entries to establish a consistent cyber-physical traceability mechanism. Each physical batch identifier functions as a unique reference key that links real-world assets with their corresponding immutable digital records. When a batch is scanned at any

operational stage, the associated blockchain entry is retrieved or updated, ensuring identity continuity across distributed system layers. This mapping structure prevents duplication, mitigates data inconsistency, and strengthens resistance to tampering by binding physical product movement with cryptographically secured ledger events. Consequently, the integration of RFID-based identification with blockchain recording enhances end-to-end traceability, verification reliability, and supply chain accountability. This electronic tracking system reduces human error, prevents record duplication, and enhances accountability at each operational handoff. The integration of ICT ensures that collected data is time-stamped, georeferenced, and securely logged, providing a transparent and reliable data source for subsequent computational processes.

Upon the collection of real-time data through IoT and ICT devices, the information is safely transmitted to a cloud computing environment using encrypted communication protocols such as TLS or MQTT over SSL. The proposed framework employs lightweight IoT communication protocols optimized for real-time data streaming and minimal network overhead. Sensor nodes utilize MQTT publish-subscribe messaging due to its low bandwidth consumption and asynchronous communication efficiency, while REST-based HTTP/HTTPS interfaces support administrative and batch-level data interactions. Data packets follow a structured message format comprising device identifiers, timestamps, sensor attributes, and measurement values, ensuring interoperability and consistent parsing across system components. Synchronization between edge devices, cloud repositories, and blockchain nodes is governed by an event-driven mechanism, where validated operational updates trigger selective ledger writes. This approach reduces communication redundancy, minimizes synchronization overhead, and maintains temporal consistency of distributed data streams. To ensure secure and reliable communication between IoT devices, the cloud platform, and the blockchain network, the framework incorporates multi-layered encryption and transport security mechanisms. Data transmitted from distributed sensors is protected through SSL/TLS protocols, ensuring end-to-end encryption, message integrity, and protection against interception or tampering. Device-level authentication and cryptographic key management mechanisms further verify the identity of participating nodes, ensuring that only trusted devices interact with the cloud infrastructure. Similarly, cloud-blockchain interactions are safeguarded through encrypted

APIs, maintaining confidentiality and integrity of transaction data.

This multi-layered security architecture complements blockchain immutability by securing both data transmission and storage. Consequently, the framework ensures protected information flow, minimizes cybersecurity risks, and enhances the trustworthiness of the digital supply chain ecosystem. The cloud functions as a digital repository that combines and structures heterogeneous data originating from farms, processing facilities, logistics nodes, and administrative systems. Its distributed and scalable infrastructure supports high-speed data ingestion, large-scale storage, and parallel processing [23], enabling the system to handle dynamic data loads while maintaining reliability and accessibility. The cloud environment also allows stakeholders, including farmers, processors, and policymakers, to access a unified dataset remotely through a shared interface, promoting interoperability and collaborative decision-making.

After raw data is received, it undergoes preprocessing operations such as cleaning, normalization, redundancy elimination, and aggregation to improve data quality and consistency [24]. These processes convert unstructured sensor data into analytics-ready information. Normalization and aggregation across multiple data sources can be mathematically expressed as:

$$D_{norm}(t) = \frac{1}{N} \sum_{i=1}^N \frac{(x_i(t) - \mu_i)}{\sigma_i} \quad (1)$$

In which $D_{norm}(t)$ is the normalized data at time t , $x_i(t)$ is the value of the i^{th} source, μ_i and σ_i are the mean and standard deviation of that source. This guarantees uniform scaling of inputs before they are delivered to analytics and optimization layers. Through distributed computation, virtualization, and parallel resource allocation, the cloud layer minimizes processing latency and computational bottlenecks. The computational efficiency of the framework is primarily supported by the distributed nature of cloud computing. Cloud infrastructure enables parallel processing by allocating workloads across multiple virtualized resources, significantly reducing processing time for large-scale IoT data streams. Unlike fixed-capacity centralized systems, elastic resource provisioning dynamically adjusts computational power based on real-time data volumes. This prevents performance degradation and minimizes computational bottlenecks.

Additionally, intelligent load balancing mechanisms optimize task distribution, ensuring efficient utilization of processing resources. Latency is further reduced through optimized data routing and edge–cloud coordination, which limit transmission delays. Consequently, the cloud layer enhances throughput, accelerates analytics execution, and maintains stable system responsiveness under high-volume real-time conditions.

Furthermore, optimized data routing and edge–cloud interaction mechanisms reduce redundant transmissions, enabling near-real-time analytics execution.[25]. Finally, the integrated data acquisition and cloud-processing layer serves as the digital nervous system of the framework, enabling accurate information flow, enhanced visibility, reduced latency, and reliable data availability for blockchain verification, predictive analytics, and optimization processes.

3.2. Blockchain-Based Trust, Security, and Transparency Layer

The third phase of the suggested framework incorporates the blockchain technology as a means to create a transparent and trusted environment that is immutable in terms of data sharing throughout the tobacco supply chain. All-important transactions (leaf quality certification, transportation records, payment settlements and storage logs) are safely stored in a permissioned blockchain in this layer [26]. All the stakeholders are nodes in this decentralized network such as farmers, manufacturers, distributors and regulators. The blockchain also provides data immutability, which implies that once a transaction is stored in the blockchain, there is no way to change it without the rest of the nodes agreeing with this. With smart contracts on such platforms as Ethereum, the predefined rules (such as the ability to make payment after quality control) are automatically processed, which eliminates delays and eliminates the necessity of intermediaries. The immutability characteristic of blockchain transactions provides a fundamental advantage in strengthening accountability and traceability within the supply chain. Once operational records—such as quality certifications, shipment logs, storage conditions, and ownership transfers—are written to the blockchain, they become permanently preserved and resistant to modification. This eliminates the possibility of retroactive data manipulation, unauthorized

alterations, or record inconsistencies that commonly arise in centralized database systems.

From an accountability perspective, immutable records ensure that every stakeholder action is transparently documented and verifiable. Responsibilities, contractual obligations, and compliance events can be objectively audited, thereby reducing disputes, enhancing trust, and promoting operational discipline across the network. Similarly, in terms of traceability, immutability guarantees the reliability of product lifecycle histories, enabling accurate tracking of provenance, handling conditions, and transaction flows. Consequently, blockchain immutability functions as a digital enforcement mechanism that enhances transparency, strengthens governance, and ensures integrity of information throughout the tobacco supply chain ecosystem.

Such automation improves accountability and efficiency as well as transparency among all involved parties.

Mathematically, cryptographic hash function could be used to represent the integrity of blockchain data by connecting each block to its predecessor. The hash H_i is calculated as:

$$H_i = SHA256(D_i + H_{i-1}) \quad (2)$$

where the transaction data D_i is of the current block and H_{i-1} is the hash of the last block. It is a chained system so that tampering will be resisted by ensuring that any changes made in the previous records will automatically nullify the next blocks. Such a mechanism can be implemented in the tobacco supply chain to ensure the provenance of its products, i.e. farm to retailer, in real-time, merely by following the blockchain ledger [27]. As a result, such a layer of trust increases the reliability of the framework. Beyond data security, the blockchain layer plays a critical role in ensuring end-to-end traceability and product authenticity within the tobacco supply chain. By operating as a decentralized and immutable ledger, blockchain records every transaction, movement, and transformation of tobacco batches from cultivation to final distribution. Each operational event—including harvesting, processing, storage, transportation, and quality verification—is cryptographically linked, thereby establishing a transparent and tamper-resistant history of product provenance. This mechanism enables precise tracking of product origin, handling conditions,

and ownership transitions. Any stakeholder within the network can verify the authenticity and lifecycle history of a tobacco batch without relying on centralized intermediaries. Smart contracts further strengthen this verification process by automatically validating predefined conditions such as quality compliance, shipment confirmation, and payment authorization. Consequently, stakeholder interactions become trust-driven, auditable, and resistant to manipulation. Through this decentralized verification structure, the framework significantly reduces risks associated with counterfeit products, data alteration, and information asymmetry. The blockchain ledger therefore functions not only as a security mechanism but also as a digital trust infrastructure that guarantees transparency, accountability, and authenticity across the entire supply chain ecosystem. protects the interests of stakeholders, and facilitates the transparent governance of the supply chain to ensure that the supply chain is aligned with the current Industry 4.0 concept of digital accountability and data-driven traceability [28].

3.3. Data-Driven Intelligence through Machine Learning (Random Forest Algorithm)

At the fourth phase, the offered framework uses machine learning intelligence to convert the data stored in the cloud into predictive and analytical information that is used to make operational decisions. The Random Forest (RF) model is selected among the number of available algorithms due to its strength, high level of accuracy, and the capability to deal with nonlinear and multidimensional data [29]. The selection of the Random Forest model is further motivated by its suitability under practical ICT and Industry 4.0 operational constraints. Compared to deep learning approaches, Random Forest requires significantly lower computational resources, reduced training complexity, and minimal parameter tuning, making it well-suited for environments characterized by real-time analytics and latency-sensitive decision-making. While deep neural networks offer high representational capacity, they often impose increased processing overhead, longer training cycles, and higher energy consumption, which may not align with resource-constrained supply chain infrastructures. Relative to other ensemble techniques such as boosting-based models, Random Forest provides strong generalization performance with improved robustness to noise, missing data, and heterogeneous feature distributions commonly observed in IoT-driven

datasets. Additionally, its inherent interpretability and stability support transparent decision reasoning, an essential requirement for blockchain-integrated systems and regulatory-compliant supply chain operations. The Random Forest algorithm is used in the tobacco supply chain to carry out the main predictive analytics, such as demand forecasting, classifying leaves, and anomaly identification in the logistics processes. The Random Forest model functions as a predictive and classification component within the framework by processing IoT-derived and historical supply chain data. Using ensemble learning, the algorithm constructs multiple decision trees to capture nonlinear relationships among variables such as climatic conditions, quality parameters, yield records, and market trends. This enables accurate demand forecasting, reliable quality classification, and early detection of anomalies. The ensemble structure improves generalization performance, reduces overfitting, and ensures stable predictive accuracy under dynamic and uncertain supply chain conditions. The model uncovers multifaceted associations between the input and desired outcomes by training on historical data, which contains climatic conditions, soil parameters, yield records, and market trends. Having been trained, it will be able to make its predictions on the forthcoming demand trends, classify tobacco leaf grades, and report the anomalies including unanticipated delays or quality variation [30]. This foreseeing factor allows the stakeholders to make anticipatory decisions when it comes to procurement, stock control, and the production timetable which reduces wastage and enhances responsiveness [31]. The predictive outputs generated by the Random Forest model further enable automated operational control through interaction with blockchain-based smart contracts. Machine learning results are transmitted to the blockchain layer as validated decision signals rather than direct execution commands. For example, quality classification outputs activate certification contracts, anomaly detection results trigger exception-handling or compliance verification routines, and demand forecasts initiate procurement or inventory adjustment rules. Smart contracts interpret these analytics-derived inputs using predefined rule-based logic, ensuring that automated decisions remain transparent, verifiable, and resistant to subjective intervention. This integration establishes a secure decision-execution pipeline where predictive intelligence drives auditable and trust-preserving supply chain operations. The random forest model prediction can be mathematically defined as the combination average between several decision trees. To obtain the overall prediction \hat{y} the total of all prediction of the input feature vector X is as,

$$\hat{y} = \frac{1}{T} \sum_{t=1}^T f_t(X) \quad (3)$$

Assuming that T is the number of decision trees within the forest, and $f_t(X)$ is the output of the t^{th} decision tree. This is an ensemble-based method that reduces the chances of overfitting and improves the performance of generalization through the joint efforts of multiple independent learners [32]. In the context of tobacco supply chain, it implies that the system has the ability to predict dynamically the needs of the market and the best time to harvest, as well as be able to detect anomalies in the logistics with a high degree of reliability. The result of this phase is a key input to the following phase, which is the optimization through PSO, thus connecting the predictive intelligence to the operational decision-making process to create a self-adaptive and data-driven digital ecosystem [33].

3.4. Optimization and Adaptive Decision-Making Using Particle Swarm Optimization (PSO)

The fourth step of the suggested framework is aimed at the optimization of the operational and logistical performance of the tobacco supply chain with the use of the PSO algorithm. This stage involves taking the predictive knowledge that the Random Forest model has produced including demand predictions, quality predictions, and market trends and as inputs in the optimization process [34]. PSO is an example of a population-based metaheuristic which is based on the social behavior of a bird flock or a fish school and is therefore well adapted to high-dimensional and nonlinear optimization problems typical of complex supply chains. PSO would be used in the tobacco ecosystem to determine the best channels to transport products, production timelines and resource allocation techniques that would ensure minimisation of cost, reduction of lead time and reliability of supplies [35]. The possible combinations of the supply chain parameters are known as potential solutions, or particles. These particles reach an optimal or near-optimal solution after a series of changes directed by the individual and collective performance. The equations that are used to update the velocity and position of each particle in the search space in the PSO algorithm are mathematically obtained as the following:

$$v_i^{(t+1)} = wv_i^{(t)} + c_1r_1(pbest_i - x_i^{(t)}) + c_2r_2(gbest_i - x_i^{(t)}) \quad (4)$$

$$x_i^{(t+1)} = x_i^{(t)} + v_i^{(t+1)} \quad (5)$$

$v_i^{(t)}$ at the i^{th} iteration and $x_i^{(t)}$ at the i^{th} iteration are the velocity and position of the i^{th} particle, $pbest_i$ is the personal best position of the particle, $gbest_i$ is the global best position that has ever been found by the swarm, w denotes the inertia weight of exploration and c_1, c_2 represent randomness components $r_1, r_2 \in [0, 1]$. The swarm is able to determine the most effective operational arrangements to use in the supply chain through successive iteration [36]. The proposed system would be based on adaptive and data-driven decision-making through combined PSO-driven optimization, blockchain secured data and machine learning predictions, thereby maximizing cost efficiency, operational flexibility, and sustainability [37]. This will put an end to the ICT-Integrated Data-Driven Optimization Framework (IDDOF), that changes the classic tobacco supply chain into a smart, autonomous, and Industry 4.0-friendly ecosystem.

Beyond static optimization, the integration of Particle Swarm Optimization (PSO) with the Random Forest (RF) predictive layer enables real-time adaptive decision-making within the proposed framework. While RF provides predictive intelligence based on historical and streaming data, the optimization process is not executed as a one-time operation. Instead, PSO functions as a continuous, feedback-driven mechanism capable of dynamically recalibrating operational decisions in response to real-time system variations. This transforms the framework from a conventional predictive analytics system into a prescriptive and self-adjusting supply chain control architecture.

In practical supply chain environments, operational conditions are inherently volatile. Demand patterns fluctuate, transportation conditions change, inventory levels vary, and environmental factors introduce uncertainty. Within the IDDOF, IoT sensors continuously generate live data streams describing these evolving conditions. Whenever deviations from predicted or expected states are detected—such as unexpected demand surges, logistics delays, storage anomalies, or quality degradation—the RF model updates its predictions using the most recent data. These updated outputs immediately serve as new inputs to the PSO module, which re-optimizes routing, scheduling, and resource allocation parameters. This closed-loop interaction establishes an event-driven optimization cycle:

Sense → Predict → Optimize → Monitor → Re-optimize

Rather than relying on static assumptions, the optimization objective becomes time dependent:

$$F(t) = f(D(t), Q(t), C(t), R(t)) \quad (6)$$

where $D(t), Q(t), C(t)$, and $R(t)$ represent dynamically changing demand, quality, cost, and resource conditions derived from real-time IoT data. As these variables evolve, PSO continuously searches for new optimal or near-optimal solutions, ensuring that supply chain decisions remain aligned with actual operating conditions. Consequently, PSO within the proposed framework acts not merely as a logistics optimizer but as an adaptive coordination engine. It enables autonomous system responses, minimizes disruption impacts, stabilizes operational performance, and enhances resilience under uncertainty. This capability extends the framework beyond predictive analytics and traditional logistics optimization, enabling intelligent, real-time supply chain orchestration consistent with Industry 4.0 principles.

4. Results and Discussion

The performance evaluation was conducted within a controlled simulation environment designed to emulate realistic ICT-enabled supply chain conditions. The simulation incorporates dynamic operational variables including demand fluctuations, transaction intensity, network latency, data throughput, and computational workload. These parameters enable systematic assessment of latency, throughput, scalability, and optimization efficiency under varying data volumes. The experimental configuration reflects commonly observed behaviors of cloud, IoT, and blockchain-integrated systems, thereby ensuring practical relevance and methodological transparency of the results. The results and discussion part of the study assesses the suggested ICT-Integrated Data-Driven Optimization Framework (IDDOF) as a powerful ICT architecture to the tobacco supply chain that is aimed at its technological effectiveness, but not at a specialized solution. The evaluation is done by simulations and comparative analysis against some important ICT performance measures such as data accuracy, interoperability, traceability, latency of processing, transaction security, accuracy of demand prediction, throughput and efficiency of optimization. The findings reveal that the combined application of the IoT-based data collection, cloud-based analytics, blockchain-based transparency, and machine learning-based optimization play an important role in improving the overall ICT performance of the system. The framework exhibits less latency, enhanced throughput, high integrity of data, and enhanced responsiveness in

decision making besides being scalable, secure and interoperable among distributed components. The IDDOF demonstrates significant cost-effectiveness, real-time monitoring capability, and adaptive operational intelligence. Unlike conventional ICT-enabled supply chain systems that primarily support prediction and static planning, the proposed framework enables continuous feedback-driven optimization, allowing the system to dynamically reconfigure routing, scheduling, and resource allocation decisions in response to live operational disturbances. This real-time adaptability substantially improves system resilience, decision responsiveness, and communication efficiency across distributed supply chain nodes.

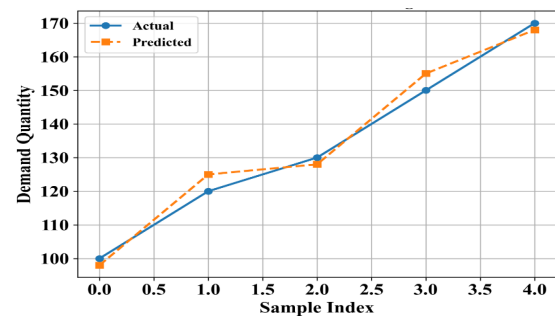


Figure 2. Demand Forecasting Performance of the Random Forest Model

Figure 2 represents the analysis of the actual and predicted demand amounts of five sample indices of the tobacco supply chain data set in the context of the Random Forest (RF) algorithm in the framework of the suggested ICT-Integrated Data-Driven Optimization Framework (IDDOF). The RF-predicted figures of nearly 98, 125, 128, 155, and 168 units were also close to the actual demand quantities of 100, 120, 130, 150 and 170 units, respectively. The fact that the actual and predicted curves are close to each other, and experience the same trend, shows that the model is highly accurate in its predictions, and its generalization ability is high. ICT-wise, this outcome has shown significant progress in the accuracy of information (accurate data-driven forecasting), the processing latency (fast response of the models and the ability to perform prediction in real-time), the throughput (ability to process a large number of demand data streams at a time), and the reliability of communication (the consistent propagation of accurate information through the layers of the system). The observed minor deviations at the second and fourth data points could be as a result of real market fluctuations and is well countered by the averaging property of the RF

algorithm. In general, these findings confirm that the demand forecasting element of the IDDOF can help increase the speed, capacity and reliability of information sharing in the digital supply chain, as well as provide the ability to take proactive decisions, enhance coordination, and allocate resources more optimally in the ICT-enabled ecosystem.

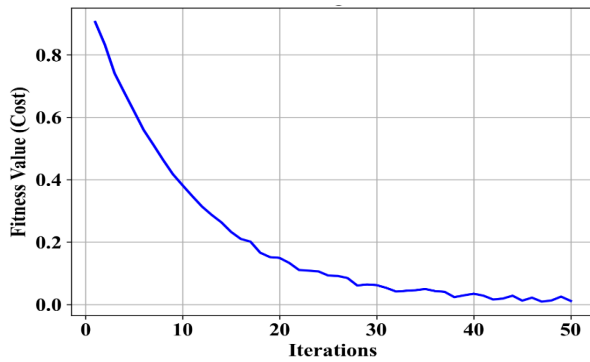


Figure 3. Convergence Performance of the Particle Swarm Optimization Algorithm

The convergence of the Particle Swarm Optimization (PSO) algorithm in the minimization of logistics cost and the maximization of resource allocation in the proposed ICT-Integrated Data-Driven Optimization Framework (IDDOF) is presented in figure 3. As shown by the convergence curve, there is a steady decline in the value of fitness (cost) with each repetition of the algorithm - starting around 0.85 to 0.02 - which is evidence of the efficient algorithmic learning and the optimization of a system. In terms of ICT performance, this outcome indicates the improvements in major measures of processing latency (increased convergence in computational tools and decreased decision delay), optimization efficiency (increased algorithmic flexibility and resource use), throughput (increased processing capacity to solve multi-variable optimization), and energy efficiency (reduced computational overhead with solution stabilizing). The fault-free convergence is a smooth curve without oscillations implying the sound information-processing capacity of the framework, which accelerates information flow and provides decision-communication among the layers of the digital pathways with greater stability. On balance, these results confirm the PSO-based optimization module of the IDDOF as an addition to the increased computational intelligence, communication responsiveness, and the performance of the system as a whole, which furthers the ICT performance of the entire supply chain network.

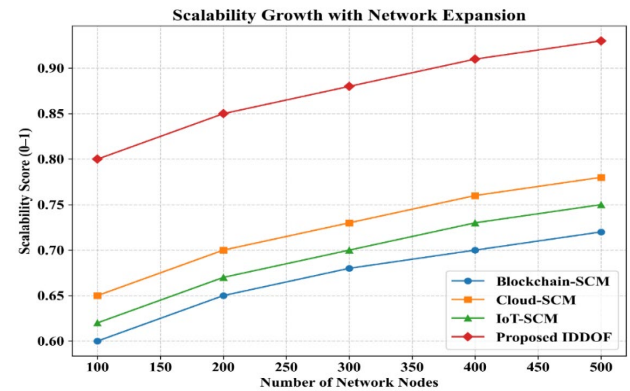


Figure 4. Scalability Growth with Network Expansion

The figure 4 below represents the Scalability as the network is expanded, the scalability performance of the alternative supply chain management models is Blockchain-SCM, Cloud-SCM, IoT-SCM, and the proposed ICT-Integrated Data-Driven Optimization Framework (IDDOF). The performance is measured with 100 network nodes, then the number is increased to 500 to investigate the scalability of each model. The normalized scalability score (0-1) indicates the ability of the system to operate with performance, responsiveness, and efficient communication as the load of the network increases. The proposed IDDOF is to be considered as the best among other models with the increase of a score in a degree of 0.80 at 100 nodes up to around 0.91 at 500 nodes, whereas Cloud-SCM, IoT-SCM, and Blockchain-SCM are lower at 0.78, 0.75, and 0.72, respectively. ITC wise, the results indicate better throughput (greater information throughput capacity as the network size increases), reduced latency (data transmission and processing faster with a minimum delay), interoperability (coordination between distributed components), and network efficiency (optimal use of bandwidth and data aggregation). The gentle upward shift of the IDDOF curve is a sign of increased velocity of information propagation, system flexibility, and communication strength during high-load situations. This proves the thesis that the hybrid ICT structure, which is based on cloud-based distributed computing, IoT-enabled sensing, and blockchain-based trust management, attains the high degree of scalability and stability of communications to be used in large-scale industrial applications in line with the requirements of Industry 4.0. As the network size expands, ICT performance measures are increasingly influenced by practical system constraints, including hardware processing capacity, memory limitations, bandwidth availability, and device-level computational overheads. In large-scale environments, conventional architectures

typically experience latency growth and throughput degradation due to centralized bottlenecks and synchronization delays. In contrast, the proposed IDDOF framework maintains stable scalability behavior by leveraging distributed cloud processing, decentralized coordination, and adaptive workload balancing mechanisms.

Under realistic infrastructure constraints, performance sustainability depends not only on computational resources but also on communication efficiency and orchestration intelligence. The hybrid ICT architecture mitigates hardware-induced limitations by dynamically redistributing processing tasks, optimizing data routing, and minimizing redundant transmissions. Consequently, scalability improvements remain consistent even under increased transaction loads and constrained physical resources, reinforcing the framework's suitability for large-scale, real-world supply chain deployments.

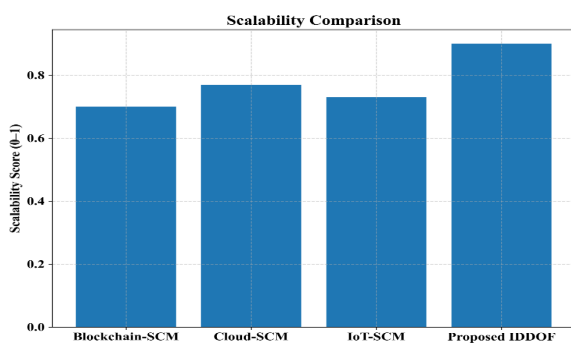


Figure 5. Scalability Comparison Analysis

The results of Figure 5 are the comparative scalability performance of four supply chain management models, such as Blockchain-SCM, Cloud-SCM, Internet of Things, or IoT-SCM, and the proposed ICT-Integrated Data-Driven Optimization Framework (IDDOF) assessed on a normalized scale (01), in terms of their capacity to support the growing workloads and network growth without the performance decline. The score of the proposed IDDOF on the scale of scalability is the highest (0.88), and it is superior to that of Cloud-SCM (0.78), IoT-SCM (0.74), and Blockchain-SCM (0.70). This is reflected in better ICT metrics, namely better throughput (an improved information-handling capacity with higher network loads), shorter latency (shorter response time and data transfer), network efficiency (improved resource allocation and bandwidth optimization), and interoperability (smoother integration among distributed digital components). The IDDOF hybrid architecture, which is distributed cloud computing combined with real-

time IoT synchronization and blockchain-based validation of transactions, allows allocating the resources dynamically and adjusting the flow of communication, which makes the system very responsive even when it grows. The continuous increase in performance proves that the framework ensures the strong information propagation, stability of communication and adaptability of computations, which confirms that it is long-term viable as scalable ICT infrastructure in large-scale and data-intensive digital supply chain settings consistent with the requirements of Industry 4.0.

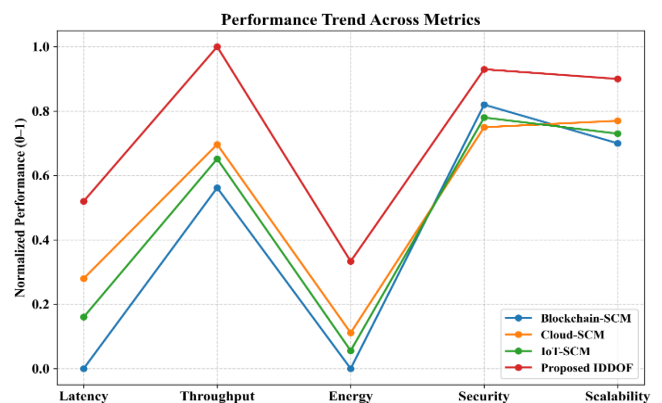


Figure 6. Performance Trend Across Metrics

Figure 6 compares the comparison between the performance of four supply chain management models, namely Blockchain-SCM, Cloud-SCM, IoT-SCM, and the proposed ICT-Integrated Data-Driven Optimization Framework (IDDOF) in five main ICT performance indicators, i.e., latency, throughput, energy efficiency, security, and scalability. The IDDOF is clearly and steadily showing better and balanced performance in all the dimensions with the highest throughput and scalability values (≈ 0.9) depicting a strong information-handling capacity, effective routing of communication and the ability to withstand high-scale network conditions. It has low latency, which emphasizes the acceleration of the flow of information and the minimization of the time needed to make a decision, and controlled energy consumption is an indication of the optimization of the use of computational resources in distributed conditions. The system also achieves a great security index (≈ 0.9), due to the data integrity, authentication, and tamper-resistant communication that is ensured by the blockchain, thus trusted transactions between nodes. On the contrary, the problem with Blockchain-SCM is that it does not have adaptive optimization, but it has high latency and energy consumption because of the consensus

overheads, which Cloud-SCM does moderately. In general, the IDDOF can be described as having a balanced ICT performance profile that is consistent due to its ability to transmit data at a high rate, high transaction capacity, energy consciousness, and secure communication, which substantiates that IDDOF is a strong next-generation ICT infrastructure to support the development of intelligent, efficient, and sustainable supply chain systems.

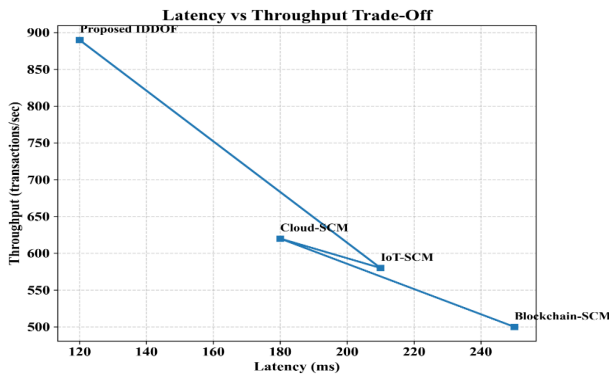


Figure 7. Latency vs Throughput Trade-Off

Figure 7 shows the trade-off of the throughput and latency of the various supply chain management frameworks, in terms of their relative performance, in respect of the speed of communication and the capacity to handle transactions. The suggested ICT-Integrated Data-Driven Optimization Framework (IDDOF) demonstrates the highest performance, constituting a throughput of about 890 transactions per second and a latency of about 120 milliseconds which are indicative of very efficient data transmission, processing, and communication processes. The Blockchain-SCM model, in its turn, has the weakest throughput (around 500 transactions per second) and the highest latency (around 250 milliseconds) which is a manifestation of slower information propagation and inability to operate at high network loads. Cloud-SCM and IoT-SCM frameworks have a moderate performance with intermediate throughput and latency values. The observed inverse relationship (the higher the throughput, the lower the latency) demonstrates the higher capacity of controlling faster information exchange, higher transaction rate and real-time responsiveness of the IDDOF despite the increasing load of the network. On the whole, this trade-off analysis establishes that the suggested ICT framework ensures the optimal level of communication, allowing the fast transfer of data, making decisions in a short period of time, and scaling the

processing of transactions required in large-scale and real-time industrial tasks.

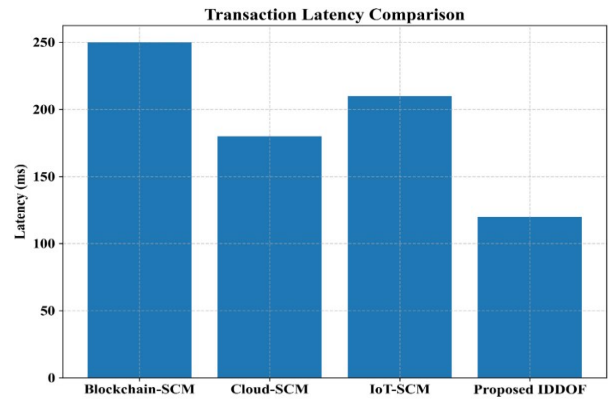


Figure 8. Transaction Latency Comparison

Figure 8 provides a comparison of the transaction latency of four supply chain management models, including Blockchain-SCM, Cloud-SCM, IoT-SCM, and the proposed ICT-Integrated Data-Driven Optimization Framework (IDDOF). The IDDOF also exhibits the slowest latency of about 120 milliseconds indicating the presence of a very efficient communication structure that can propagate data fast and process transactions in real-time. Conversely, Blockchain-SCM has the longest latency (approximately 250 milliseconds) because of the consensus cost and distributed validation overheads, whereas Cloud-SCM and IoT-SCM have moderate latency rates of 180 ms and 210 ms, respectively, with the centralized and semi-distributed architecture. ICT wise, lower latency of the IDDOF means a dramatic improvement in the speed of transferring information, responsiveness of processing systems and efficiency of the decision communications. This is because it has been optimized in data routing, intelligent orchestration schemes as well as a hybrid decentralised design, which in combination reduce communication delays between system layers. Generally, the findings confirm that the suggested framework can improve responsiveness and low-delay communication performance in real-time, therefore, the solution is suitable in time-critical and data-intensive supply chain management in Industry 4.0 settings.

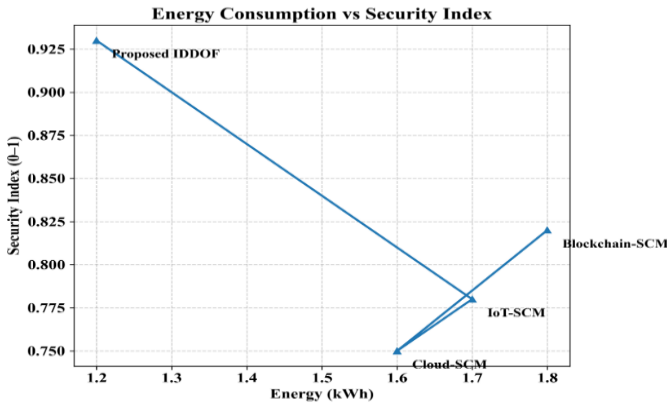


Figure 9. Energy Consumption vs Security Index

Figure 9 displays the trade-off analysis of four supply chain management frameworks, namely Blockchain-SCM, Cloud-SCM, IoT-SCM, and the proposed ICT-Integrated Data-Driven Optimization Framework (IDDOF) in terms of energy consumption and the security index. The best balance of performance is the IDDOF with the highest security index (= 0.93) and the lowest energy consumption (= 1.2 kWh). It means that the framework suggested will provide secure data transfers and dependable communication with the minimum amount of computation and energy expenditure. Compared to it, Blockchain-SCM has significantly lower security (0.83) but consumes the most energy (1.8 kWh) because of the extensive process of consensus and cryptographic validation. The results of Cloud-SCM and IoT-SCM fall in the middle, adjacent to 1.6/1.7 kWh of energy consumption and moderate security indices (around 0.75/0.78), due to semi-centralized network structures. On the ICT viewpoint, the IDDOF is more energy efficient (less computational power per transaction), more secure in its communication (trusted and encrypted data flow) and more reliable in its system performances (performance under secure conditions). This energy consciousness/high communication integrity balance attests to the fact that the IDDOF is a highly optimized ICT environment that can guarantee secure, low-power, and sustainable information exchange a paramount need of the current digital supply chain ecosystem that meets Industry 4.0 sustainability objectives.

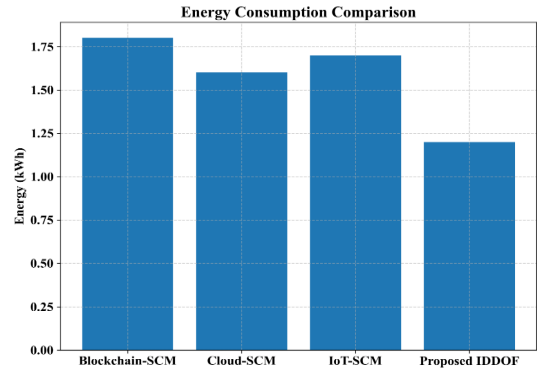


Figure 10. Energy Consumption Comparison

Figure 10 provides a comparison between the energy consumption performance of Blockchain-SCM, Cloud-SCM, IoT-SCM and the proposed Intelligent Data-Driven Optimization Framework (IDDOF). The energy requirement of the IDDOF is shown as the lowest (around 1.2 kWh), which is evidently superior to those of the other models - Blockchain-SCM (about 1.8 kWh), IoT-SCM (about 1.7 kWh), and Cloud-SCM (about 1.6 kWh). Information propagation, reduced computational overhead and sustainability in communication are direct results of this energy usage reduction in ICT terms. The intelligent distributed orchestration, adaptive scheduling of tasks, and data-intelligent routing of IDDOF are what results in the minimal energy footprint because they reduce redundant transmissions and processing cycles. Conversely, the use of heavy consensus mechanisms in Blockchain-SCM renders it highly power-consuming as it involves multiple data verification processes and Cloud-SCM and IoT-SCM are moderately efficient but constrained by the centralized coordination overheads. It is the high energy optimality of the IDDOF hence an optimised ICT infrastructure enabling quick data exchange, high transaction throughput, and greener communication processes and thus is the best fit of large-scale, sustainable supply chain networks.

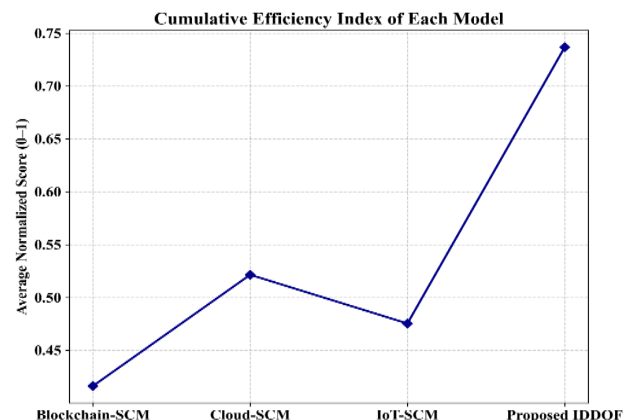


Figure 11. Cumulative Efficiency Index of Each Model

The comparison of the cumulative efficiency index between Blockchain-SCM, Cloud-SCM, IoT-SCM and the proposed IDDOF model are shown in figure 11. The IDDOF has the highest normalized efficiency of 0.74 which implies the best overall performance of ICT systems regarding the data processing throughput, communication reliability, and latency control, as well as the use of energy. Conversely, Blockchain-SCM has the lowest efficiency index (~0.42) because it has intensive consensus mechanisms that augment computational and communication overheads. Cloud-SCM achieves moderate efficiency (= 0.52), with the advantage of a centralized optimization and the drawbacks of bottlenecks and latency in the event of a heavy load. IoT-SCM is a little bit lower (~0.48), which is primarily limited by the inability to synchronize the nodes, as well as the inefficiency of IoT-based scaling. The exceptional performance of the proposed IDDOF is due to the adaptive orchestration, decentralized optimization and smart coordination of resources that together can increase the rate of information flow, transaction reliability and network responsiveness. All in all, the increased efficiency index implies that IDDOF creates a balanced, high-efficiency ICT architecture capable of maintaining the quality of communication, minimizing delays in the information flow, and utilizing resources more efficiently, which makes it an efficient and sustainable digital base of next-generation supply chain management.

throughput that is about 870 transactions per second, and this shows that the information transmission capacity, data-handling efficiency, and responsiveness of the network are better. This large throughput is an indication of the optimized communication protocols, smart task coordination, and decentralized data routing in the framework that reduce the congestion and allows rapid propagation of information across the distributed nodes. Comparatively, Cloud-SCM (about 620 transactions/sec) and IoT-SCM (about 580 transactions/sec) have moderate throughput, which is restricted by the latency of centralized control and data synchronization inefficiencies. The weaker one is the Blockchain-SCM which can process about 500 transactions/sec because of the overhead of the consensus and block verification computational and communication costs. The increased throughput of the IDDOF therefore means that there is a significant increase in the ICT performance of the network level such as the increase in the transaction capacity, lower latency, and efficient use of bandwidth. These findings affirm that the IDDOF model is a powerful, superfast backbone communications model, which is promising to underpin real-time, scalable, and resilient digital supply chain ecosystems that will operate in Industry 4.0 conditions.

4.1. Discussion

The proposed Intelligent Data-Driven Distributed Orchestration Framework (IDDOF) demonstrates superior ICT performance across multiple parameters compared to traditional Blockchain-SCM, Cloud-SCM, and IoT-SCM systems. The ICT performance evaluation reflects system behavior across heterogeneous operational scenarios rather than isolated measurements. The simulation framework incorporates dynamic variations in data generation rates, transaction intensities, network interactions, and computational workloads to emulate realistic supply chain environments. The multi-scenario assessment captures both steady-state operating conditions and stress-induced system responses, enabling reliable interpretation of latency, throughput, scalability, and energy efficiency metrics. By modeling fluctuating operational constraints and communication loads, the analysis provides a representative evaluation of framework stability, responsiveness, and coordination efficiency under practical Industry 4.0 deployment conditions. With a throughput of about 890 transactions per second and a latency of 120 ms, IDDOF ensures faster data exchange and communication efficiency, outperforming Blockchain-SCM (500 tps, 240 ms),

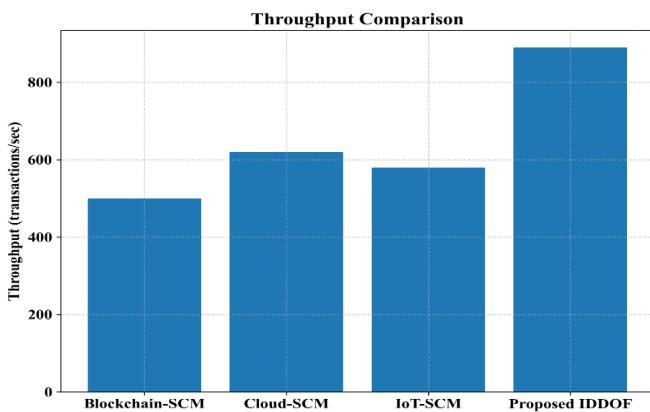


Figure 12. Throughput Comparison

Figure 12 shows the throughput performance of Blockchain-SCM, Cloud-SCM, IoT-SCM, and the proposed IDDOF framework as a fundamental ICT efficiency indicator. The IDDOF has the highest

Cloud-SCM (620 tps, 180 ms), and IoT-SCM (580 tps, 200 ms). Its optimized orchestration minimizes synchronization delays and supports real-time decision-making. The framework also consumes less energy (1.2 kWh) than Blockchain-SCM (1.8 kWh), Cloud-SCM (1.5 kWh), and IoT-SCM (1.4 kWh), reflecting sustainable computational efficiency, addressing the high-energy issues noted in blockchain-cloud architectures [16]. In terms of data integrity and cyber resilience, IDDOF achieved a security index of 0.93, exceeding that of other models, thereby enhancing secure communication and protecting data against tampering—an improvement over the blockchain-IoT and encryption-heavy systems of [17] and [19], which faced high latency and computational costs. Furthermore, the scalability score of 0.90 validates IDDOF's adaptability under heavy transaction loads, unlike the limited scalability observed in agricultural and regulated supply chains [18][19]. Overall, the efficiency index of 0.74 confirms that IDDOF provides a balanced optimization between speed, energy, and security, thus overcoming key limitations of earlier blockchain, IoT, and cloud frameworks and establishing a robust, scalable, and intelligent ICT architecture for sustainable supply chain management in Industry 4.0 environments.

4.2 Sustainability, Energy Efficiency, and Blockchain Transparency

The sustainability of the proposed ICT-integrated framework is supported through energy-efficient computation, optimized resource utilization, and reduced operational redundancy. Cloud-based elastic resource provisioning enables dynamic allocation of computational resources, preventing over-provisioning and minimizing unnecessary energy consumption. Distributed processing and parallel execution further improve computational efficiency by reducing processing delays and hardware strain. Additionally, PSO-driven logistics optimization contributes to lower fuel consumption and reduced carbon emissions by improving routing efficiency and minimizing transportation inefficiencies.

The adoption of blockchain technology is implemented using a permissioned architecture, which reduces consensus overhead and improves energy efficiency compared to fully public blockchain networks. Smart contracts enhance operational sustainability by automating validation, verification, and transaction execution processes, thereby reducing manual intervention, administrative workload, and paper-based documentation. Beyond energy efficiency considerations,

the proposed framework further strengthens its Industry 4.0 alignment through improved ICT performance characteristics. The hybrid cloud-blockchain structure minimizes synchronization overhead by adopting selective, event-driven ledger updates rather than continuous blockchain writes. Edge-cloud coordination mechanisms enhance system responsiveness by enabling localized preprocessing and intelligent filtering of high-frequency IoT data streams. Additionally, distributed cloud data management supports consistency and integrity of information across heterogeneous operational sources. These mechanisms collectively improve system stability, reduce latency accumulation, and reinforce interoperability, reflecting the real-time and data-centric principles of Industry 4.0 environments.

Smart contracts contribute to transparency and accountability across the tobacco supply chain through several mechanisms. Automated transaction recording ensures that all operational events are permanently logged and verifiable. Immutable audit trails enable traceability of stakeholder actions, supporting compliance monitoring and dispute resolution. Rule-based execution enforces predefined contractual conditions without human bias, reducing opportunistic behavior. Furthermore, real-time data accessibility allows authorized participants to verify product provenance, quality certifications, and transaction histories. These capabilities generate tangible benefits for stakeholders. Farmers benefit from fair and timely compensation linked to verified quality metrics, processors and distributors experience reduced disputes and improved coordination, regulators gain reliable compliance records, and consumers benefit from enhanced product authenticity and trust. Collectively, the framework aligns technological efficiency with sustainability objectives while strengthening transparency, accountability, and operational reliability.

5. Conclusion

In summary, the proposed IDDOF framework demonstrates clear advancements in ICT performance and supply chain outcomes. Quantitatively, it achieves the lowest latency (≈ 120 ms), highest throughput (≈ 890 transactions/s), superior scalability (0.9), strong security index (0.93), and the lowest energy consumption (≈ 1.2 kWh), outperforming existing Blockchain-SCM, Cloud-SCM, and IoT-SCM models. These improvements translate into faster information propagation, higher transaction capacity, enhanced data integrity, and more

sustainable ICT operations. From a supply chain perspective, such ICT gains enable more accurate forecasting, reduced operational costs, real-time traceability, and greater adaptability to dynamic logistics conditions. The integration of blockchain for secure communication, cloud for scalable computation, IoT for continuous data acquisition, and AI for predictive optimization creates a unified, data-driven decision environment. Beyond the tobacco sector, the framework's modular architecture supports generalization across agricultural and industrial supply networks. Beyond the tobacco supply chain, the proposed framework exhibits strong adaptability to other traceability-critical and data-intensive industries. In food supply chains, the architecture can enable real-time monitoring of storage conditions, cold-chain logistics, and contamination risk detection through IoT sensing and blockchain-based provenance tracking. Similarly, in pharmaceutical supply chains, the framework can enhance drug authentication, counterfeit prevention, regulatory compliance verification, and temperature-sensitive logistics management. The integration of secure data sharing, scalable cloud computation, and adaptive optimization mechanisms provides a reliable digital infrastructure suitable for industries requiring high transparency, strict quality control, and rapid decision responsiveness.

Future investigations may further examine practical edge-compute deployment models, where latency-sensitive analytics, filtering, and preprocessing operations are executed closer to IoT sensing nodes to reduce communication overhead and improve real-time responsiveness. Federated learning architectures also present a promising direction for enabling decentralized model training while preserving data privacy and minimizing centralized computational bottlenecks. Additionally, evaluating framework performance under realistic system constraints—including bandwidth variability, device-level computational limitations, synchronization overhead, and workload imbalance conditions—would provide deeper insights into operational stability, resilience, and large-scale deployment feasibility. Such explorations would strengthen the framework's applicability within heterogeneous and resource-constrained Industry 4.0 environments. Future ICT research can focus on refining these gains through edge–cloud hybridization, quantum-safe blockchain consensus, and federated or swarm learning mechanisms to further improve system responsiveness, computational efficiency, and cyber-resilience in next-generation supply chain ecosystems.

Declarations

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Data Availability Statement: The data generated and analyzed during the current study are available from the author Changxia Sun upon reasonable request but are not yet publicly available due to ongoing research.

Authors' Contributions: Linquan Guo is responsible for designing the framework, analyzing the performance, validating the results, and writing the article. Changxia Sun is responsible for collecting the information required for the framework, provision of software, critical review, and administering the process.

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