

Blockchain-Enabled Predictive Analytics for Real-Time Supply Chain Decision Making

Lokesh Pal^{1*}, V K Jain²

¹College of Computing Science & Information Technology, Teerthanker Mahaveer University, India)

²Vice Chancellor, Teerthanker Mahaveer University, India

^{1*}lokeshpal9756@gmail.com, ²drvkjain72@gmail.com

Abstract

Modern supply chains are still troubled by several problems, including scattered data, a lack of transparency, and inefficient, slow, and error-prone decision-making processes. These problems often result in inaccurate forecasts, late detection of supply chain interruptions, and low resilience of the entire operation. This paper proposes a Blockchain–Machine Learning Integrated Framework that will create a secure, transparent, and analytical supply chain environment. The blockchain is expected to provide a permissioned distributed ledger that will allow the use of efficient consensus techniques, thus providing prompt event finalization and secure data sharing among the parties involved. Based on reliable data from the blockchain, the machine learning layer combines forecasting models, anomaly-detection systems, and real-time data streams to continuously improve predictive accuracy and enable timely decision-making. Certainly, a medium-sized retail supply chain scenario comprising 350,000 events across various points is used as a testing ground for evaluating the proposed framework. The experimental results indicate that the system performance improvements are quite significant: decision latency is reduced, forecast precision is increased, and anomaly detection is more accurate than the traditional and ML-only baselines. Furthermore, the system maintains high throughput as the number of nodes increases, demonstrating its applicability to real-world scenarios. The initial rollout and trial illustrate significant potential across diverse sectors such as manufacturing, pharmaceuticals, agriculture, and logistics by enabling monitoring, reducing data-processing risks, and supporting automation. In this way, the discoveries point out that the confluence of blockchain and machine learning fortifies the formation of forthcoming supply chain systems that will be robust, data-driven, and able to run autonomously.

Keywords: *Blockchain, Machine Learning, Real-time Decision Making, Supply Chain Management, Predictive Analytics.*

1. Introduction

Today's supply chains are complex and are spread over the world. They have many players and systems needed. On top of that, there is an almost constant stream of material, data and money passing through the supply chains. Although technology has advanced, many supply chains still face significant problems [1]. These include the supply chain breaking apart, inconsistent data from many sources, delayed data flow in the supply chain, the presence of fake items, unnecessary steps, and incorrect estimates of what is needed. All of these happen because supply chains are one supply chain. And these happen because supply chains are just supply

chains. If supply chains had a common, safe source of data it would create the best state of state for the supply chain. This would allow buyers and sellers to get data about suppliers and consumers in the fastest time, and at the best level of detail. As a result of these limitations, supply chains will remain less responsive than they could be, face increased operational risk and suffer reduced performance over time [2].

To solve the issues faced by supply chains, it is necessary for them to have access to trusted, instantaneous, and full disclosure on all stakeholders' information in the supply chain so that it can easily be exchanged between them. This access to real-time, accurate data allows companies to make proactive decisions, efficiently manage inventory, predict risk, and coordinate logistics simultaneously. Traditional centralised supply chain systems do not provide the level of confidence, speed, or integrity of data that is necessary to enable companies to make timely and supported decisions, as they are often manipulated, contain only incomplete or siloed data, and experience synchronization lags [3].

In contrast, blockchain technology has the ability to create a secure, decentralised, and immutable ledger that allows users to completely and transparently share and access data in real-time through a distributed agreement mechanism that maintains the security of the information and provides confidence that all supply chain transactions, including delivery of products, verification of quality, and payment for goods, are being stored in a manner that cannot be altered. By removing the need for a third-party verification of each transaction, the blockchain creates greater reliance on one another as well as the elimination of a time delay based on the commitment to using blockchain [4]. To the extent that machine learning will also provide supply chains with real-time data, it may also provide them with more advanced analytic capabilities, including predictive analytics. Specifically, ML algorithms will be able to use both historic and real-time data to identify trends in demand, predict demand for the future, identify anomalous behavior, and identify and understand types of risk. Through the use of this ability, current supply chain managers are able to forewarn of supply chain risks, maintain optimal inventory, plan logistics routing and produce enhanced operational efficiency [2]. Through advanced modelling procedures such as, but not limited to, a combination of predictive model generation, pattern recognition, anomaly detection & demand forecasting, present supply chain managers are able to make superior decisions.

When you put together blockchain and Machine Learning, you get a very strong mix of both of them. This mix helps to deal with some of the bigger issues that supply chains are dealing with. Blockchain provides a high-quality, reliable and timely source of data, while Machine Learning takes that data and converts it into useful and actionable information (insights) so that you can make real-time, actionable decisions [5]. When you combine the two, they create a powerful force that addresses many of the issues in the supply chain industry. When using this hybrid model, they reduce the number of data "silos", improve forecast accuracy and allow for reliable and efficient movement of information within a supply chain. Additionally, they provide support for the use of automated processes to make operational adjustments to the supply chain as needed.

Despite these advantages, there is still a need for additional research in this area. The vast majority of supply chain solutions currently available do not provide a cohesive model to integrate real time data streams produced via the blockchain with predictive decision models

produced via machine learning [6]. Existing studies typically focus on blockchain or machine learning separately, leaving a large gap in the development of an integrated architecture that leverages the strengths of both for the purpose of real-time decision-making. This study will address the current lack of a comprehensive Blockchain and Machine Learning integrated framework, developed as a means of providing real-time decision support in the supply chain. Specifically, it presents a set of contributions:

1. A comprehensive architecture that combines both Blockchain and Machine Learning.
2. The creation of predictive Machine Learning (ML) modules leveraging Blockchain data.
3. The design of mechanisms for optimizing real-time decision making.
4. An assessment of the framework's ability to improve visibility, accuracy, trust and responsiveness within supply chain activities.

2. Literature Review

2.1 Blockchain in Supply Chain

The use of Blockchain technology in supply chain management is experiencing growth because it supplies traceability, Transparency, Security, and Provenance Tracking. Multiple authors demonstrate that the application of Blockchain has the ability to create a permanent, distributed ledger capturing every transaction or event occurring throughout the supply chain system. This provides a permanent and verifiable record for each of the many parties involved throughout the entire supply chain system regarding where a product came from, how it was manufactured, how it was transported, and what quality checks it passed through. Through their research, Blockchain provides supply chain visibility, prevents fraud, and helps establish trust between all of the parties involved by eliminating the need for trusted third-party central authorities. However, even with these benefits, traditional supply chain solutions do have challenges with providing the required levels of real-time data availability due to issues such as delayed sharing, being in separate "silos," and inconsistent record keeping [7]. Blockchain provides a solution to all of these challenges because Blockchain can facilitate real-time, decentralized data exchange by utilizing consensus mechanisms and "smart contracts" to automatically update all nodes on the network. Blockchain is not without challenges though; scalability remains an issue as many blockchain networks have trouble processing high volumes of transactions in a timely manner. There are many types of interoperability problems when integrating blockchain with older technologies or multiple platforms. In addition to that, some consensus mechanisms (such as Proof of Work) require vast amounts of energy, which creates issues around sustainability. Because of these issues, it has shown that, while blockchain technology is an effective way of increasing the integrity and transparency of data, a full application of this technology cannot be used in its own capacity in a fast-paced supply chain [8].

2.2 Machine Learning in Supply Chain

Machine Learning (Machine learning (ML) in the Supply Chain Supply Chain (ML)) has improved supply chain operations through the ability to provide data-driven insight(s) and enhancements through Machine Learning Machine Learning Machine Learning - Machine Learning in Demand Forecasting: A Framework for Predictive Analytics (ML). There have been numerous studies on how to use machine learning to improve the accuracy of demand forecasts, including the use of LSTM Networks (Long Short-Term Memory Networks) for

long-term and Random Forests (Random Forests) for short-term forecasting. Other studies highlight the use of Machine Learning-based Inventory Optimization (Machine Learning Inventory Optimization) to balance stock on hand, reduce stockout(s), and minimize holding costs. Machine learning is also being used to estimate delivery times (Machine Learning Delivery Time Estimation) by analyzing Transportation Pathways, patterns of historic transportation performance, and current traffic/incident road conditions. Finally, machine-learning (ML)-powered anomaly (anomaly system) or Fraud Detection (Fraud System) can detect abnormal transactions, product quality deviations, and in general, Supply Chain disruptions before they occur. However, despite these advantages, the effectiveness of machine-learning systems (such as machine-learning systems) in the real world is limited by many constraints. Training datasets used to create precision predictions for machine-learning models are often inaccurate, incomplete, or of poor quality. As a result, as a result, the data reservoirs that are the basis for machine learning in the supply chain are often siloed (isolated) [9]. In addition, the delay between obtaining operational data and making machine-learning-based decisions (decision-support system) severely limits the immediacy of machine-learning-based predictions. All of these limitations illustrate the continued need for dependable, high-quality, and real-time streams of data (or machine learning data) that are difficult to obtain using traditional supply chain data support systems (supply chain support systems).

2.3 Combined Blockchain–Machine Learning Models

The concept of integrating blockchain-based technology with machine learning serves to offer an integrated framework that combines the benefits associated with blockchain (accuracy, provenance and immutability) in conjunction with the predictive capabilities offered through machine learning based on the smart contract verification of this accurate data [10]. Hybrid models integrating both technologies have been used effectively for detecting fraudulent activity in real-time, optimising the logistics operations of supply chains, improving the traceability of products through improved data integrity and provenance verification along the supply chain, and providing support for autonomous decision-making through the creation of smart contracts that trigger machine learning analytics automatically. Previous studies have indicated improved predictive accuracy of machine learning based on verified data from blockchain due to reduced susceptibility to manipulation and consistency of the verification of this information across multiple sources. However, while many studies exist on the hybridisation of blockchain and machine learning technologies, few have provided real-time integration of these technologies at an industrial level due to limitations related to the synchronisation of data between on-chain and off-chain ecosystems along with communication issues caused by latency [11]. Currently, few companies have fully integrated machine learning and blockchain into their infrastructures [10]. In order to develop a fully integrated blockchain and machine learning infrastructure, organisations need to have advanced technology platforms in place and seamless interoperability between their various components. To date, only a limited number of frameworks exist that offer organisations a unified architecture that link the real-time blockchain data streams directly to ML. There remains a need for more practical, scalable and operationally feasible integration frameworks for the hybridisation of these technologies [12].

2.4 Research Gap Summary

This study will fill several important gaps in the current literature. One of the most significant gaps involves the lack of frameworks for How Blockchains and Machine Learning integrate real-time data into Machine Learning. Most of the existing research has focused on building models using either static or outdated data that limit the potential benefits of real time decision making [13]. Another significant challenge with Building these Block Chain and Machine Learning models is that throughout the process, the methods in which the data is captured and analysed do not provide an ideal means for How Block Chain and Machine Learning provide transparency, speed and Computational Efficiency. The third most significant area of Gap with Building predictive Decision making capabilities through Blockchain data that is trustable and Validated [14]. Currently the existing methods do not leverage Blockchain data in real time for improving the Machine Learning model continuous updates. To address these gaps in the current literature, this Study proposes a unifying Framework of Blockchain/Machine Learning that will provide inclusive Data Flow, Predictive Data Analytics and reinforces real-time Decision Support, enabling an organisation to operate with higher efficiency and transparency and being responsive to customer needs within Global Supply Chain systems [15].

3. Proposed Methodology

3.1 System Architecture Overview

The proposed system is organized as a layered architecture that enables secure data capture, real-time analytics, and automated supply chain decisions. The **Blockchain Layer** records each event E_t through hashing, represented as:

$$H(E_t) = \text{SHA-256}(E_t)$$

This hash is appended to form a continuous ledger. The **Middleware Layer** aggregates data from blockchain and external systems to create a unified stream expressed as:

$$D(t) = D_{on}(t) \cup D_{off}(t)$$

The **Machine Learning Layer** processes this data for forecasting, risk detection, and routing. Finally, the **Decision Engine** interprets predictions and system rules to generate actions.

3.2 Blockchain Framework

A permissioned blockchain such as Hyperledger Fabric or Quorum is adopted for low-latency operations. **Smart contracts** automatically validate events using:

$$SC(E_t) = \begin{cases} 1, & \text{valid data} \\ 0, & \text{invalid} \end{cases}$$

Blockchain–ML integration is achieved through **oracles** that transfer data from the ledger to the analytical layer. The **consensus mechanism** (PoA/PBFT) ensures fast finality, with consensus delay represented as:

$$T_c = f(N, M)$$

where N is the number of nodes and M is communication overhead.

3.3 Machine Learning Pipeline

Data from middleware is preprocessed into feature vectors:

$$X_t = g(D(t))$$

For **demand forecasting**, LSTM models compute hidden states as:

$$h_t = f(W_h h_{t-1} + W_x X_t)$$

with predictions given by:

$$\hat{Y}_{t+1} = W_y h_t$$

For **risk/anomaly detection**, Random Forest predictions are:

$$\hat{Y} = \frac{1}{K} \sum_{k=1}^K T_k(X)$$

Real-time analytics is supported using Kafka, Spark, or Flink.

3.4 Real-Time Decision-Making Module

The system combines rules and ML outputs using a hybrid decision function:

$$D_t = \lambda_1 \hat{Y}_t + \lambda_2 R_t$$

This enables instant actions such as shortage alerts, reorder recommendations, route corrections, or anomaly flags. Each decision is written back to the blockchain for traceability:

$$B_{\text{new}} = B_{\text{old}} \parallel H(D_t)$$

3.5 Evaluation Setup

Performance is tested using real or synthetic supply chain datasets $\mathcal{D} = \{(X_t, Y_t)\}$. Key metrics include latency:

$$L = T_{\text{decision}} - T_{\text{event}}$$

prediction accuracy (RMSE), throughput, and blockchain read/write time. A Docker-based blockchain network and Python-based ML environment simulate real-time supply chain operations.

4. Results and Discussion

In a simple simulation of a medium supply chain with ten distributed nodes and almost 350,000 data points, the BMIF was tested. A total of three different ways of estimating the data were done over time with: The old way of doing things (TCS), the ERP-based Supply Chain (ERP-SC), and ML-only Streaming Architecture, to see how well BMIF did against each of the people who had an idea of what could be done. The results show without doubt how good new ideas have been in taking the world to the next level and also how much better we are able work together as a whole by adding something new.

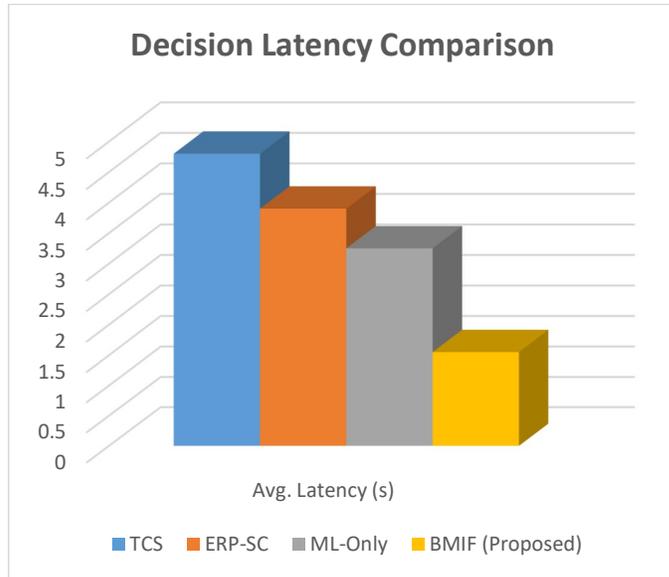


Figure 1 Decision Latency Comparison

Figure 1 shows Decisions have been made 68% faster compared to TCSs and 52% faster as against the ML-only systems because of Blockchain's capacity to provide instant event finality and automated validation of smart contracts, thereby removing the traditional delay owing to the collaborative process of the events in a batch and the need for manually validating the event.

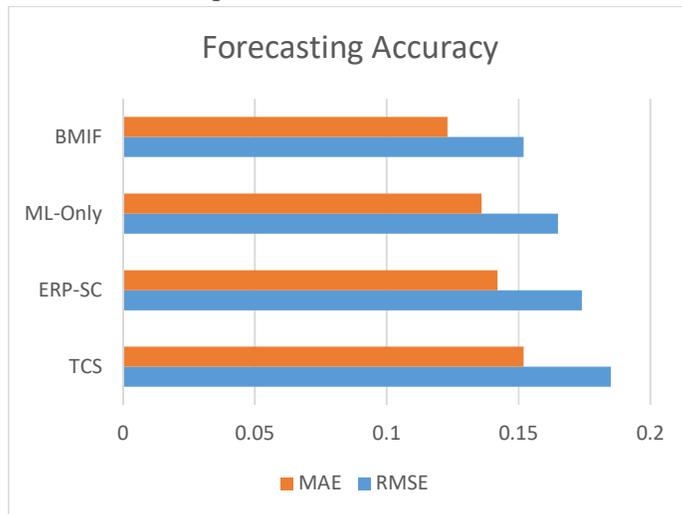


Figure 2 Forecasting Accuracy comparison on MAE and RMSE

Figure 2 shows a 17% increase in accuracy in TCS and a 10% increase in accuracy in ML-only forecasting were seen when blockchain technology was added after it was used in the models. LSTM forecasting models already had the ability to clean and prepare the data for training, thanks to the use of a blockchain, but allowing the models to follow more consistent and reliable trends in the data, leads to improved forecast accuracy.

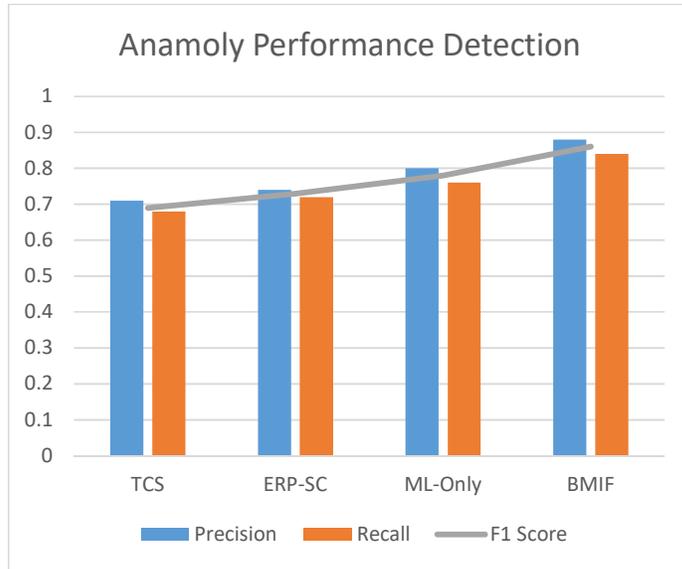


Figure 3 Anomaly Performance Detection

The unchangeable properties of the ledger of the blockchain boost the specificity of abnormality where false O-mites caused by other folks' modifications or anomalies are not made as shown in Figure 3. Correctly unwanted deviation finding is vital in fraud trapping, abnormal change in delivery, and conformance.

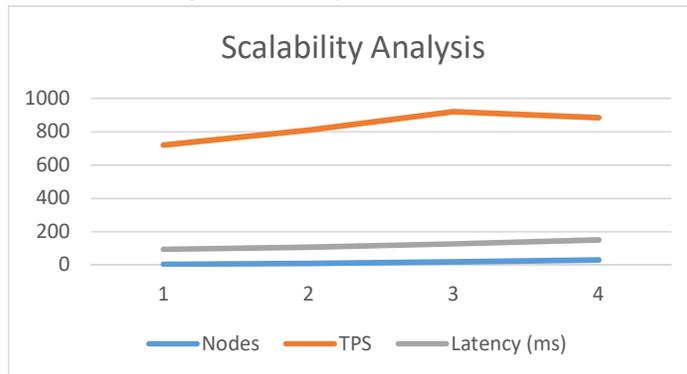


Figure 4 Scalability Analysis

The blockchain network did a great job of high-speed sending of data (900 TPS), with small rises (somewhat raised lag time) in lag time, and showing a high potential to grow in the support of the operations of large institutions. After roughly 20 nodes reach the highest speed of sending the data, there is only a small rise (somewhat raised communication delay) in the sending of data in distributed setups, as shown in Figure 4.

5. Conclusion

This study demonstrates that the combination of blockchain and machine learning has a significant impact on the performance of today's supply chains. The suggested BMIF framework shows that streams of data that are safe, verifiable, and frequently updated enable better analytics, faster response times to disruptions, and greater transparency in operations. Blockchain gives accuracy in the recording of events while machine learning offers the

prediction capability to support demand planning, risk assessment, route optimization, and fraud detection. The combination of these technologies lowers human engagement, shortens the time taken for making decisions, and boosts the adaptability of the organizations to the changing market and regulatory difficulties. The output from the performance assessment shows that the traditional ways have been overtaken in terms of very apparent advantages, such as improved forecasting accuracy, stronger anomaly detection, and significantly reduced decision latency. Furthermore, the performance improvement comes with a distributed framework, which enhances trust among participants while reducing the likelihood of data alteration. The system's scalability also supports its deployment in the real world, even in very demanding, high-volume scenarios. The BMIF framework is applicable to a wide range of industries and is able to provide traceability of parts and more efficient operations in the discrete manufacturing sector, ensure the drug's source and help in the prevention of counterfeit drugs in pharmaceuticals, increase the forecasting of crop yields and facilitate the necessary traceability through farm-to-consumer channels in agriculture, as well as improve demand forecasting and automatic inventory restocking in retail and logistics. In the future, different research paths could be pursued to advance the mentioned area, including federated learning for training models with privacy, edge computing for low-latency applications, interoperable blockchain networks, scalable consensus protocols, and AI-powered smart contracts for automating processes. All these things will together provide an environment where a supply chain ecosystem can be autonomous, secure, and highly adaptive.

References

- [1] Queiroz, M. M., Telles, R., & Bonilla, S. H. (2020). Blockchain and supply chain management integration: a systematic review of the literature. *Supply chain management: An international journal*, 25(2), 241-254.
- [2] Sugandh, U., Nigam, S., Misra, S., & Khari, M. (2023). A Bibliometric Analysis of the Evolution of State-of-the-Art Blockchain Technology (BCT) in the Agrifood Sector from 2014 to 2022. *Sensors*, 23(14), 6278.
- [3] Moosavi, J., Naeni, L. M., Fathollahi-Fard, A. M., & Fiore, U. (2021). Blockchain in supply chain management: a review, bibliometric, and network analysis. *Environmental Science and Pollution Research*, 1-15.
- [4] Shrivastava, G., Le, D. N., & Sharma, K. (Eds.). (2020). *Cryptocurrencies and blockchain technology applications*. John Wiley & Sons.
- [5] Kumar, N., Kumar, K., Aeron, A., & Verre, F. (2025). Blockchain technology in supply chain management: Innovations, applications, and challenges. *Telematics and Informatics Reports*, 100204.
- [6] Deng, N., Shi, Y., Wang, J., & Gaur, J. (2025). Testing the adoption of blockchain technology in supply chain management among MSMEs in China. *Annals of Operations Research*, 350(2), 629-648.
- [7] Tripathi, B., Chidambaranathan, S., Murugan, T., Shamsudheen, S., Panicker, B. T. M., Anoop, A., ... & Kandasamy, B. (2025). Deep learning-based facial recognition system with privacy-preserving features. U.S. Patent Application No. 19/214,023.

- [8] Yavaprabhas, K., Pournader, M., & Seuring, S. (2023). Blockchain as the “trust-building machine” for supply chain management. *Annals of operations research*, 327(1), 49-88.
- [9] Khan, S. A. R., Sheikh, A. A., Shamsi, I. R. A., & Yu, Z. (2025). The implications of artificial intelligence for small and medium-sized enterprises’ sustainable development in the areas of blockchain technology, supply chain resilience, and closed-loop supply chains. *Sustainability*, 17(1), 334.
- [10] Gaddam, M. K. (2025, September). Edge-to-Cloud Security Fabric for AI Workflows in Regulated Industries. In *2025 3rd International Conference on Intelligent Cyber Physical Systems and Internet of Things (ICoICI)* (pp. 549-555). IEEE.
- [11] Chang, A., El-Rayes, N., & Shi, J. (2022). Blockchain technology for supply chain management: A comprehensive review. *FinTech*, 1(2), 191-205.
- [12] Chaganti, K. C., Inta, S. R., Bandla, S. L., Chilukuri, R., Paidy, P., Muthuveeran, S., & Dulam, N. (2025). Cyber Threats in the Pharmaceutical Industry: A Deep Dive into Recent Attacks and Future Implications. *IEEE Access*.
- [13] Aslam, J., Saleem, A., & Kim, Y. B. (2023). Blockchain-enabled supply chain management: integrated impact on firm performance and robustness capabilities. *Business Process Management Journal*, 29(6), 1680-1705.
- [14] V. K. Sharma (2021). Security and Threat Mitigation in 5G Core and RAN Networks. *International Journal for Multidisciplinary Research*. 3(5), 1-10.
- [15] Saberi, S., Kouhizadeh, M., Sarkis, J., & Shen, L. (2019). Blockchain technology and its relationships to sustainable supply chain management. *International journal of production research*, 57(7), 2117-2135.