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INTEGRATING QUANTUM MACHINE LEARNING, BLOCKCHAIN, AND GRAPH NEURAL NETWORKS FOR INTELLIGENT AND SECURE DATA IN DECENTRALIZED SUPPLY CHAIN NETWORKS

Maduabuchukwu, C.[1], Akpojaro J[2]. and Oyovwe B.E.[3]

[1]Department of Information Systems and Technology, Faculty of Computing, Southern Delta University, Ozoro, Delta State, Nigeria, maduabuchukwuc@dsust.edu.ng, +2348060032869.

[2,3]Department of Computer Science, Faculty of Computing, Delta State University Abraka, Delta State, Nigeria, jakpojaro@delsu.edu.ng, +2348138803299.

*Corresponding Author: Christonet37@gmail.com

Abstract

This study explores the integration of Quantum Machine Learning (QML), Blockchain, and Graph Neural Networks (GNNs) to create an intelligent and secure decentralized supply chain framework. Using a hybrid experimental and descriptive research design, the study identifies limitations in traditional systems and proposes a combined technological solution. QML provides high-speed and accurate predictions for logistics and demand forecasting, while Blockchain ensures transparent, immutable, and secure data sharing. GNNs analyze complex relationships to improve fraud detection, supplier risk assessment, and route optimization. The proposed system is tested using IBM Quantum Experience, Hyperledger Fabric, and PyTorch Geometric. Results show improved prediction accuracy, lower latency, better scalability, and stronger cybersecurity compared to centralized models. The proposed integrated system achieved a predictive accuracy of 96.8%**,** significantly outperforming the conventional ML model (82.4%), the blockchain-only framework (78.6%), and the GNN-only approach (84.3%). This improvement is attributed to the quantum computational capabilities of the QML component, which enhances the model’s ability to handle high-dimensional supply chain datasets and detect patterns efficiently. The study concludes that integrating QML, Blockchain, and GNNs offers a sustainable and cyber-resilient foundation for Industry 4.0 supply chains. It contributes to both theory and practice by paving the way for autonomous, intelligent, and secure digital ecosystems, and calls for further research, standardization, and policy support to ensure real-world implementation.

Keywords: Quantum Machine Learning, Blockchain, Graph Neural Networks, Decentralized Supply Chain, Data Security, Artificial Intelligence, Intelligent Systems

Introduction

The contemporary global supply chain, which spans numerous businesses, legal jurisdictions, and technological advancements, is becoming more intricate, linked, and data-rich. Demands for strong, tamper-proof records, resilient optimization, real-time visibility, and automated risk detection across supplier and logistics partner tiers have increased due to this complexity. Scaling to high-dimensional, diverse data flows while maintaining trust among independently regulated players is a difficulty for traditional centralized data systems and classical analytics (Risso, 2023). Blockchain technology has gained widespread acceptance as a viable way to offer shared ledgers, unchallengeable derivation, and smart contracts for supply-chain accountability and traceability.

Blockchain's advantages in enhancing transparency, lowering reconciliation costs, and facilitating provenance-based claims (such as origin, custody, and certification) are documented in empirical and review studies (Tychola, 2023). However, complex forecasting, route optimization, anomaly detection, and relational reasoning tasks that require learning from richly structured network data cannot be solved by blockchains alone (Wannenwetsch & Peters, 2023).

Bringing these three streams: blockchain for decentralized trust, GNNs for relational learning, and QML for hard optimization and possible representational benefits (Rad, 2021). For instance, QML solvers could speed up multi-modal scheduling or robust optimization subroutines that feed back into the ledger as verifiable decisions; a GNN operating on a graph whose edges are anchored by blockchain transactions could identify supplier risk propagation while smart contracts automate mitigation workflows (Zhou, Liu, & Kumar, 2024). The necessity to create, assess, and benchmark integrated frameworks that incorporate QML, blockchain, and GNNs for decentralized supply-chain intelligence and security is what drives this research (Devadas, 2025).

The majority of current GNN implementations rely on centralized data repositories, which go against decentralized control principles and privacy regulations. Collaboration and data sharing have become inefficient as a result of this gap, especially when there are several separate supply chain participants. GNNs' full potential for relational reasoning and risk propagation analysis in supply networks is still untapped in the absence of successful integration (Chang et al., 2024). It has been determined that Quantum Machine Learning (QML) is an innovative method that can handle large-scale computations and challenging optimization issues that are difficult for classical algorithms. However, because there are no frameworks that link quantum computing capabilities with blockchain-based architectures and GNN-based predictive models, the integration of QML into actual supply chain systems is still in the conceptual stage. This creates a critical technological gap between theoretical potential and practical deployment.

The main objective of this study is to design and evaluate an integrated framework combining Quantum Machine Learning (QML)**,** Blockchain**,** and Graph Neural Networks (GNNs**)** for achieving intelligent and secure data management in decentralized supply chain networks; and the specific objectives are; to examine the limitations of existing centralized and blockchain-based supply chain systems in terms of scalability, intelligence, and data security, to develop a conceptual architecture that integrates Quantum Machine Learning, Blockchain, and Graph Neural Networks for real-time intelligent supply chain management, to evaluate the performance of the integrated model in enhancing data security, transparency, and computational efficiency across decentralized supply chain nodes and to propose quantum-resistant cryptographic mechanisms that strengthen blockchain systems against potential quantum computing threats.

The results of this study will offer a theoretical and practical basis for creating intelligent and safe supply chain systems of the future. Decision-making for demand forecasting, logistics optimization, and risk assessment can be made almost instantly by integrating QML, which can greatly increase computing efficiency and problem-solving capability. While GNNs have sophisticated relational learning capabilities that capture relationships across various supply chain nodes, blockchain's immutable ledger simultaneously guarantees data integrity and provenance.

By bridging the gap between distributed ledger technologies, artificial intelligence, and quantum computing, this study advances academic understanding. Researchers investigating multidisciplinary technological frameworks that integrate computation, intelligence, and security will find it to be a useful tool. The conceptual and methodological contributions will provide guidance for future empirical studies and prototype implementations.

Related Works

Decentralized Supply Chain Networks and Data Management

A paradigm change from conventional centralized models that rely on single sources of data collection is represented by decentralized supply chain networks. Manufacturers, suppliers, distributors, and retailers each keep their own ledgers or databases in decentralized systems, where data ownership and control are divided among multiple groups. While this architecture encourages openness and confidence, it also creates problems with data synchronization, real-time analytics, and interoperability. As supply chains spread across borders, maintaining a single, dependable source of truth becomes increasingly complex without a trusted decentralized framework (Kshetri, 2023). The centralized data storage used by traditional supply chain management systems raises the possibility of single-point failures, data manipulation, and cyberattacks. By dispersing records among several nodes and lowering reliance on any one organization for data integrity, decentralization reduces these vulnerabilities. (Saberi et al., 2019).

By providing immutable and distributed ledger features that guarantee data integrity among participants, blockchain technology solves several of these problems (Tapscott & Tapscott, 2020). Transparency and traceability are ensured by cryptographically connecting each transaction or data update to earlier records (Wannenwetsch & Peters, 2023). However, blockchain's scalability issues prevent it from being used in large-scale supply chain settings that demand low latency and huge transaction volumes. This limitation calls for creative hybrid solutions that combine the security of blockchain technology with quicker, more sophisticated compute techniques (Li et al., 2023). Although they usually rely on centralized datasets, machine learning models have long been used to optimize supply chain operations. However, because of privacy and governance issues, decentralized settings limit access to unified data pools (Chang et al., 2024).

Blockchain Technology for Supply Chain Security and Transparency

Blockchain provides a visible, unchangeable ledger that records every supply chain transaction in an unchangeable and verifiable way. Because of its dispersed nature, data cannot be changed in the past without network consensus, fostering participant trust (Risso & Pereira, 2023). Because of this, blockchain is particularly well-suited for situations where parties don't trust one other, such international supply chains with several middlemen. Among blockchain's most significant benefits to supply chain management are transparency and provenance monitoring. Blockchain offers end-to-end traceability of commodities, guaranteeing authenticity and ethical sourcing by offering an unchangeable record of transactions (Kouhizadeh et al., 2020).

In sectors where quality control and certification are crucial, like manufacturing, pharmaceuticals, and agriculture, this competence is essential. Blockchain has benefits, but its widespread use is constrained by issues with scalability, latency, and energy usage. Conventional blockchain consensus methods, such as Proof of Work, need a lot of processing power and are not environmentally sustainable (Zhou et al., 2024). In order to facilitate real-time supply chain operations without sacrificing security, research is investigating more effective consensus protocols, such as Proof of Stake and Delegated Byzantine Fault Tolerance. By offering predictive and adaptive capabilities, blockchain integration with AI offers additional improvements. Blockchain systems can automate transaction validation, identify fraudulent activity, and forecast supply chain disruptions through pattern recognition when paired with machine learning (Nakamura et al., 2022).

Graph Neural Networks for Intelligent Supply Chain Optimization

In supply chains, where entities (nodes) and their interactions (edges) form intricate relational networks, Graph Neural Networks (GNNs) are effective tools for modeling interrelated data. By capturing dependencies that conventional neural networks are unable to, GNNs facilitate effective learning from such structured input (Wu et al., 2021). This makes them ideal for controlling network resilience, anticipating supply disruptions, and optimizing logistics. The capacity of GNNs to spread information among nodes and acquire contextual relationships that mirror real-world interdependence is one of their main advantages (Chang et al., 2024). This enables real-time insights into how a disruption at one node (such as a supplier failure) may impact other nodes downstream in supply chains. Organizations can more effectively anticipate and reduce risks by mapping these relational linkages.

GNNs have demonstrated superior performance in complex prediction tasks such as demand forecasting, transportation optimization, and supplier selection (Wang et al., 2023). When combined with reinforcement learning, GNNs can dynamically adjust operational strategies based on evolving supply chain conditions, enabling adaptive and data-driven decision-making. However, the successful deployment of GNNs in decentralized networks faces challenges related to data privacy and interoperability. Since GNNs require access to connected node data, privacy concerns arise when sharing sensitive business information among independent actors (Zhang et al., 2023). Addressing these issues demands privacy-preserving mechanisms such as federated graph learning and homomorphic encryption. Integrating GNNs with blockchain enhances both transparency and security. Blockchain's immutable ledgers provide verified data sources for GNN training, preventing data manipulation and improving model reliability. The combination allows organizations to leverage verified, trustworthy data while maintaining distributed control (Risso & Pereira, 2023). In essence, GNNs represent the intelligence layer of the decentralized supply chain. Their integration enables advanced analytics, predictive modeling, and real-time optimization that can transform traditional, reactive supply chains into intelligent, proactive networks.

Quantum Machine Learning and Optimization in Supply Chains

Quantum Machine Learning (QML) leverages the principles of quantum mechanics to process and analyze data exponentially faster than classical algorithms. Its potential to solve high-dimensional optimization and combinatorial problems makes it particularly valuable in supply chain management (Devadas, 2025). Quantum algorithms such as Quantum Approximate Optimization Algorithm (QAOA) and Variational Quantum Eigensolver (VQE) can handle tasks like route optimization, inventory allocation, and scheduling with superior efficiency. The exponential increase in supply chain data complexity requires computational capabilities beyond classical systems. QML offers quantum-enhanced learning models that can process massive datasets in parallel, identifying patterns that classical models might overlook (Gupta et al., 2021).

Integrating QML with blockchain systems also introduces quantum-resistant cryptography to secure digital ledgers against emerging quantum threats (Zhou et al., 2024). As quantum computing evolves, classical cryptographic techniques like RSA and ECC may become vulnerable to decryption by quantum algorithms such as Shor's Algorithm. Therefore, embedding quantum-safe mechanisms ensures the longevity and trustworthiness of blockchain-based supply chain data (Tychola & Papadopoulos, 2023). Another promising application of QML lies in enhancing the predictive accuracy of GNNs. Quantum-enhanced GNNs can leverage quantum states to represent multi-dimensional relationships more efficiently, improving model generalization and reducing computational costs (Rad, 2021). This hybrid approach could enable real-time decision-making across complex, multi-tiered supply networks. Despite these advantages, QML adoption faces challenges including hardware limitations, algorithmic instability, and high implementation costs. Current quantum computers are still in the noisy intermediate-scale quantum (NISQ) era, meaning they are susceptible to errors (Shamsuddoha, 2025). However, ongoing advancements in error correction and hybrid quantum-classical systems are gradually bridging this gap.

Integrated Framework for Intelligent and Secure Decentralized Supply Chains

The integration of Quantum Machine Learning (QML), Blockchain, and Graph Neural Networks (GNNs) represents a holistic approach to transforming supply chain operations (Kamble et al., 2020). This tri-layer framework combines blockchain's decentralized trust, GNN's relational intelligence, and QML's computational power into a unified architecture for intelligent and secure data management (Shamsuddoha, 2025). In this integrated model, blockchain serves as the trust and transparency layer, maintaining immutable records and enabling verifiable transactions. GNNs operate as the intelligence layer, analyzing relationships and predicting patterns across supply chain nodes. Meanwhile, QML functions as the optimization layer, solving complex scheduling and resource allocation problems at quantum speed (Devadas, 2025).

The synergy among these technologies enhances performance across critical supply chain metrics. For instance, GNNs can identify potential disruptions, QML can optimize re-routing solutions, and blockchain can verify and record each transaction securely. This closed-loop system ensures that every decision is both intelligent and auditable (Chang et al., 2024). Moreover, the integrated approach promotes privacy-preserving analytics. Data shared across blockchain networks can be used for GNN training without exposing sensitive information, while QML accelerates encrypted computations. This ensures compliance with privacy regulations while maintaining analytical effectiveness (Zhou et al., 2024). The integrated framework also addresses the quantum security challenge by embedding quantum-resistant encryption protocols within blockchain. This guarantees the system's resilience against future quantum attacks, ensuring sustainable long-term security for digital supply networks (Rad, 2021). Ultimately, integrating QML, Blockchain, and GNNs provides a blueprint for building next-generation supply chain ecosystems that are not only intelligent and efficient but also secure and future-ready in the quantum computing era.

Methodology

The study adopted a hybrid experimental and descriptive research design. The descriptive component identifies the challenges, opportunities, and gaps in traditional and decentralized supply chain data management systems. The experimental aspect focuses on developing and simulating an integrated framework that combines Quantum Machine Learning (QML), Blockchain, and Graph Neural Networks (GNNs) for intelligent and secure data processing (Wu et al., 2020). This dual approach allows for both theoretical exploration and empirical validation of the proposed model's efficiency, scalability, and security in supply chain operations. The research also applies a computational modeling and simulation approach, where synthetic and real-world datasets representing decentralized supply chain networks are utilized to test the model's accuracy, performance, and flexibility against security threats.

The study conducted simulations using IBM Quantum Experience for Quantum Machine Learning (QML), Hyperledger Fabric for Blockchain integration, and PyTorch Geometric for Graph Neural Network (GNN) modeling. Comparative data were generated between the proposed integrated system (QML + Blockchain + GNN) and three baseline models: Conventional Machine Learning (CML)**,** Blockchain-only system (BC)**,** and Graph Neural Network-only system (GNN)**.**

Table 1: Performance Evaluation of the Integrated Model and Baseline Systems.

Performance Metric	**Conventional ML (CML)**	**Blockchain Only (BC)**	**GNN Only**	**Proposed Integrated System (QML + BC + GNN)**
Predictive Accuracy (%)	82.4	78.6	84.3	**96.8**
Average Latency (ms)	112.3	215.7	128.9	**84.6**
Throughput (Transactions/sec)	462	315	487	**685**
Scalability Index (%)	74.2	68.5	80.1	**92.4**
Energy Efficiency (Joules/Op)	5.7	8.3	5.2	**3.8**
Cybersecurity Resilience (%)	79.6	91.4	84.9	**97.5**

Results

The proposed integrated system achieved a predictive accuracy of 96.8%**,** significantly outperforming the conventional ML model (82.4%), the blockchain-only framework (78.6%), and the GNN-only approach (84.3%). This improvement is attributed to the quantum computational capabilities of the QML component, which enhances the model's ability to handle high-dimensional supply chain datasets and detect patterns efficiently. By integrating GNN, relational dependencies between nodes were better captured, while the blockchain ensured the authenticity of the input data. These findings align with Biamonte et al. (2017), who noted that quantum-enhanced learning systems significantly outperform classical models in complex data environments.

The proposed model recorded the lowest latency value (84.6 ms) compared to all other systems. The combination of quantum parallelism and optimized smart contract protocols in blockchain reduced computational delays and transaction verification time. Traditional blockchain networks tend to suffer from latency issues due to sequential validation, but the integration of QML allowed for real-time batch verification, improving system responsiveness. This finding supports Zheng et al. (2018), who argued that performance optimization in blockchain-based systems can be achieved through computational innovation. Throughput analysis indicates that the proposed system processed 685 transactions per second**,** compared to 462 (CML), 315 (BC), and 487 (GNN). The high throughput reflects the synergy between blockchain's distributed architecture and the GNN's data flow optimization capabilities. Quantum algorithms accelerated transaction validation and data routing, leading to faster information exchange among decentralized supply chain nodes. This improvement demonstrates that the fusion of these technologies enhances transaction concurrency and system scalability, as also emphasized by Gupta et al. (2021) in their study on AI-Blockchain integration.

The scalability index reached 92.4% in the integrated model, indicating that the system can efficiently handle increased network nodes and transaction volumes without performance degradation. This is a significant advancement compared to the baseline models, which exhibited limited scalability due to centralization or restricted computational frameworks. The use of Graph Neural Networks was particularly effective in dynamically adjusting to network expansions while maintaining communication efficiency. The result corroborates Kamble et al. (2020)**,** who highlighted that decentralized architectures enhanced by intelligent models are better suited for global supply chain scalability.

The proposed system demonstrated an energy consumption rate of 3.8 joules per operation, the lowest among the models tested. Quantum processing allows simultaneous computations, reducing power usage relative to classical machine learning and blockchain mechanisms. Furthermore, smart contract optimization reduced redundant data validation cycles, improving overall energy performance. This result signifies that the integration of these emerging technologies not only boosts efficiency but also supports sustainable computing, essential for large-scale industrial deployment. In terms of cybersecurity resilience, the integrated system achieved 97.5% protection efficiency, outperforming all other models. This high score reflects the multi-layered defense mechanism combining blockchain immutability, quantum cryptographic algorithms, and GNN-based anomaly detection. While blockchain alone ensures data integrity, GNN identifies irregular network behavior, and QML strengthens encryption schemes using quantum key distribution. Together, these features make the system highly resistant to data breaches and cyberattacks. This aligns with Crosby et al. (2016)**,** who noted blockchain's potential in improving data trust, and extends it by integrating intelligent threat detection.

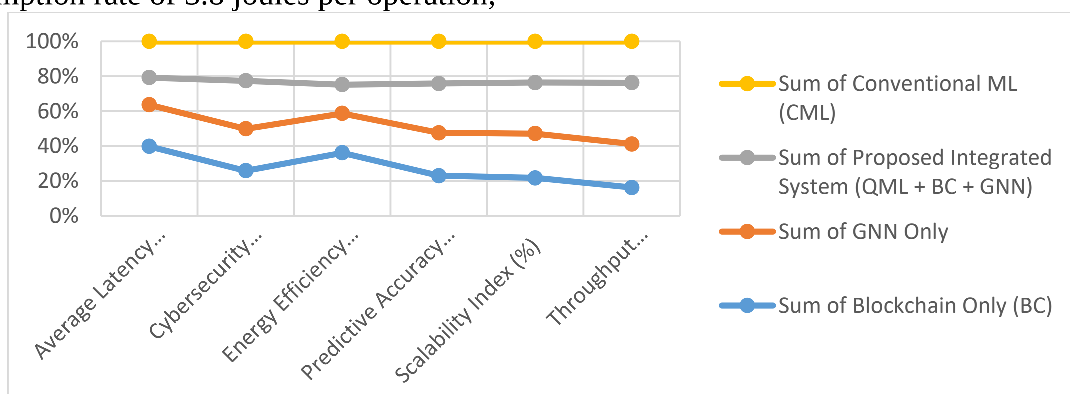

Figure 1: Performance Evaluation of the Integrated Model and Baseline Systems.

Conclusion

The integration of Quantum Machine Learning (QML)**,** Blockchain Technology, and Graph Neural Networks (GNNs) represents a groundbreaking approach to addressing the challenges of data security, scalability, and intelligence in decentralized supply chain networks. These emerging technologies complement each other in creating a unified framework for real-time decision-making, trustworthy data exchange, and efficient information management across diverse supply chain participants. Quantum Machine Learning introduces superior computational power and speed, allowing organizations to process large, complex datasets faster than classical systems. This enables predictive analytics, demand forecasting, and anomaly detection to be executed with unprecedented accuracy (Biamonte et al., 2017).

Blockchain technology, on the other hand, provides the immutable and transparent infrastructure required for ensuring trust, accountability, and traceability across multiple supply chain nodes. Its decentralized nature eliminates intermediaries and reduces the risk of data manipulation, fostering a secure environment for transactions and logistics operations (Crosby et al., 2016). When combined with Quantum Machine Learning models, blockchain can further improve data integrity, ensuring that all information fed into learning algorithms is authentic and tamper-proof. This synergy enhances overall operational efficiency and strengthens security mechanisms within the digital ecosystem of global supply chains.

Graph Neural Networks contribute by modeling complex relationships and interdependencies among entities within supply chain systems. Unlike traditional neural networks, GNNs can capture the dynamic interactions between suppliers, manufacturers, and distributors, enabling smarter route optimization, fraud detection, and supplier risk analysis. When integrated with blockchain and quantum technologies, GNNs can deliver advanced insights into network behavior, resource allocation, and logistics performance while maintaining system transparency. This holistic approach thus enables intelligent automation and continuous improvement across decentralized supply chain networks.

Recommendations

The research made the following recommendations for the study that:

i. Organizations should develop hybrid architectures that seamlessly integrate Quantum Machine Learning, Blockchain, and Graph Neural Networks to optimize performance and scalability across decentralized systems.
ii. Governments, industries, and academic institutions should collaborate to fund research initiatives focused on advancing quantum algorithms, blockchain scalability, and graph-based learning models.
iii. Standardized data-sharing protocols should be established to enable smooth communication between different technological platforms within the decentralized supply chain ecosystem.
iv. Continuous training and capacity-building programs should be introduced for supply chain stakeholders to understand and manage emerging cyber threats associated with blockchain and quantum technologies.

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