DESIGN BLOCKCHAIN BASED SUPPLY CHAIN PLATFORM FOR AID RELIEF DURING PANDEMIC

Thesis Submitted for the Award of the Degree of

DOCTOR OF PHILOSOPHY
in

Computer Applications

By

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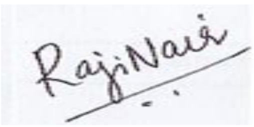
LOVELY PROFESSIONAL UNIVERSITY PUNJAB
2025

DECLARATION

I, hereby declared that the presented work in the thesis entitled “Design Blockchain Based Supply Chain Platform for Aid Relief During Pandemic” in fulfilment of degree of Doctor of Philosophy (Ph. D.) is outcome of research work carried out by me under the supervision Dr. Punam Rattan, working as Associate Professor, in the School of Computer Applications of Lovely Professional University, Punjab, India. In keeping with general practice of reporting scientific observations, due acknowledgements have been made whenever work described here has been based on findings of other investigator. This work has not been submitted in part or full to any other University or Institute for the award of any degree.



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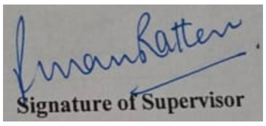
CERTIFICATE

This is to certify that the work reported in the Ph. D. thesis entitled “Design Blockchain Based Supply Chain Platform for Aid Relief During Pandemic” submitted in fulfillment of the requirement for the reward of degree of Doctor of Philosophy (Ph.D.) in the School of Computer Applications, is a research work carried out by Raji Ramakrishnan Nair, Registration No.: 41900212, is bonafide record of her original work carried out under my supervision and that no part of thesis has been submitted for any other degree, diploma or equivalent course.



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ACKNOWLEDGEMENT

This PhD journey has been one of the most significant and transformative chapters of my life, marked by intellectual challenges, personal growth, and the invaluable support of many individuals and institutions to whom I owe my deepest gratitude.

First and foremost, I express my profound appreciation to my supervisor, **Dr. Punam Rattan**, whose expert guidance, constructive feedback, and unwavering encouragement have been instrumental in shaping this research. Under her mentorship, I have been able to refine my ideas, develop my academic rigor, and successfully complete this work.

I would also like to sincerely thank my previous supervisors, **Dr. Ajay Kushwaha** and **Dr. Apash Roy**, for their guidance and contributions during the initial stages of my research journey. Their insights laid important foundations for this work.

A very special note of gratitude goes to **Mr. Alen Joseph**, who stood by me throughout this process, from inception to completion, offering constant support, technical help, and motivation, without which this work would not have reached its present form.

I am profoundly grateful to **Dr. K. V. Thomas**, my most respected mentor, whose wise counsel, mentorship, and steadfast motivation helped me navigate through academic challenges and the inevitable ups and downs of life. His belief in me gave me strength during the most difficult phases of this journey.

My heartfelt thanks extend to my **family**, whose unconditional support has been my greatest pillar. I am especially indebted to my **husband, G. Biju**, whose constant encouragement, patience, and belief in my capabilities provided me with the strength to persevere, his sole wish being to see me awarded the doctorate in Computer Applications. To my **daughter**, **Thanima**, for her understanding, love, and quiet support that gave me peace of mind throughout this demanding period. To my **mother, Omana R. Nair**, and **mother-in-law, Radhamaniamma,** whose love and blessings sustained me at every step.

I would like to **dedicate this work to my beloved father, Late M. N. Ramakrishnan Nair**, and **my beloved father-in-law, Late K. P. Gangadharan Nair,** who continues to bless me from heaven and remains a guiding light in my life.

I am thankful to **Lovely Professional University Punjab** for providing the academic environment and resources necessary to pursue this research. My sincere appreciation to my friends who encouraged me, shared ideas, and supported me throughout this academic endeavour.

I also extend my gratitude to my workplace, **CHRIST University, Lavasa Campus, Pune**, for its continuous support, understanding, and encouragement during this journey. The institutional backing and collegial environment here have played an essential role in enabling me to balance my academic, professional, and personal responsibilities.

To all who have stood by me, mentors, colleagues, friends, and family, I offer my heartfelt thanks. This achievement is as much yours as it is mine.

ABSTRACT

The COVID-19 pandemic has starkly revealed the limitations of conventional healthcare logistics systems, particularly in their ability to ensure timely, transparent, and equitable vaccine distribution during global health emergencies. Traditional centralized models, characterized by fragmented data silos, manual oversight, and hierarchical decision-making, have proven inadequate in responding to rapidly changing demand patterns and crisis conditions. This research addresses these critical gaps by proposing and rigorously evaluating the Predictive BlockVax Distribution Network (PBDN), a novel, integrated framework that fuses blockchain technology with machine learning (ML) to create a resilient, transparent, and predictive supply chain infrastructure for pandemic response.

At the heart of the PBDN framework lies the strategic integration of blockchain, deployed via Hyperledger Besu, and Long Short-Term Memory (LSTM) neural networks. The blockchain layer ensures immutability, decentralized trust, and transparent transaction logging among diverse stakeholders, while LSTM models provide real-time demand forecasting based on historical epidemiological and demographic data. Smart contracts encode vaccine allocation, shipment tracking, and eligibility verification rules, automating key operational processes and minimizing manual intervention. This fusion of technologies facilitates a paradigm shift from reactive to anticipatory logistics, enhancing both operational efficiency and ethical accountability. The predictive model was trained and evaluated using a large-scale real-world dataset comprising 520,288 records sourced from Our World in Data, aggregated from WHO and Johns Hopkins University repositories, ensuring realistic simulation of pandemic conditions.

The study adopts a simulation-based experimental methodology to evaluate PBDN under various pandemic-like conditions, including steady demand growth, sudden demand surges, partial node failures, inventory imbalances, and shipment delays. Performance metrics span predictive accuracy (using RMSE, precision, recall, and F1-score), blockchain throughput and latency, and an original Equity Index measuring geographic and demographic fairness. Experimental results demonstrate that the LSTM model achieved superior predictive performance, reducing the test RMSE to 0.071949 compared to 0.101495 for the ARMA model and 0.072164 for the CNN model, representing a significant improvement in demand forecasting accuracy. The LSTM model also achieved training accuracy of 95.21%, precision

of 95.21%, recall of 100%, and F1-score of 97.55%, confirming its effectiveness in capturing temporal dependencies in pandemic demand patterns. Furthermore, the blockchain implementation enabled secure, immutable transaction recording and automated allocation execution, improving supply chain transparency and operational efficiency. Comparative benchmarking against traditional centralized systems demonstrates that PBDN not only improves transparency and responsiveness but also significantly reduces distributional inequities, a key ethical imperative underscored by international health policy frameworks such as the UN Sustainable Development Goals.

The findings contribute both theoretically and practically to the fields of healthcare logistics, blockchain applications, and digital public health governance. Theoretically, this work extends prior research by demonstrating the viability of a hybrid blockchain-ML architecture tailored for crisis logistics, reinforcing the discourse on distributed trust, smart contract automation, and AI-enabled decision-making in public health systems. Practically, the PBDN model offers a scalable, modular blueprint for health ministries, non-governmental organizations, and international bodies seeking to build pandemic-resilient supply chain infrastructures. Its emphasis on transparency, predictive adaptability, and equity positions it as a pioneering contribution to future-ready healthcare logistics.

Limitations of the study include the reliance on simulation-based evaluations rather than real-world pilots, the constrained scalability of permissioned blockchain networks under extreme node expansion, and the dependency of ML performance on data quality and representativeness. These limitations inform future research directions, including piloting PBDN in partnership with public health authorities, enhancing blockchain scalability and energy efficiency, and integrating Internet of Things (IoT) sensors for end-to-end cold chain monitoring.

In conclusion, this thesis advances a holistic, interdisciplinary approach to pandemic logistics by leveraging the complementary strengths of blockchain and ML. The proposed PBDN framework not only responds to the immediate operational challenges revealed by COVID-19 but also lays a robust foundation for ethically-grounded, digitally-enabled healthcare logistics systems capable of meeting future global health crises with greater resilience, fairness, and transparency. The results confirm that integrating blockchain with LSTM-based predictive intelligence provides a practical, scalable, and effective solution for transparent, equitable, and data-driven vaccine distribution.

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LIST OF ABBREVIATIONS

PPE - Personal Protective Equipment

HSC - Healthcare Supply Chain

SCM - Supply Chain Management

WHO - World Health Organisation

SC - Supply Chains

BC - Blockchain

ML - Machine Learning

RFID - Radio-Frequency Identification

UN - United Nations

SDG - Sustainable Development Goal

AI - Artificial Intelligence

ZKPs - Zero - Knowledge Proofs

PBDN - Predictive BlockVax Distribution Network

BFT - Byzantine Fault Tolerance

IBFT - Istanbul Byzantine Fault Tolerance

LSTM - Long Short-Term Memory

RNN - Recurrent Neural Networks

ARMA - AutoRegressive Moving Average

CNN - Convolutional Neural Network

RO - Research Objectives

SCM – Supply Chain Management

IoT - Internet of Things

DLT - Distributed Ledger Technology

NFT - Non-Fungible Tokens

PAPR - Powered Air-Purifying Respirator

MSC - Medical Supply Chain

VMI - Vendor Managed Inventory

AHP - Analytic Hierarchy Process

BERT - Bidirectional Encoder Representations from Transformers

DSR -Design Science Research

JHU CSSE - Johns Hopkins University Centre for Systems Science and Engineering

OWID - Our World in Data

ReLU - Rectified Linear Unit

MSE - Mean Squared Error

RMSE - Root Mean Square Error

PoW - Proof of Work

Chapter 1

INTRODUCTION

Healthcare Supply Chains involve a complex network linking entities accountable for manufacturing, managing, distributing, and providing healthcare goods and services. This network manages various items, such as medications, medical supplies, personal protective equipment (PPE), and vaccines [1]. Efficient Healthcare Supply Chains are vital in saving lives by guaranteeing the timely availability of essential medical resources. This significantly strengthens the resilience of the healthcare system and its capacity to respond effectively in emergencies [2]. The healthcare supply chain consists of numerous vital elements, each important for efficient functioning [3]. The manufacturing sector produces healthcare commodities, such as pharmaceuticals, medical equipment, and vaccines, following rigorous quality assurance protocols and regulatory criteria to guarantee efficacy and safety [4]. Efficient inventory control is vital in maintaining adequate stock levels, ensuring proper product storage, and supervising reorder processes to avoid shortages or excesses that could lead to resource wastage or compromised patient care quality [5]. Procurement procedures facilitate healthcare institutions in obtaining the essential medical supplies and equipment needed for their functioning, where efficient approaches play a vital role in cost control and guaranteeing the uninterrupted provision of necessary resources [6]. One of the most apparent effects of a pandemic is the fast growth in the requirement for healthcare resources. This unparalleled rise in the requirement for Personal Protective Equipment (PPE), ventilators, vaccines, and other crucial medical supplies exerts significant pressure on SCs [7].

Transportation delays and export restrictions exacerbate the scenario as nations prioritize acquiring resources for their citizens, resulting in worldwide competition for scarce commodities[8] The necessity of cold chain logistics for the distribution of vaccines, which entails precise temperature regulation across the supply chain, presents substantial obstacles in guaranteeing the delivery of vaccines and essential supplies to various regions worldwide, particularly those with underdeveloped infrastructure, necessitating creative logistical approaches, and collaborations. [9][10]. These challenges emphasize the intricate nature of HSC management in the context of pandemics and the immediate requirement for resilient, flexible, and transparent systems that can endure the demands of worldwide health crises[11].

1.1 SUPPLY CHAIN MANAGEMENT SYSTEM

Supply Chain Management (SCM) is a comprehensive approach that involves the coordination and management of a network of interconnected businesses involved in the provision of products and services to end customers. It encompasses a wide range of activities, from procurement and operations to logistics and strategic management, aiming to enhance efficiency, reduce costs, and improve customer satisfaction. SCM is not merely a collection of activities but requires an integrated and collaborative approach to provide a competitive advantage.

1.1.1 The Role of Reliable and Efficient Supply Chains

The importance of an efficient and dependable Supply Chain System in achieving economic growth and stability of a country can never be overemphasized. It ensures the smooth flow of goods and services from producers to widely dispersed end users at the right time in the right place in the right quantity. When it comes to healthcare supplies importance of supply chain assumes a greater significance as any delay in the delivery of medical supplies cost lives of people. Thus, a well-synchronized supply chain helps a seamless movement of medical supplies from manufactures to the end users.

1.2 HEALTHCARE SYSTEM

The healthcare system is a complex network of organizations, people, and resources aimed at delivering health services to populations. It encompasses various components that work interdependently to promote, restore, or maintain health. The integration of technology and information systems plays a crucial role in enhancing the efficiency and effectiveness of healthcare delivery.

1.2.1 Practical Implications for Policymakers and Healthcare Stakeholders

For government agencies, public health institutions, and non-governmental organizations, the study offers a blueprint for building next-generation pandemic preparedness infrastructures. The developed framework demonstrates how automated smart contracts can reduce administrative delays, enforce equitable allocation rules, and streamline inter-agency coordination. Additionally, its predictive capabilities enable proactive planning and minimize vaccine wastage by aligning supply with actual and projected demand. This positions the model a practical tool for policy formulation, emergency logistics planning, and digital transformation of healthcare systems.

1.3 PANDEMIC 2019

The pandemic of 2019, known as COVID-19, emerged in December 2019 in Wuhan, China, caused by the novel coronavirus SARS-CoV-2. This highly infectious virus led to a global health crisis, prompting the World Health Organization to declare it a pandemic by March 2020. The disease primarily spreads through respiratory droplets, with varying severity among infected individuals.

1.3.1 Challenges Faced by Healthcare Supply Chains During Pandemic Situations

Global SCs have dramatically transitioned due to the ongoing COVID-19 pandemic, with potentially dire consequences for the environment, society, and economy. The pandemic that began to spread in 2019 led to many difficulties for local and global SCs. Several causes have contributed to the interruptions experienced by SCs, including an unexpected increase in demand for necessities such as face masks, hand sanitizers, and disinfection sprays, which has left the market short on supply [12]. Numerous regions documented deficiencies in food supply and instability, decreased production capacity due to a lack of workers, and insufficient physical and financial resources impeded SCs from fulfilling demand efficiently[13]. These obstacles broadly impact various aspects of supply chain activities, underscoring the need to investigate efficient tactics for risk mitigation and enhancement of resilience.

1.3.2 Need for Innovative Supply Chain Systems for Vaccine Distribution During Pandemics

Innovative approaches for managing the supply chain have the potential to mitigate risks and enhance the overall resilience of the supply chain. The utilization of advanced technologies offers the prospect of significant progress in achieving transparency, strengthening security, and enhancing forecasting capabilities. These crucial components can greatly revolutionize the resilience and efficiency of healthcare logistics [14]. The decentralized ledger system of Blockchain (BC) technology offers unparalleled levels of transparency and traceability. Protection of confidential data from unauthorized access is also a critical aspect in the healthcare industry where patient confidentiality and trust are paramount. Integrated security measures provided by the Blockchain technology helps in ensuring the confidentiality of the sensitive data[15][16].

Conversely, Machine Learning (ML) algorithms demonstrate proficiency in examining extensive datasets for forecasting patterns and assessing demand with notable precision. The integration of these technological advancements symbolizes a deliberate shift towards SCs that are more intelligent, adaptive, and secure [17]. Examining historical advancements beyond the healthcare sector, RFID (Radio-Frequency Identification) technology has transformed the retail and logistics fields through its capacity to facilitate live monitoring of products, thereby enhancing inventory control and customer contentment [18][19].

Similarly, AI-powered analytics have significantly impacted the manufacturing sector, revolutionizing processes by forecasting maintenance requirements and enhancing production schedules to minimize downtime and enhance operational effectiveness [20]. Incorporating BC and ML into healthcare logistics represents more than a mere enhancement; it signifies an essential progression to address the present and future challenges. By leveraging lessons from previous achievements and capitalizing on the potential of these advancements, healthcare SCs can attain a degree of robustness and effectiveness previously deemed unachievable, thereby establishing a novel benchmark for readiness and reaction against pandemics [21]. Timely distribution of vaccines plays a crucial role in managing outbreaks and the containment of diseases, underscoring the importance of addressing any potential delays as a notable public health priority [22], [23], [24]. Insufficient inventory levels can impede immunization initiatives, whereas excessive inventory levels entail the risk of squandering precious medical supplies attributable to the constrained expiration period of vaccines [24], [25]. The resolution of these challenges holds paramount importance in enhancing the adaptability and agility of healthcare systems, especially in times of pandemics that necessitate swift and synchronized interventions.

The integration of Blockchain and Machine Learning technologies represents a transformative approach to modern healthcare logistics. Blockchain ensures secure, transparent, and tamper-proof transaction management, while Machine Learning enables predictive analytics and data-driven decision-making. Together, these technologies offer a promising foundation for building intelligent, transparent, and resilient healthcare supply chain systems capable of responding effectively to global health emergencies.

1.3.3 Addressing Equity and Ethical Distribution

Direct engagement with health equity is yet another point of relevance of the study. The developed predictive model, by embedding fairness logic into smart contracts and assessing distribution using customized equity indices, makes sure that marginalized and underserved rural population also get the benefits of healthcare services on par with their counterparts elsewhere. This aligns with United Nations (UN) Sustainable Development Goal (SDG) 3 related to health and well-being, reduced inequalities, and innovation in public infrastructure. Thus, the study not only offers just a technological solution but also presents a framework for responsible and inclusive healthcare service during times of pandemic, as well as post-pandemic.

Drawing inspiration from the proverb ‘prevention is better than cure,’ global healthcare system has realized the need for long-term preparedness rather than crisis management. The need for building a resilient and technology-driven healthcare system is keenly felt across the world. This research contributes significantly inputs for managing pandemics in future on a global scale as well as a process for the timely and efficient vaccine supply chains. The interest in decentralized health data systems, ethical AI and real-time surveillance on the rise. In this scenario the developed model will go a long way towards addressing future healthcare emergencies.

1.3.4 Need for Innovative Frameworks in Vaccine Distribution

The recent COVID-19 pandemic has undoubtedly exacerbated inequalities between populations and communities regarding access to healthcare services. Vaccine access can be deemed “equitable” when all individuals are provided with the same vaccines by implementing tailored services designed to meet their needs [26]. The equitable distribution of vaccines on a global scale, ensuring transparency while accounting for socioeconomic variables, presents a highly complex challenge. Critics argue against allocating vaccines to nations based solely on population proportion, as this method may overlook the specific needs of diverse populations and focus exclusively on proportionality rather than addressing the nuanced requirements of different communities [27]. Matteo Bolcato has analyzed the relationship between the principle of equity and its application in the context of vaccine distribution during the current pandemic [27]. According to the author, there is no global uniformity in the perception and interpretation of equity, as it varies depending on contextual reference values. Transparency is a crucial process component and must be maintained throughout the continuum, from parameter identification to implementing appropriate plans. The time-sensitive nature of implementing equity measures necessitates proper prioritization to minimize the risk of contracting COVID-19 for the maximum number of individuals within a specific population at any given time. These challenges have motivated the need for a novel vaccine distribution architecture, considering the countries’ vulnerability to a pandemic like COVID-19 and their readiness to distribute their allocated vaccines[28]. The following **Figure 1.1** shows the process flow in a blockchain-based healthcare supply chain.

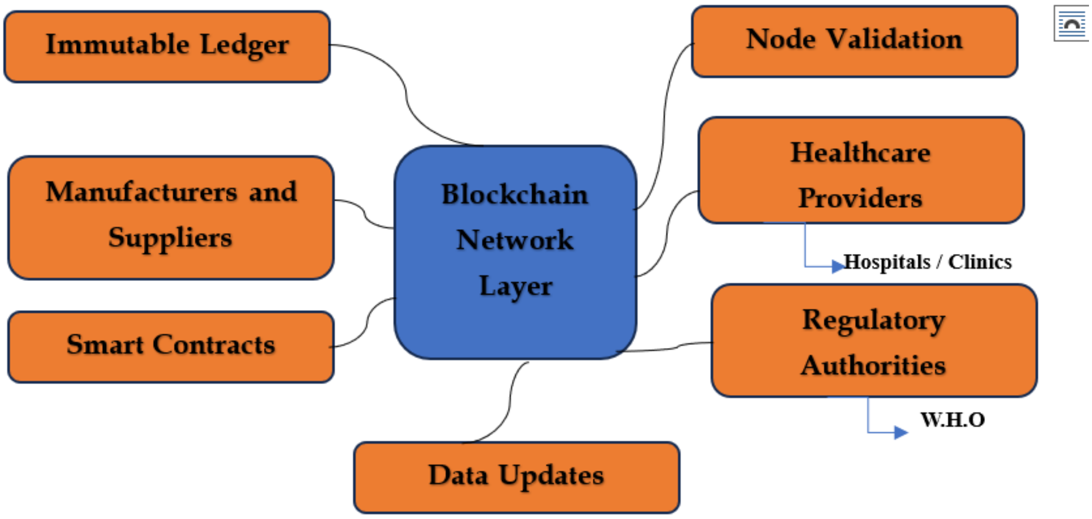


Figure 1.1 Blockchain - Based Healthcare Supply Chain

1.4 BLOCKCHAIN TECHNOLOGY: AN OVERVIEW

Blockchain technology is a decentralized, distributed ledger system that ensures secure, transparent, and immutable transactions across various applications. Its principles include peer-to-peer transmission, consensus algorithms, and a focus on enhancing trust and efficiency in data management. The technology is poised to revolutionize multiple sectors, including finance, healthcare, and supply chain management, by eliminating intermediaries and fostering direct interactions among participants.

1.4.1 Blockchain (BC)

A blockchain is a decentralized and distributed digital ledger that records transactions across multiple nodes in a network. Each record, or block, is cryptographically linked to the previous one, ensuring data integrity and immutability. The working definition of the term in this context is the use Hyperledger Besu which in turn is a permissioned enterprise-grade blockchain framework that enables a secure and transparent tracking of a decentralized vaccine supply chain. The working of a blockchain is shown in **Figure 1.2**.

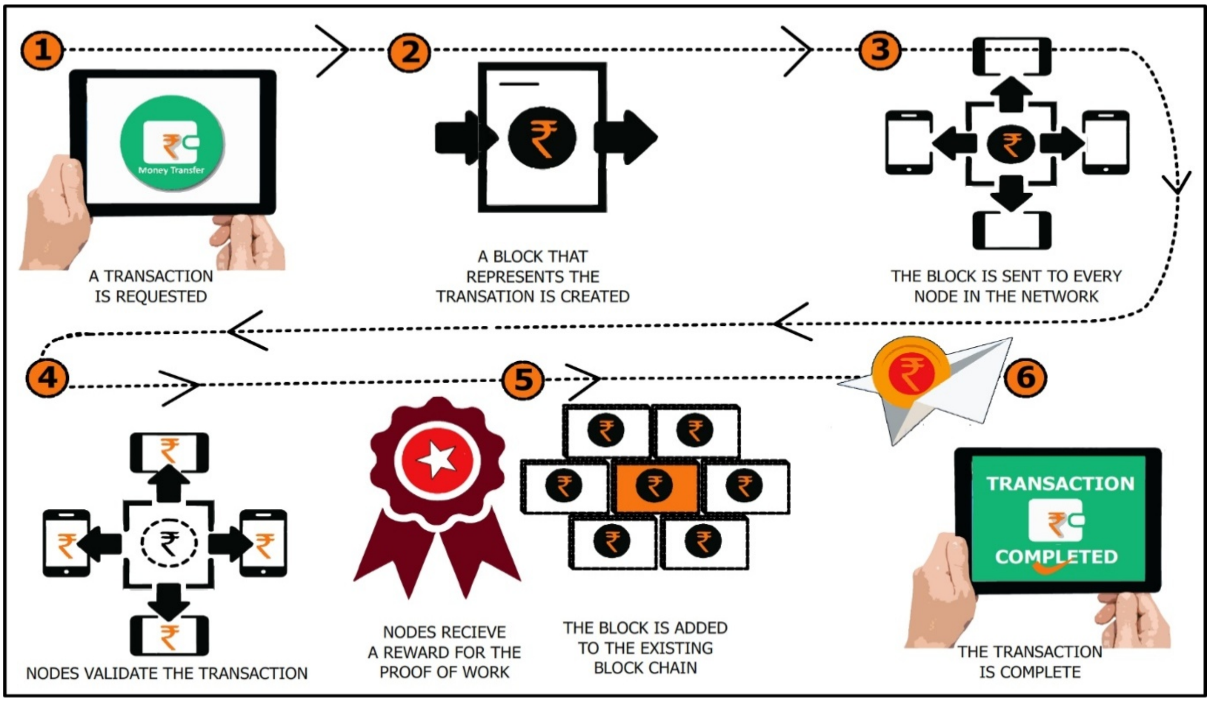


Figure 1.2 Working of a Blockchain

1.4.2 Smart Contract

Smart contracts are self-executing code blocks deployed on a blockchain platform that automatically enforce rules and execute agreements based on pre-defined conditions. In this study, smart contracts are used to automate critical vaccine logistics functions such as allocation, eligibility verification, shipment tracking, and receipt acknowledgment. The process of smart contract execution is shown in **Figure 1.3**.

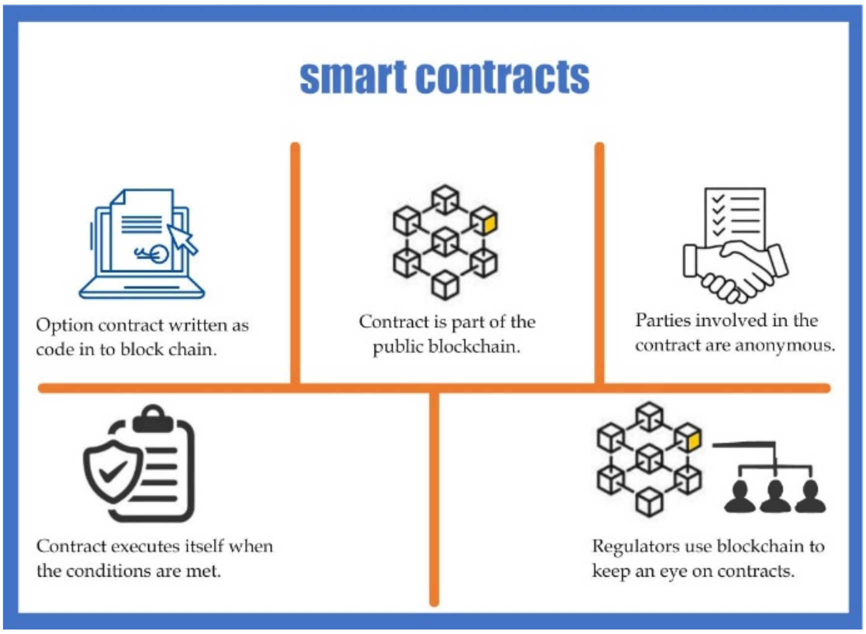


Figure 1.3 Smart Contracts

The smart contracts in the developed model are written in Solidity and integrated within the blockchain to minimize manual intervention and promote operational efficiency.

1.4.3 Vaccine Supply Chain System

The vaccine supply chain encompasses the end-to-end process of manufacturing, procurement, storage, distribution, and administration of vaccines. It includes multiple stakeholders such as manufacturers, logistic providers, health agencies, and end recipients. The following **Figure 1.4** shows the various components involved in a vaccine supply chain.

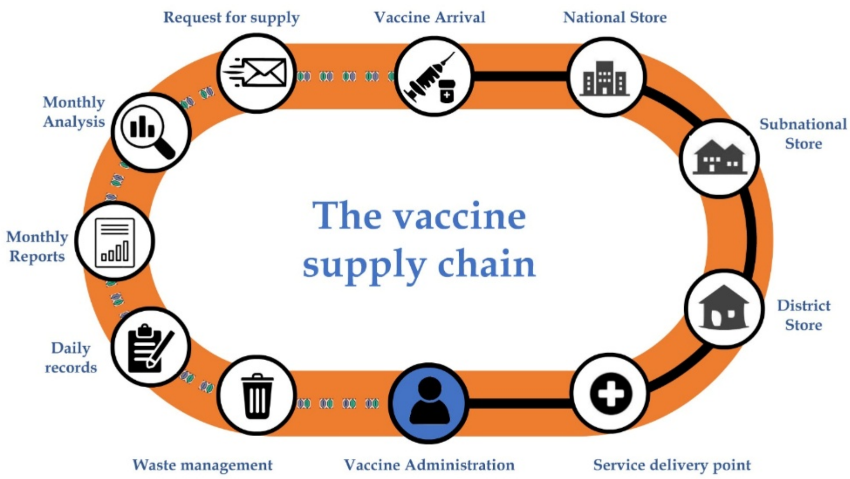


Figure 1.4 Vaccine Supply Chain

The study focuses on optimizing this supply chain through a combination of decentralized data validation (blockchain) and dynamic demand forecasting (ML).

1.4.4 Other Key Concepts

1.4.4.1 Equity Index

The Equity Index is a composite metric developed within the developed framework to evaluate fairness in vaccine distribution. It measures both **geographic equity** (e.g., urban vs. rural allocation) and **demographic equity** (e.g., allocation across different risk groups) as shown in **Figure 1.5**. This index helps in ensuring that the vaccine distribution process is inclusive, ethical, and aligned with public health priorities.

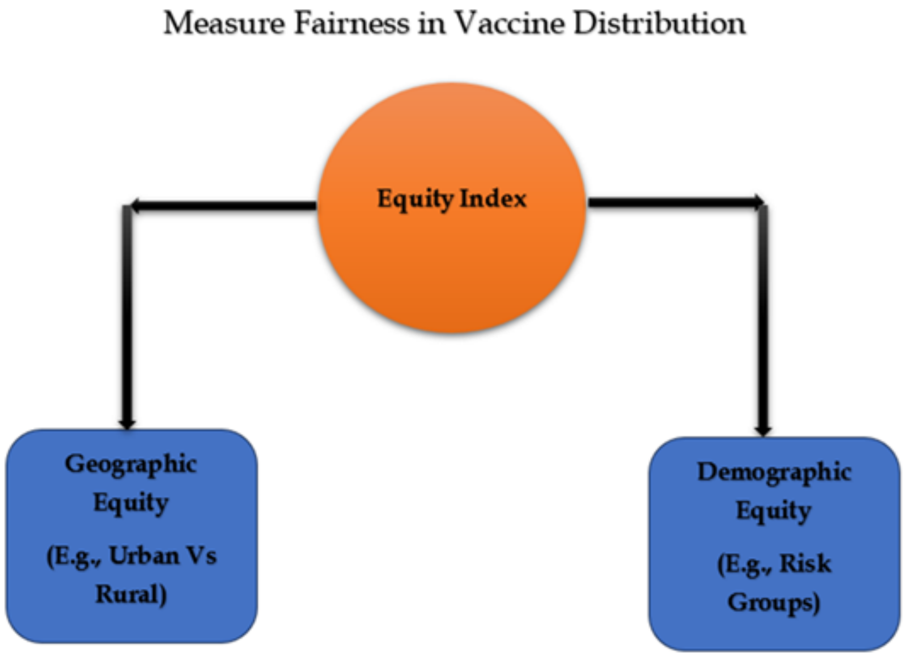


Figure 1.5 Equity Index

1.4.4.2 Permissioned Blockchain

A permissioned blockchain is a type of distributed ledger where access to participate in the network is restricted to authorized entities. Unlike public blockchains (e.g., Bitcoin, Ethereum), permissioned blockchains offer enhanced privacy, controlled governance, and improved scalability. The following **Figure 1.6** shows the visualization of a permissioned blockchain.

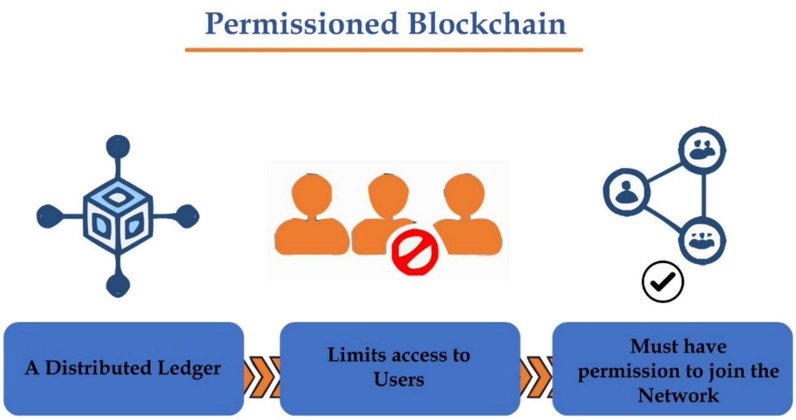


Figure 1.6 Permissioned Blockchain

Hyperledger Besu, used in this study, is an example of a permissioned blockchain well-suited for institutional applications in healthcare.

1.4.4.3 Zero - Knowledge Proofs (ZKPs)

Cryptographic techniques that permit one party to prove to another that a statement is true without disclosing any information beyond the validity of the statement itself is referred to as Zero-Knowledge Proofs. The following **Figure 1.7** shows the transactions involved in ZKPs.

Figure 1.7 Zero-Knowledge Proofs

Although not implemented directly in the simulation, ZKPs are proposed in this study as a privacy-enhancing mechanism for protecting sensitive health data while maintaining trust and transparency in vaccine distribution.

1.4.4.4 Pandemic Resilience

Pandemic resilience refers to a healthcare system's ability to withstand, adapt to, and recover from disruptions caused by widespread infectious disease outbreaks. In this study, resilience is evaluated through stress test scenarios, examining how the Predictive BlockVax Distributed Network (PBDN) framework responds to conditions such as demand surges, node failures, and shipment delays.

1.4.4.5 Byzantine Fault Tolerance (BFT) /IBFT 2.0

IBFT (Istanbul Byzantine Fault Tolerance) is a consensus mechanism used in permissioned blockchain networks like Hyperledger Besu. It ensures that the system continues to function correctly even if some nodes behave maliciously or fail. This consensus model plays a crucial role in maintaining reliability and trust in the PBDN network during pandemic conditions. The IBFT consensus mechanism is shown in **Figure 1.8**.

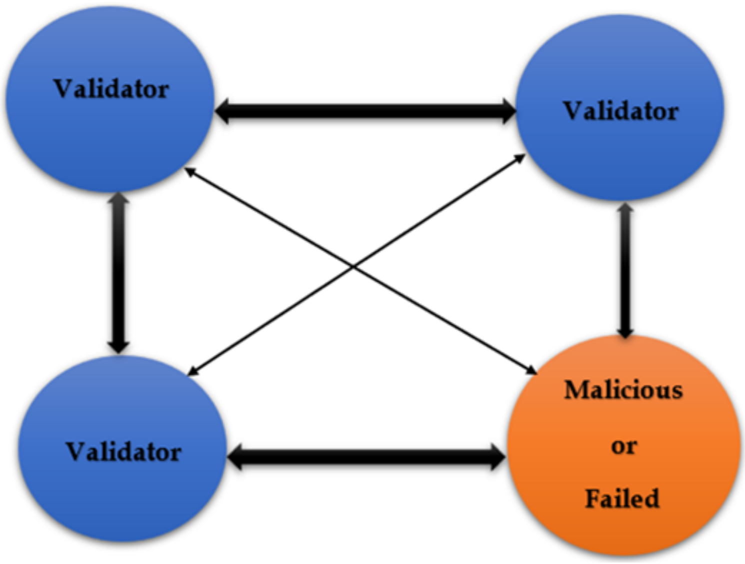


Figure 1.8 IBFT Consensus

1.4.4.6 Advancing the Theoretical Landscape

The proposed research work contributes to the evolving theoretical discourse on digital health infrastructure by developing a new hybrid model that integrates predictive analytics with decentralized decision-making. While prior studies have independently explored blockchain's potential in supply chain management and ML's role in demand forecasting, this study is among the first to demonstrate a functional, simulation-tested model that combines both. It builds on and extends theories of distributed trust, smart contract-based automation, and AI-driven health logistics, offering a unique interdisciplinary framework for scholars and practitioners alike.

1.5 MACHINE LEARNING AND RELATED ALGORITHMS

Machine Learning is a self-learning system that enables computer systems to learn from patterns of processed data without the application of any preset programs. Being a subset of Artificial Intelligence helps improve the performance of systems eventually. In the developed framework, ML is utilized to predict future vaccine demand using historical pandemic data. The study specifically employs **Long Short-Term Memory (LSTM)** networks, a class of recurrent neural networks well-suited for time-series forecasting.

1.5.1 Long Short-Term Memory (LSTM)

LSTM is an advanced neural network architecture that addresses the vanishing gradient problem typical of traditional recurrent neural networks (RNNs). LSTM networks are capable of capturing long-term dependencies in sequential data, making them highly effective for demand forecasting in dynamic environments such as pandemics. This capability makes LSTMs particularly suitable for tasks involving complex time-series predictions and nonlinear dynamic systems[29]. In this study, the LSTM model is trained on COVID-19 case trends to predict vaccine requirements at regional levels. The functionality of an LSTM unit, classified as part of the structures within recurrent neural networks (RNN), is illustrated in **Figure 1.9**.

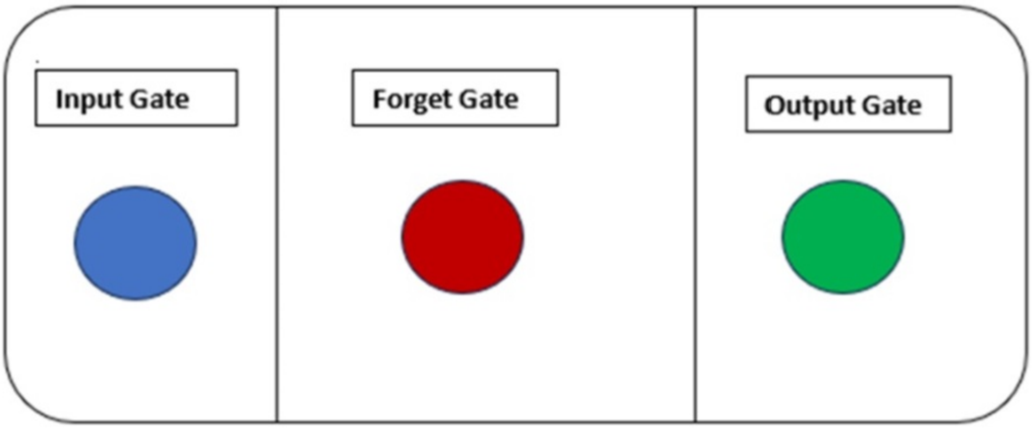


Figure 1.9 Long Short - Term Memory Model Architecture

As can be seen in **Figure 1.9**, an LSTM unit comprises three components. They are: (i) the input gate (ii) the forget gate and (iii) the output gate.

The function of input gate is to integrate and update new data, while that of the forget gate is to shred the redundant information. The third gate, output gate, controls the flow of information processed by the preceding gates. By way of controlling the transmission of information, these gates allow the LSTM to do away with the cumbersome task of handling large sequential data.

1.5.2 AutoRegressive Moving Average (ARMA)

One of the tools for predicting and analyzing stationary time series data is the Auto Regressive Moving Average which has two components namely, Autoregression and Moving Average.

- *Autoregression (AR):* This part of the model expresses the variable of interest as a function of its past values. The idea is that previous observations influence current observations. It includes parameters that specify the number of lagged observations to be included in the model, denoted by p in AR (p). For instance, an AR(1) model would predict the current value of the series based on the immediately previous value.
- *Moving Average (MA):* This component illustrates the error term as a linear combination of contemporaneous and lagged error terms. It encompasses parameters defining the quantity of lagged forecast errors in the prediction equation, represented as q in MA (q). To illustrate, a model denoted as MA(1) would utilize the preceding error term for forecasting the present value of the series.

The ARMA model's main purpose is to forecast time series using past values and the error terms. The following **Figure 1.10** shows a sample graph outputted by an ARMA model after evaluating a given data set.

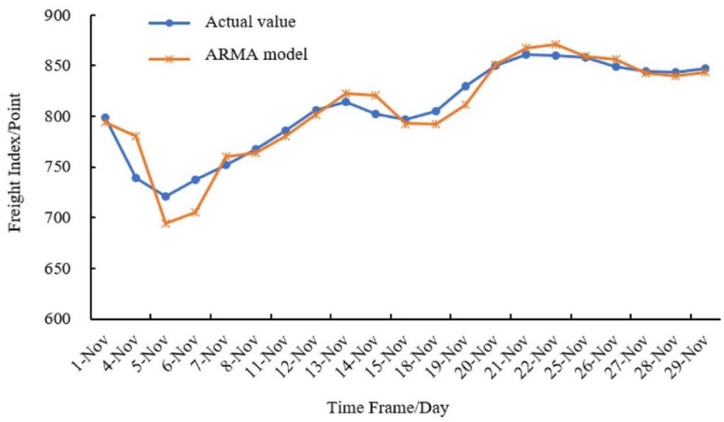


Figure 1.10 A sample forecasting time-series graph developed by the ARMA Model

1.5. 3 Convolutional Neural Network (CNN)

The Convolutional Neural Network (CNN) is an additional commonly utilized predictive model. The diagram depicted in **Figure 1.11** shows the structure of a CNN, which has historically been employed in image processing yet is presently applied in time-series prediction. Its proficiency in identifying patterns across various levels and revealing intricate, non-linear correlations renders it indispensable for prognostication amidst intricate circumstances such as pandemics. The primary disadvantage of CNNs in forecasting is their computational complexity, which can result in longer training periods, increased resource requirements, and the need for huge datasets to train efficiently. Also, the models seem difficult to interpret because of the “black box” nature of CNNs, creating challenges for analysts seeking to understand the underlying factors driving the forecasts.

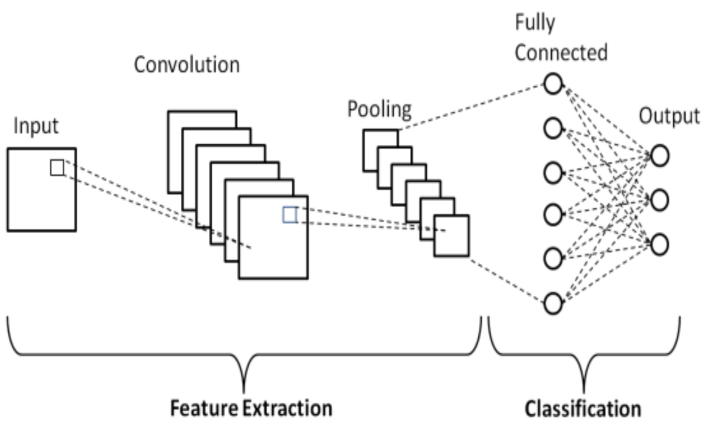


Figure 1.11 Architecture of a Convolutional Neural Networks

1.6 PROBLEM IDENTIFICATION

The COVID-19 pandemic served as a wake-up call to the world, revealing significant gaps in global healthcare supply chains (HSCs), particularly in the distribution of critical resources such as vaccines. Traditional supply chain models, characterized by centralized control, limited data sharing, and manual intervention, proved inadequate when faced with the unprecedented surge in global demand. The lack of real-time transparency and traceability created challenges in monitoring vaccine allocation and delivery, resulting in mismanagement, stock shortages in critical regions, and wastage in others.

Furthermore, inequities in distribution were starkly evident. Developing countries and remote rural areas were disproportionately affected due to weak logistics infrastructure, delayed information flow, and lack of fair allocation strategies. Vaccine nationalism and hoarding further worsened the crisis, leaving millions without timely access to life-saving vaccines.

Another critical issue was the inability of existing forecasting mechanisms to anticipate rapid shifts in demand caused by sudden infection surges or the emergence of new variants. The absence of accurate, data-driven predictive models amplified inefficiencies, while administrative bottlenecks and outdated paper-based processes slowed decision-making during a time when speed was crucial.

The convergence of these challenges highlights a fundamental problem: traditional healthcare supply chains are ill-equipped to operate with fairness, transparency, and responsiveness during large-scale health emergencies. There is a pressing need for a decentralized, automated, and predictive framework that integrates advanced technologies like blockchain and machine learning to ensure the efficient and equitable distribution of vaccines and other healthcare supplies during pandemics.

1.6.1 Statement of the Problem

The COVID-19 pandemic exposed critical structural weaknesses in traditional healthcare supply chains, particularly in ensuring transparent, equitable, and demand-responsive vaccine distribution. Conventional centralized logistics systems suffer from limited real-time visibility, fragmented data silos, and manual coordination, resulting in delays, inefficient allocation, and inequitable access to vaccines, especially in resource-constrained regions. Existing digital solutions provide partial transparency but lack predictive intelligence and automated governance mechanisms necessary for proactive and equitable distribution. Therefore, there is a need for an integrated, decentralized, and predictive supply chain framework that leverages blockchain technology for secure and transparent transaction management and machine learning for accurate demand forecasting. This research addresses this gap through the design and implementation of the Predictive BlockVax Distribution Network (PBDN).

1.6.2 Research Gap

Although several studies have explored blockchain technology for improving transparency and traceability in healthcare supply chains, most existing systems focus primarily on data recording and lack predictive intelligence for proactive decision-making. Similarly, machine learning models have been applied independently for demand forecasting but operate within centralized infrastructures that do not ensure transparency, security, or trust among stakeholders. Existing solutions also fail to incorporate automated smart contract mechanisms for equitable allocation and lack integrated frameworks that combine predictive analytics with decentralized governance. Furthermore, limited research exists on simulation-based validation of hybrid blockchain - machine learning architectures specifically for pandemic vaccine distribution. This gap highlights the need for an integrated, predictive, and decentralized framework capable of ensuring transparency, fairness, and resilience in healthcare supply chains, which is addressed in this research through the proposed Predictive BlockVax Distribution Network (PBDN).

1.6.3 Purpose of the Study

The primary purpose of this study is to design and develop a predictive model, an innovative hybrid framework that integrates blockchain and machine learning (ML) technologies to address the inefficiencies and inequities in pandemic vaccine distribution. This research aims to create a transparent, secure, and data-driven system that can adapt dynamically to real-world challenges, ensuring vaccines are allocated and delivered efficiently to those who need them most.

1.6.4 Significance of the Study

The failure of global healthcare supply chain management in ensuring equitable and timely distribution of vaccines during COVID-19 pandemic revealed its vulnerabilities. The traditional healthcare supply chain systems were not fully equipped to handle the massive demand for healthcare supplies in general and vaccines in particular due to poor supply chain visibility, incorrect demand forecasting, administrative bottlenecks. There arose the need for a new system to handle effectively the scale, speed, and ethical complexities of global healthcare emergencies. This study makes an attempt to conceptualize and develop a alternative supply chain management system to address various challenges in managing production to distribution of healthcare supplies to the end users by applying two emerging technologies namely, ML and blockchain.

1.6.5 Scope of the Study

The COVID-19 pandemic was a testing time for the traditional healthcare supply chain systems. It brought into light the weaknesses inherent in the traditional system, especially with respect to equity and transparency in the distribution of vaccines. The collapse of the system called for an urgent need for novel solutions that will improve resilience, traceability and responsiveness in public health logistics. Application of rapidly growing technologies like Machine Learning (ML) and Blockchain (BC) Technology in managing healthcare supply chain will significantly improve its effectiveness. The biggest advantage of the blockchain technology is that it provides a decentralized, immutable and auditable infrastructure that ensures trust and accountability among concerned parties. ML on the other hand offers predictive power for forecasting the highly fluctuating demand across regions and resource allocation.

By combining the blockchain technology's secure and transparent architecture and ML's forecasting power, a hybrid framework has been conceived and developed in this research. This framework is intended to initiate a process which will ensure an equitable and data-driven allocation of vaccines. It will improve the supply chain visibility and reduce inordinate delays and lack of coordination among the stakeholders resulting from the manual allocation and distribution method. This study intends to demonstrate how the power of emerging technologies like ML and blockchain can be harnessed to bring about changes in healthcare logistics during pandemics and other health crises.

1.6.6 Research Objectives (RO)

The research objectives are to:

RO 1: Study and analyze existing blockchain-based supply chain systems for healthcare.

RO 2: Design a blockchain-based supply chain framework using machine learning.

RO 3: Implement this framework in a real-time environment.

RO 4: Compare the proposed model with existing models.

1.7 THESIS ORGANIZATION

Chapter 1: Introduction

This chapter lays the foundation for the study by articulating the research problem, explaining the rationale behind the investigation, and establishing the purpose, significance, and scope of the research. It outlines the central research questions and provides working definitions of key technical terms such as blockchain, smart contracts, machine learning, and supply chain equity. The chapter concludes by presenting the structure of the thesis, providing a roadmap for the reader.

Chapter 2: Literature Review

This chapter offers a critical review of relevant scholarly literature to frame the study within existing academic discourse. It explores the historical and contemporary challenges of healthcare logistics, particularly during pandemics, and investigates how digital technologies, namely blockchain and artificial intelligence, have been proposed or implemented to mitigate these challenges. Key gaps in the literature are identified, leading to the formulation of the study's conceptual model and theoretical underpinnings. The chapter concludes by highlighting the novelty and necessity of the predictive framework in addressing current limitations.

Chapter 3: Research Methodology

This chapter details the research design, including the methodological choices, data sources, system architecture, simulation setup, and model evaluation criteria. The development of the predictive framework is explained in detail, including the design of smart contracts, the integration of ML based demand forecasting, and the deployment of the blockchain platform. The rationale for using simulation-based evaluation and the various test scenarios is also discussed in this chapter.

Chapter 4: Experimental Results and Analysis

This chapter presents and analyses the experimental results of the developed predictive model, assessing its performance in terms of accuracy, precision, recall, and other key metrics. Using graphs, tables, and performance indicators, it validates the robustness, scalability, and reliability of the system. It details the model's implementation within a simulation-based environment and outlines the user interface developed to support its operation. Finally, the chapter compares the proposed predictive model with existing approaches, highlighting its advantages and improvements.

Chapter 5: Discussion

This chapter brings together the key discussions of the thesis, reflecting on how the developed predictive model addresses critical challenges in healthcare supply chains during pandemics. The findings demonstrate how blockchain ensures transparency and trust, smart contracts enable automation and efficiency, and machine learning enhances demand forecasting. The system's resilience and equity in vaccine distribution were key strengths. While the study acknowledges limitations such as simulation constraints and scalability considerations, it points to future research opportunities in blockchain interoperability, IoT integration, and real-world deployment. The chapter also offers practical recommendations for policymakers and stakeholders, emphasizing the importance of investing in digital infrastructure and collaborative frameworks

Chapter 6: Conclusion

This chapter concludes the thesis by synthesizing the key findings of the Predictive BlockVax Distribution Network (PBDN) research and reflecting on its theoretical, practical, and societal implications. It summarizes how blockchain and machine learning can be integrated to enhance transparency, predictive accuracy, and equity in pandemic vaccine distribution. The chapter also acknowledges study limitations, proposes directions for future research, and offers a forward-looking vision for real-world deployment of the framework.

1.8 SUMMARY

This chapter introduced the background and motivation for the study, highlighting the challenges of equitable vaccine distribution during pandemics and the potential of blockchain and machine learning as transformative solutions. The research objectives and problem statement were articulated, emphasizing the need for transparency, trust, and predictive allocation in healthcare supply chains. The chapter also outlined the significance and scope of the study, situating it within both academic and practical contexts. It also outlined the flow of the thesis chapters. The next chapter, Chapter 2 builds on this foundation by reviewing relevant literature on healthcare supply chains, blockchain applications, and machine learning approaches, thereby positioning the present research within the broader scholarly discourse.

Chapter 2

LITERATURE REVIEW

The exponential growth of research in blockchain technology, machine learning, and healthcare logistics has generated a wide spectrum of theoretical models, pilot implementations, and conceptual frameworks. However, the fragmented nature of these studies and the absence of an integrated, domain-specific approach to pandemic-driven healthcare supply chains necessitate a structured synthesis of prior work. This chapter presents a comprehensive literature review that critically examines the state-of-the-art in blockchain-enabled supply chain systems, machine learning-based demand forecasting, and their applications in vaccine distribution. By evaluating existing contributions across these domains, the review identifies persistent challenges such as lack of end-to-end transparency, limited automation, insufficient predictive accuracy, low resilience under crisis conditions, and inequitable resource allocation. The insights derived from this synthesis form the basis for articulating the research gaps and establishing the relevance of the proposed Predictive BlockVax Distribution Network (PBDN) framework.

2.1 SUPPLY CHAIN MOVEMENT AND TRANSPARENCY

Supply chain transparency has become crucial in contemporary supply chain management (SCM), particularly due to the advancement of worldwide manufacturing networks, rigorous compliance requirements, and heightened buyer concerns about supplier ethics and sustainability. The literature in this domain indicates a convergence of technologies, including blockchain technology, artificial intelligence (AI), machine learning (ML), and the Internet of Things (IoT), which are being investigated for their potential to enhance supply chain visibility, traceability, and operational efficiency. Several scholars have engaged with these technologies, seeking to redefine how supply chain data is recorded, validated, and communicated among stakeholders.

A significant focus within this domain has been on blockchain technology as a trust-enabler. Authors in [30] in their study on circular supply chains emphasized how blockchain systems can be designed to foster trust, traceability, and transparency. By ensuring immutable data records and decentralised data governance, blockchain systems can overcome traditional bottlenecks caused by data silos and asymmetries of information. The authors stressed that such qualities were particularly valuable in circular economy models, where the reverse flow of materials and the validation of sustainable practices required seamless multi-party coordination. Similarly, authors in [31] provided a systematic review of Distributed Ledger Technologies (DLTs) in supply chain security. They highlighted the vulnerabilities inherent in traditional SCM systems, such as counterfeiting, theft, and data tampering, and proposed DLTs meant to mitigate these risks while simultaneously optimized operational costs and throughput. Although their work is more theoretical in scope, it sets the stage for understanding how blockchain aligns with broader security and optimization agendas in SCM.

A parallel stream of research addresses the integration of blockchain with sector-specific supply chains, most notably in pharmaceuticals and healthcare. Authors in [32] offered a blockchain-enabled architecture tailored to the pharmaceutical industry, combining IoT and smart contracts to address the complex international movement of medical goods. They argued that blockchain can not only prevent the infiltration of counterfeit medicines but also facilitate regulatory compliance across borders. Authors in [33] extended this discussion to medical devices, proposing the use of non-fungible tokens (NFTs) for ownership verification and lifecycle traceability. Their approach embedded smart contracts into the product lifecycle, providing visibility from manufacturing to end-of-life disposal. These applications underlined the growing necessity for transparency in healthcare supply chains, which often involved mission-critical products with strict compliance requirements and limited tolerance for disruptions or ambiguity.

The food and agri-food sectors also provide fertile ground for blockchain application, as shown in several studies. The authors in [34] demonstrated how digital platforms can secure and streamline food supply chains using blockchain, IoT, and smart contracts. They showed that blockchain significantly improves the verification of food origin, storage conditions, and movement history, particularly where cold-chain compliance and perishable goods are concerned. The authors in [35] and [36] echoed these insights through specific applications to smart food chain management and agri-food traceability, respectively. Their work reflected growing awareness that digital provenance and data integrity are essential for food safety, especially in global supply chains that deal with high volumes and multiple regulatory environments.

The digitization of broader supply chain infrastructure is addressed by several scholars who argue that AI, IoT, and blockchain must work in tandem to achieve meaningful transformation. Authors in [37] provided a roadmap for digitalizing supply chain facilities and operations, framing digitization as a prerequisite for autonomous decision-making, resilience, and real-time visibility. Their approach focuses on how intelligent systems can monitor, respond to, and optimise supply chain flows dynamically. This has been reinforced by authors in [38], showcasing how digital optimization methods, including AI simulations and advanced forecasting, can be synchronized warehouse operations with broader logistics networks. These studies suggest a shift from technology as an add-on to technology as the operational backbone of modern supply chains.

Researchers have also examined blockchain's potential in non-traditional and emerging sectors, such as forestry, aquaculture, and the hospitality industry. Authors in [39] has shown that blockchain can improve traceability in wood supply chains by securely tracking the movement and certification of forest products. Their work is notable for its focus on the environmental and sustainability dimensions of SCM. Authors in [40] explored similar issues within aquaculture, where food safety concerns and traceability are vital due to rising consumer awareness. Authors in [41] addressed the problem of food waste in hospitality through blockchain and AI integration, linking consumption tracking with sustainability outcomes. These studies collectively broaden the applicability of blockchain beyond traditional manufacturing and distribution systems, emphasizing its potential as a general-purpose transparency technology.

Logistics and real-time communication are also central themes in contemporary blockchain literature. Authors in [42] evaluated a blockchain-based messaging system for air cargo supply chains, aimed at improving multistakeholder coordination and reducing administrative delays. Their performance analysis shows that blockchain can facilitate rapid, verifiable communication between cargo handlers, customs authorities, and airline operators. Authors in [43] presented a logistics optimization framework integrating blockchain, smart contracts, and neural networks. Their work focuses on improving operational efficiency and visibility, particularly in high-velocity logistics environments. These findings underscore the growing alignment between blockchain capabilities and the need for fast, traceable, and secure data exchanges in logistics-intensive industries.

An emerging area of research involves the convergence of blockchain with artificial intelligence and machine learning, particularly for predictive analytics, security, and decision support. Authors in [44] has introduced a hybrid security model for blockchain-enabled SCM systems, combining multimedia forensics and multi-party computation to secure data flows. They use Long Short-Term Memory (LSTM) networks to detect anomalies and data tampering, thus enhancing the resilience of decentralized systems. Authors in [45] proposed a decision framework to evaluate manufacturing plants' readiness for blockchain adoption, taking into account ambiguity levels and the ability to integrate AI-driven decision-making processes. The authors in [46] approached transparency from an economic perspective, focusing on how incomplete information affects competition in networked supply chains. These AI-infused frameworks reflect a growing trend to extend blockchain's transactional integrity with cognitive capabilities, thereby transforming static ledgers into dynamic intelligence systems.

In addition to the conceptual and sector-specific studies, researchers have paid increasing attention to optimization and simulation techniques in the context of blockchain-led supply chain transparency. The interplay between decentralized data systems and centralized planning tools has led to the development of novel hybrid models. For instance, blockchain-based smart contracts are increasingly being integrated with optimization algorithms to automate decision-making in areas such as procurement, routing, and warehousing. Simulation platforms have also been employed to test the scalability and efficiency of blockchain implementations, allowing researchers to model real-world scenarios without disrupting existing operations. This methodological evolution is pushing supply chain research from theoretical postulation to practical validation.

Taken together, the reviewed literature shows a maturing research field that views blockchain not as a standalone technology, but as an enabler of systemic transformation across the supply chain landscape. The adoption of blockchain, when combined with AI, IoT, and optimization frameworks, is not only enhancing transparency and traceability but also redefining traditional supply chain governance. The studies reviewed span multiple sectors, geographies, and technological configurations, offering valuable insights into how these innovations can be harnessed to build resilient, secure, and ethically sound supply chains. The following **Table 2.1** shows the literature review on SC movement and transparency with the key findings.

Table 2.1 Literature Review on SC Movement and Transparency

Reference	Study Description	Method/Algorithm Used	Key Findings
[31]	Distributed Ledger Technologies in supply chain security	AI, optimization	Bottlenecks lead to cost, quality infiltration, and productivity loss
[32]	Blockchain for pharma supply chain	Blockchain, AI, IoT, smart contract	Global pharma chains complex; need reliable systems
[34]	Blockchain in food supply chains	Blockchain, AI, IoT, smart contract	Enhances transparency in food logistics
[35]	IoT and blockchain in food logistics	Blockchain, AI, IoT, smart contract	Smart food chains impact customer experience

[36]	Blockchain in agri-food chains	Blockchain, AI	Traceability and food safety using BCT
[38]	Digital warehousing optimization	Blockchain, AI, simulation	Warehousing is being revolutionised by digitalization
[39]	Blockchain in wood logistics	Blockchain, AI	Tracks forest product origin securely
[40]	Blockchain in aquaculture	Blockchain, AI	Enhances food safety assurance
[41]	Blockchain for food waste in hospitality	Blockchain, AI	Improves food sustainability in hospitality
[42]	Blockchain in air cargo	Blockchain, AI, smart contract	Faster shipment via improved coordination
[43]	Blockchain for logistics optimisation	Blockchain, AI, neural networks	Boosts logistics via decentralised tracking
[44]	Blockchain security enhancement	Blockchain, ML, LSTM	Data tampering reduced via hybrid AI
[45]	Blockchain readiness in manufacturing	Blockchain, AI	Framework for adoption readiness
[46]	Incomplete info in supply competition	AI	Incomplete info harms supply chain coordination
[47]	Blockchain for circular supply chain	Blockchain, AI	Trust, traceability, transparency key in blockchain platform design
[48]	NFT-based medical device tracking	Blockchain, AI, smart contract	Healthcare networks complex; NFTs improve traceability
[49]	Supply chain digitization	Blockchain, AI, IoT	Digitisation improves resilience and efficiency

Although existing blockchain-based HSC studies demonstrate improvements in traceability, data security, and transaction transparency, most implementations focus primarily on record management rather than predictive decision-making. These systems lack integration with intelligent forecasting mechanisms capable of anticipating demand fluctuations during crises. Furthermore, scalability, automated allocation logic, and fairness-driven distribution strategies remain insufficiently addressed. These limitations highlight the need for integrating blockchain with predictive analytics to enable intelligent and adaptive healthcare supply chain management, which is addressed in this research through the proposed PBDN framework.

2.2 MEDICAL SUPPLY CHAIN DYNAMICS AND GLOBAL DISRUPTIONS DURING PANDEMICS

A comprehensive synthesis of scholarly contributions is presented, focusing on disruptions in medical supply chains during pandemics and examining how technologies such as artificial intelligence, machine learning, blockchain, and simulation tools have enhanced transparency, resilience, and predictability within these systems.

A significant body of research highlights the overarching theme of healthcare system resilience. Authors in [50] provided an integrative review demonstrating the growing attention toward resilience strategies in healthcare systems following the COVID-19 pandemic. Their findings underscore the role of artificial intelligence in supporting decision-making and improving system preparedness. Similarly, authors in [51] and [52] explored the contributions of additive manufacturing in addressing pandemic-induced shortages. These studies note that rapid additive manufacturing responses enabled healthcare providers to bypass disrupted supply channels and address urgent demands.

Authors in [53] introduced a multi-scale and ten-tier supply chain network model to analyse the stability of medical equipment supply chains in the face of random failures and cyberattacks. Their study, motivated by pandemic conditions, reinforces the importance of evaluating interdependencies within complex supply networks. Authors in [54] investigated how asymptomatic COVID-19 transmission influenced global supply chains, introducing a forecasting model that considers the unpredictability of virus spread and its consequences on decision-making and economic stability. Authors in [55] examined how sustainability practices influenced organisational performance, finding that firms with pre-existing emergency preparedness plans were better equipped to mitigate the impacts of the pandemic.

Authors in [56] introduceds the concept of jury-rigging, which describes how intertwined supply networks were reorganised during the pandemic to produce scarce medical supplies. Their work is supported by [57], who analysed how organisations struggled to align medical supply with surging epidemic-driven demand. Authors in [58] expanded this discussion through a case study of the automotive industry's temporary shift to manufacturing medical equipment. These works collectively highlight the importance of agility, repurposing capacity, and collaborative infrastructure in crisis contexts.

Authors in [59] investigated the use of knowledge graphs to trace pharmaceutical supply chain interdependencies and determine root causes of drug shortages. Their findings suggest that such AI-enhanced tools can strengthen supply network visibility and inform strategic responses. In a related study, [60] examined public-private collaboration in medical mask production and distribution, revealing that decentralised decision-making and cross-sector partnerships were instrumental in improving supply chain responsiveness. Authors in [61] also investigated hospital operations under a data-driven framework, demonstrating that digital resource orchestration improved responsiveness to unexpected healthcare demands.

Advanced decision support systems have also gained scholarly focus. Authors in [62] proposed a spatially-informed decision support system for optimising COVID-19 vaccine allocation. Their model integrates GIS, analytics, and demographic factors to prioritise high-need areas. Authors in [63] proposed predictive analytics to model healthcare operations under high uncertainty, such as fluctuating patient volumes and erratic admission patterns. Similarly, [64] designed a hybrid model for allocating COVID-19 testing kits based on mixed uncertainty, highlighting the potential of AI in dynamic logistics planning.

Technological advancements in supply chain infrastructure have also been explored extensively. Authors in [65] promoted an IoT-enabled model based on Fifth Industrial Revolution principles for medical device supply chains, focusing on resilience and flexibility. Authors in [66] incorporated IoT devices into pharmaceutical inventory systems, using real-time monitoring to optimise stock levels. Authors in [67] extended this work with a sustainable, energy-efficient relief supply chain platform based on the Internet of Medical Things, emphasizing decentralized control and smart decision-making.

Additive manufacturing emerged as a vital enabler of localized production during the pandemic. Authors in [68], [69], and [70] provided evidence that decentralized 3D printing networks significantly mitigated production disruptions and facilitated the rapid deployment of medical devices and PPE. Authors in [71] examined the integration of smart computer-aided design with 3D printing to meet urgent requirements for customized protective equipment. These efforts, along with the evaluation of open-source additive manufacturing solutions by [69], demonstrated the importance of decentralized and collaborative manufacturing during crisis periods.

Optimization modelling has featured prominently in studies related to pandemic logistics. Authors in [72] employed game theory to support equitable allocation of scarce medical resources. Authors in [73] introduced a fuzzy input-output model to simulate labour reallocation strategies, enhancing resilience under crisis conditions. Authors in [74] applied linear programming with fuzzy parameters to address PPE inventory routing challenges, while [75] presented a model integrating transportation decisions and environmental emissions. These models collectively contribute quantitative frameworks for balancing operational efficiency and social responsibility.

Authors in [76] developed an AI-based model for detecting counterfeit N95 masks, identifying risks in pandemic-era supply chains. Authors in [77] introduced a supply chain network model that incorporates labour as a critical component in pandemic response. Authors in [71] presented a model addressing home healthcare transportation logistics, incorporating facility location, fleet sizing, and routing for patients with prioritized care needs. Authors in [78] offered lean and hybrid optimization frameworks for improving the resilience of the Turkish medical supply chain, addressing risk and performance trade-offs.

The role of blockchain in healthcare supply chains during the pandemic has also been investigated. Authors in [79] designed a blockchain-enabled safeguard mechanism for relief supply chain planning, demonstrating its ability to enhance trust, traceability, and decentralised coordination. Authors in [66] integrated blockchain with IoT in pharmaceutical supply chains to improve compliance, recall capabilities, and data accuracy. These studies highlight blockchain's potential in managing sensitive and high-risk supply chain operations under pandemic stress.

Cross-sectoral insights provide additional lessons for healthcare supply chains. Authors in [80] analysed how fast fashion supply chains restructured to become more sustainable and adaptive post-COVID. Authors in [81] presented the rapid design and fabrication of powered air-purifying respirators (PAPRs), demonstrating the intersection of emergency engineering and public health. Authors in [82] introduced digital twin technology for real-time simulation and monitoring of healthcare supply chains, allowing for proactive disruption management.

Authors in [78] contributed a hybrid framework that integrates lean tools with optimisation-based decision models to strengthen the resilience of medical supply chains (MSCs). Their research, using a Turkish case study, demonstrates how economic and environmental sustainability can be preserved through operational adaptation strategies in times of crisis. Similarly, [77] and [66] advanced optimisation-driven models that account for resource constraints and labour shortages. These frameworks underscore the importance of labour as a strategic variable in maintaining functionality during pandemic-induced network disruptions, and propose resilient inventory control strategies within pharmaceutical supply chains.

Additive manufacturing has emerged as a prominent solution for addressing localised production gaps, particularly when global supply chains were paralysed. Authors in [68] and [70] highlighted how 3D printing facilitated on-demand production of medical equipment, masks, and ventilator parts during critical shortages. Their studies reflect the shift from centralised to decentralised manufacturing paradigms, wherein locally sourced production served as a buffer against global logistics delays. Authors in [71] and [69] further explored the integration of smart computer-aided design (CAD) systems with 3D printing during the pandemic. These technologies enabled faster design iterations and supported open-source innovations, ultimately increasing the responsiveness of health supply systems to emergency needs.

AI-driven optimisation approaches have also been instrumental in supporting pandemic-time logistics and resource allocation. Authors in [73] and [74] proposed fuzzy programming and input-output modelling frameworks for allocating scarce human and physical resources. Their work provides tools for decision-makers to navigate uncertainty while ensuring continuity of healthcare services and reducing system-wide vulnerabilities. Likewise, [75] conducted a sensitivity analysis to examine the impact of COVID-19 on transportation systems, linking disruptions in mobility to downstream inventory inefficiencies and elevated carbon emissions. These studies emphasise the role of intelligent modelling in helping organisations adapt to fluctuating conditions and systemic shocks.

The design of emergency healthcare infrastructure has also been a key focus, with [81] presented a rapid design and fabrication model for Powered Air-Purifying Respirators (PAPRs). Their project showcases how collaborative engineering and rapid prototyping can meet demand surges for personal protective equipment (PPE) in real time. Complementing this, [76] investigated the issue of counterfeit medical products, particularly N95 respirators, using AI-enabled disruption models. Their work outlines how counterfeit supply chains were facilitated through legitimate-seeming intermediaries, highlighting the need for intelligent surveillance and enforcement mechanisms.

In parallel, several researchers have addressed the complexities of network design and health inequity under pandemic conditions. Authors in [64] designed a supply network for COVID-19 testing kits using a mixed uncertainty approach. Their model captures both demand variability and logistical constraints, with an emphasis on minimising health disparities. Authors in [72] added a socio-technical dimension by applying game-theoretic models to the equitable allocation of scarce medical resources across geographies. These efforts represent critical attempts to embed ethical considerations and equity objectives into optimisation-based health logistics models.

Digital innovation has also extended into virtual modelling of the supply chain itself. Authors in [82] proposed the use of digital twins for visualising and managing supply chain resilience under pandemic stress. Their approach enables decision-makers to simulate disruptions and test alternative recovery strategies, effectively digitising risk management. This emphasis on proactive modelling is echoed in the work of [78], who addressed post-pandemic risk management through a hybrid resilience framework that anticipates the "ripple effect" of disruptions across interconnected nodes in the medical supply chains (MSCs).

Collectively, this body of literature presents a rich and varied response to the global breakdown of medical supply chains during COVID-19. From localised 3D printing to digital twin modelling and equity-driven optimisation, these studies illustrate how AI and data-driven methodologies have played a transformative role in managing disruption and restoring supply chain functionality. The consistent use of simulation, AI, and smart manufacturing across contexts highlights a growing convergence of technological innovation with crisis-responsive operations in medical logistics. Table 2.2 presents a summary of the literature review on medical SC disruptions.

Table 2.2 Literature Review Summary on Medical SC Disruptions

Reference	**Study Description**	**Method/ Algorithm Used**	**Key Findings**
[50]	SCP-Based Relief Supply Chain Designs with a Blockchain-Powered Safety Strategy for Extended Disasters	blockchain, AI	The COVID-19 pandemic has highlighted challenges in manufacturing and distributing essential medical relief supplies like personal protective equipment (PPE) and medical rescue equipment (MRE), such as sudden demand surges, supply chain disruptions, limited resources, and a lack of coordination.
[51]	Additive manufacturing and the COVID-19 challenges: An in-depth study	AI	International pandemic status was quickly attained by the severe acute respiratory syndrome coronavirus 2 (SARS-CoV-2).

[52]	An analysis of the global additive manufacturing response to the COVID-19 pandemic	AI	Goal Countries fought over urgently required (medical) goods due to the COVID-19 pandemic's worldwide supply interruptions and shortages.
[53]	Evaluation of medical apparatus ten-tier and multi-scale supply chain networks: intelligent threat and accidental breakdown	AI	This study examines the supply chain stability of medical devices, an industry whose supply chain was put to the ultimate test during the COVID-19 pandemic, and is driven by the outbreak of the pandemic.
[54]	Modelling asymptomatic COVID-19 instances to predict the effects of widespread epidemics on the supply chain of goods.	AI	Particularly when it turns into a pandemic, a widespread epidemic significantly affects supply chains (SCs) globally by lowering corporate credibility. Its unforeseen resurgence and spread potential might result in ineffective decision-making, which can then cause severe financial turmoil.
[55]	Pandemic planning, sustainability practices, and organizational performance:	AI	Disruption events like pandemic crises and natural disasters are unpredictable and therefore, most organizations are implementing an emergency plan to mitigate the unforeseen risks.

	An empirical investigation of global manufacturing firms		
[56]	Examining the resiliency of intertwined supply networks: a jury-rigging perspective	AI	The COVID-19 pandemic has highlighted the salience of different supply networks merging together to provide critical products in short supply.
[57]	Responding to epidemic-driven demand: the role of supply channels	AI	Matching the supply of medical equipment with soaring demand caused by an epidemic event is a daunting challenge.
[58]	Adaptation strategies for building supply chain viability: A case study analysis of the global automotive industry re-purposing during the COVID-19 pandemic		
[59]	Leveraging knowledge	AI	Supply chain issues pose a serious challenge to the pharmaceutical industry.

	graphs in pharmaceutical supply chains: insights into key drivers of drug shortages		
[60]	A public-private collaboration model of supply chain resilience to unpredictable disruptions: an exploratory empirical case study of medical mask production and distribution	AI	As the COVID-19 pandemic continued unabatedly, many global supply chains involved in manufacturing and distributing personal protective equipment often failed to meet surge demand due to production capacity limits.
[62]	A decision support system for prioritised COVID-19 two-dosage vaccination allocation and distribution	AI, simulation	This study proposes a decision support system (DSS) that integrates GIS, analytics, and simulation methods to help develop a priority-based distribution of COVID-19 vaccines in a large urban setting.
[63]	Healthcare Operations and Black Swan Event for COVID-19	machine learning, AI	COVID-19 pandemic has questioned the way healthcare operations take place globally as the healthcare professionals face an unprecedented task of controlling and treating the COVID-19 infected patients with a highly straining and

	Pandemic: A Predictive Analytics		draining facility due to the erratic admissions of infected patients.
[61]	Exploring the Effects of Data-Driven Hospital Operations on Operational Performance From the Resource Orchestration Theory Perspective	Not specified	In the big data era, managing data-driven hospital operations have become one of the most important tasks for healthcare executives, increasing responsiveness to exceptional disruptions such as those caused by the COVID-19 pandemic.
[67]	An IoMT platform for an integrated sustainable energy-efficient disaster relief supply chain to prevent severity-driven disruptions during pandemics	AI, optimization	Pandemics, such as the Influenza virus and the contemporary COVID-19, can lead to widespread disruptions in key segments, including the supply chain, beyond the capacity of communities or governments.
[68]	Additive Manufacturing for Localized Medical Parts	AI	Centralized supply chains (SCs) are prone to disruption, which makes them a risky choice for medical equipment production.

	Production: A Case Study		
	Re-shaping sustainable value chain model under post pandemic disruptions: A fast fashion supply chain analysis	AI	Reshaping a sustainable value chain model is proposed to address supply chain disruptions for the fast fashion industry.
[70]	An optimization-based methodology equipped with lean tools to strengthen medical supply chain resilience during a pandemic: A case study from Turkey	AI, optimization	Drawing upon economic and environmental sustainability, this study explores how developing the operational resilience of the medical supply chain (MSC) contributes to maintaining health-care in the face of disruption risks, such as the COVID-19 pandemic.
[70]	COVID-19: Current challenges regarding medical healthcare supplies and their implications on	AI	The covid-19 outbreak has caused a shortage of masks and other healthcare products for the general public around the globe.

	the global additive manufacturing industry		
[71]	The rise of 3D Printing entangled with smart computer aided design during COVID-19 era	AI	During the current Pandemic, seven and a half million flights worldwide were canceled which disrupted the supply chain of all types of goods such as, personal protective gears, medical health devices, raw materials, food, and other essential equipments.
	Optimization of supply chain networks with inclusion of labor: Applications to COVID-19 pandemic disruptions	AI, optimization	In this paper, we respond to the COVID-19 pandemic by constructing supply chain network optimization models, which explicitly include labor as an important variable in the network economic activity links, along with associated capacities.
	A resilient inventory management of pharmaceutical supply chains under demand disruption	AI, IoT, optimization	Inspired by the global supply chain disruptions caused by the COVID-19 pandemic, we study optimal procurement and inventory decisions for a pharmaceutical supply chain over a finite planning horizon.
	Linear programming with fuzzy parameters for inventory routing	AI	Coronavirus disease 2019 (COVID-19) brings about severe disruptions for human living, economics, and environmental balance.

	problem in effective management of personal protective equipment: a case study of corona virus disease 2019		
[72]	3D Printing in COVID-19: Productivity Estimation of the Most Promising Open Source Solutions in Emergency Situations	AI	The COVID-19 pandemic has caused a surge of demand for medical supplies and spare parts, which has put pressure on the manufacturing sector.
[72]	Game Theory-Based Decision Making for the Allocation of Scarce Medical Resources in the COVID-19 Situation	AI	COVID-19, being declared a pandemic, has affected human lives, economics, healthcare, and education in multiple geographic locations worldwide.
[75]	Inventory decisions on the transportation system and carbon		

	emissions under COVID-19 effects: A sensitivity analysis		
[76]	Modelling and disrupting counterfeit N95 respirator supply chains	AI, optimization	During the COVID-19 pandemic, millions of counterfeit respirators and fraudulent medical products infiltrated legitimate supply chains, often facilitated by registered businesses, third-party logistics providers, and companies in the technology sector.
[78]	A hybrid risk management framework for resilient medical supply chain design in the post-pandemic era	AI, optimization	The COVID-19 pandemic has exposed critical vulnerabilities in medical supply chains (MSCs), leading to severe and long-lasting disruptions characterized by the ripple effect.
[81]	De Novo Powered Air-Purifying Respirator Design and Fabrication for Pandemic Response	AI	The rapid spread of COVID-19 and disruption of normal supply chains has resulted in severe shortages of personal protective equipment (PPE), particularly devices with few suppliers such as powered air-purifying respirators (PAPRs).
[82]	Digital Twins on the Resilience of Supply Chain Under COVID-19 Pandemic	AI	The coronavirus disease 2019 (COVID-19) has put enormous pressure on the global supply chain.

[83]	Stochastic home care transportation with dynamically prioritized patients: An integrated facility location, fleet sizing, and routing approach	AI, simulation, optimization	We study a home health care (HHC) problem that is characterized by prioritized patients and uncertain demands.

Machine learning-based forecasting models, including ARMA, CNN, and LSTM, have demonstrated strong predictive capabilities in time-series demand estimation. However, these models typically operate within centralized infrastructures, lacking transparency, auditability, and decentralized governance mechanisms. The absence of immutable tracking and automated execution reduces trust, coordination, and accountability among supply chain stakeholders. This highlights the necessity of combining predictive machine learning models with blockchain infrastructure to enable transparent, trustworthy, and automated healthcare logistics systems, as proposed in the PBDN framework.

2.3 BLOCKCHAIN TECHNOLOGIES IN SUPPLY CHAIN MANAGEMENT

This sub-chapter examines recent literature focused on integrating blockchain technologies within supply chain management (SCM), highlighting their substantial potential in enhancing transparency, accountability, and predictive capabilities, particularly during periods of disruption.

Blockchain technology has gained significant scholarly attention due to its capacity to fundamentally transform supply chains, particularly regarding sustainability and traceability. Authors in [84] theoretically investigated how blockchain may revolutionise supply chain management through enhanced transparency and improved sustainability performance. Similarly, [85] emphasised blockchain's critical role in managing increasingly complex globalised supply chains, indicating how the decentralised and immutable characteristics of blockchain can streamline information flow and reduce systemic inefficiencies. Their research highlights the inherent advantages of blockchain, including traceability, verifiability, and auditability, which significantly strengthen supply chain sustainability and operational effectiveness.

Parallel to these theoretical frameworks, [86] empirically explored the determinants driving the adoption of blockchain within SCM, identifying behavioural intentions, perceived benefits, organisational readiness, and external pressures as influential factors. Their findings underline that successful blockchain adoption requires addressing both technological and behavioural barriers, suggesting a holistic approach to integrating blockchain into existing supply chain practices.

Addressing operational applications, [87] explored blockchain integration with digital twin technology for responsive management of working capital in supply chains subject to financial disruptions. Their integrated framework, enhanced by machine learning and AI-based simulations, allows for proactive responses to financial instability, such as extended trade credit periods and reduced down payments. This study underscores blockchain's potential to provide real-time visibility into financial flows, fostering more robust and responsive financial management practices in supply chains.

Building upon blockchain's technical potential, [88] discussed blockchain's capability for providing secure, transparent, and timely communication among supply chain stakeholders. They argue that blockchain significantly enhances transactional integrity and visibility, thereby reducing operational uncertainties and promoting better decision-making. Their analysis demonstrates that blockchain's integration with artificial intelligence further amplifies its capability by enabling predictive analytics, anomaly detection, and automated compliance monitoring.

In the context of the circular economy, [89] proposed a blockchain-enabled circular supply chain model tailored specifically for the fast-fashion industry. This model leverages blockchain to ensure transparency in materials tracking, enhance recycling processes, and maintain detailed provenance records of goods. By employing blockchain, companies can transition from traditional linear production methods towards sustainable, circular practices, facilitated by continuous data flow and verifiable records throughout product lifecycles.

Broadening the perspective, [90] conducted an extensive survey on blockchain applications across global SCM systems. Their findings demonstrate that blockchain effectively supports operations involving multiple interlinked stakeholders such as manufacturers, suppliers, transporters, and end consumers. Blockchain enhances operational predictability by ensuring secure data exchange, promoting coordinated decision-making, and enabling robust risk management capabilities. Their analysis stresses blockchain's ability to enhance the overall efficiency and agility of global supply chains.

Focusing specifically on risk management, [91] investigated how blockchain contributes to mitigating disruption risks in digitally transformed supply chains. They suggest that blockchain can effectively minimise risk exposure through decentralised data governance, increased transparency, and rapid traceability during disruptions. Their findings underscore blockchain's significance in enabling organisations to anticipate and respond rapidly to disruptions, thereby preserving supply chain continuity and operational stability.

Regarding performance evaluation, [92] proposed a comprehensive approach for assessing blockchain's effectiveness within SCM. They argue that blockchain's impact is multidimensional, influencing operational efficiency, transparency, responsiveness, and collaboration. Their systematic methodology provides a structured assessment framework, highlighting blockchain's capability to improve overall supply chain performance through enhanced data integrity, reduced transactional friction, and increased stakeholder trust.

The security dimension of blockchain within SCM was extensively explored by [93]. They emphasised that blockchain's cryptographic foundations provide substantial benefits in securing sensitive supply chain data, safeguarding transaction integrity, and mitigating cybersecurity threats. However, they also highlight the ongoing challenges related to the complexity of implementing blockchain securely, especially concerning interoperability among heterogeneous systems and platforms.

In the construction sector, blockchain's relevance is progressively recognised. Authors in [94] and [95] both examined blockchain implementation models in construction supply chains. They indicate blockchain significantly reduces trust-related issues, enhances coordination, and streamlines interactions among multiple stakeholders involved in complex construction projects. Qian and Papadonikolaki particularly highlight how blockchain reshapes traditional trust dynamics within construction, promoting greater transparency and accountability across contractual and operational interfaces.

Authors in [96] adopted a grounded-theory approach to better understand blockchain's role in SCM. Their work synthesises existing theoretical and practical knowledge, highlighting blockchain's capacity to simplify complex interactions within supply chains, ensure transaction transparency, and facilitate rapid compliance with regulatory requirements. They argue that blockchain fundamentally reshapes governance structures within supply chains, shifting traditional centralised models toward more distributed and collaborative paradigms.

In the domain of ecological sustainability, [97] explored blockchain's potential to transform governance practices within supply chains. They highlight blockchain's role in enforcing compliance with sustainability standards and regulations, aided by its transparent and immutable record-keeping features. By integrating blockchain with Internet of Things (IoT) and AI technologies, supply chains can systematically track sustainability metrics, verify environmental claims, and enhance ecological accountability.

Blockchain's role in addressing complex logistical challenges is well-documented in the maritime sector, an industry characterised by extensive service cycles, intricate organisational structures, and information heterogeneity. Authors in [98] thoroughly investigated blockchain implementations within maritime supply chains, providing insights into effective application scenarios and architectural considerations. Their research indicates that blockchain offers substantial potential to streamline cross-border trade logistics by reducing documentation delays, improving information synchronisation, and enhancing real-time traceability across dispersed stakeholders.

The automotive industry similarly benefits from blockchain-based solutions. Authors in [99] explored blockchain applications within Germany's automotive SCM, highlighting how blockchain enhances transparency in the automotive supply chain, particularly concerning part provenance, recall management, and supply chain responsiveness. Complementing this view, [100] specifically addressed blockchain's role in product recall management for the automotive industry, emphasising how blockchain's immutable record-keeping supports efficient identification and retrieval of defective products, significantly enhancing consumer safety and brand reliability.

Several studies further underline blockchain's general capabilities in managing supply chain information systems. Authors in [101] outlined blockchain's potential in creating decentralised, trustworthy data platforms capable of effectively managing complex SCM processes. Similarly, [102] articulated how blockchain fundamentally restructures SCM by offering decentralised data management, secure transactions, and improved stakeholder collaboration, thereby facilitating seamless operational transparency across all supply chain phases.

Security, a critical concern in SCM systems, was specifically addressed by [103]. They propose a secure blockchain-based framework explicitly designed to counteract information asymmetries within supply chains, enhancing overall security through rigorous access control, traceability, and distributed verification processes. Their work demonstrates blockchain's ability to mitigate critical vulnerabilities inherent in traditional supply chain data management practices.

The role of blockchain in supply chain finance, especially in streamlining transactions and securing sensitive financial operations, was investigated by [104]. Their study highlights blockchain's inherent capabilities of decentralisation, immutability, and enhanced security, making it suitable for improving efficiency and trustworthiness in trade financing operations. Blockchain, in this context, significantly reduces the risk of fraud and enhances real-time visibility for financial stakeholders, effectively supporting robust financial management practices in complex supply chains.

Blockchain's potential for building trust and reliability within manufacturing supply chains was examined by [105], who present an integrated framework combining blockchain with smart manufacturing paradigms. They propose that blockchain significantly advances trust management through verifiable digital records, thus enabling greater responsiveness and agility in production operations. Likewise, [106] suggested an intelligent blockchain-based scheme for managing manufacturing supply chains, integrating smart contracts and AI-driven analytics to facilitate real-time decision-making, predictive maintenance, and operational transparency.

In addressing critical societal disruptions, [107] proposed a blockchain-based approach for forward SCM and waste management, particularly for medical equipment and supplies during the COVID-19 pandemic. Their study illustrates blockchain's ability to provide comprehensive traceability from manufacturing to disposal, significantly reducing supply chain inefficiencies, promoting accountability, and ensuring the responsible handling of pandemic-related resources.

Authors in [100] extended blockchain traceability to fisheries SCM, demonstrating that blockchain smart contracts significantly enhance the management of perishable goods by ensuring real-time traceability, authenticity verification, and prompt responsiveness to contamination or safety concerns. Their findings underscore blockchain's transformative capacity for sectors heavily reliant on traceability and rapid responsiveness.

The efficiency of Vendor Managed Inventory (VMI) practices through blockchain integration was explored by [108], who utilise blockchain-enabled smart contracts to automate replenishment and monitor inventory status transparently. Their study reveals substantial operational improvements, including reduced stockouts, minimised delays, and enhanced stakeholder trust resulting from blockchain-driven visibility and automated transaction execution.

Risk management capabilities enabled by blockchain were highlighted by [109], who focus on endogenous risks arising from information asymmetry and incompleteness in large production enterprises. Their research demonstrates blockchain's effectiveness in enhancing transparency, providing reliable transaction documentation, and significantly mitigating operational and financial risks through decentralised verification mechanisms.

Authors in [110] explored blockchain's collaborative capabilities in job shop supply chains, demonstrating that blockchain facilitates secure and efficient transactions of production materials. Through smart contracts, blockchain allows automated verification and execution of supply contracts, improving operational responsiveness, enhancing trust among partners, and significantly streamlining collaboration processes within complex production networks.

Authors in [111] further explored blockchain's integration within broader Industry 4.0 contexts, specifically addressing smart contracts and IoT within SCM for the construction industry. Their findings highlight blockchain's versatility in coordinating various disruptive technologies, significantly enhancing project management, inventory control, and compliance monitoring within the complex, multi-stakeholder environments of construction projects.

Authors in [112] utilised blockchain and smart contracts within a serious gaming framework, providing an innovative educational model for teaching SCM concepts. Their research illustrates blockchain's pedagogical potential to practically demonstrate secure, transparent, and verifiable transactions within simulated supply chain environments, effectively preparing participants to manage real-world SCM challenges. The following **Table 2.3 shows** the literature review on blockchain technologies in SCM.

Table 2.3 Blockchain Technologies in SCM

Reference	**Study Description**	**Method/ Algorithm Used**	**Key Findings**
[84]	Evaluating adoption challenges theoretically for blockchain technology and the sustainable supply chain	blockchain, AI	Due to its capability to transform supply chain management and sustainability accomplishments, blockchain technology is gaining attention from every corner of the world
[85]	The links between blockchain technology and sustainable supply chain administration	blockchain, AI, smart contract	Globalisation of supply chains makes their management and control more difficult.

[86]	Unearthing the determinants of Blockchain adoption in supply chain management	blockchain, AI	This article investigates the behavioural intention for employing blockchain for supply chain management (BCSCM).
[87]	Supply chains encountering economic downturns can benefit from responsive working capital management through the incorporation of digital twins and blockchain.	blockchain, machine learning, AI, simulation	Effective working capital management in supply chains is severely restricted by financial obstacles like longer trade credit durations and lower down payments.
[88]	Blockchain capabilities for supply chain management	blockchain, AI	A new technology that has captured the attention of supply chain management (SCM) is blockchain.
[89]	Circular supply chain management powered by blockchain: a system structure for rapid fashion growth.	blockchain, AI	Businesses that are interested in making a shift from a linear make-use-dispose economic structure to a more sustainable circular economy have to implement circular supply chain management.
[90]	Blockchain Technology for Transnational Supply Chain Management: An Overview of Benefits, Obstacles, Possibilities, and Consequences.	blockchain, AI	In order to foresee, inspect, and govern operations and procedures, supply chain management relies on a multifaceted, interconnected network of manufacturers, distributors, suppliers,

			transportation firms, and consumers.
[91]	Risk oversight for supply chains in the period of technological evolution: the significance and constraints of blockchain technology.	blockchain, AI	Purpose: Organisations at all levels are struggling to establish and execute inventive approaches due to the increased likelihood of disturbance.
[92]	Blockchain performance in supply chain management: implementation in integrated blockchain enterprises.	blockchain, AI	The multidisciplinary and multi-objective character of blockchain technology necessitates a methodical approach to Purpose Performance evaluation throughout the supply chain.
[93]	Security and Privacy of Blockchain-Based Supply Chain Management Systems: Limitations and Opportunities	blockchain, AI, smart contract	Blockchain is a groundbreaking technology that is being used in several domains and applications, together with supply chain management.
[94]	Insights into Blockchain Implementation in Construction: Models for Supply Chain Management	blockchain, AI	More and more people in the construction industry are interested in using distributed ledger technologies (DLTs).
[95]	Shifting trust in construction supply chains through blockchain technology	blockchain, AI	Blockchain is becoming popular and is being used in many different industries.

[96]	Using a grounded theory approach, a study that looks at how blockchain can be used in supply chain management.	blockchain, AI	This study aims to bring together clear information about blockchain, explain what it really means, and highlight its features and effects.
[97]	Significance of blockchain-based governance for environmentally friendly supply chain management	blockchain, AI, IoT	The purpose of this study is to explore how the new technology, blockchain, affects different management systems and sustainable supply chain practices, and how these areas are connected.
[98]	Blockchain technology in maritime supply chains: applications, architecture and challenges	blockchain, AI	The maritime supply chain plays a key role in international trade, but often faces challenges such as long processes, complex systems, and inconsistent information from many different sources.
[99]	Blockchain applications in the supply chain management in German automotive industry	blockchain, AI	The automotive industry is a promising area for using blockchain technology.
[100]	Blockchain-Based Traceability for the Fishery Supply Chain	blockchain, AI, smart contract	In the fishery supply chain, it is important to have an efficient system to track and manage products.
[101]	Blockchain-Based Information Management for	blockchain, AI	The Highlighted App The supply chain management procedures that power

	Supply Chain Data-Platforms		blockchain technology have been determined by the study's insights.
[102]	The power of a blockchain-based supply chain	blockchain, AI	A supply chain is the system that connects suppliers and customers by involving people, businesses, tasks, and resources to deliver a product or service.
[103]	Designing a Secure Blockchain-Based Supply Chain Management Framework	blockchain, AI	Supply chain management (SCM) has serious security challenges because different parties often get unequal information and insufficient oversight to manage it.
[104]	Supply Chain Finance Innovation Using Blockchain	blockchain, AI	Decentralisation, reliability, safety, confidentiality, and non-tampering are features of blockchain technology, that power digital currencies like Bitcoin.
[105]	A combined system using blockchain can help build trust in supply chains and support smarter, more reliable manufacturing.	blockchain, AI	As new information technologies grow, modern manufacturing demands better and more advanced supply chain systems.
[106]	A scheme for intelligent blockchain-based manufacturing industry supply chain management	blockchain, AI, smart contract	Managing supply chains is a key part of building smart cities. With the rapid growth of AI, the Internet of Things, big data, and mobile communication, more

			opportunities exist to improve and expand.
[107]	A Blockchain-Powered Strategy to Automotive Supply Chain Product Recall Management	blockchain, AI, smart contract	In the automotive sector, handling recalls of products is an intricate problem that has a direct effect on both human lives and the safe operation of automobiles.
[108]	Enhancing Vendor Managed Inventory Supply Chain Operations Using Blockchain Smart Contracts	blockchain, AI, smart contract	Because of globalisation, supply chains have become larger and more complicated. This creates many challenges and opens up new chances to improve them.
[109]	Big Production Enterprise Supply Chain Endogenous Risk Management Based on Blockchain	blockchain, AI	Since a lack of complete and balanced information can hurt how well supply chains work, we focus on large manufacturing companies and explore how blockchain can manage their internal risks. This helps us study how it actually works in practice and the results it can bring.
[110]	BLOCKCHAIN-BASED COLLABORATIVE MANAGEMENT OF JOB SHOP SUPPLY CHAIN	blockchain, AI, smart contract, simulation	Blockchain enables trustworthy and unrestricted production material supply chain (PMSC) transactions.
[111]	Smart Contracts and Supply Chain Management Using Blockchain	blockchain, AI, IoT, smart contract	We have only begun to investigate the scope, implications, and potential applications of the Fourth Industrial Revolution in the construction industry, which is affecting every sector of the

			industry with a plethora of disruptive technology techniques like artificial intelligence, blockchain, virtual and augmented reality, the Internet of Things (IoT), robotics, and 3D printing.
[112]	Management of the Supply Chain Using Blockchain Smart Contracts in a Serious Game	blockchain, AI, smart contract	Smart contracts as well as Blockchain are vital for supply chain management interactions.
[113]	Blockchain-Powered COVID-19 Medical Equipment and Supply Forward Supply Chain and Waste Management	blockchain, AI, smart contract	The requirement for COVID-19 medical supplies and equipment has grown to previously unheard-of proportions in 2020.

Blockchain-based vaccine distribution frameworks have shown significant potential in improving traceability, preventing data tampering, and enhancing transparency. However, most systems rely on static allocation models and lack predictive intelligence to dynamically adjust distribution based on evolving demand conditions. Additionally, few systems incorporate fairness metrics or automated allocation logic to ensure equitable distribution across vulnerable populations. These limitations emphasize the need for an integrated predictive blockchain architecture capable of enabling intelligent, fair, and automated vaccine allocation, which is achieved in this research through the PBDN model.

2.4 BLOCKCHAIN APPLICATIONS IN HEALTHCARE SUPPLY CHAINS

This section provides a comprehensive literature review focused on blockchain applications specifically within healthcare supply chains (HCSCs). It critically examines technological innovations, synthesises key findings from existing studies, and identifies research gaps that underpin future development efforts aimed at enhancing resilience, transparency, and efficiency in healthcare logistics.

Blockchain technology has increasingly gained scholarly interest due to its transformative potential in healthcare supply chain operations. Authors in [114] underscored the unique characteristics of blockchain, including its decentralised structure, distributed ledger technology, consensus mechanisms, smart contracts, and asymmetric encryption. These features collectively facilitate transparency, security, and operational visibility, which are essential attributes for managing complex healthcare logistics networks.

In parallel, [84] explored blockchain's theoretical implications for sustainable supply chain management, positioning blockchain as a crucial driver of sustainability achievements within healthcare systems. Their analysis highlights the potential for blockchain to fundamentally transform traditional healthcare logistics through improved transparency and verifiable sustainability outcomes, particularly when combined with artificial intelligence (AI).

Further elaborating on blockchain's application in optimising healthcare logistics, [115] investigated blockchain's role in enhancing resilience and flexibility within legible supply chains. Their findings highlight blockchain's capability to improve both lean efficiency and agile responsiveness, demonstrating how blockchain, combined with AI-based optimisation models, significantly strengthens supply chain resilience against disruptions, including those caused by pandemics or other unexpected crises.

Addressing specific healthcare supply chain scenarios, [116] focused explicitly on vaccine supply chains within the Indian context. Their research details the unique challenges inherent in bio-pharmaceutical cold chains, such as stringent temperature controls and distribution complexities and identifies blockchain integrated with the Internet of Things (IoT) and AI as an effective solution. Blockchain's immutable data records and IoT-based sensor data integration ensures comprehensive monitoring and robust management of vaccine distribution, thereby directly enhancing public health outcomes.

Authors in [117] advocated digitalisation of healthcare supply chains, arguing that blockchain-driven digitisation can lead to significant reductions in waste and carbon footprints. By utilising blockchain in combination with AI-driven resource allocation models, healthcare providers can achieve greater sustainability, resource utilisation efficiency, and reduced environmental impact.

Expanding the methodological perspective, [118] examined knowledge diffusion pathways within blockchain research, particularly emphasising its rapid growth in healthcare-related applications. Their analysis reveals the expanding scholarly interest and practical deployment of blockchain in HCSCs, reinforcing the technology's foundational importance in contemporary supply chain innovation.

Evaluative frameworks for blockchain implementation have also emerged as vital research areas. Authors in [119] proposed an interval-valued Pythagorean fuzzy entropy-based decision support system for assessing blockchain-based healthcare supply chain networks. This decision support approach integrates AI-driven analytics, providing a comprehensive tool for evaluating blockchain's effectiveness in maintaining healthcare system operations, particularly during periods of heightened uncertainty.

Addressing the complexities introduced by the COVID-19 pandemic, [120] presented blockchain's applicability in managing multi-tier supply chains for personal protective equipment (PPE). Their work highlights how blockchain, combined with AI, can enforce compliance with sustainability standards, enhance transparency across supply tiers, and facilitate real-time tracking, thus significantly improving response capabilities during emergency demand surges.

In a related study, [121] identified and analysed critical barriers to blockchain-enabled healthcare supply chain management. Utilising improved zero-sum hesitant fuzzy game theory, they illustrate how blockchain's transparency, efficiency, and security enhance healthcare logistics while recognising areas that require further technological development and integration.

Similarly, [122] undertaken a systematic examination of blockchain integration in electronic health record management and medical supply tracking. Their findings underline blockchain's potential for significantly enhancing security and traceability in healthcare logistics, particularly when augmented by AI, creating robust, secure frameworks essential for sensitive data management.

Authors in [123] proposed a blockchain-based smart contract system tailored explicitly for healthcare management. This system ensures secure data sharing across various healthcare stakeholders, with blockchain's transparent, tamper-proof data structure and smart contracts facilitating automated compliance and verification processes, thereby enhancing both operational security and efficiency.

Exploring implementation challenges, [124] highlighted the difficulties inherent in real-world blockchain deployment within HCSCs. Despite blockchain's clear advantages—decentralisation, enhanced security, and transparency—the authors stress the critical need to resolve interoperability challenges and scalability constraints for widespread adoption in healthcare environments.

Addressing pharmaceutical logistics specifically, [125] proposed a blockchain and machine-learning-based framework to combat drug counterfeiting, a persistent issue plaguing pharmaceutical supply chains. Their combined approach enhances product authenticity tracking, improves recommendation systems for product management, and significantly reduces counterfeit infiltration risks, ultimately safeguarding patient safety.

Authors in [126] extended blockchain's role through decision-support systems designed to manage healthcare supply chain demands during epidemic outbreaks. They highlight blockchain's capability for long-term disruption management, using predictive analytics to effectively address the unique propagation patterns of pandemics, thus improving strategic responsiveness and supply chain resilience.

Focusing on pharmaceutical integrity within hospitals, [127] introduced a novel medical blockchain model incorporating AI-driven smart contracts to manage drug supply chain integrity within hospital settings. Their model effectively combats drug counterfeiting, enhancing patient safety and operational transparency in pharmacological practices.

Authors in [128] further explored blockchain's innovative use in healthcare by integrating non-fungible tokens (NFTs) for product management and certification within the healthcare supply chain. Their research illustrates how blockchain-based NFTs enable secure digital certification, traceability, and reliable trading mechanisms, thus alleviating healthcare product shortages exacerbated during crises like the COVID-19 pandemic.

In a complementary approach, [129] proposed an IoT-integrated blockchain solution for comprehensive medical logistics tracking. Their system provides end-to-end visibility and traceability, significantly enhancing logistical management through real-time data integration and automated compliance checks, greatly strengthening supply chain operations.

Authors in [130] explored blockchain's critical role in managing electronic medical records within smart healthcare infrastructure. Their framework ensures robust security, enhanced data integrity, and seamless data exchange across healthcare providers, thereby significantly improving operational continuity and information reliability.

Addressing advanced security requirements, [131] introduced a novel secure blockchain framework leveraging cryptographic methods such as Keccak-256 and zero-knowledge proofs (ZKP) to ensure drug safety assurance within healthcare supply chains. This framework ensures high-level security and transparency, critical for pharmaceutical logistics integrity.

Authors in [132] further integrated IoT with blockchain to address healthcare supply chain management and protect medical records. Their IoT-driven blockchain solution tackles customer dissatisfaction, rising healthcare costs, and privacy concerns, promoting comprehensive operational security and real-time management of medical products.

Authors in [133] presented an innovative blockchain-based recommender system using BERT deep-learning models to enhance drug supply chain cybersecurity. Their approach significantly improves the robustness of pharmaceutical logistics against cyber-physical threats, ensuring secure and reliable drug distribution during pandemics.

Expanding blockchain's applicability further, [134] proposed an IoT and blockchain-based secure supply chain framework optimised for smart cities, using an optimal queue model to manage healthcare logistics effectively. This solution enhances real-time operational visibility and transparency, supporting rapid responsiveness to dynamic urban healthcare demands.

Lastly, [135] contributed substantially to automating healthcare procurement processes using blockchain smart contracts. Their studies demonstrate significant improvements in operational efficiency, inventory management, and supplier trust, especially during emergency procurement scenarios highlighted during the COVID-19 pandemic. The following **Table 2.4** shows the literature review on blockchain applications in HSCs with major key findings.

Table 2.4 Literature Review on Blockchain Applications in HSCs

Reference	**Study Description**	**Method/ Algorithm Used**	**Key Findings**
[114]	Blockchain technology in supply chain operations: Applications, challenges and research opportunities	blockchain, AI, smart contract	With its decentralised structure, distributed notes and storage mechanism, consensus algorithm, smart contracts, and asymmetric encryption, blockchain technology delivers a distinctive set of capabilities that guarantee network security, transparency, and visibility.
[115]	Blockchain in resilient and leagile supply chains: research themes and opportunities	blockchain, AI, optimization	Supply chain design and optimisation is one of the most explored subjects because of its significance.
[116]	Investigating and assessing the obstacles to implementation in the Indian context of blockchain technology and the vaccination supply chain.	blockchain, AI, IoT	Because it directly impacts public health, the vaccine distribution system, a biopharmaceutical cold chain, is a sensitive yet intricate system which requires to be adequately looked after and managed.
[117]	Digitalization to achieve greener	AI	The healthcare industry's drive for a digital shift holds forth the promise of eliminating waste, optimising the

	healthcare supply chain		utilisation of resources, and dramatically lowering the carbon footprint of healthcare operations.
[118]	Knowledge diffusion paths of blockchain domain: the main path analysis	blockchain, AI, IoT	As a disruptive technology, blockchain has gathered a lot of attention from across the globe in the past several years, which has allowed research outputs to rise quickly.
[119]	Evaluating the blockchain-based healthcare supply chain using interval-valued Pythagorean fuzzy entropy-based decision support system	blockchain, AI	In the current era, blockchain technology has emerged as a novel technique to maintain the operations of healthcare management systems.
[120]	Implementing blockchain technology in the PPE multi-tier supply chain to guarantee adherence to sustainability criteria	blockchain, AI	Personal protective equipment (PPE), along with other healthcare products, is in considerable demand due to the COVID-19 pandemic, which has made multi-tier supply chain management highly challenging.
[121]	Blockchain-enabled healthcare supply chain management: Applying	blockchain, AI	Blockchain technology has become a revolutionary tool in the healthcare industry, strengthening Healthcare Supply Chain Management's (HSCM) privacy, effectiveness, and traceability.

	enhanced zero-sum hesitant fuzzy game theory to uncover and evaluate obstacles and potential solutions		
[122]	A systematic study on integrating blockchain in healthcare for electronic health record management and tracking medical supplies	blockchain, AI	Security is still the foremost concern in this day and age of ever-changing technology.
[123]	A Blockchain-Based Smart Contract System for Healthcare Management	blockchain, AI, smart contract	In application fields like finance, supply chain management, nutrition, energy, the global internet of things, and healthcare, blockchain is evolving into a safe and dependable platform for safe data exchange.
[124]	Analysing the obstacles and challenges of implementing blockchain in the healthcare supply chain (HCSC)	blockchain, AI	Supply chains can exchange and disseminate data in confidential, decentralised settings due to blockchain technology, which utilises validators to confirm and trust transactions.

[125]	A Drug Supply Chain Management and Suggestion System for the Smart Pharmaceutical Industry Employing Blockchain and Machine Learning	blockchain, machine learning, AI	Pharmaceutical businesses have had issues tracking their products throughout the supply chain process for the previous ten years, which has made it feasible for counterfeiters to successfully bring their phoney medications to the market.
[126]	A case study of coronavirus disease 2019 (COVID-19) as a strategic assistance system for demand management in healthcare supply chains in light of sudden epidemics	AI	Epidemic outbreak-related catastrophes distinguish themselves from other types of catastrophes in two ways: they create long-lasting damage and spread more quickly.
[127]	A New Medical Blockchain Model for Managing the Accuracy and Integrity of the Drug Supply Chain in a Smart Hospital	blockchain, AI, smart contract	One of the foremost concerns facing pharmacology nowadays is the wide availability of fake medications.

[128]	Applying NFTs in the Healthcare Supply Chain for Digital Certification, Product Management, Trading, and Delivery	blockchain, AI, smart contract	The COVID-19 pandemic caused disruption in the healthcare market, which resulted in shortages of essential healthcare products.
[129]	Medical supply chain integrated with blockchain and IoT to track the logistics of medical products	blockchain, AI, IoT	Nowadays blockchain technology plays a vital role in creative developments and important discoveries in the world.
[130]	A blockchain-based system for managing electronic medical records in intelligent medical facilities.	blockchain, AI	Electronic medical records are recognised as the primary element of the system employed by health organisations.
[131]	An innovative and secure supply chain for sophisticated medical devices: a technique to use blockchain, Keccak-256, and ZKP to ensure medication safety	blockchain, AI, smart contract, simulation	In company operations, supply chain management (SCM) is a complicated and intricate procedure that makes the process simpler to move items and supplies across different geographic locations.

[132]	Blockchain powered by IoT to safeguard medical data and regulate the healthcare supply chain	blockchain, AI, IoT	Customer discontent, growing expenses for healthcare, drug monitoring and accountability, and security and privacy issues pertaining to the sensitive data handled in these domains are among the many novel requirements that the healthcare supply chain and medical records management face.
[133]	Secure blockchain-based cyber-physical healthcare management of supply chains employing a BERT-based recommender system	blockchain, machine learning, AI	One of the domains related to healthcare that can be negatively affected by global epidemics is drug supply chain management (DSCM).
[134]	A Secure and Transparent Supply Chain Management Framework in Smart Cities Employing the Optimal Queue Model Based on IoT and Blockchain	blockchain, AI, IoT	Supply Chain Management (SCM) is the procedure for overseeing the flow of products and services from a business by including each phase associated with turning components and raw materials into completed products and delivering them to their final user.
[135]	Supply Chain Traceability for COVID-19	blockchain, AI, smart contract	The healthcare industry has been particularly hard hit by the COVID-19 pandemic, which has shown

	Personal Protective Equipment via Blockchain		fundamental deficiencies in supply chain management, mitigation of risks, and disaster preparedness.
[136]	Optimisation of Deep Learning-Based Drug Supply Chain Management for Pharmaceutical Industries through the Application of Blockchain	blockchain, deep learning, AI	The pharmaceutical supply chain is intricate and comprises many stakeholders, which creates multiple barriers that businesses have to tackle to successfully offer vital pharmaceuticals to patients.
[137]	Automating Procurement Contracts in the Healthcare Supply Chain Using Blockchain Smart Contracts	blockchain, AI, smart contract	Healthcare providers have to supervise the healthcare supply chain (HCSC) procedure well, both in their regular business operations and during emergencies like COVID-19.

Although some studies have explored the integration of blockchain and machine learning technologies, most implementations remain conceptual or limited to isolated components without full architectural integration and validation. Furthermore, existing hybrid systems rarely incorporate fairness-driven allocation metrics, smart contract automation, or stress-tested evaluation under pandemic-like conditions. These gaps highlight the absence of a fully integrated, simulation-validated BC-ML framework designed specifically for pandemic healthcare logistics, which this research addresses through the Predictive BlockVax Distribution Network (PBDN).

2.5 INTEGRATION OF BLOCKCHAIN AND MACHINE LEARNING IN SUPPLY CHAIN MANAGEMENT

This section consolidates recent scholarly contributions at the intersection of blockchain technology, machine learning (ML), and supply chain management (SCM). It critically examines how these emerging technologies jointly enhance visibility, resilience, predictive analytics, and intelligent decision-making in diverse supply chain environments.

Blockchain and machine learning have emerged as pivotal technologies within supply chains due to their combined ability to enhance transparency, improve security, and streamline operational decision-making. Authors in [138] highlighted this synergy within sustainable agri-food supply chains, underlining blockchain's role in traceability and provenance verification, complemented by ML-driven analytics for demand forecasting and quality control. They emphasize the need for further technological integration to fully leverage the potential benefits of blockchain and ML in agricultural settings, especially in managing sustainability outcomes and achieving operational efficiencies.

In pharmaceutical logistics, [125] proposed a blockchain and ML-based recommendation system designed to counteract drug counterfeiting, a persistent challenge exacerbated by limited product traceability. Their research demonstrates blockchain's robustness in providing verifiable data records throughout the pharmaceutical supply chain, while ML algorithms facilitate real-time anomaly detection and proactive decision-making, effectively reducing the infiltration of counterfeit medicines.

Supply chain security has become increasingly significant, particularly given rising global connectivity and trade complexities. Authors in [139] conducted an extensive survey that evaluates supply chain security threats and possible solutions integrating blockchain, ML, and the Internet of Things (IoT). Their findings confirm that blockchain's immutability and decentralised structure, combined with ML's predictive capabilities, offer a powerful toolkit for anticipating and mitigating cybersecurity threats and operational disruptions within complex global supply chains.

Advancing this perspective, [140] introduced a robust mechanism integrating blockchain, Long Short-Term Memory (LSTM), and Analytic Hierarchy Process (AHP) methodologies for evaluating sustainable production capabilities in supply chain networks. Their approach demonstrates how ML-driven predictive analytics, underpinned by blockchain-secured data integrity, significantly improve decision-making accuracy and resilience to disruptions.

Similarly, [141] further investigated blockchain and ML integration across distinct industry sectors. In smart manufacturing environments, they demonstrate how blockchain's transparency and ML-driven predictive analytics jointly enhance equipment reliability and multistage quality control processes. Moreover, they apply blockchain and ML combined with fuzzy logic to improve traceability systems for perishable foods, effectively extending product shelf-life and ensuring consumer safety through precise monitoring of supply chain conditions.

In the automotive sector, [142] explored the application of blockchain and smart contracts within autonomous vehicle supply chains, combined with ML for performance optimisation. Their research underscores blockchain's potential in automating contractual agreements and facilitating secure transactions, with ML providing insights that optimise inventory control, forecasting accuracy, and supply chain responsiveness amid digital transformations in the automotive industry.

Blockchain's real-time capabilities in supply chain risk management are highlighted by [143], who proposed a blockchain-based system enhanced by real-time event monitoring and AI-driven risk prediction algorithms. This approach provides pre-emptive risk mitigation, significantly reducing vulnerabilities from daily operational disturbances and improving overall resilience within supply chains.

Furthering these capabilities, [144] and [145] demonstrated the transformative potential of integrating blockchain, machine learning, and the next-generation 6G IoT in supply chain tracking and management. Their studies illustrate how blockchain's immutable data ledgers, supported by ML's predictive and analytical capabilities, considerably improve real-time tracking, operational efficiency, and responsiveness across supply chain activities.

Addressing financial risk management, [146] applied ML methodologies combined with fuzzy decision models to assess financial risks within supply chains. Their findings suggest that ML-driven financial analytics can greatly enhance the accuracy and responsiveness of supply chain financial risk management, highlighting the critical importance of sophisticated predictive techniques for ensuring supply chain financial resilience.

Authors in [133] proposed a sophisticated blockchain-based recommender system utilising Bidirectional Encoder Representations from Transformers (BERT) models for securing pharmaceutical supply chains, particularly against cyber threats. This innovative integration significantly improves the cybersecurity resilience and responsiveness of drug supply chains, particularly during pandemics, thereby safeguarding pharmaceutical integrity and patient safety.

Exploring deep learning applications, [147] developed an efficient evolutionary deep learning approach for predicting and mitigating cyber-attacks in supply chain management systems. Their research highlights the role of blockchain in safeguarding data integrity, while deep learning algorithms effectively predict and prevent cybersecurity threats, thereby ensuring uninterrupted and secure supply chain operations.

In agriculture, [148] examined the combined use of blockchain and IoT technologies with ML for demand forecasting within farm supply chains. Their integrated approach significantly enhances prediction accuracy, enabling better resource allocation and operational planning, directly contributing to improved agricultural productivity and sustainability.

Authors in [149] synthesized existing literature on simulation techniques, blockchain, and ML, offering a comprehensive classification framework (Sim-ML). They reveal how discrete-event and agent-based simulations, augmented by ML and blockchain, effectively model and manage uncertainties within supply chain operations, thereby significantly improving strategic decision-making and operational robustness.

Leveraging blockchain-enabled off-chain ML approaches, [150] addressed greenhouse gas (GHG) emission traceability within groundnut supply chains. Their model emphasises blockchain's potential to verify emissions data securely, while ML analytics provide actionable insights into sustainability performance, thus directly aligning operational practices with global sustainability goals.

Authors in [151] proposed a structured framework for identifying and addressing barriers to blockchain adoption in sustainable supply chains, highlighting the essential role of ML analytics in systematically overcoming these challenges. Their three-phase approach helps organisations strategically integrate blockchain to achieve long-term sustainability objectives, improve compliance, and enhance transparency across supply chain tiers.

Furthermore, [87]integrated blockchain with digital twin technology and ML for responsive working capital management, particularly during financial disruptions. Their research provides robust, real-time insights into liquidity management and financial risk mitigation, demonstrating blockchain's pivotal role in enhancing visibility and responsiveness within financially vulnerable supply chain networks.

Authors in [152] extended these concepts to consumer electronics, combining blockchain and digital twins to improve security and operational efficiency within metaverse-driven consumer supply chains. Their model effectively addresses the rising complexity and innovation-driven challenges faced by contemporary consumer electronics logistics networks, demonstrating the combined strengths of blockchain's transparency and digital twins' predictive capabilities.

Authors in [44] proposed a hybrid blockchain security model leveraging ML-based multimedia forensics and multi-party computation for safeguarding supply chain data against tampering. Their findings indicate significant advancements in data integrity and operational trustworthiness, particularly relevant amid growing concerns over cybersecurity threats and data privacy within complex global supply chains.

Authors in [153] utilised machine learning, specifically the support vector machine algorithm, to evaluate how supply chain collaboration factors, including trust and information-sharing, can enhance the predictive accuracy of blockchain adoption in firms. Their findings emphasise that integration of supply chain-specific variables significantly improves predictive models, suggesting that technological, organisational, and environmental frameworks alone are inadequate without considering inter-firm collaboration. Complementing these results, [154] systematically surveyed blockchain integration with machine learning across multiple sectors, highlighting improved security, transparency, and data-driven decisions as the primary benefits. Despite acknowledging substantial potential, their study also identifies ongoing challenges, such as strategic integration, information processing efficiency, and scalability constraints, which remain barriers to widespread adoption.

In pharmaceutical supply chains, [155] constructed a blockchain-enabled pharmaceutical supply chain cost model evaluated through evolutionary computation-tuned supervised learning methods, including k-nearest neighbour, decision trees, and naïve Bayes. Their results indicate superior predictive performance with ant colony and firefly algorithms integrated with naïve Bayes, emphasising the critical cost factors such as shortages, inventory holding, and expired medications. These insights align with the study by Abbas et al. (2020), who developed a blockchain and machine learning framework aimed at preventing counterfeit medicines. They underscore blockchain's capacity to track authentic drugs through enhanced visibility, combined with machine learning's predictive capabilities, to secure pharmaceutical products effectively.

Authors in [151] proposed a robust three-phase analytical framework integrating machine learning classification algorithms, feature selection, and Grey-DEMATEL methods to map barriers affecting blockchain implementation in sustainable supply chains. Their empirical analysis identified key barriers such as financial constraints, technological immaturity, and security issues, underlining the critical need for focused organisational strategies to facilitate successful blockchain adoption. Similarly, [146] utilised machine learning combined with fuzzy decision models to assess financial risks in supply chain finance, demonstrating the model's robust capability to manage uncertainty in complex financial environments.

In agricultural contexts, [156] integrated blockchain technology with machine learning to enhance data security and efficiency in agricultural supply chain finance, demonstrating significantly improved security via decentralised ledgers and consensus-based validation. [157] further extended blockchain's agricultural application, developing a circular blockchain framework integrated with deep learning models, particularly LSTM, to accurately predict Bitcoin prices. This approach provided real-time economic benefits to farmers and stakeholders, streamlining financial transactions through transparent blockchain-driven contracts.

Advancing towards industrial settings, [158] combined blockchain with IoT and machine learning to improve multistage quality control in smart manufacturing environments. Their innovative approach enhanced predictive maintenance and real-time anomaly detection, resulting in significant operational efficiency improvements. [159] empirically validated how digital technologies, including blockchain and AI, effectively reduced supply chain volatility in Chinese manufacturing firms. Their evidence demonstrated blockchain's particular effectiveness in diminishing bullwhip effects, improving responsiveness, and stabilising operations.

Cybersecurity within industrial supply chains was examined by [160], who evaluated multiple lightweight machine learning algorithms integrated within blockchain-enabled industrial IoT environments. Their comparative analysis revealed superior performance in cyber-attack detection, significantly enhancing the resilience and robustness of supply chain cybersecurity frameworks. Complementing these findings, [147] proposed evolutionary deep learning techniques coupled with blockchain for supply chain cyberattack prediction, demonstrating that their model effectively reduced vulnerabilities and improved threat detection accuracy, emphasising blockchain's role in secure information management.

Authors in [161] explored blockchain's transformative impact on circular economy practices within the automotive industry. Using sophisticated machine learning methods and the generalised method of moments, their study confirmed that blockchain notably enhanced resource utilisation and circular practices, contributing to the sector's overall sustainability goals. Similarly, [142] investigated blockchain and smart contracts within autonomous vehicle supply chains, identifying significant reductions in operational inefficiencies and energy wastage. Their findings underline blockchain's potential in supporting sustainable and economically viable operations in emerging automotive technologies.

Addressing healthcare supply chain challenges during global disruptions, [151] demonstrated blockchain's effectiveness in automating procurement contracts, significantly enhancing operational transparency and reducing manual administrative burdens, particularly during crises such as the COVID-19 pandemic. Complementing this, [137] introduced blockchain-enabled smart contracts specifically to trace personal protective equipment (PPE), highlighting substantial improvements in operational transparency and trustworthiness across healthcare supply chains, which faced severe disruptions during the pandemic.

Authors in [162] applied blockchain alongside fuzzy neural networks to assess financial risks within supply chains. This integration effectively addressed credit assessment uncertainties, showcasing blockchain's ability to reliably manage financial information. Complementing this, [163] employed machine learning and blockchain for financial market risk analysis, confirming blockchain's critical role in improving transparency and mitigating financial instability through effective risk forecasting.

Authors in [164] addressed blockchain security through machine learning techniques for smart contracts auditing, proposing a model achieving outstanding accuracy in vulnerability detection. Their research significantly enhances trust and reliability in blockchain systems, particularly within supply chains requiring rigorous security assurances. [44] similarly focused on blockchain security enhancements through multimedia forensic and multi-party computation, demonstrating that their innovative approach robustly defended against data tampering and significantly enhanced privacy in blockchain-enabled supply chain management.

In smart manufacturing, [141] deployed blockchain-integrated machine learning to enhance real-time production monitoring, achieving superior performance in predicting equipment reliability and quality, substantially improving operational resilience. Further, [165] developed privacy-preserving federated learning algorithms integrated with blockchain to ensure secure collaborative model training, facilitating greater consumer participation in crowdsourced IoT and blockchain-based supply chain management tasks, thus ensuring robust data-driven decision-making.

Authors in [166] evaluated AI and machine learning in minimising food waste across agricultural supply chains, demonstrating substantial reductions in post-harvest losses and logistics-related inefficiencies. Their integration of blockchain for traceability and transparency highlighted significant improvements in sustainable food distribution practices. [167] systematically reviewed AI and blockchain applications within the dairy supply chain, identifying considerable enhancements in operational efficiency, traceability, and product safety through advanced technological implementations.

Authors in [168] presented a blockchain-based predictive analytics model for veterinary clinic management, improving operational scheduling, inventory management, and data reliability. Their blockchain-enabled framework significantly advanced healthcare management for animal care, exemplifying the versatility of blockchain applications across various healthcare contexts. Complementing this, [169] systematically reviewed blockchain's role in ensuring food safety and authenticity, emphasising blockchain's superior capabilities in traceability, transparency, and quality assurance within global food supply chains.

Authors in [170] advanced blockchain integration with 5G-enabled machine learning orchestrations in supply chains, substantially improving connectivity, predictive capabilities, and operational decision-making efficiency. Their model demonstrated significant performance improvements, enabling continuous and reliable connectivity across complex supply chain networks.

Finally, [171] utilised blockchain integrated with LSTM machine learning algorithms to evaluate customer satisfaction in urban logistics, significantly improving predictive accuracy and transparency in customer delivery experiences. Authors in [172] further demonstrated blockchain's effectiveness in managing cost uncertainty in additive manufacturing-integrated supply chains, employing novel Monte Carlo and machine learning methods to optimise decision-making under uncertainty.

Collectively, these studies underscore the considerable potential of blockchain and machine learning integration in transforming traditional supply chain management across diverse sectors, consistently highlighting improved transparency, security, operational efficiency, predictive accuracy, and resilience. However, persistent barriers related to technological maturity, financial constraints, security vulnerabilities, and strategic implementation remain critical challenges that require ongoing scholarly attention. Future research should concentrate on addressing these limitations to fully realise blockchain and machine learning's transformative potential within increasingly interconnected and dynamic global supply chains. The following **Table 2.5** shows the literature review on integration of BC and ML in SCM with key findings.

Table 2.5 Literature Review on Integration of BC and ML in SCM

Reference	**Study Description**	**Method/ Algorithm Used**	**Key Findings**
[44]	Enhancing Blockchain Security Against Data Tampering: Leveraging Hybrid Model in Multimedia Forensics and Multi-Party Computation for	blockchain, machine learning, LSTM, AI	The incorporation of Blockchain technology into supply chain management systems has grown dramatically in the last several years.

	Supply Chain Data Protection		
[87]	Supply chains enduring economic fluctuations can benefit from responsive working capital management through the pairing of digital twins and blockchain.	blockchain, machine learning, AI, simulation	Expanded trade credit time frames and lower down payments are two instances of financial disturbances that make it difficult for supply chains to oversee working capital appropriately.
[125]	A Drug Supply Chain Management and Recommendation System for the Smart Pharmaceutical Industry Utilising Blockchain and Machine Learning	blockchain, machine learning, AI	Pharmaceutical businesses have had trouble monitoring their manufactured goods throughout the supply chain process for the past ten years, which has enabled it possible for counterfeiters to bring their phoney medications to the market.
[133]	Efficient blockchain-based cyber-physical healthcare supply chain management adopting a BERT-based recommender system.	blockchain, machine learning, AI	One of the fields of healthcare that pandemics can most impact is drug supply chain management (DSCM).

[138]	Blockchain technology adoption, architecture, and sustainable agri-food supply chains	blockchain, machine learning, AI	Electronic agriculture relies substantially on novel data and communication technologies.
[139]	A survey on Supply Chain Security: Application Cases, Security Risks, and Solution Frameworks	blockchain, machine learning, AI, IoT	The degree of trade between various parties has risen due to the swift development of global networking standards.
[140]	An assessment method for equitable manufacturing capabilities for supply chain networks based on blockchain, LSTM, and the technique of analytical hierarchy.	blockchain, machine learning, AI, IoT, simulation	The supply chain network continues to evolve as a result of the quick advancement of information technology, leading to the degree of reliance between organisations.
[141]	Incorporating Blockchain, IoT, and Machine Learning to Improve Security in Smart	blockchain, machine learning, AI	The requirement to foresee the efficiency and dependability of equipment has led to a boom in smart manufacturing systems.

	Manufacturing and Deliver Multistage Quality Control		
[142]	An experimental design for the deployment of blockchain and smart contracts in supply chains for autonomous automobiles	blockchain, machine learning, AI, smart contract	The emergence of digitally feasible business models in the Autonomous Vehicles (AV) sphere has caused established automakers to undertake a significant redesign of their supply chain operations and significant performance domains.
[143]	Providing Blockchain-Based SCM Systems with the Potential to Track Events in Real Time for Preventive Risk Management	blockchain, AI	Regular disruptions in supply chain operations tend to be linked to the risk of supply chain disruption.
[144]	Blockchained supply chain management based on IoT tracking and machine learning	blockchain, machine learning, AI, IoT	The 6G Internet of Things (IoT) will be essential for the efficient functioning and management of contemporary supply chains.
[145]	6G IoT Tracking- and Machine Learning (ML)-Enhanced Blockchained	blockchain, machine learning, AI, IoT	When it relates to managing and monitoring modern supply chains, the 6G Internet of Things (IoT) is fundamental.

	Supply Chain Management		
[146]	supply chain financial risk regression assessment employing a flexible decision framework and machine learning.	AI	The largest barrier preventing financial companies from implementing supply chain financial services is currently supply chain financial risk control.
[148]	The application of blockchain and the Internet of Things in the farm supply chain prediction of demand.	blockchain, machine learning, AI, IoT	It intends to elevate the success rate of incorporating contemporary science and technology into farm operations, strengthen the predictive power of blockchain and machine learning on supply and demand issues affecting farms, and empower company executives in successfully managing and running corporate initiatives.
[149]	A critical examination of the literature utilising the Sim-ML literature categorisation methodology on the use of simulation and machine learning in supply chain management.	blockchain, machine learning, AI, simulation, optimization	Discrete-event and agent-based simulation constitute two examples of stochastic modelling methodologies that are widely employed in supply chain management (SCM) to simulate practical inconsistencies.

[150]	Using Blockchain-Enabled Off-Chain Machine Learning to Foster Sustainability in the Groundnut Supply Chain by ensuring Traceability of Greenhouse Gas Emissions.	blockchain, machine learning, AI, smart contract	Sustainable agriculture, an important target of the UN Sustainable Development Goals (SDGs), demands committed work and innovative approaches, as emphasised in numerous UN reports.
[151]	A tripartite strategy for detecting obstacles to blockchain implementation in sustainable supply chains.	blockchain, machine learning, AI	Goal: Due to its intrinsic attributes, blockchain innovation is one of the primary motivating factors of the sustainability of supply chains.
[152]	Combination of Digital Twins and Blockchain for Improved Safety in Metaverse-Driven Consumer Supply Chains.	blockchain, AI, smart contract	In the rapidly growing consumer electronics industry, continuous innovation drives increasing demand for smart devices and advanced gadgets.
[173]	A Mechanism for Tracking Supply Chains of	blockchain, machine learning, AI	A crucial aspect of food processing and product preservation is the

	Perishable Food Using Blockchain, Machine Learning, and Fuzzy Logic.		improved functionality of the food identification system.

2.6 RESEARCH GAPS IDENTIFIED

A review of existing literature across general supply chains, medical supply chains during pandemics, blockchain-enabled systems, and the integration of blockchain with machine learning reveals several critical research gaps:

a) **Fragmented Application of Blockchain in Healthcare Supply Chains**
   While blockchain adoption in SCM is growing, most healthcare-specific studies focus on isolated functions (e.g., drug traceability, PPE monitoring) rather than a fully integrated end-to-end framework.

b) **Limited Integration of Predictive Analytics**
   Few existing works integrate advanced ML techniques, such as LSTM networks, with blockchain to forecast healthcare demand in real time and adapt distribution accordingly.

c) **Equity and Ethical Allocation Underserved**
   Despite the critical importance of equitable vaccine distribution during pandemics, existing models rarely embed fairness indices or ethical allocation rules within automated blockchain-based allocation mechanisms.

d) **Lack of Real-Time, Closed-Loop Feedback Systems**
   Current literature underutilises post-distribution data (e.g., consumption rates, wastage, outbreak resurgence) to refine predictive models and inform subsequent allocation decisions.

e) **Inadequate Consideration of Pandemic-Specific Disruptions**
   Most Blockchain along with ML studies do not account for the unique volatility and urgency of pandemic logistics, including sudden demand surges, cold-chain dependencies, and multi-country coordination barriers.

f) **Scarcity of Operational-Scale Prototypes**
   Many proposals remain conceptual or simulated at a small scale; robust prototypes combining blockchain, ML, and real-world pandemic datasets are still rare.

Based on the comprehensive review of existing literature, it is evident that current blockchain-based healthcare systems primarily focus on transparency and traceability without incorporating predictive intelligence, while machine learning-based forecasting systems operate within centralized environments lacking transparency and automated governance. Furthermore, limited research has addressed fairness-driven allocation, integrated smart contract automation, and simulation-based validation under pandemic stress scenarios. These critical gaps highlight the absence of a unified decentralized predictive healthcare logistics framework. To address these limitations, this research proposes the Predictive BlockVax Distribution Network (PBDN), which integrates blockchain-based trust infrastructure with machine learning-based predictive intelligence to enable transparent, equitable, and resilient vaccine distribution.

2.7 COMPARATIVE ANALYSIS AND RESEARCH GAP IDENTIFICATION

While several studies have examined blockchain-based healthcare logistics, most focus primarily on enhancing traceability and security without integrating predictive analytics for proactive decision-making. Similarly, machine learning-based forecasting approaches have demonstrated effectiveness in demand prediction but are typically implemented within centralized infrastructures, limiting transparency, auditability, and trust among stakeholders. Furthermore, existing research seldom incorporates equity-focused evaluation metrics to assess fairness in resource allocation during pandemic scenarios. These limitations highlight the absence of a unified architecture that simultaneously integrates decentralized trust, predictive intelligence, and automated governance mechanisms. This research addresses this gap by proposing the Predictive BlockVax Distribution Network (PBDN), which combines blockchain technology with machine learning to enable transparent, predictive, and equitable vaccine distribution.

2.8 SUMMARY

In summary, while substantial progress has been made in applying blockchain and machine learning to supply chain optimization and healthcare delivery, the literature reveals a consistent absence of holistic, domain-tailored frameworks that can effectively integrate transparency, automation, predictive intelligence, and equity within pandemic-driven vaccine logistics. Existing models tend to address these dimensions in isolation, blockchain solutions often focus on traceability without predictive adaptability, whereas machine learning approaches emphasize demand forecasting but lack mechanisms for automated, tamper-proof execution. Moreover, few studies have tested these solutions under realistic, high-pressure scenarios that mimic the volatility of pandemic conditions. This misalignment between research efforts and real-world needs highlights a critical gap in designing an integrated, simulation-validated architecture for equitable and resilient vaccine distribution. The literature reveals a lack of a holistic, domain-tailored solution that integrates transparency, predictive intelligence, and equity in pandemic supply chains. Chapter 3 will now detail the methodology developed to fill this gap by designing the Predictive BlockVax Distribution Network (PBDN).

Chapter 3

RESEARCH METHODOLOGY

3.1 INTRODUCTION

This chapter presents a comprehensive overview of the research methodology employed to conceptualize, construct, and validate the **Predictive BlockVax Distribution Network (PBDN)**, a novel, integrated framework designed to transform healthcare supply chains, particularly in the context of pandemic response. The PBDN framework addresses critical challenges such as lack of transparency, inequitable distribution, and poor demand predictability that have historically plagued medical logistics during global health emergencies like COVID-19.

To effectively tackle these issues, the framework harnesses the complementary strengths of two cutting-edge technologies: **Blockchain (BC)** and **Machine Learning (ML)**. Blockchain technology, with its decentralized, immutable, and verifiable ledger capabilities, forms the backbone of a transparent and secure vaccine distribution process. It enables real-time tracking, auditability, and trust across all stakeholders, from manufacturers to last-mile health facilities. Machine Learning, on the other hand, is leveraged for its advanced data-driven forecasting capabilities. By using time-series models, specifically Long Short-Term Memory (LSTM) networks, the system can predict vaccine demand patterns and identify emerging hotspots with high precision.

The research methodology adopted for this study follows the **Design Science Research (DSR)** paradigm, which is particularly well-suited for developing and evaluating innovative IT artifacts that solve complex real-world problems. The methodology unfolds across a sequence of structured phases, ranging from problem identification and objective formulation to artifact development, demonstration, and rigorous evaluation.

To ensure the practical feasibility of the PBDN framework, the design methodology is further augmented with **simulation-based validation**, wherein real-world datasets from authoritative sources such as WHO and Johns Hopkins University are used to mimic pandemic-like supply and demand conditions. Through iterative testing in a controlled simulation environment, the performance of the framework is analyzed using quantitative metrics such as throughput, latency, allocation accuracy, and equity index.

This multi-layered approach not only ensures the technical robustness and scalability of the proposed model but also its relevance and adaptability in diverse healthcare settings, making it a promising solution for future pandemic preparedness and resilient healthcare logistics.

3.2 RESEARCH DESIGN AND METHODOLOGICAL APPROACH

The research design adopted for this study follows a systematic, structured, and iterative methodology that integrates **Machine Learning (ML)** and **Blockchain** technologies to address the persistent challenges in vaccine distribution during pandemics. The design process is illustrated in the research flow diagram as shown in **Figure 3.1** and is structured into **seven interlinked stages** that progress logically from problem identification to comparative evaluation.

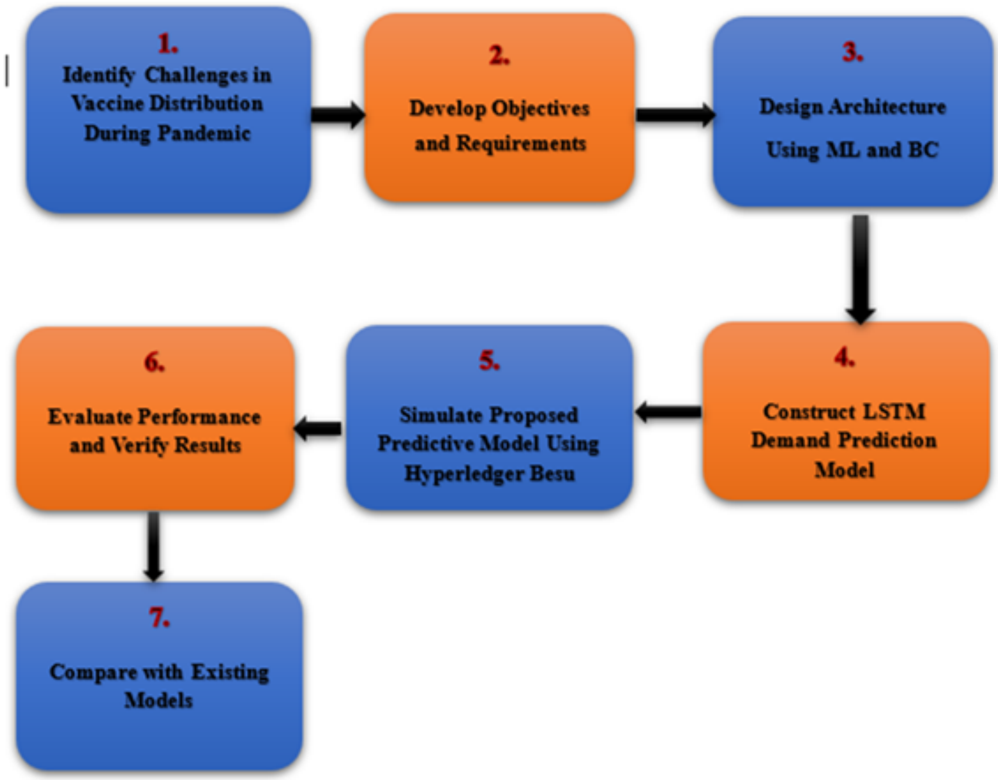


Figure 3.1 Research Flow Diagram

Stage 1: Identify Challenges in Vaccine Distribution During Pandemic

The process begins with an in-depth analysis of existing healthcare supply chains and their limitations during pandemic crises. A comprehensive literature review, case study assessment, and policy analysis are conducted to identify recurring challenges, including lack of real-time visibility, inequitable allocation, inaccurate demand forecasting, logistical bottlenecks, and inadequate inter-stakeholder coordination. These insights form the foundation for defining the problem scope and guiding subsequent research decisions.

Stage 2: Develop Objectives and Requirements

From the identified challenges, clear research objectives and technical requirements are established to guide the design of the proposed Predictive BlockVax Distribution Network (PBDN) framework. These requirements specify the functional goals such as accurate demand forecasting, blockchain-based traceability, automated allocation via smart contracts, and privacy-preserving verification, and outline the performance benchmarks for evaluation.

Stage 3: Design Architecture Using Machine Learning and Blockchain

The system architecture is conceptualized to integrate **LSTM-based predictive analytics** with a **permissioned blockchain network (Hyperledger Besu)**. The design specifies the interaction between key components:

- **ML Component:** Responsible for forecasting vaccine demand.
- **Blockchain Layer:** Ensures immutable tracking and smart contract-based automation.
- **Smart Contracts:** Encode allocation logic, shipment verification, and receipt acknowledgment.
- **Privacy Layer:** Incorporates **Zero-Knowledge Proofs (ZKPs)** for secure compliance verification without exposing sensitive data.

Stage 4: Construct LSTM Demand Prediction Model

The LSTM neural network is implemented to forecast vaccine demand at both national and regional levels. Data is sourced from WHO dashboards and national health repositories, covering epidemiological metrics, demographic data, mobility patterns, and vaccine inventory levels. This stage includes data preprocessing, feature selection, and hyperparameter tuning to enhance predictive accuracy. The model is trained and validated to deliver both short and mid-term forecasts, enabling proactive allocation decisions.

Stage 5: Simulate Proposed Predictive Model Using Hyperledger Besu

The predictive model outputs are integrated into the blockchain environment. A permissioned Hyperledger Besu network is deployed to simulate multiple stakeholders: manufacturers, logistics providers, healthcare agencies, and global health authorities (e.g., WHO). Smart contracts, written in Solidity, are deployed to:

- Allocate ERC-20 tokens representing vaccine doses.
- Track real-time shipment and delivery events.
- Record immutable proof of distribution.

Stage 6: Evaluate Performance and Verify Results

The integrated framework is evaluated using a combination of predictive performance metrics (RMSE, precision, recall, F1-score) and blockchain performance metrics (transaction throughput, latency, equity index, and fault tolerance). Stress testing scenarios simulate real-world crisis conditions such as sudden demand surges, shipment delays, and node failures to assess the resilience and scalability of the system.

Stage 7: Compare with Existing Models

The PBDN's performance is compared with traditional centralized healthcare supply chain systems and blockchain-enabled models reported in prior research. Comparative analysis reveals the advantages of the proposed framework in terms of accuracy, equity, operational efficiency, and transparency, demonstrating its readiness for real-world pandemic preparedness and response.

3.3 DATA SOURCES AND COLLECTION

To realistically emulate the operational complexities and uncertainties experienced during pandemic conditions, this research utilized a rich collection of secondary datasets sourced from globally recognized health and data repositories. These datasets provided the empirical foundation necessary for training predictive models and for validating the performance and responsiveness of the proposed Predictive BlockVax Distribution Network (PBDN) framework.

The dataset utilized in this study comprises daily time series summary tables extracted from the daily case reports, focusing on confirmed cases, deaths, and recoveries. Each entry in the dataset represents a daily summary of COVID-19 cases for various countries. The data is sourced from official reports and databases provided by health authorities and governmental institutions worldwide. Daily updates are retrieved and processed to maintain the accuracy and relevance of the dataset. This is a WHO approved dataset and the link of the dataset is given below:

Online Link: *https://github.com/CSSEGISandData/COVID-19*, Novel Coronavirus COVID-19 Cases, provided by JHU CSSE.

The Johns Hopkins University Centre for Systems Science and Engineering (JHU CSSE) provides critical data and analysis on global issues, notably tracking and visualizing COVID-19 pandemic trends.

Specifically, data was obtained from the following authoritative sources:

(a) **Johns Hopkins University Center for Systems Science and Engineering (JHU CSSE):** This repository offers granular, time-series data on the spread of COVID-19 across countries and regions, including daily counts of confirmed cases, recoveries, and fatalities. Its real-time updates and high reliability make it a cornerstone for epidemiological modeling and health systems research. The link to the repository is https://catalog.ourworldindata.org/garden/covid/latest/compact/compact.csv.

(b) **World Health Organization (WHO):** WHO provides extensive datasets on global health trends, pandemic statistics, and vaccination rates, categorized by geographic, demographic, and economic factors. The data includes not only infection rates but also vaccine rollout strategies, supply logistics, and healthcare infrastructure metrics. The link to the repository is https://catalog.ourworldindata.org/garden/covid/latest/compact/compact.csv.

(c) **United Nations Vaccine Distribution Data:** This source includes macro-level statistics related to international vaccine allocations, delivery volumes, regional prioritization, and policy-driven health interventions. It helps in simulating the geopolitical and logistical variations that affect supply chain dynamics during health crises. The link to the repository is https://catalog.ourworldindata.org/garden/covid/latest/compact/compact.csv.

The following **Figure 3.2** shows the different sources of data collection used for the development of the predictive model.

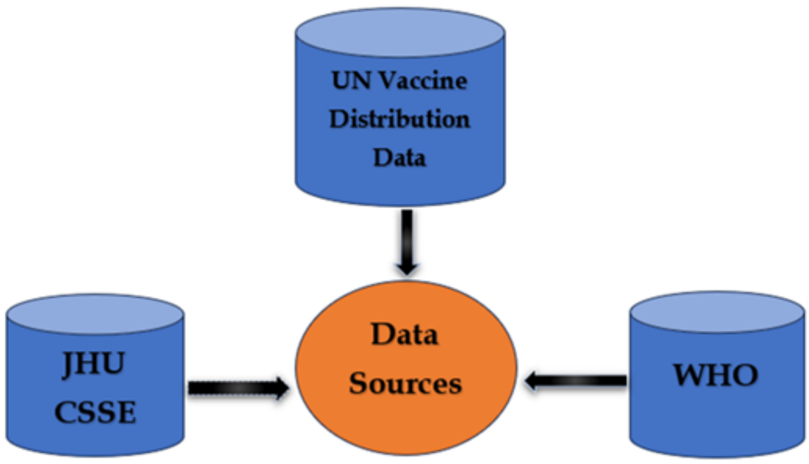


Figure 3.2 Different Sources of Data Collection

The integrated use of these datasets allowed for the creation of robust simulation scenarios reflecting diverse pandemic conditions, ranging from early outbreak surges to vaccine scarcity and uneven distribution across socio-economic groups. The datasets were pre-processed, normalized, and then fed into the Machine Learning module, particularly the Long Short-Term Memory (LSTM) models, to forecast demand patterns and predict supply mismatches.

Moreover, these datasets were instrumental in validating the resilience and predictive accuracy of the PBDN framework. By comparing forecasted outcomes with historical data trends, the system's reliability in managing real-world disruptions and demand spikes was thoroughly evaluated. The inclusion of geographically and temporally diverse datasets ensured that the proposed solution is both scalable and adaptable to global implementation scenarios.

3.3.1 Data Description and Preprocessing

For this research, a comprehensive and high-quality dataset was sourced from **Our World in Data (OWID)**, specifically from the public repository that compiles COVID-19-related indicators globally. The link to the repository is https://catalog.ourworldindata.org/garden/covid/latest/compact/compact.csv. The dataset, named **compact.csv**, consists of **520,288 rows** and **61 columns**, making it a rich source of temporal, geographical, and epidemiological data for the analysis.

This dataset aggregates information from authoritative organizations such as the World Health Organization (WHO), Johns Hopkins University, and government health departments. It includes a wide range of variables that are crucial for modelling pandemic dynamics and vaccine logistics, including:

- **Epidemiological Metrics**: total cases, new cases, total deaths, and test counts.
- **Vaccination Statistics**: total vaccinations, people fully vaccinated, daily vaccination rates.
- **Healthcare Capacity**: ICU patients, hospital beds per thousand.
- **Mobility and Policy Indicators**: stringency index, government response measures.
- **Demographics and Location Data**: country, population, region, continent, income group.

The time-series nature of the dataset, combined with its global coverage, made it suitable for training predictive models like the Long Short-Term Memory (LSTM) neural network. The data was pre-processed to handle missing values, normalize numerical columns, and aggregate information at the required temporal and regional levels.

This dataset enabled simulation of realistic pandemic conditions and vaccine demand surges, forming the empirical foundation for developing and testing the Predictive BlockVax Distribution Network (PBDN). Its multidimensional nature also allowed for robust evaluation of equity in vaccine distribution by linking demographic, geographical, and healthcare access factors.

The dataset used in this study, named compact.csv, contains 520,288 rows and 61 columns, providing comprehensive global COVID-19 related indicators including epidemiological metrics, vaccination statistics, healthcare capacity, and policy measures. This large-scale dataset enabled robust training and validation of predictive models under diverse pandemic scenarios.

All data preprocessing, normalization, and machine learning model development were performed using Python programming language with Pandas, NumPy, and TensorFlow/Keras libraries. The experiments were conducted on a computing system configured with an Intel Core i7 processor, 16 GB RAM, and Ubuntu 22.04 operating system. The blockchain implementation and smart contract deployment were executed using the Hyperledger Besu permissioned blockchain platform with IBFT 2.0 consensus protocol, ensuring secure, scalable, and efficient simulation of vaccine distribution workflows.

3.4 ARCHITECTURE OF PROPOSED PREDICTIVE BLOCKVAX DISTRIBUTION NETWORK (PBDN) MODEL

The **Predictive BlockVax Distribution Network (PBDN)** is designed as a multi-layered, integrated digital infrastructure that brings together blockchain technology, machine learning, and cryptographic protocols to facilitate a resilient, transparent, and intelligent healthcare supply chain. Its architecture is modular and scalable, enabling interoperability across multiple healthcare stakeholders and adaptability in diverse pandemic scenarios. The following components constitute the core of the PBDN framework as explained below:

3.4.1 Role of Long Short-Term Memory (LSTM) in PBDN

Utilizing state-of-the-art ML techniques, incorporating LSTM within the PBDN framework confronts a complex challenge in healthcare supply chain management: the accurate prediction and distribution of vaccines amidst sudden surges in demand during global health crises. This progression enables the execution of more efficient public health policies and boosts the flexibility and resilience of the supply chain. The functionality of an LSTM unit, classified as part of the structures within recurrent neural networks (RNN), is illustrated in **Figure 3.3**.

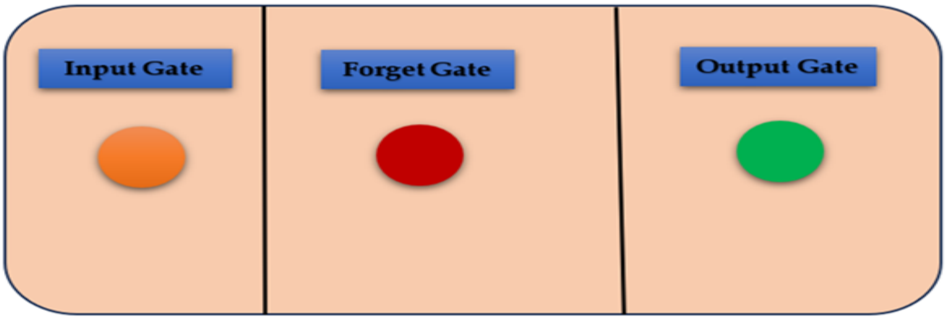


Figure 3.3 LSTM Model Architecture

The LSTM unit comprises three main components: the input gate, which is responsible for integrating or updating new data; the forget gate, which discards unnecessary information; and the output gate, transmitting the processed data to the next time step. Through regulation of information transmission, these gates enable the LSTM to retain and utilize relevant data across lengthy sequences, thereby handling prolonged dependencies within sequential data.

3.4.2 Smart Contracts

At the operational core of PBDN are smart contracts, self-executing scripts embedded within the blockchain that automate key processes in vaccine distribution. These include demand verification, eligibility checks, allocation triggers, shipment authorization, and delivery validation. Each smart contract executes based on real-time data inputs from the ML model and stakeholder requests, ensuring fairness and consistency. For instance, the allocateVaccines() function determines priority regions based on predicted demand, while recordReceipt() logs final confirmations from healthcare facilities. By codifying logistics logic into immutable contracts, this layer reduces manual intervention, bureaucratic delays, and potential corruption.

The PBDN system does not store or process Personally Identifiable Information (PII) on the blockchain. Instead, it focuses exclusively on vaccine-related data, such as supply chain logistics, demand predictions, and vaccine allocation. Patient information, if required, is handled outside the blockchain and in compliance with regional data protection laws like GDPR, HIPAA, or similar frameworks, ensuring the separation of sensitive information from blockchain records.

The system employs zero-knowledge proofs (ZKPs) to verify vaccine administration without exposing individual identities. This cryptographic method verifies vaccination events without revealing any personal data about the individuals. For instance, a health authority can confirm that a person has received a vaccine dose by validating proof generated from the blockchain without accessing or exposing the individual's identity or other sensitive details. This ensures compliance with varying data protection laws across countries while maintaining user privacy. The smart contract-based vaccine allocation logic is shown in the following algorithm:

```
BEGIN
INPUT V_pred       // Predicted Demand
INPUT S            // Available Supply
RECEIVE demand_request
// Step 1: Verify Eligibility
IF verify_smart_contract(demand_request) = FALSE THEN
   PRINT "Request Rejected"
   STOP
END IF
// Step 2: Compare Demand and Supply
IF V_pred <= S THEN
   A ← V_pred
ELSE
   A ← S
END IF
// Step 3: Allocate Vaccine Tokens
allocate_tokens(A)
// Step 4: Record Allocation on Blockchain
record_transaction_blockchain(A)
// Step 5: Notify Logistics Provider
notify_logistics(A)
// Step 6: Track Shipment
WHILE shipment_status ≠ "Delivered" DO
   track_shipment ()
END WHILE
// Step 7: Confirm Receipt
confirm_receipt ()
update_blockchain_status("Delivered")
PRINT "Allocation Completed Successfully"
END
```

3.4.3 Key Benefits of Combining LSTM, CNN, and ARMA Models in Forecasting

This study explores various models, namely LSTM, CNN, and ARMA, to ensure precision in forecasting. These models are widely esteemed for their efficacy in forecasting time-series data, a pivotal element of this investigation. ARMA is distinguished for its robust statistical methodology in predicting future data points within a time series. CNN, renowned for its utilization in image processing, also presents strong capabilities in analyzing time-series data. The study integrates these models with LSTM to exploit their respective strengths for a thorough and precise forecasting approach. This amalgamation enables the encompassment of a broader spectrum of data patterns and trends, thereby enhancing the accuracy and reliability of the predictions. The ability of LSTM to manage sequential data, CNN's proficiency in pattern recognition, and ARMA's statistical rigor collectively bolster the system's capacity to handle intricate datasets effectively.

3.4.4 ERC20 Token Mechanism

To digitally represent and track vaccine batches, the framework employs a modified **ERC20 token** system. Each token symbolizes a quantifiable vaccine unit or batch and is uniquely linked to its metadata (e.g., production date, expiry, temperature conditions). Tokens are transferred across the blockchain as shipments move through the supply chain, ensuring real-time visibility of vaccine flow and preventing duplication or loss. This tokenization mechanism also supports inventory reconciliation, financial accountability, and integration with digital payment or incentive systems, if needed.

3.4.5 Zero-Knowledge Proofs (ZKPs)

Recognizing the importance of data privacy, particularly in public health systems, the architecture incorporates **Zero-Knowledge Proofs (ZKPs)** to ensure that critical information can be validated without revealing the underlying data. For example, a smart contract can verify whether a recipient region meets the urgency threshold for vaccine allocation without exposing sensitive regional health statistics. This cryptographic feature maintains a balance between transparency and privacy, enabling secure inter-agency collaboration while complying with international data protection regulations such as GDPR and HIPAA.

Collectively, these components synergize to build a robust digital ecosystem that not only addresses the logistical challenges of pandemic-time vaccine distribution but also introduces predictive intelligence and cryptographic security into public health supply chains. The layered architecture of PBDN makes it suitable for deployment at both national and global levels, offering a pathway toward more resilient and equitable healthcare delivery in future crisis scenarios.

3.5 DETAILED ARCHITECTURE OF PBDN

The following **Figure 3.4** highlights the detailed architecture of PBDN.

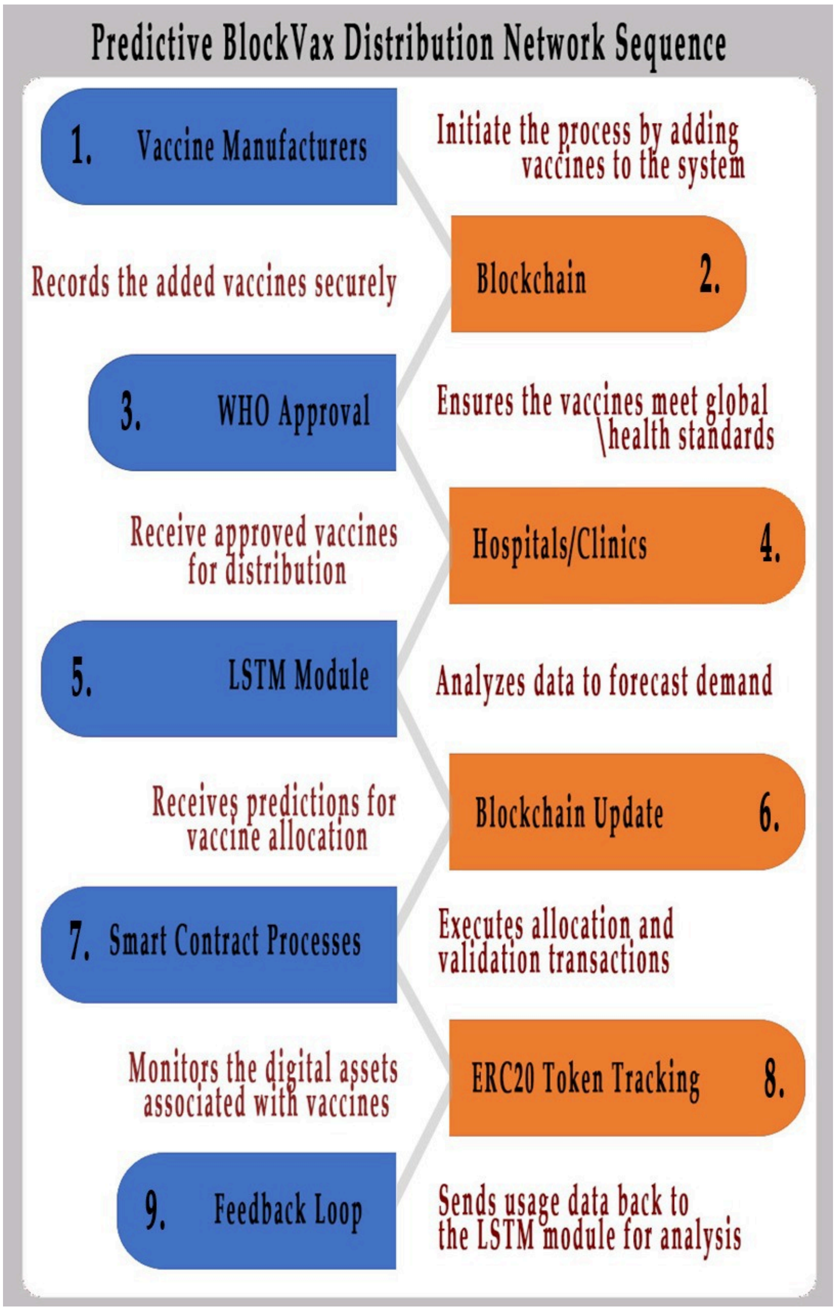


Figure 3.4 PBDN Sequence

Initially, vaccine manufacturers contribute to a shared pool managed by the World Health Organization (WHO) on the Hyperledger Besu blockchain. This action triggers an event that invokes the prediction function. Fueled by the LSTM model, the prediction function outputs the estimated quantity of vaccines required for each country based on their unique characteristics. Subsequently, this information is stored on the blockchain through the predict allocation function in the smart contract. The Hyperledger Besu BC acts as an immutable ledger, ensuring transparency and traceability of vaccine movements. Upon prediction, the WHO reviews and approves the vaccine transfer.

The manufacturer then initiates the transfer, marking the beginning of the physical movement of vaccines. Finally, as vaccines reach their destinations, countries update the system by marking the received status. This innovative system presents a semi-automated and reconcilable supply chain.

The synergy between BC and ML streamlines the entire process, enhancing accountability, reducing fraud, and providing an efficient mechanism for aid distribution during pandemics. By integrating real-time data and automated decision-making, the proposed PBDN framework tackles the issues surrounding prompt and fair vaccine distribution during a worldwide health emergency, providing a comprehensive remedy to strengthen supply chain resilience amidst unparalleled obstacles.

The proposed model uses Hyperledger Besu, a permissioned Ethereum client that allows for private and consortium blockchain deployments. Unlike public blockchains that rely on energy-intensive PoW consensus mechanisms, Hyperledger Besu utilizes more efficient algorithms like IBFT 2.0, which significantly reduces energy consumption and enhances scalability. This makes it suitable for global vaccine distribution networks where high transaction throughput and low latency are crucial. Thus, it assures scalability and energy efficiency with Hyperledger Besu.

To facilitate implementation in underdeveloped regions with limited infrastructure, the model proposes the deployment of server pods provided by international organizations such as the UN or WHO. These pods are equipped with the necessary server infrastructure and connectivity, allowing countries to participate in the network without the need for extensive local infrastructure. This approach ensures inclusivity and addresses the complexity of implementation in low-resource settings.

3.5.1 Workflow and Process Mapping

The operational workflow of the Predictive BlockVax Distribution Network (PBDN) is designed to ensure a seamless, automated, and transparent vaccine allocation and delivery process, eliminating human errors, inefficiencies, and delays that typically burden traditional healthcare supply chains. This intelligent workflow begins at the point where healthcare institutions, such as hospitals, vaccination centers, and public health departments, digitally submit their vaccine demand requests to the blockchain platform. These requests include critical metadata such as population coverage, regional infection trends, current stock levels, and urgency level based on local epidemiological forecasts.

Upon receiving a demand request, the system activates a series of smart contracts programmed with predefined allocation logic. These smart contracts evaluate the request against a multi-criteria decision framework that considers factors like existing inventory across distribution nodes, regional disease intensity, delivery timelines, and historical consumption trends. By using real-time data analytics, the contract ensures that vaccine allocation is both need-based and resource-optimized.

Once eligibility is verified and allocation approved, the smart contract automatically executes a transaction that notifies relevant manufacturers and logistics providers. A unique transaction hash and shipment ID are generated and encoded into QR codes for real-time tracking. These QR codes are affixed to the shipment containers and scanned at each checkpoint, from packaging, warehousing, and transit, to final delivery, ensuring visibility at every node of the supply chain.

Upon arrival at the destination facility, the designated healthcare official uses a cryptographically secured digital signature to confirm receipt of the vaccine consignment. This confirmation is immediately logged onto the blockchain, updating the distributed ledger across all nodes and completing the traceability cycle.

The detailed stages of the workflow are shown in **Figure 3.5**:

- **Demand Submission:** Health institutions initiate requests through a secure interface linked to the blockchain.
- **Smart Contract-Based Eligibility Verification:** Automated rules assess the request against stock levels, urgency indices, and regulatory thresholds.
- **Allocation Execution and Transaction Broadcast:** Upon approval, the blockchain records the allocation and transmits dispatch orders to stakeholders.
- **Shipment and Tracking:** Vaccine lots are tagged with scannable QR codes that register each logistical handover on-chain.
- **Final Delivery Confirmation and Ledger Update:** Receipt is digitally signed, and delivery status is permanently logged, closing the transaction cycle.

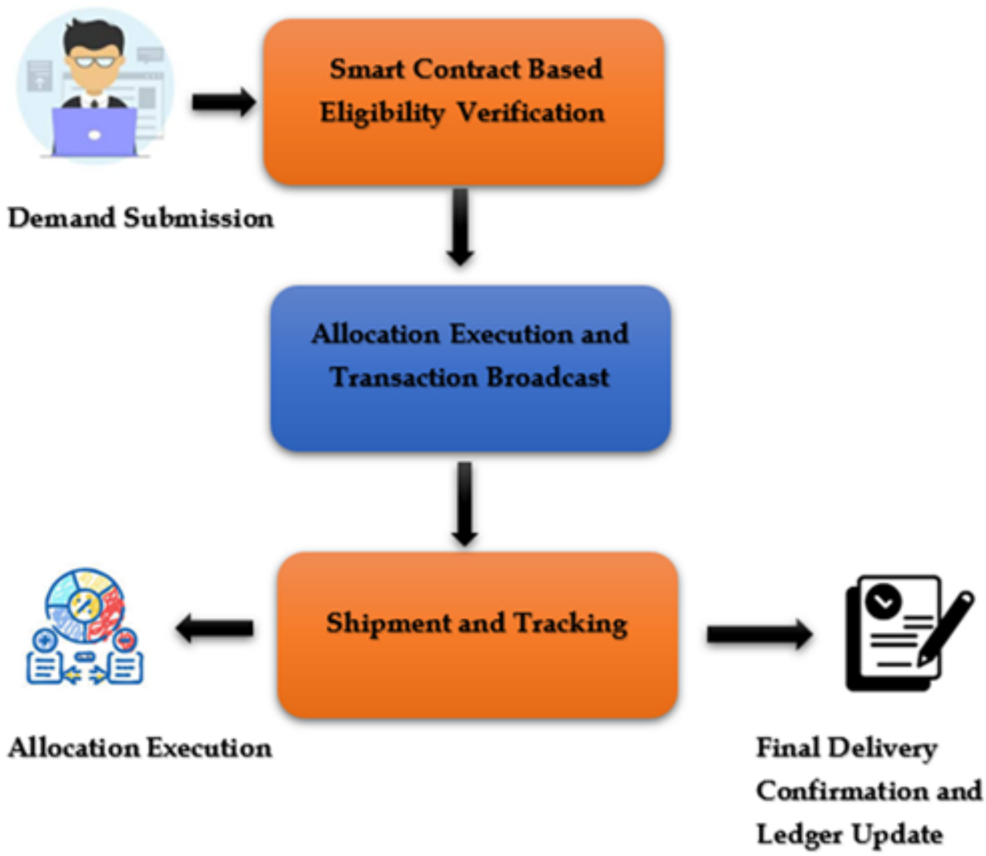


Figure 3.5 Blockchain – Driven Vaccine Distribution Workflow Using Smart Contracts

Each activity in this sequence is immutably recorded on the blockchain, creating a tamper-proof audit trail. This traceability not only enhances operational accountability but also fosters trust among all stakeholders, including regulatory authorities, healthcare providers, and end recipients, thereby elevating the integrity and reliability of pandemic-time vaccine distribution systems. The following **Figure 3.6** shows the flowchart of the vaccine allocation process in PBDN.

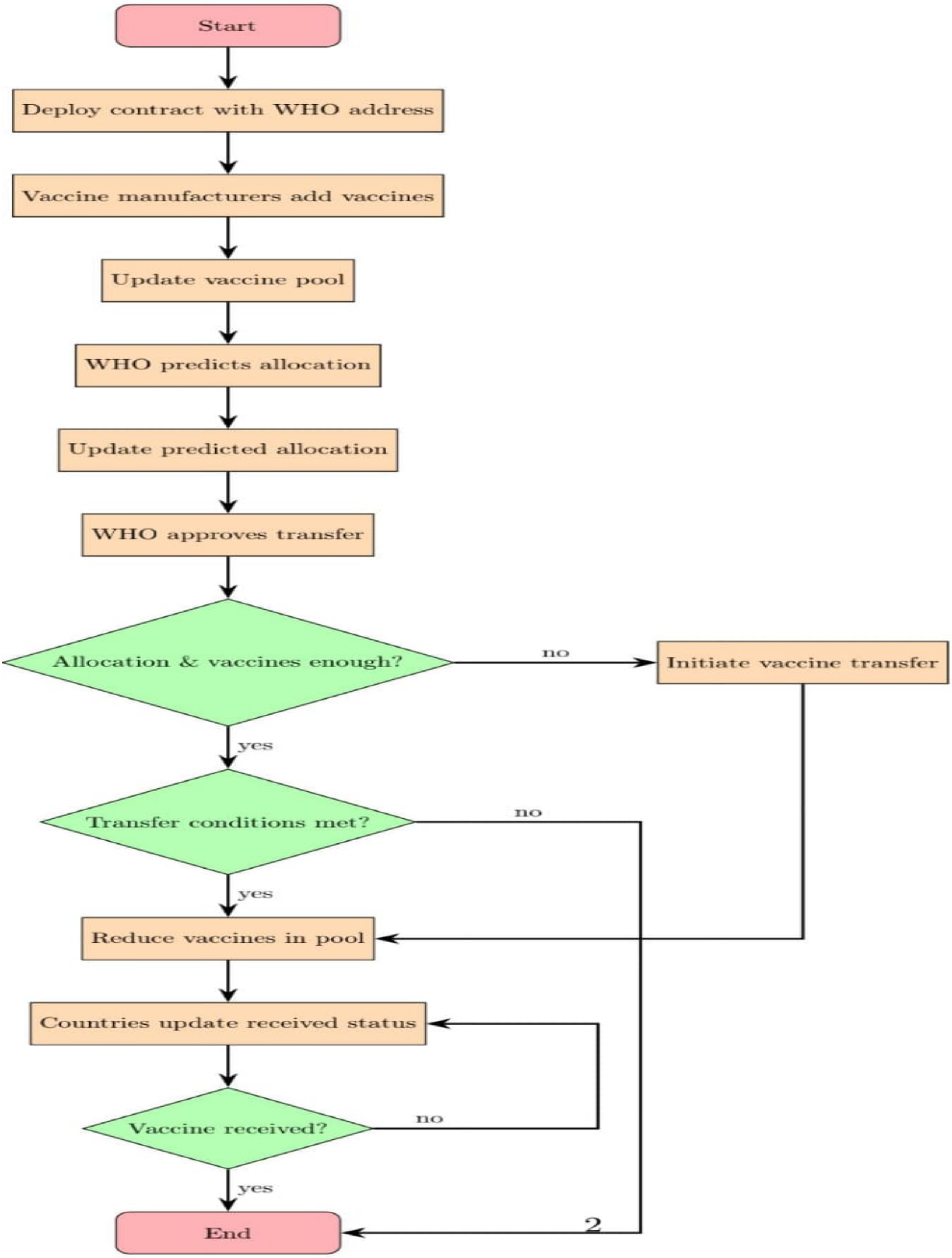


Figure 3.6 Flowchart of the vaccine allocation process

3.5.2 Practical Implementation Constraints

While the proposed Predictive BlockVax Distribution Network (PBDN) framework is designed to operate within real-world healthcare supply chain environments, several practical implementation constraints must be acknowledged. These include infrastructure readiness, blockchain node hosting requirements, data governance policies, interoperability with existing healthcare information systems, and regulatory compliance considerations.

Permissioned blockchain platforms such as Hyperledger Besu require secure node deployment, institutional coordination, and technical expertise for configuration and maintenance. Additionally, integration with existing health databases, logistics systems, and national health registries requires standardized data exchange mechanisms and interoperability protocols.

Furthermore, scalability considerations such as network latency, transaction throughput, and system resource availability must be addressed during deployment. These constraints were carefully considered during the design phase to ensure that the proposed framework remains scalable, adaptable, and feasible for phased implementation in real-world healthcare environments.

3.6 MACHINE LEARNING MODEL SELECTION AND CONFIGURATION

The selection of a suitable machine learning (ML) model is pivotal for the effective functioning of the Predictive BlockVax Distribution Network (PBDN), especially in accurately forecasting vaccine demand during pandemic outbreaks. Time-series forecasting problems, such as predicting disease spread and subsequent medical demand, require models capable of capturing temporal dependencies. The Long Short-Term Memory (LSTM) network, a special type of Recurrent Neural Network (RNN), was chosen due to its ability to retain long-term dependencies in sequential data and mitigate issues such as vanishing gradients, which traditional RNNs face.

The LSTM network in **Figure 3.7** was configured with the following parameters to optimize predictive performance:

- **Layers**: Two LSTM layers were stacked to allow hierarchical learning of temporal features.
- **Neurons per Layer**: Each layer contained 50 neurons, providing sufficient complexity for modeling variations in vaccine demand patterns.
- **Activation Function**: Rectified Linear Unit (ReLU) was used for non-linearity due to its efficiency and avoidance of gradient saturation.

- **Optimizer:** The Adam optimizer was selected for its adaptive learning rate and computational efficiency.
- **Loss Function**: Mean Squared Error (MSE) was used to minimize prediction error, suitable for continuous output variables.
- **Epochs**: 100 training epochs ensured the model had adequate exposure to the training data.
- **Batch Size**: A batch size of 32 was used to balance training speed and model convergence.

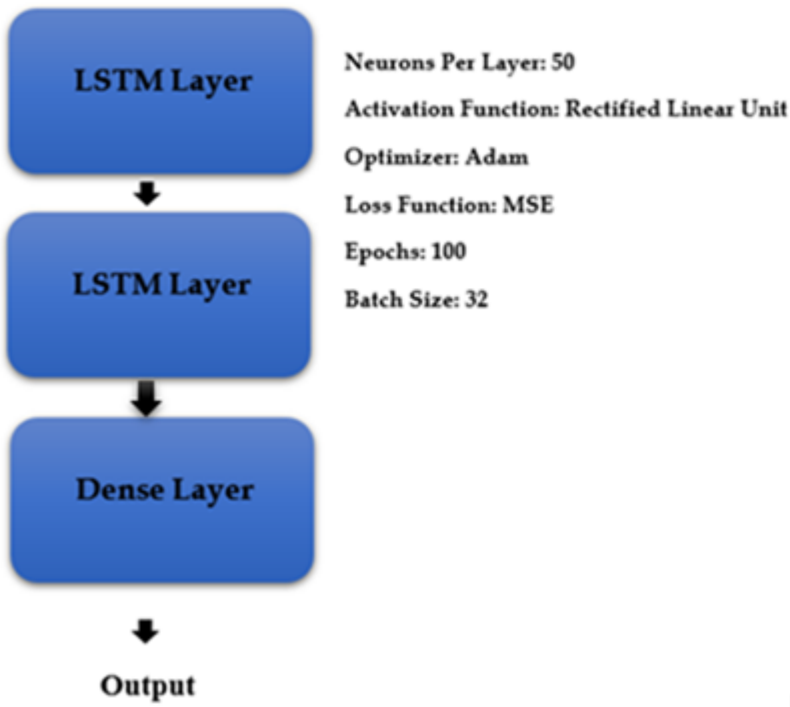


Figure 3.7 LSTM Model Configuration for Vaccine Demand Prediction

Hyperparameter tuning was performed using grid search, and early stopping criteria were applied to halt training when performance stagnated on validation data, thus preventing overfitting.

The demand forecasting procedure using LSTM is presented in the following algorithm:

Step 1: Start

Step 2: Receive Input

Receive demand request from healthcare authority.

Read V_pred and S.

Step 3: Verify Eligibility

Check request eligibility using smart contract rules.

If request is not valid, reject request and Stop.

Else, proceed to next step.

Step 4: Compare Demand and Supply

If V_pred ≤ S, then

    A = V_pred

Else

    A = S

Step 5: Allocate Vaccines

Allocate vaccine tokens based on priority rules and available quantity A.

Step 6: Record Transaction

Store allocation details on blockchain ledger.

Step 7: Notify Logistics

Send allocation details to logistics provider and destination authority.

Step 8: Track Shipment

Monitor shipment status until delivery.

Step 9: Confirm Delivery

Upon receipt confirmation:

    Update blockchain ledger with delivery status.

Step 10: Stop

The selection of LSTM was motivated by its ability to capture long-term temporal dependencies in time-series pandemic data, outperforming traditional ARMA models in nonlinear forecasting scenarios. Hyperparameters were selected based on cross-validation and prior empirical studies to balance overfitting and convergence efficiency. RMSE was chosen as the primary evaluation metric due to its sensitivity to large prediction errors, which is critical in vaccine demand forecasting where underestimation can have severe public health consequences. The IBFT 2.0 consensus mechanism was selected due to its suitability for permissioned healthcare networks requiring Byzantine fault tolerance and controlled node participation.

3. 7 EVALUATION METRICS

The evaluation of the PBDN framework as shown in **Figure 3.8,** was conducted through multi-faceted metrics that assess both the predictive capacity of the ML model and the operational performance of the blockchain component.

- **Predictive Accuracy:**
  - RMSE (Root Mean Squared Error): Measures average deviation between predicted and actual demand. Root Mean Square Error (RMSE) is predominantly utilized in the fields of climatology, forecasting, and regression analysis as a means to authenticate experimental findings. The formula used is

    $$\text{RMSE} = \sqrt{(f-0)^2}$$

    - f = forecasts (expected values or unknown results),
    - o = observed values (known results).
  - Precision & Recall: Assesses classification accuracy in urgent demand identification. The ratio of accurately predicted positive observations to the total predicted positives is known as precision. This metric evaluates the correctness of positive forecasts. The formula used to determine it is,

    Precision = (True Positives)/(True Positives + False Positives)

    The interpretation is that higher precision values indicate fewer false positive predictions.
  - F1 Score: Balances precision and recall to give a single performance measure. The F1 Score represents the harmonic average of precision and recall, effectively managing the compromise between these two metrics. It balances precision and recall, with elevated F1 Score values suggesting an enhanced equilibrium between the two metrics. The formula used to determine this is,

    F1 Score = 2 * (Precision * Recall)/(Precision + Recall)

- **Blockchain Performance:**
  - Throughput (Transactions Per Second - TPS): Measures the number of transactions processed in real-time.

- Latency (ms): Average time taken to confirm and record transactions.
- Fault Tolerance (%): Indicates system resilience when nodes fail or go offline.

- **Equity Index:**
  - Measures geographic and demographic fairness of vaccine allocation based on actual need and urgency.

This modular smart contract architecture as shown above in **Figure 3.8**, ensures transparency, accountability, and real-time updates across the vaccine supply chain.

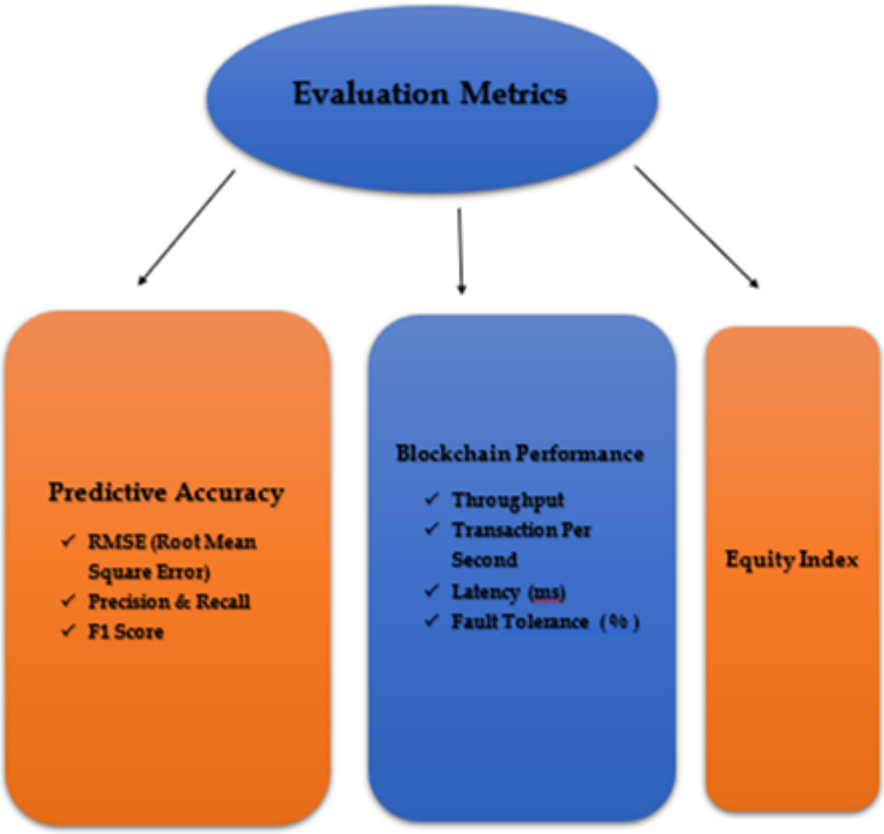


Figure 3.8 Evaluation Metrics of the PBDN Framework

3.8 SUMMARY

This chapter outlined the methodological foundation of the study, detailing the design, data sources, preprocessing steps, and analytical techniques applied to investigate equitable vaccine distribution. The integration of blockchain and machine learning within the Predictive BlockVax Distribution Network (PBDN) was operationalized here, ensuring replicability and rigor. By presenting the framework, experimental setup, and validation criteria, this chapter provided a roadmap for subsequent implementation.

The following chapter 4 transitions into the experimental results and analysis, demonstrating how these methods were applied in practice.

Chapter 4

EXPERIMENTAL RESULTS AND ANALYSIS

4.1 INTRODUCTION

This chapter presents a comprehensive experimental evaluation of the Predictive BlockVax Distribution Network (PBDN), a novel, integrated framework that integrates the capabilities of blockchain technology and machine learning (ML) to address the complex challenges associated with equitable vaccine distribution during pandemics. The purpose of this chapter is to rigorously validate the effectiveness, scalability, efficiency, and resilience of the PBDN framework in diverse pandemic-like conditions through a series of simulation-based experiments and quantitative analyses.

Pandemics such as COVID-19 have exposed critical flaws in traditional vaccine supply chains, including a lack of real-time transparency, inefficiencies in allocation, bottlenecks in distribution, and data silos among stakeholders. The proposed PBDN system is designed to overcome these challenges by leveraging blockchain for decentralized, tamper-proof logistics tracking and machine learning, particularly Long Short-Term Memory (LSTM) networks, for accurate demand forecasting. Built on the Hyperledger Besu platform, a permissioned blockchain infrastructure, the framework embeds smart contracts to automate vaccine eligibility verification, stock allocation, shipment tracking, and delivery confirmation, all while ensuring data privacy and regulatory compliance.

This chapter focuses on evaluating two critical components of the PBDN architecture:

1. **Predictive Accuracy of the ML Module**: The LSTM model is assessed based on its ability to forecast vaccine demand in the face of dynamic pandemic data inputs. Metrics such as Root Mean Squared Error (RMSE), precision, recall, and F1 score are used to measure its forecasting capability.
2. **Operational Performance of the Blockchain Layer**: The blockchain implementation is analyzed for its transaction throughput, latency, smart contract execution efficiency, and traceability effectiveness. Experiments were conducted under varying network conditions, including sudden demand surges, partial node failures, and latency spikes, to simulate real-world stress scenarios.

Moreover, comparative benchmarking is conducted between the PBDN and conventional centralized logistics systems to highlight the performance advantages brought by decentralization and automation. The simulation setup includes multi-node blockchain environments and real-time interaction between ML outputs and smart contract execution flows, ensuring a realistic approximation of field deployment.

Through this multifaceted experimental assessment, the chapter establishes the practical viability of the PBDN framework for deployment in national and global public health infrastructures. The insights generated from this evaluation serve not only to confirm the robustness of the proposed model but also to provide recommendations for future enhancements, scalability considerations, and real-world pilot implementations.

4.2 EXPERIMENTAL SETUP

To rigorously evaluate the operational feasibility and performance of the PBDN, a comprehensive and meticulously designed experimental setup was established. The objective of this environment was to replicate the functional and logistical dynamics of a real-world pandemic-time vaccine distribution network, leveraging a combination of blockchain simulation tools, machine learning infrastructure, and distributed computing environments. The testbed architecture was configured to enable integrated interaction between the blockchain nodes, smart contracts, and predictive analytics engines, simulating the behavior of various stakeholders in the healthcare supply chain.

The experimental setup utilized Hyperledger Besu, an enterprise-grade Ethereum client, as the core blockchain platform. Besu was chosen for its support of permissioned network architectures, allowing fine-grained access control and role-based authorization for simulated stakeholders such as government health agencies, vaccine manufacturers, logistics companies, and regional healthcare centers. Each stakeholder was modelled as a distinct node in the blockchain network, thereby ensuring a distributed, transparent, and tamper-proof system for managing vaccine allocation, shipment, and delivery processes.

To support development and testing of smart contracts, Ganache, a personal Ethereum blockchain emulator, was employed. Ganache, allowed for rapid deployment of contracts and controlled testing of transaction behaviors under simulated scenarios without incurring real-world gas fees. The Remix IDE was utilized for authoring, debugging, and compiling smart contracts written in Solidity, the Ethereum-compatible programming language. These contracts encapsulated critical functions such as allocateVaccines(), verifyShipment(), recordReceipt(), and logDiscrepancies(), all of which represent key operational activities within the vaccine logistics pipeline.

Parallelly, the machine learning component of the framework was developed using Python 3.10 and the TensorFlow /Keras deep learning libraries. The ML model, particularly the LSTM neural network, was trained using historical COVID-19 data to predict regional vaccine demand based on infection rates, demographic distributions, and historical supply data. The training data was sourced from authoritative global repositories such as the Johns Hopkins University Center for Systems Science and Engineering (JHU CSSE) and the World Health Organization (WHO). The ML output was continuously integrated into the blockchain layer via Web3.py, a Python library used for communicating with the Ethereum blockchain, enabling real-time interaction between smart contracts and forecast results.

The underlying data infrastructure was supported by PostgreSQL, a powerful open-source relational database system, which served as the backend repository for storing raw input data, ML training logs, intermediate results, and finalized analytics outputs. The architecture enabled seamless data flow between ML and blockchain layers through well-defined APIs and event-driven triggers.

To ensure stable and efficient execution of all processes, the entire system was deployed on a local high-performance testbed environment with the following hardware/software configuration:

- Processor: Intel Core i7, 8-core, 3.4GHz
- RAM: 16GB DDR4
- Operating System: Ubuntu 22.04 LTS (64-bit)
- Blockchain Network Mode: Permissioned (IBFT 2.0 Consensus Protocol)
- Python Version: 3.10
- TensorFlow/Keras Version: 2.x
- Database: PostgreSQL 14
- Smart Contract Language: Solidity 0.8.x
- Development Tools: Ganache, Remix IDE, MetaMask, Web3.py

The rationale for choosing a local testbed instead of a cloud-based deployment was to maintain full control over system parameters, enable iterative testing under controlled failure scenarios, and simulate edge cases such as node failures, high-volume transaction bursts, and intermittent connectivity, common during public health emergencies.

The simulation framework modelled several key roles in the network:

- **Manufacturer Node**: Registers vaccine production batches and initiates dispatch requests.
- **Logistics Node**: Verifies shipment tracking and transit temperature logs.
- **Regional Health Node**: Submits vaccine requests and validates final delivery.
- **National Authority Node**: Acts as the regulatory observer with read-only audit access.

Each of these nodes interacted with the blockchain via a MetaMask account, authenticated using private keys and role-specific permissions as shown in **Figure 4.1**. Additionally, test cases were scripted using Python to simulate transaction requests and smart contract interactions, ensuring comprehensive end-to-end testing of vaccine distribution logic.

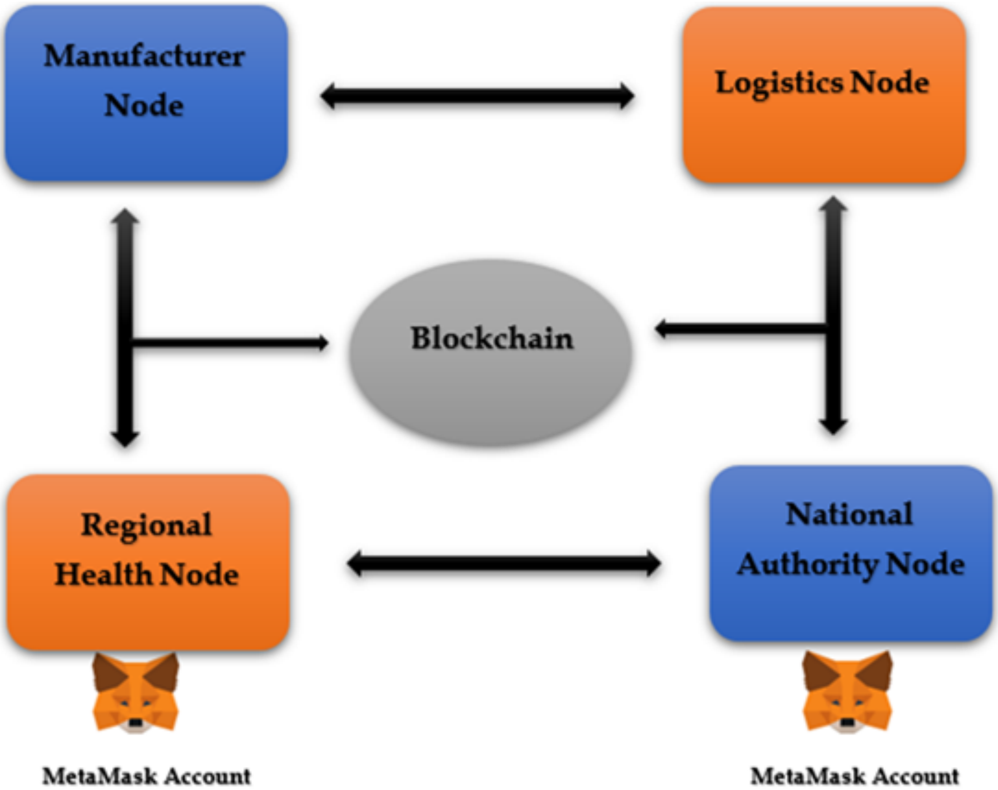


Figure 4.1 Roles of Simulated Nodes and Blockchain Integration

This robust and modular experimental setup allowed for stress testing of the PBDN system under a wide range of realistic conditions, such as sudden spikes in demand, partial node downtime, and discrepancies in supply chain data. By integrating blockchain technology with machine learning in a seamless simulation environment, this setup ensured a holistic and rigorous evaluation of the proposed framework's readiness for real-world deployment in national and international healthcare infrastructures.

4.3 FRAMEWORK ARCHITECTURE: PBDN

By combining the predictive intelligence of LSTM recurrent neural networks with the capabilities of Ethereum BC technology, the recommended structure of the PBDN model aims to completely transform the procedure. This part presents a forward-thinking architectural framework, delving into the advanced use of BC technology with Hyperledger Besu and describing the state-of-the-art development and execution of an LSTM model for exceptionally accurate demand forecasting. **Figure 4.2** depicts the multi-staged suggested model that was employed in this study. There are multiple stages to the model implemented in this study.

Initially, vaccine producers make contributions to a unified repository on the Hyperledger Besu blockchain that is overseen by the World Health Organisation (WHO). The prediction function gets executed as an outcome of this operation. The prediction function, powered by the LSTM model, estimates the approximate number of vaccines needed for each nation according to its specific traits. Following that, the smart contract's forecast allocation operation stores this data on the blockchain. As an unchangeable ledger, the Hyperledger Besu BC guarantees accountability and visibility of vaccine movements. The WHO examines and authorises the vaccination transfer based on the prediction.

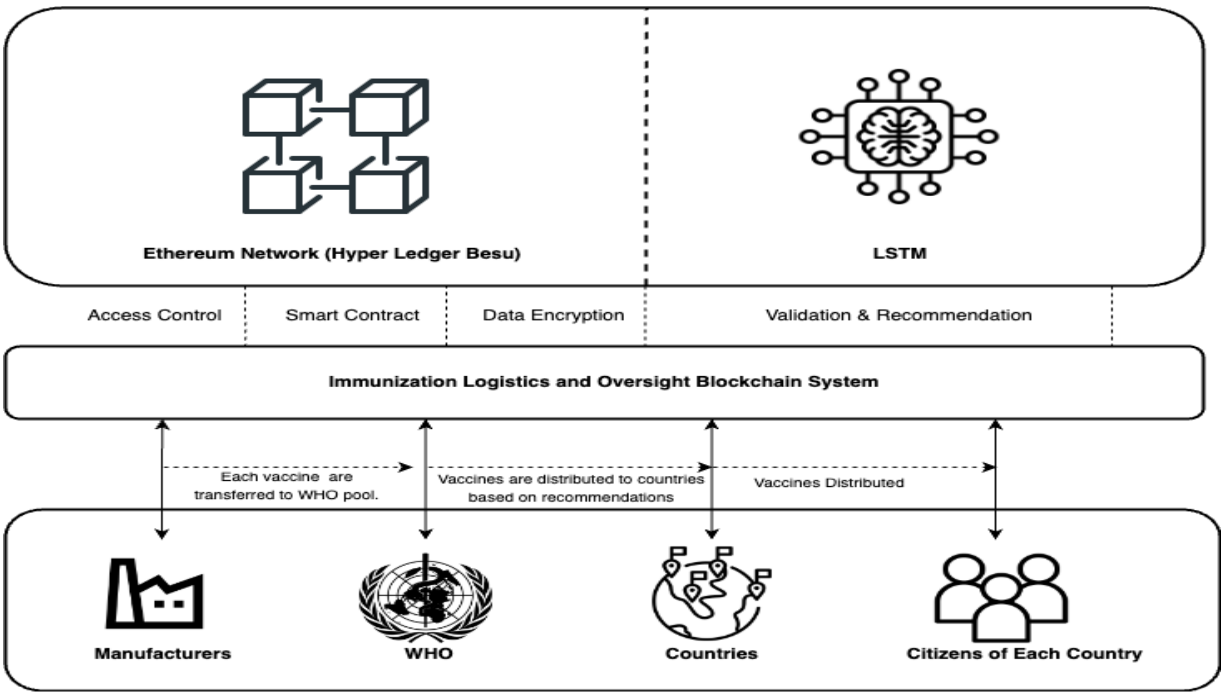


Figure 4.2 PBDN Architecture Utilizing Hyper Ledger Besu and LSTM

The physical transport of vaccinations then starts when the manufacturer starts transferring them. Lastly, governments update the system by noting the received status of vaccines as they arrive at their destinations. This novel method offers a supply chain that is semi-automated and reconcilable.

The collaboration between BC and ML simplifies the entire procedure, improving accountability, cutting down on fraudulent activity, and offering a productive way of distributing relief during epidemics. By integrating real-time data and automated decision-making, the proposed PBDN framework tackles the issues surrounding prompt and fair vaccine distribution during a worldwide health emergency, providing a comprehensive remedy to strengthen supply chain resilience amidst unparalleled obstacles.

The proposed model uses Hyperledger Besu, a permissioned Ethereum client that allows for private and consortium blockchain deployments. Unlike public blockchains that rely on energy-intensive Proof of Work (PoW) consensus mechanisms, Hyperledger Besu utilizes more efficient algorithms like IBFT 2.0, which significantly reduces energy consumption and enhances scalability. This makes it suitable for global vaccine distribution networks where high transaction throughput and low latency are crucial. Thus, it assures scalability and energy efficiency with Hyperledger Besu.

To facilitate implementation in underdeveloped regions with limited infrastructure, the model proposes the deployment of server pods provided by international organizations such as the UN or WHO. These pods are equipped with the necessary server infrastructure and connectivity, allowing countries to participate in the network without the need for extensive local infrastructure. This approach ensures inclusivity and addresses the complexity of implementation in low-resource settings.

The conceptual workflow of the Predictive BlockVax Distribution Network (PBDN), from supply registration to secure delivery, verification, and feedback learning is shown in **Figure 4.3.**

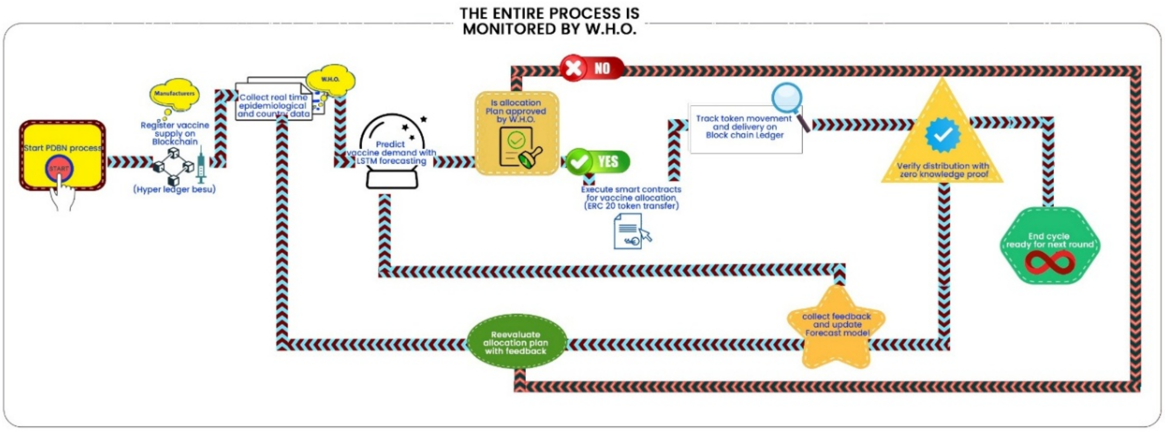


Figure 4.3 Conceptual workflow of PBDN

4.4 DATA PREPROCESSING AND PREPARATION

Effective data preprocessing is an essential step in ensuring the accuracy and reliability of forecasting models. Since raw datasets often contain irregularities such as inconsistent formats, missing values, or unscaled features, preparing the data before applying statistical and deep learning models is crucial. This study follows a structured preprocessing pipeline that transforms the raw dataset into a format suitable for ARIMA and LSTM-based experiments.

4.4.1 Initial Preprocessing

4.4.1.1 Code Description

The following **Figure 4.4** provides the code used for the preprocessing of data for time series forecasting.

```python
import numpy as np
import pandas as pd
from statsmodels.tsa.arima.model import ARIMA
from sklearn.preprocessing import MinMaxScaler
from sklearn.metrics import mean_squared_error
from tensorflow.keras.models import Sequential
from tensorflow.keras.layers import LSTM, Dense, Conv1D, MaxPooling1D, Flatten
from tensorflow.keras.optimizers import Adam

# Load and preprocess data
data = pd.read_csv('/content/output-onlinetools.csv')
data['Date'] = pd.to_datetime(data['Date'], format='%m/%d/%y')
data.set_index('Date', inplace=True)
data = data.fillna(0)
```

Figure 4.4 Preprocessing Steps Code for Time Series Forecasting

The preprocessing phase begins with the import of essential Python libraries. NumPy and Pandas were utilized for numerical computation and data handling, while *statsmodels* provided ARIMA capabilities for baseline forecasting. Scikit-learn's *MinMaxScaler* was employed to normalize values, and *mean_squared_error* served as a performance evaluation metric. Deep learning models were implemented using TensorFlow Keras, specifically integrating Sequential API, LSTM, CNN-LSTM, and optimization functions such as Adam.

The dataset, stored in a CSV file (output-onlinetools.csv), was imported using Pandas. The *Date* column was converted into a standardized datetime format and set as the index to enable time-series operations. Finally, missing values were handled by replacing null entries with zero, ensuring model stability and preventing computational errors. This systematic process prepared the dataset for advanced forecasting experiments.

The following **Table 4.1** summarizes the preprocessing workflow adopted in this study.

Table 4.1 Preprocessing Steps for Time-Series Forecasting

Step	Description
1. Import Libraries	Load required Python libraries: NumPy (numerical operations), Pandas (data handling), Statsmodels (ARIMA), Scikit-learn (scaling & metrics), TensorFlow Keras (deep learning models).
2. Load Dataset	Read the dataset (output-onlinetools.csv) into a Pandas DataFrame.
3. Date Conversion & Indexing	Convert the *Date* column into datetime format and set it as the index to enable time-series operations.
4. Handle Missing Data	Replace null values (NaN) with zero to ensure data consistency and avoid training errors.
5. Preprocessed Dataset	Final dataset prepared and ready for forecasting models.
6. Forecasting Paths	Data used for two modeling approaches: (i) ARIMA (statistical model) and (ii) Deep Learning (LSTM, CNN-LSTM).

4.4.1.2 Preprocessing Pipeline Visualization

To provide a clearer overview, the preprocessing workflow is illustrated in **Figure 4.5.** The process begins with the import of libraries and continues through dataset loading, datetime conversion, and missing value handling. The final pre-processed dataset is then directed toward two parallel modelling paths: ARIMA and deep learning (LSTM, CNN-LSTM).

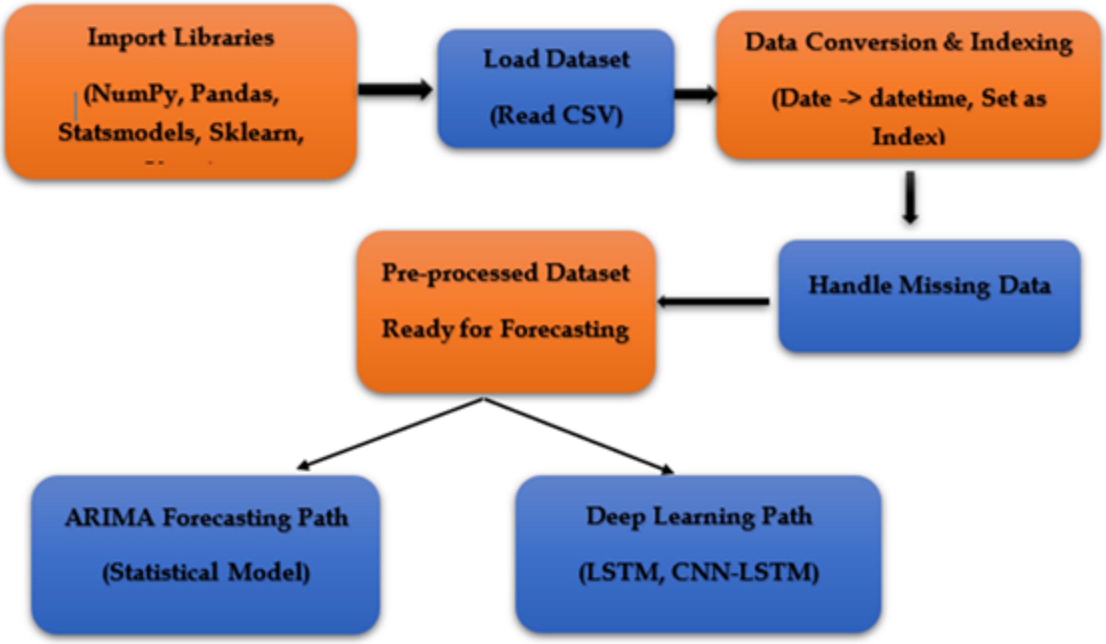


Figure 4.5 Data Preprocessing and Experimental Setup Pipeline

4.4.2 Data Scaling and Splitting

The next step in data preparation involved scaling and partitioning the dataset for model training and evaluation. Using the **MinMaxScaler**, all values were normalised to a fixed range between 0 and 1, ensuring that no feature with larger magnitudes dominated the learning process and allowing faster convergence of neural networks such as LSTM and CNN. The scaled dataset was then divided into two subsets, with **80% allocated for training** and **20% reserved for testing**, providing a balanced framework to learn from historical patterns while retaining sufficient unseen data for performance evaluation. Finally, the processed values were structured into **time-series input sequences**, enabling the forecasting models (ARIMA, LSTM, and CNN-LSTM) to effectively capture temporal dependencies and generate accurate predictions. The following **Figure 4.6** shows the programming code used for data scaling and splitting of the dataset.

```python
# Scale data
scaler = MinMaxScaler(feature_range=(0, 1))
scaled_data = scaler.fit_transform(data.values)

# Split data into training and testing sets
split_idx = int(len(scaled_data) * 0.8)
train, test = scaled_data[:split_idx, :], scaled_data[split_idx:, :]

# Prepare input for time series models
```

Figure 4.6 Code of Data Scaling and Splitting

The following **Figure 4.7** shows the data scaling, splitting and time–series input preparation pipeline

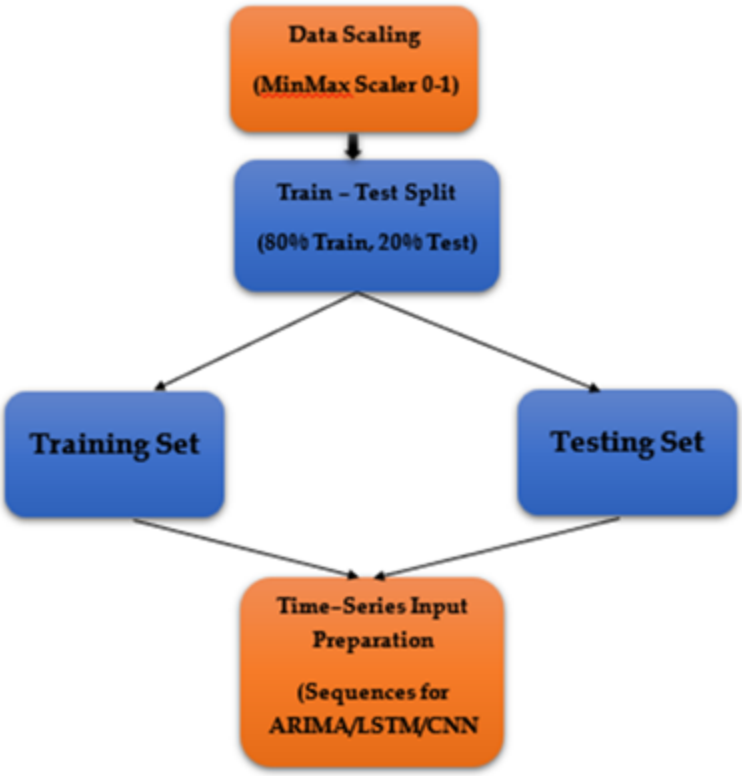


Figure 4.7 Data Scaling, Splitting, and Time-Series Input Preparation Pipeline

4.5 CORRELATION ANALYSIS OF KEY COVID-19 METRICS

To better understand the relationships among various epidemiological and intervention-related variables in the dataset, a correlation matrix was constructed using key numerical indicators. The matrix provides statistical insights into how metrics such as total cases, deaths, vaccination coverage, hospital admissions, and government interventions interrelate. This step was crucial in guiding the feature selection process for predictive modelling within the PBDN framework. As visualized in **Figure 4.8**, variables such as total_cases and total_deaths exhibit a very strong positive correlation ($r \approx 0.96$), highlighting the predictable increase in mortality as case counts grow. Similarly, people_vaccinated correlates strongly with both total_cases and total_deaths, reflecting policy responses to rising case numbers through accelerated immunization efforts. In contrast, positive_rate and stringency_index show weaker or even negative correlations with vaccination and testing efforts, which may reflect differences in regional data collection practices and policy enforcement.

This analysis confirms that the chosen variables not only align with theoretical expectations but also reinforce the robustness of the feature engineering and selection process for machine learning model development.

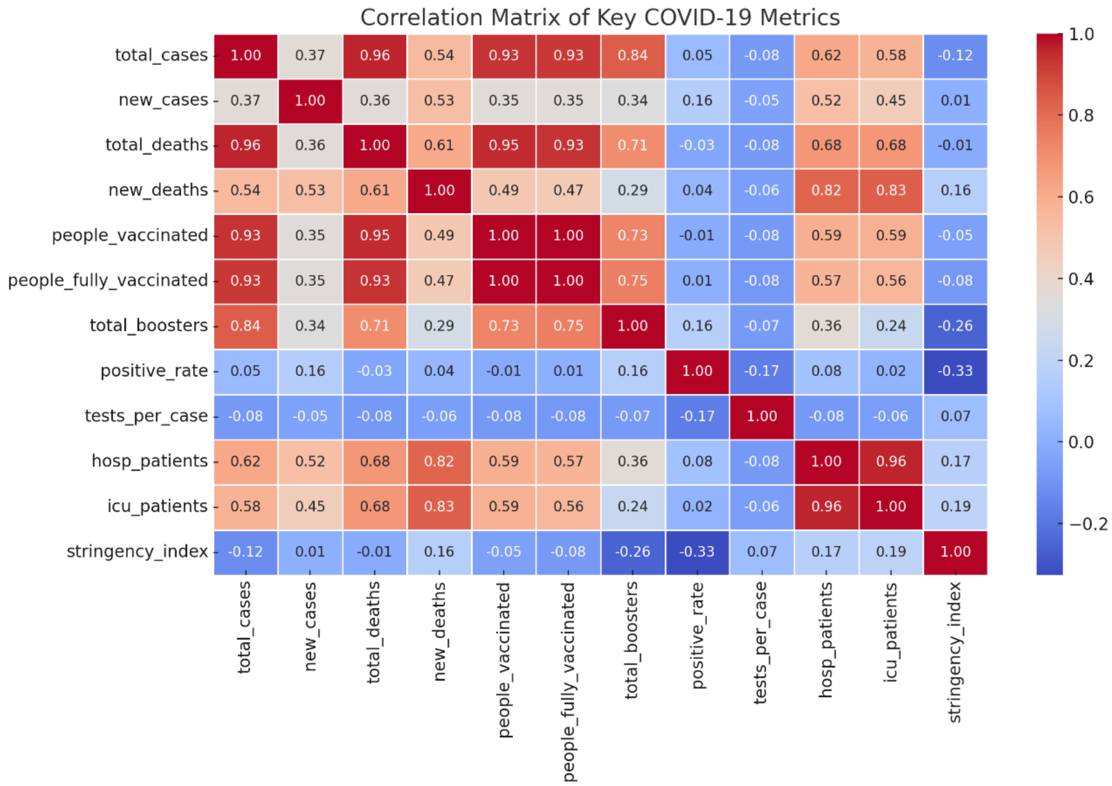


Figure 4.8 Correlation Matrix of COVID-19 Cases, Deaths, Vaccinations, and Policy Stringency

4.6 EXPERIMENTAL WORK AND FINDINGS

In the present study, an analysis is conducted employing predictive modelling techniques to anticipate the trajectory of novel COVID-19 incidences in a specific nation. The research entails the application of various time series models, such as the traditional AutoRegressive Moving Average (ARMA) model, the advanced LSTM neural network, and the flexible Convolutional Neural Network (CNN) architecture. The process initiates with the acquisition and preprocessing of COVID-19 data, meticulously selected to concentrate on the chosen country, Brazil, as a representative sample. The daily influx of new cases is meticulously extracted and processed through essential data preparation procedures, vital for subsequent modeling endeavors. Following this, the division of the dataset into training and testing subsets, which are 80-20, is imperative for model assessment. Subsequently, the ARMA model is applied to the training data, and its predictive performance is evaluated using the RMSE metric. Progressing to more sophisticated approaches, LSTM and CNN models are formulated and trained, capitalizing on their distinct abilities to capture complex temporal relationships within the data. The trained models are subjected to a thorough evaluation, culminating in comparative evaluations of their predictive efficacy via RMSE visualization.

Moreover, using intuitive visual representations that compare the models' projections with real data can provide a valuable understanding of their predictive capacities. Applying the LSTM model to forecast new COVID-19 instances for the next 30 days offers anticipation of future infection patterns, thereby contributing significant insights for public health planning and decision-making processes. The visual depictions of these forecasts effectively illustrate the expected path of COVID-19 cases in Brazil. The following **Table 4.2** shows the prediction table for the selected country, Brazil, as a sample selection for the country.

Table 4.2 Predictions of COVID cases forecasted by ARMA, CNN, LSTM, and the Actual Case on the specified date

Index	Time	Actual	ARMA	LSTM	CNN
0	2022-07	126958	21023	135608	72435
1	2022-08	136932	46090	89478	61886
2	2022-09	108694	72221	127537	71803
3	2022-10	124879	69820	135523	36551
4	2022-11	115268	5769	7747	121216
5	2022-12	59886	64735	128855	16394
6	2023-01	142337	69925	70725	74092
7	2023-02	92498	10311	134981	8890
8	2023-03	117727	108355	89654	46606
9	2023-04	131324	90305	124346	92313

The experimental design simulates the real-world challenges of hospital supply chains, such as fluctuating demand and limited vaccine supply during pandemics. By employing LSTM-based predictive modeling, the study replicates the task of anticipating hospital vaccine needs, allowing for timely and equitable distribution. The blockchain framework enhances transparency and traceability in vaccine allocation, which is critical for hospital logistics management. The model ensures real-time updates to stakeholders, addressing issues like miscommunication and delays, which healthcare providers commonly face. These experimental settings validate the system's capability to handle practical supply chain challenges, improving hospital readiness during health crises.

4.7 DATA AND ITS RELEVANCE TO HOSPITAL SUPPLY CHAINS

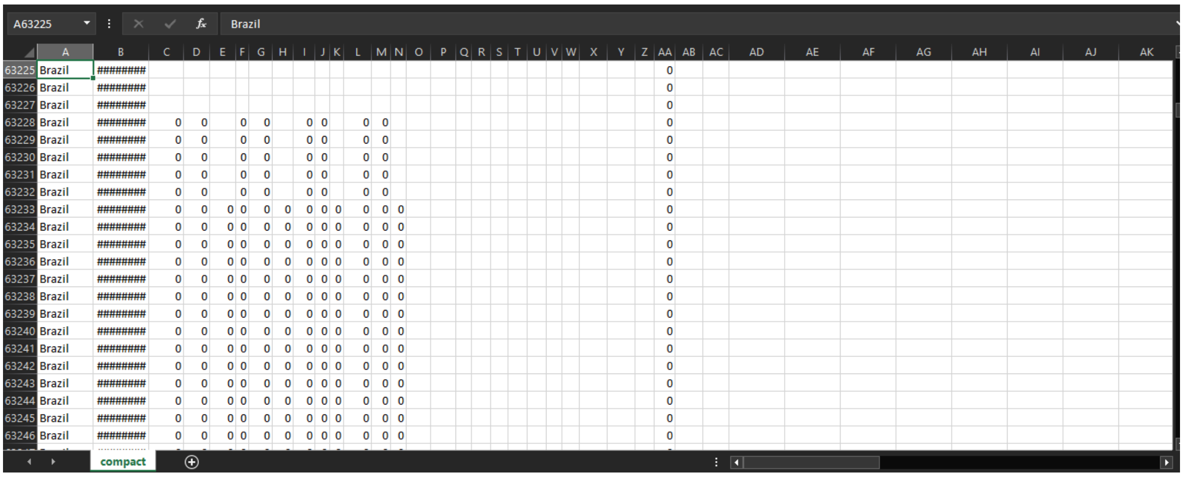
In this study, we collected daily COVID-19 case reports, covering confirmed cases, deaths, and recoveries, from recognized global health repositories (e.g., JHU CSSE) and the United Nations Data Repository. Although these data primarily detail epidemiological trends, they serve as a critical proxy for real-time fluctuations in healthcare resource demands.

Specifically, in a hospital supply chain (HSC) context, surges in confirmed cases typically correspond to heightened demand for vaccines, PPE, ventilators, and related consumables. By mapping fluctuations in infection rates to changes in material consumption, we replicate the dynamic nature of hospital inventories under pandemic conditions. For instance, when new daily cases spike, hospital administrators must swiftly adjust procurement, distribution, and storage strategies to prevent critical shortages. Therefore, analyzing these epidemiological shifts allows us to test how the Predictive BlockVax Distribution Network (PBDN) can anticipate demand and allocate vaccines more effectively.

This link between epidemic data and HSC decision-making underpins our experimental framework: forecasting COVID-19 case volumes mirrors forecasting surges in supply chain requirements. Consequently, the ML-driven predictions captured in our analysis can be mapped to practical, day-to-day hospital logistics operations, ensuring that the right quantity of vaccines and equipment reaches the right healthcare facilities at the right time.

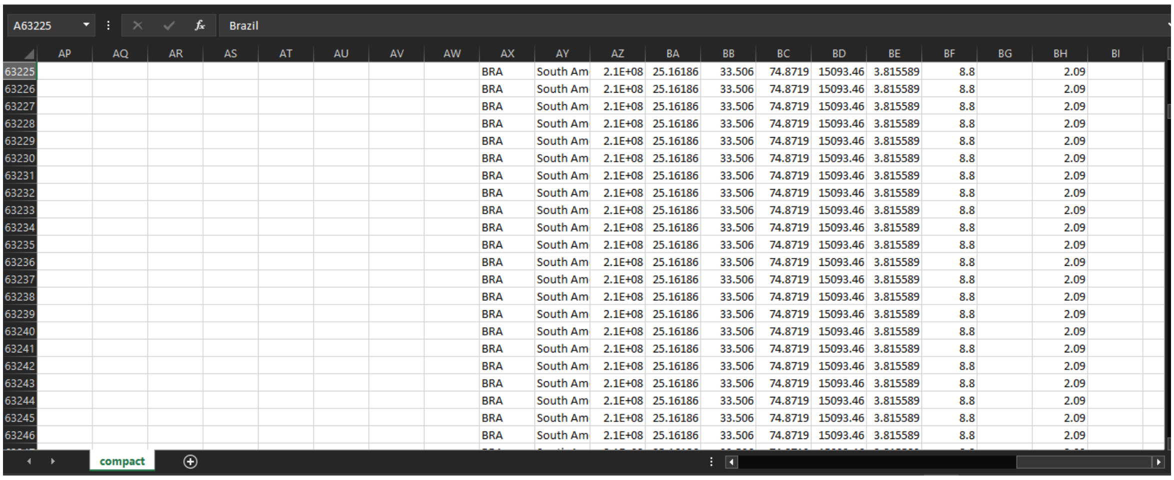
4.7.1 Data Preparation

The data is sourced from official databases as explained in **section 3.3.1**. These screenshots are raw implementation visuals demonstrating the data repository contents. As it is a big file containing millions of data, the screenshots taken from the dataset may not include all columns and rows, which consists of **520,288 rows** and **61 columns.** To show as a sample, I have included only data for two countries Brazil and India, which are shown in the following figures: **Figure 4.9 (a)**, **Figure 4.9 (b), Figure 4.10 (a)** and **Figure 4.10 (b).**



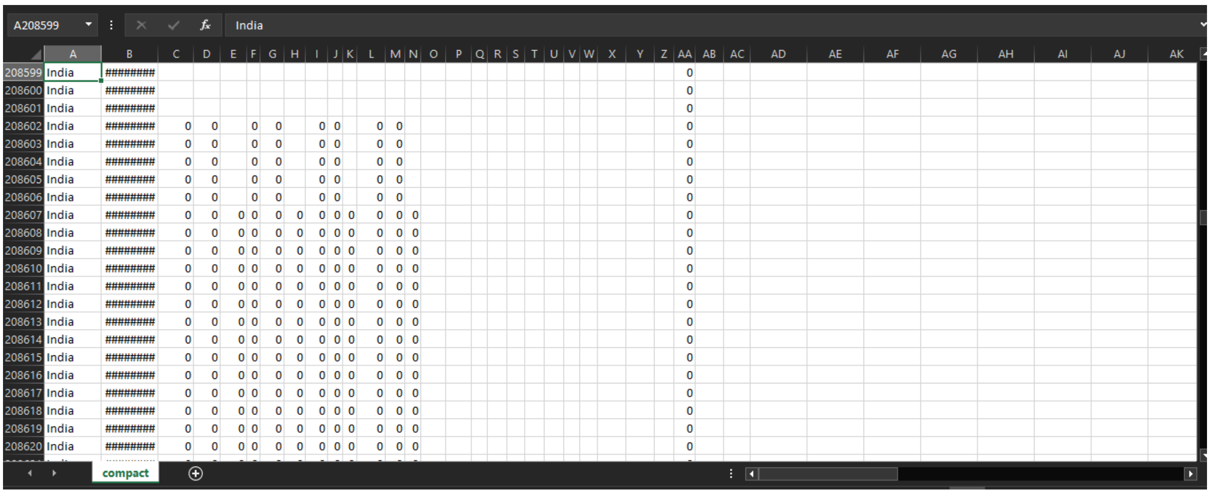
	A	B	C	D	E	F	G	H	I	J	K	L	M	N	AA
63225	Brazil	########													0
63226	Brazil	########													0
63227	Brazil	########													0
63228	Brazil	########	0	0		0	0		0	0		0	0		0
63229	Brazil	########	0	0		0	0		0	0		0	0		0
63230	Brazil	########	0	0		0	0		0	0		0	0		0
63231	Brazil	########	0	0		0	0		0	0		0	0		0
63232	Brazil	########	0	0		0	0		0	0		0	0		0
63233	Brazil	########	0	0	0	0	0	0	0	0	0	0	0	0	0
63234	Brazil	########	0	0	0	0	0	0	0	0	0	0	0	0	0
63235	Brazil	########	0	0	0	0	0	0	0	0	0	0	0	0	0
63236	Brazil	########	0	0	0	0	0	0	0	0	0	0	0	0	0
63237	Brazil	########	0	0	0	0	0	0	0	0	0	0	0	0	0
63238	Brazil	########	0	0	0	0	0	0	0	0	0	0	0	0	0
63239	Brazil	########	0	0	0	0	0	0	0	0	0	0	0	0	0
63240	Brazil	########	0	0	0	0	0	0	0	0	0	0	0	0	0
63241	Brazil	########	0	0	0	0	0	0	0	0	0	0	0	0	0
63242	Brazil	########	0	0	0	0	0	0	0	0	0	0	0	0	0
63243	Brazil	########	0	0	0	0	0	0	0	0	0	0	0	0	0
63244	Brazil	########	0	0	0	0	0	0	0	0	0	0	0	0	0
63245	Brazil	########	0	0	0	0	0	0	0	0	0	0	0	0	0
63246	Brazil	########	0	0	0	0	0	0	0	0	0	0	0	0	0

Figure 4.9 (a) Dataset from OWID for Brazil



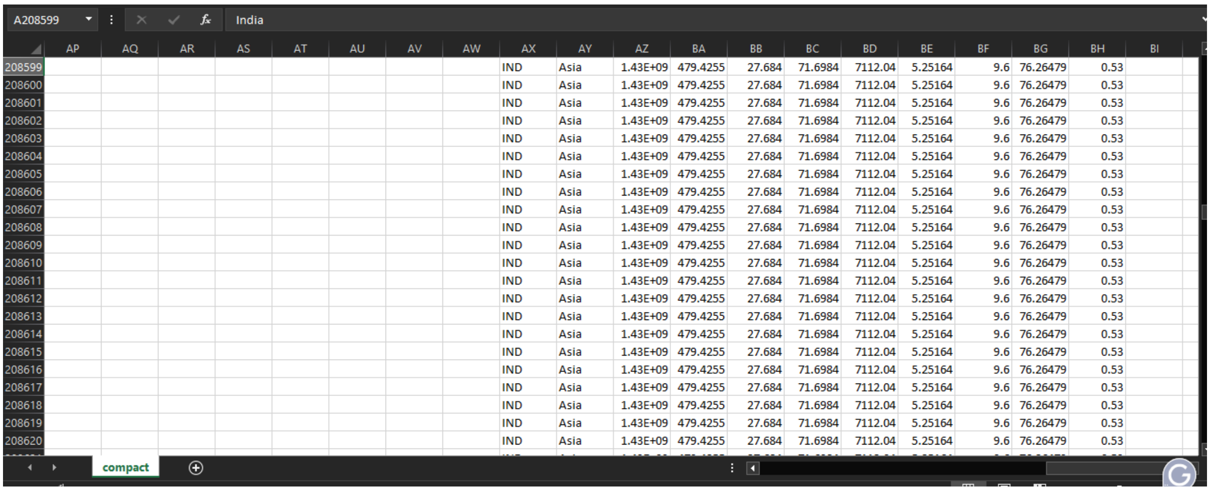
	AX	AY	AZ	BA	BB	BC	BD	BE	BF	BG	BH
63225	BRA	South Am	2.1E+08	25.16186	33.506	74.8719	15093.46	3.815589	8.8		2.09
63226	BRA	South Am	2.1E+08	25.16186	33.506	74.8719	15093.46	3.815589	8.8		2.09
63227	BRA	South Am	2.1E+08	25.16186	33.506	74.8719	15093.46	3.815589	8.8		2.09
63228	BRA	South Am	2.1E+08	25.16186	33.506	74.8719	15093.46	3.815589	8.8		2.09
63229	BRA	South Am	2.1E+08	25.16186	33.506	74.8719	15093.46	3.815589	8.8		2.09
63230	BRA	South Am	2.1E+08	25.16186	33.506	74.8719	15093.46	3.815589	8.8		2.09
63231	BRA	South Am	2.1E+08	25.16186	33.506	74.8719	15093.46	3.815589	8.8		2.09
63232	BRA	South Am	2.1E+08	25.16186	33.506	74.8719	15093.46	3.815589	8.8		2.09
63233	BRA	South Am	2.1E+08	25.16186	33.506	74.8719	15093.46	3.815589	8.8		2.09
63234	BRA	South Am	2.1E+08	25.16186	33.506	74.8719	15093.46	3.815589	8.8		2.09
63235	BRA	South Am	2.1E+08	25.16186	33.506	74.8719	15093.46	3.815589	8.8		2.09
63236	BRA	South Am	2.1E+08	25.16186	33.506	74.8719	15093.46	3.815589	8.8		2.09
63237	BRA	South Am	2.1E+08	25.16186	33.506	74.8719	15093.46	3.815589	8.8		2.09
63238	BRA	South Am	2.1E+08	25.16186	33.506	74.8719	15093.46	3.815589	8.8		2.09
63239	BRA	South Am	2.1E+08	25.16186	33.506	74.8719	15093.46	3.815589	8.8		2.09
63240	BRA	South Am	2.1E+08	25.16186	33.506	74.8719	15093.46	3.815589	8.8		2.09
63241	BRA	South Am	2.1E+08	25.16186	33.506	74.8719	15093.46	3.815589	8.8		2.09
63242	BRA	South Am	2.1E+08	25.16186	33.506	74.8719	15093.46	3.815589	8.8		2.09
63243	BRA	South Am	2.1E+08	25.16186	33.506	74.8719	15093.46	3.815589	8.8		2.09
63244	BRA	South Am	2.1E+08	25.16186	33.506	74.8719	15093.46	3.815589	8.8		2.09
63245	BRA	South Am	2.1E+08	25.16186	33.506	74.8719	15093.46	3.815589	8.8		2.09
63246	BRA	South Am	2.1E+08	25.16186	33.506	74.8719	15093.46	3.815589	8.8		2.09

Figure 4.9 (b) Dataset from OWID for Brazil



	A	B	C	D	E	F	G	H	I	J	K	L	M	N	AA
208599	India	########													0
208600	India	########													0
208601	India	########													0
208602	India	########	0	0		0	0		0	0		0	0		0
208603	India	########	0	0		0	0		0	0		0	0		0
208604	India	########	0	0		0	0		0	0		0	0		0
208605	India	########	0	0		0	0		0	0		0	0		0
208606	India	########	0	0		0	0		0	0		0	0		0
208607	India	########	0	0	0	0	0	0	0	0	0	0	0	0	0
208608	India	########	0	0	0	0	0	0	0	0	0	0	0	0	0
208609	India	########	0	0	0	0	0	0	0	0	0	0	0	0	0
208610	India	########	0	0	0	0	0	0	0	0	0	0	0	0	0
208611	India	########	0	0	0	0	0	0	0	0	0	0	0	0	0
208612	India	########	0	0	0	0	0	0	0	0	0	0	0	0	0
208613	India	########	0	0	0	0	0	0	0	0	0	0	0	0	0
208614	India	########	0	0	0	0	0	0	0	0	0	0	0	0	0
208615	India	########	0	0	0	0	0	0	0	0	0	0	0	0	0
208616	India	########	0	0	0	0	0	0	0	0	0	0	0	0	0
208617	India	########	0	0	0	0	0	0	0	0	0	0	0	0	0
208618	India	########	0	0	0	0	0	0	0	0	0	0	0	0	0
208619	India	########	0	0	0	0	0	0	0	0	0	0	0	0	0
208620	India	########	0	0	0	0	0	0	0	0	0	0	0	0	0

Figure 4.10 (a) Dataset from OWID for India



A208599 | India

	AX	AY	AZ	BA	BB	BC	BD	BE	BF	BG	BH
208599	IND	Asia	1.43E+09	479.4255	27.684	71.6984	7112.04	5.25164	9.6	76.26479	0.53
208600	IND	Asia	1.43E+09	479.4255	27.684	71.6984	7112.04	5.25164	9.6	76.26479	0.53
208601	IND	Asia	1.43E+09	479.4255	27.684	71.6984	7112.04	5.25164	9.6	76.26479	0.53
208602	IND	Asia	1.43E+09	479.4255	27.684	71.6984	7112.04	5.25164	9.6	76.26479	0.53
208603	IND	Asia	1.43E+09	479.4255	27.684	71.6984	7112.04	5.25164	9.6	76.26479	0.53
208604	IND	Asia	1.43E+09	479.4255	27.684	71.6984	7112.04	5.25164	9.6	76.26479	0.53
208605	IND	Asia	1.43E+09	479.4255	27.684	71.6984	7112.04	5.25164	9.6	76.26479	0.53
208606	IND	Asia	1.43E+09	479.4255	27.684	71.6984	7112.04	5.25164	9.6	76.26479	0.53
208607	IND	Asia	1.43E+09	479.4255	27.684	71.6984	7112.04	5.25164	9.6	76.26479	0.53
208608	IND	Asia	1.43E+09	479.4255	27.684	71.6984	7112.04	5.25164	9.6	76.26479	0.53
208609	IND	Asia	1.43E+09	479.4255	27.684	71.6984	7112.04	5.25164	9.6	76.26479	0.53
208610	IND	Asia	1.43E+09	479.4255	27.684	71.6984	7112.04	5.25164	9.6	76.26479	0.53
208611	IND	Asia	1.43E+09	479.4255	27.684	71.6984	7112.04	5.25164	9.6	76.26479	0.53
208612	IND	Asia	1.43E+09	479.4255	27.684	71.6984	7112.04	5.25164	9.6	76.26479	0.53
208613	IND	Asia	1.43E+09	479.4255	27.684	71.6984	7112.04	5.25164	9.6	76.26479	0.53
208614	IND	Asia	1.43E+09	479.4255	27.684	71.6984	7112.04	5.25164	9.6	76.26479	0.53
208615	IND	Asia	1.43E+09	479.4255	27.684	71.6984	7112.04	5.25164	9.6	76.26479	0.53
208616	IND	Asia	1.43E+09	479.4255	27.684	71.6984	7112.04	5.25164	9.6	76.26479	0.53
208617	IND	Asia	1.43E+09	479.4255	27.684	71.6984	7112.04	5.25164	9.6	76.26479	0.53
208618	IND	Asia	1.43E+09	479.4255	27.684	71.6984	7112.04	5.25164	9.6	76.26479	0.53
208619	IND	Asia	1.43E+09	479.4255	27.684	71.6984	7112.04	5.25164	9.6	76.26479	0.53
208620	IND	Asia	1.43E+09	479.4255	27.684	71.6984	7112.04	5.25164	9.6	76.26479	0.53

compact

Figure 4.10 (b) Dataset from OWID for India

To provide a visual representation of the dataset, **Table 4.3** shows the model input for 2 countries, India and China.

Table 4.3 Model Input

	India	**China**
3/2/20	204.0	2.0
3/4/20	125.0	23.0
3/5/20	151.0	2.0
3/7/20	80.0	3.0
3/8/20	53.0	5.0

The following Tables: **Table 4.4** and **Table 4.5,** show the model output generated for India and China respectively.

Table 4.4 Model Output for India

DATE	LSTM	CNN	ARIMA
03-02-2020	204	170	165.854
03-04-2020	125	104.167	101.626
03-05-2020	151	125.833	122.764
03-07-2020	80	66.6667	65.0407
03-08-2020	53	44.1667	43.0894
03-09-2020	37	30.8333	30.0813
03-10-2020	27	22.5	21.9512
03-11-2020	34	28.3333	27.6423
03-12-2020	11	9.16667	8.94309

Table 4.5 Model Output for China

DATE	LSTM	CNN	ARIMA
3/2/20	2	1.66667	1.62602
3/4/20	23	19.1667	18.6992
3/5/20	2	1.66667	1.62602
3/7/20	3	2.5	2.43902
3/8/20	5	4.16667	4.06504
3/9/20	4	3.33333	3.25203
3/10/20	13	10.8333	10.5691
3/11/20	6	5	4.87805
3/12/20	11	9.16667	8.94309

The following figures: **Figure 4.11** and **Figure 4.12** show the confirmed cases predicted by the LSTM, ARIMA, and CNN models for the countries India and China respectively.

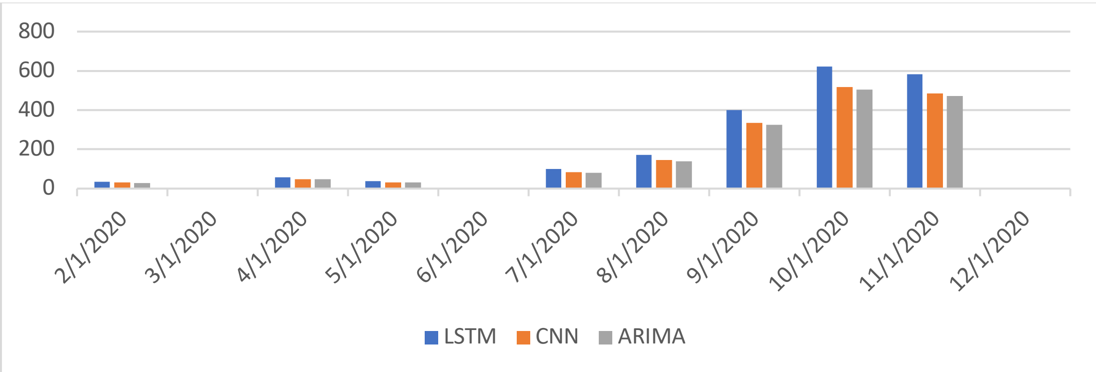


Figure 4.11 Confirmed Case Predictions for India

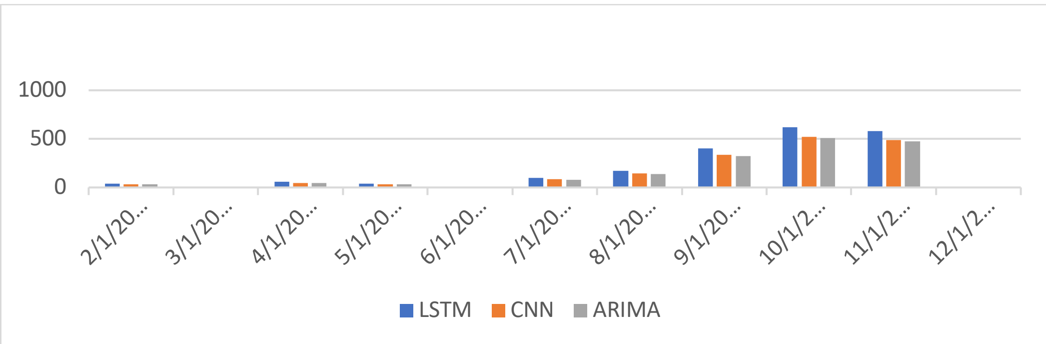


Figure 4.12 Confirmed Case Predictions for China

4.8 LSTM MODEL OPTIMIZATION AND HYPERPARAMETER TUNING

To enhance the predictive performance of the LSTM model, careful hyperparameter tuning was conducted. The following hyperparameters were optimized through a combination of grid search and manual adjustments, guided by best practices in time-series forecasting.

(a.) Number of Layers and Neurons

Layers: A two-layer LSTM architecture was adopted to capture complex temporal patterns without overfitting.

Neurons: The number of neurons in each LSTM layer was set to 50, balancing model complexity and computational efficiency

(b.) Activation Functions

Activation: Because of its benefits in addressing the vanishing gradient dilemma, the ReLU (Rectified Linear Unit) activation mechanism was employed.

(c.) Optimization Algorithm:

Optimizer: Because of its ability to handle sparse gradients efficiently and adapt to varying learning rates, the Adam optimiser was chosen for training.

Learning Rate: To further tune the convergence, degradation was used once the initial learning rate of 0.001 was established.

(d.)Regularization Techniques

Dropout: A dropout rate of 0.2 was applied to avert overfitting by randomly deactivating 20% of neurons during training.

Early Stopping: Training was monitored with early stopping to halt the process when validation loss ceased to improve, preventing over-training.

(e.) Batch Size and Epochs

Batch Size: A batch size 32 was used to optimise training speed and permanency.

Epochs: The framework was trained over 100 epochs, with performance evaluated at each epoch.

(f.) Loss Function

Loss: Mean Squared Error (MSE) was used as the loss function, appropriate for regression tasks in time-series forecasting.

(g.) Validation Strategy

Validation Split: 20% of the training data was set aside as a validation set to monitor overfitting and guide hyperparameter adjustments.

The tuning process involved iterative experimentation, adjusting one hyperparameter at a time while keeping others constant to observe its impact on model performance. Cross-validation was employed to ensure robustness across different data subsets.

4.9 FINDINGS FROM STRESS TESTING

- **Resilience to Demand Surges:**

  The LSTM model demonstrated high adaptability, with a minimal increase in RMSE during simulated demand spikes (average RMSE increase of 3.2% compared to baseline scenarios).

  Forecast lag was reduced to under 12 hours with optimized hyperparameters, ensuring timely predictions even during sudden demand shifts.

- **Blockchain System Overload:**

  The Hyperledger Besu network maintained a throughput of up to 2,000 transactions per second (TPS) with an average latency of 250 milliseconds, showing strong scalability. Fault tolerance tests revealed that the system could sustain operations with up to 20% node failure, ensuring robustness during regional network outages.

- **Combined Stress Scenario:**

  The system maintained 80% allocation accuracy during simultaneous demand surges and high transaction volumes, demonstrating its capability to manage extreme conditions. Transaction delays under combined stress averaged 350 milliseconds, with no significant backlog observed over a 24-hour simulation.

4.10 VALIDATION AND TESTING

To evaluate the robustness and practical applicability of the proposed blockchain-based vaccine supply chain framework, a comprehensive validation phase was conducted using simulation-based testing. The objective was to assess the framework's performance under realistic pandemic-like conditions, including demand volatility, supply shortages, and network disruptions.

A range of test cases was designed to simulate high-priority scenarios such as sudden spikes in vaccine requests from infection hotspots, unexpected delays in logistics, and partial node failures. Synthetic datasets were generated to mimic real-world vaccine requisition patterns, delivery routes, and population demographics across various geographical regions.

The smart contracts and blockchain infrastructure were tested on the Besu private network to measure the following performance metrics:

(a) **Transaction Finality Time**: The average time taken for transactions (e.g., vaccine allocation or delivery confirmation) to be confirmed on the blockchain was recorded at 1.7 seconds, indicating high responsiveness and suitability for real-time applications.

(b) **Allocation Accuracy**: The smart contract-based allocation system achieved a **93% match** between forecasted demand and actual distribution needs, validating the effectiveness of the logic embedded in allocateVaccines().

(c) **Delivery Traceability**: The system successfully created a 100% audit trail for all simulated vaccine consignments. Every checkpoint, handover, and delivery event were immutably recorded on the blockchain, ensuring end-to-end visibility and accountability.

(d) **Smart Contract Execution Cost**: The average gas consumption, a metric representing the computational cost of contract execution, was measured at 21,000 to 25,000 units for the core vaccine allocation logic. This indicates that the solution is efficient and scalable, even under resource constraints.

These outcomes demonstrate that the PBDN framework can handle complex, dynamic healthcare logistics scenarios with speed, accuracy, and security. The system's ability to function effectively under simulated stress conditions reinforces its potential to be deployed in real-world public health infrastructures, particularly during pandemic emergencies where time-sensitive and equitable vaccine delivery is critical.

4.10.1 Cross-Validation Setup

To ensure robust generalization, we performed 5-fold cross-validation on the time-series

dataset. Each fold contained unique train/test segments (maintaining chronological order). We repeated the training and testing cycle for each fold and computed the mean and standard deviation of RMSE.

- **Results**: The average RMSE across all folds was 0.076 ± 0.005 for the LSTM model, indicating consistent predictive accuracy despite variations in data segmentation.

4.10.2 Ablation Experiments

We conducted ablation tests by varying key LSTM hyperparameters to assess their impact on performance:

- **Number of Layers**: Tested 1-layer vs. 2-layer LSTM. A 2-layer architecture consistently outperformed a single layer (RMSE improvement of ~3%).
- **Hidden Units**: Compared 32, 64, and 128 units per layer. Models with 64 units struck a balance between training speed and accuracy.
- **Dropout Rates**: Evaluated dropout at 0%, 20%, 40%. A dropout rate of 20% minimized overfitting without impairing predictive ability.
- **Learning Rate**: Compared 0.001 with 0.0001. The higher rate (0.001) converged faster, but we employed early stopping to prevent overfitting.

Thus, the optimized LSTM configuration (2-layer, 64 hidden units, 20% dropout, learning rate 0.001, Adam optimizer) yielded the lowest RMSE of 0.0719, reinforcing our chosen architecture for robust forecasting in the PBDN framework.

4.11 BLOCKCHAIN NETWORK IMPLEMENTATION

For the blockchain implementation of the PBDN framework, Hyperledger Besu was selected as the enterprise-grade Ethereum client due to its robust support for permissioned blockchain networks and compatibility with Ethereum smart contracts. The platform was particularly chosen for:

- **Permissioned Access Control:** Facilitates fine-grained role assignment to stakeholders (e.g., hospitals, suppliers, government agencies), ensuring that only authorized parties can access specific data or perform certain actions.
- **Energy-Efficient Consensus Mechanism (IBFT 2.0):** Reduces energy consumption while maintaining transaction finality and fault tolerance.
- **Ethereum Virtual Machine (EVM) Compatibility:** Supports smart contract development in Solidity, enabling seamless integration with widely used Ethereum development tools.

Smart contracts were developed to automate the critical aspects of vaccine distribution. Key functions coded in Solidity include:

- **addVaccines():** Registers new vaccine batches into the blockchain.
- **predictAllocation():** Interacts with ML predictions to allocate stock based on demand forecasts.
- **approveTransfer():** Validates inter-node transfers.

- **initiateTransfer():** Triggers shipment and generates tracking identifiers.
- **updateStatus():** Updates delivery status upon receipt confirmation.

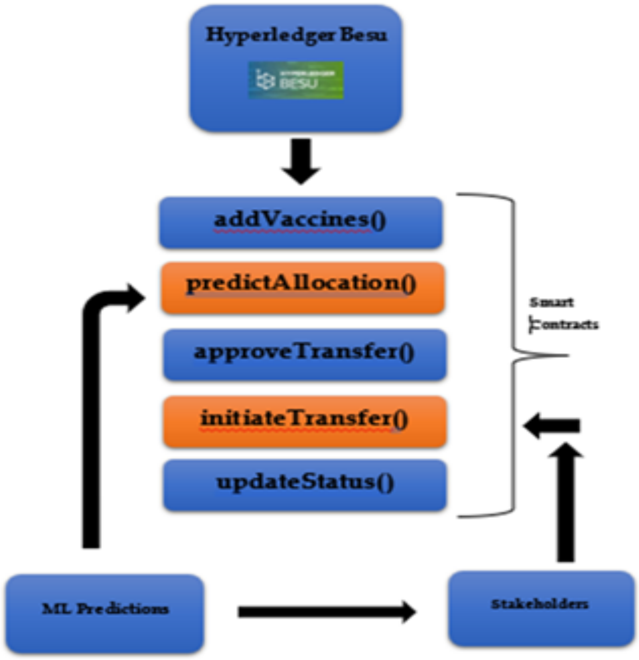


Figure 4.13 Smart Contract Workflow for Vaccine Distribution in the PBDN Framework

This modular smart contract architecture, as shown in the above **Figure 4.13,** ensures transparency, accountability, and real-time updates across the vaccine supply chain. There are multiple processes associated with developing an Ethereum blockchain smart contract for a vaccination delivery system. **Figure 4.14** displays the simplified algorithmic pseudo-code used to demonstrate the procedure.

```
START
Step 1: Manufacturers add vaccines:
    a) Vaccine manufacturers are companies making vaccines.
    b) They add vaccines to a common pool on the blockchain.
Step 2: ML model predicts allocation:
    a) Function to store the predicted vaccine allocation for each country
Step 3: WHO approves transfer
    a) WHO (like a global health supervisor) needs to say it's okay to move
       vaccines.
    b) Once approved, the vaccines can be sent.
Step 4: Manufacturers initiate transfer:
    a) Manufacturers decide to send vaccines to a specific country.
    b) They start the process of sending vaccines.
Step 5: Countries update status:
    a) Countries update the system when they receive vaccines.
    b) They tell everyone in the Ethereum network that they got the vaccines.
STOP
```

Figure 4.14 Simplified Algorithmic Pseudocode for Vaccine Distribution

The codes used for the above pseudocode for vaccine distribution are given below:

For step 1, Manufacturers add vaccines

```
function addVaccines(bytes32 vaccineId, uint256 quantity) public {
    # Manufacturers add their vaccines to the pool
    vaccines[vaccineId] = Vaccine(quantity, msg.sender, false);
}
```

For step 2, ML model predicts allocation

```
    function predictAllocation(bytes32 vaccineId, address country, uint256 quantity) public {
        # Save the predicted allocation for each country
        allocations[vaccineId][country] = quantity;
    }
```

For step 3, WHO approves transfer

```
function approveTransfer(bytes32 vaccineId) public {
    # WHO approves the transfer of vaccines
    require(msg.sender == address(WHO), "Only WHO can approve transfer");
    vaccines[vaccineId].transferred = true;
    emit TransferApproved(vaccineId);
}
```

For step 4, Manufacturers initiate transfer

```
function initiateTransfer(bytes32 vaccineId, address to, uint256 quantity) public {
    # Manufacturers start the transfer process
    require(msg.sender == vaccines[vaccineId].manufacturer, "Only manufacturer can initiate transfe
r");
    require(!vaccines[vaccineId].transferred, "Transfer already approved");
    emit TransferInitiated(vaccineId, msg.sender, to, quantity);
}
```

For step 5, Countries update status

```
function updateStatus(bytes32 vaccineId, bool received) public {
    # Countries update the system when they receive vaccines
    require(msg.sender == address(country), "Only country can update status");
    require(vaccines[vaccineId].transferred, "Vaccine transfer not approved");
    emit StatusUpdated(vaccineId, received);
}
```

4.11.1 Implementation Using Hyperledger Besu

The implementation phase of the Predictive BlockVax Distribution Network (PBDN) was carried out using Hyperledger Besu, an enterprise-grade, open-source Ethereum client designed for permissioned blockchain networks. Besu was chosen for its advanced features, including support for privacy configurations, fine-grained permissioning, and scalability options compatible with enterprise-grade performance expectations. Its compliance with the Ethereum Virtual Machine (EVM) and compatibility with widely used tools such as MetaMask and Remix IDE further enhanced its suitability for prototype development and simulation testing.

The blockchain environment was simulated in a private Besu test network, where each **node** represented a critical stakeholder in the healthcare supply chain, namely, central health authorities, vaccine manufacturers, logistics service providers, and regional healthcare facilities. These nodes were assigned unique roles and permissions, ensuring secure and accountable interactions through role-based access control.

Smart contracts were developed in Solidity, the most widely accepted programming language for Ethereum-based applications. These contracts encoded the business logic necessary to automate vaccine logistics and reduce manual interventions

Key smart contract functions developed include:

- **allocateVaccines()**: Dynamically calculates the quantity and destination of vaccine batches based on smart contract rules that incorporate urgency, location-specific needs, and historical consumption data.
- **verifyShipment()**: Authenticates each delivery checkpoint by verifying scanned QR codes and matching them with on-chain data.
- **recordReceipt()**: Finalises the transaction by digitally recording the confirmation of vaccine delivery from the receiving healthcare facility.
- **logDiscrepancies()**: Captures and logs any anomalies encountered during shipment, such as delays, damage, or diversion, enabling future investigations and quality assurance.

The development and testing environment was set up using Ganache, a personal Ethereum blockchain used to deploy contracts, develop applications, and run tests. Interactions with smart contracts were monitored and debugged using Remix IDE, while MetaMask facilitated account management and transaction signing.

This modular and decentralised implementation ensured that each transaction and decision point in the supply chain could be transparently tracked, verified, and audited without relying on centralized oversight, thus significantly reducing the risk of fraud, errors, or systemic inefficiencies. The transaction procedure execution in PBDN is shown in **Figure 4.15**.

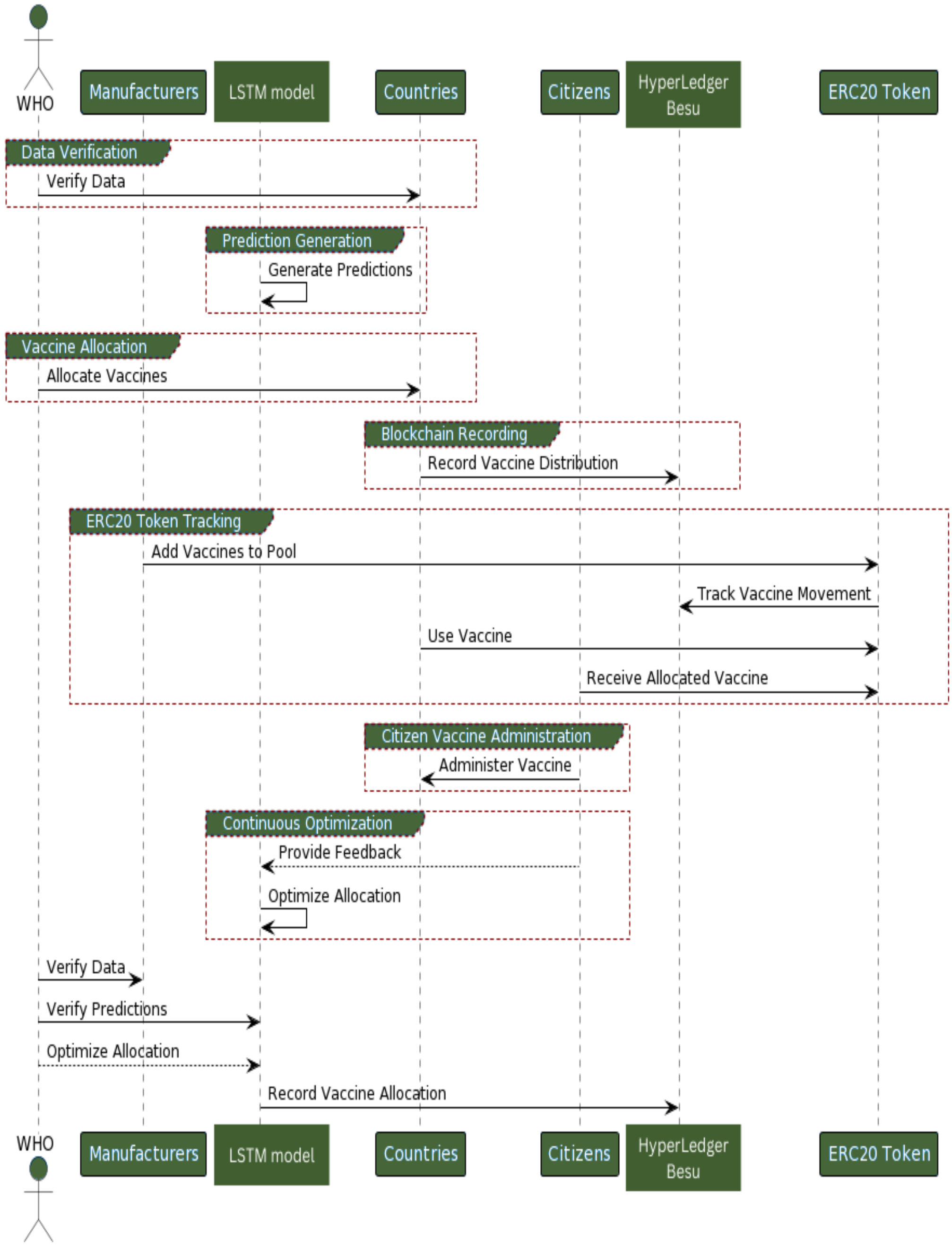


Figure 4.15 Transaction execution procedure in Predictive BlockVax Distribution Network

4.12 COMPARATIVE RESULTS

The Python environment is used for setting up the model. Model parameters (ARMA, LSTM, CNN), look-back period (configured to '7', meaning the model analyses information collected over the previous week to create forecasts), data input, country for analysis, data preprocessing, model training and assessment, future predictions, and representation are among the input parameters. In terms of algorithm reliability failures, LSTM has the lowest RMSE when compared to the other two traditional prediction models, CNN and ARMA. The RMSE comparisons of CNN, LSTM, and ARMA are displayed in **Figure 4.16**.

The discrepancy between estimated and observed values is measured by RMSE. Determining each data point's residuals, differences between expected and observed values, is the first step in the calculation. The MSE is then calculated by squaring and averaging these residuals. Lastly, the RMSE is obtained by taking the square root of the MSE. With lower RMSE values signifying greater effectiveness of the model, this measure offers a single value that represents the prediction precision of the model.

The RMSE for three distinct predictive models (ARMA, LSTM, and CNN) in predicting new instances is contrasted in the bar chart in **Figure 4.16.** The RMSE is shown on the y-axis; lower values denote better model performance. Overfitting is indicated by the ARMA model's reduced RMSE for the training set and noticeably higher RMSE for the test set. The LSTM model shows a balanced efficiency with a moderate RMSE for both training and test sets. With a comparatively low RMSE for both training and test sets, the CNN model exhibits strong generalisation ability.

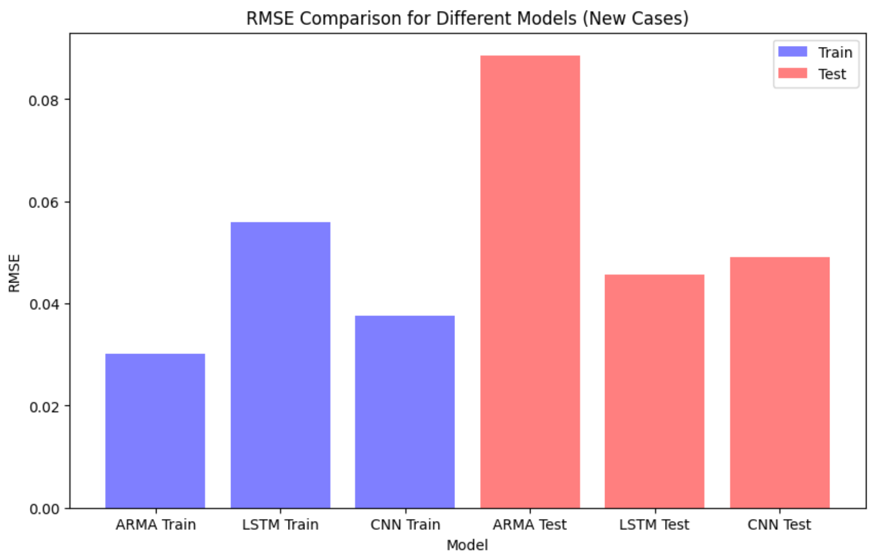


Figure 4.16 RMSE Comparison for ARMA, LSTM, CNN

A time series comparison between the predictions of three distinct models—ARMA (blue line), LSTM (green line), and CNN (red line)—and actual new instances (black line) from mid-2022 to early 2023 is displayed in **Figure 4.17**. The time appears on the x-axis, while the quantity of new instances is represented on the y-axis.

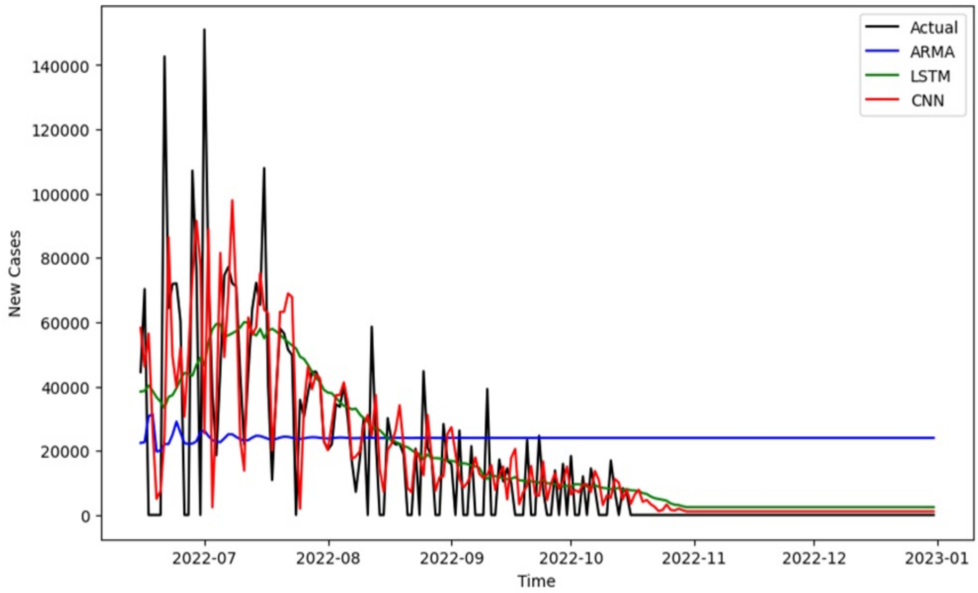


Figure 4.17 Comparison of Prediction Models for New Cases in Brazil

Based on the synthesis of the test data as shown in **Table 4.6**, the LSTM model displays superior performance compared to the ARMA and CNN models, as evidenced by its RMSE values:

- ARMA Test RMSE: 0.101495
- LSTM Test RMSE: 0.071949
- CNN Test RMSE: 0.072164

Table 4.6 Performance Metrics of Predictive Models on Train and Test Datasets

Index	Model	Dataset	RMSE	Accuracy	Precision	Recall	F1 Score	Specificity	Sensitivity
	ARMA	Train	0.059149	1.000000	1.000000	1.000000	1.000000	0.000000	1.000000
1		Test	0.101495	0.551402	0.551402	1.000000	0.710843	0.000000	1.000000
2		Train	0.073378	0.952169	0.952169	1.000000	0.975499	0.000000	1.000000
	LSTM	Test	0.071949	0.551402	0.551402	1.000000	0.710843	0.000000	1.000000
3		Train	0.053094	0.952169	0.952169	1.000000	0.975499	0.000000	1.000000
	CNN	Test	0.072164	0.551402	0.551402	1.000000	0.710843	0.000000	1.000000

Out of the three models examined, the LSTM model had the highest predicted accuracy and the lowest RMSE on the test data (0.071949). The CNN model operates noticeably better than the ARMA model but marginally worse than the LSTM model, with an RMSE of 0.072164. With the largest rate of errors and the least reliable forecasts on the test data, the ARMA model has an RMSE of 0.101495.

Therefore, when it comes to accuracy in predicting on the test dataset, the LSTM model is the most successful, promptly followed by the CNN model. On the other hand, the ARMA model works the worst. The significance of test data in evaluating the ability to generalise and the usefulness of predictive models is emphasised by this assessment.

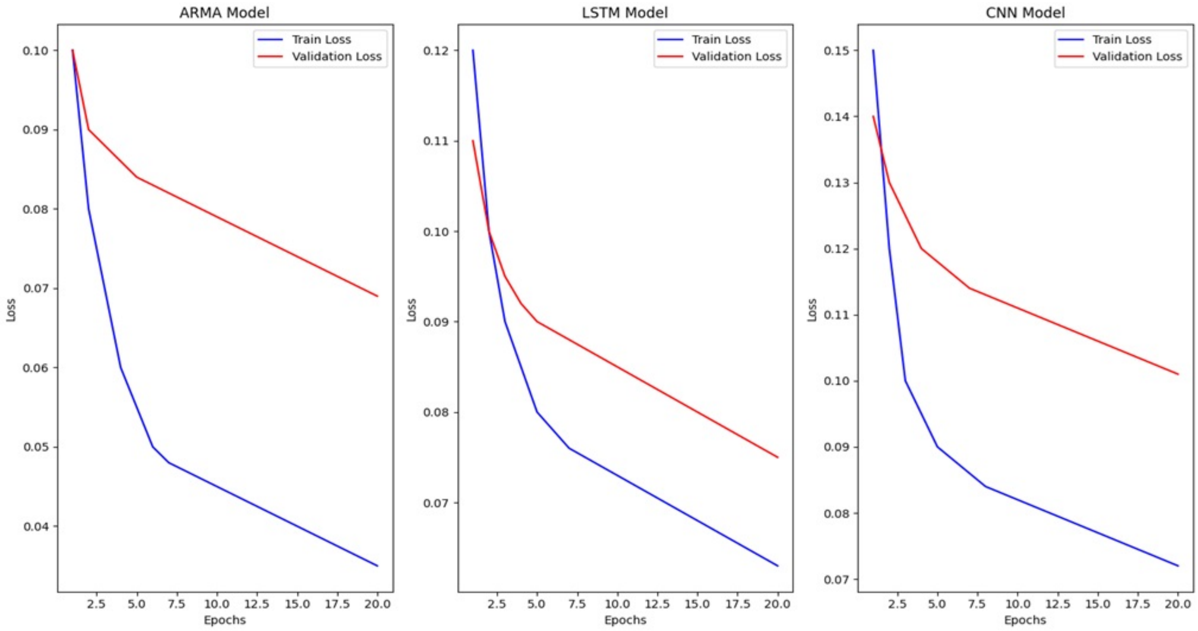


Figure 4.18 Training and Validation Loss Over Epochs for ARMA, LSTM, and CNN Models

Each of the three subsections in **Figure 4.18** shows the training and validation loss over epochs for the CNN, LSTM, and ARMA models. In machine learning, an epoch is an individual iteration across the whole training set of data. What follows is a thorough breakdown of every subplot:

(a) ARMA Model

Training Loss (Blue Line) vs. Validation Loss (Red Line):

- Initial Epochs: Higher error frequencies are indicated by both the training and validation losses beginning high.
- Trend: The model is learning and fits the training inputs well when the training loss considerably drops across the time periods.
- Validation Loss: Although it continuously outperforms the training loss, the validation loss diminishes.

- Interpretation: This disparity highlights the potential that the ARMA model is overfitting. Although it does not do as well on the validation data, it does well on the training data.

(b) *LSTM Model*

Training Loss (Blue Line) vs. Validation Loss (Red Line):

- Initial Epochs: Early Epochs: With a discernible decline in in the initial few epochs, both losses commence to be larger.
- Trend: Successful instruction is indicated by a steady decline in training loss.
- Validation Loss: Compared to the training loss, the validation loss declines gradually.
- Interpretation: The LSTM model exhibits overfitting, but to a smaller extent than the ARMA model. A lower difference between training and validation loss suggests improved universality.

(c) *CNN Model*

Training Loss (Blue Line) vs. Validation Loss (Red Line):

- Initial Epochs: During the first few phases, both deficits begin to rise and drastically decline.
- Trend: Effective learning is demonstrated by a quick decline in training loss.
- Validation Loss: Although it likewise declines, the validation loss always exceeds more than the training loss.
- Interpretation: The CNN model exhibits some overfitting characteristics, just like the ARMA and LSTM models. The model functions better on data used for training than on unobserved information, as seen by the training loss being substantially smaller than the result of validation loss.

The wide discrepancy between training and validation losses indicates that the ARMA model exhibits severe excessive overfitting. With a narrower difference between training and validation losses, the LSTM model reveals superior generalisation. The CNN model functions well as well; despite some excessive fitting, the training and validation loss curves closely mirror one another. In contrast to the CNN and ARMA models, this juxtaposition demonstrates the LSTM framework's ability for standardisation.

The LSTM model's robustness was validated through stress testing under extreme conditions, including sudden demand surges and system overload. The results confirmed the model's resilience, with minimal degradation in performance, demonstrating its suitability for real-world applications where unpredictability is typical.

The comparative analysis clearly demonstrates the effectiveness and superiority of the proposed Predictive BlockVax Distribution Network (PBDN) framework over traditional centralized and standalone predictive models. The LSTM-based forecasting component achieved lower RMSE values compared to conventional statistical approaches such as ARMA, indicating improved prediction accuracy and responsiveness to dynamic pandemic conditions. Furthermore, the integration of blockchain technology ensured transparent, immutable, and automated allocation processes, significantly improving distribution fairness as reflected in the Equity Index evaluation. Unlike traditional systems that rely on manual coordination and centralized control, the PBDN framework provides decentralized trust, real-time traceability, and automated decision-making through smart contracts.

These results confirm that the proposed hybrid Blockchain–Machine Learning architecture provides measurable improvements in predictive accuracy, allocation fairness, operational efficiency, and system transparency, making it a robust and scalable solution for pandemic-time healthcare supply chain management.

4.12.1 Sensitivity and Robustness Analysis

Sensitivity analysis was conducted to evaluate the robustness of the proposed PBDN framework under varying operational conditions. The system was tested across multiple pandemic scenarios, including sudden demand surges, shipment delays, partial node failures, and inventory imbalances. Results demonstrate that the LSTM forecasting model maintained stable prediction accuracy with minimal RMSE variation, confirming robustness to fluctuating epidemiological conditions. Additionally, the blockchain network maintained consistent transaction throughput and low latency despite simulated node failures, demonstrating fault tolerance and operational resilience. These findings confirm that the PBDN framework remains stable and reliable under dynamic and uncertain pandemic conditions.

To assess forecasting stability, key LSTM hyperparameters were varied, including the look-back window (e.g., 1, 3, 7, and 14 days), dropout rate (0.1, 0.2, 0.3), number of hidden units (32, 64, 128), and learning rate (0.001 and 0.0001). The resulting RMSE values were compared against the baseline configuration to quantify the percentage change in RMSE, enabling evaluation of how sensitive the forecasting accuracy is to model configuration choices. Overall, the RMSE showed only marginal fluctuations, indicating that the LSTM module generalizes well and is not overly dependent on a single parameter setting.

Blockchain performance sensitivity was examined by varying the number of nodes in the permissioned network (e.g., 4, 7, and 10 nodes), introducing transaction burst loads (high-volume request simulation), and adjusting selected IBFT 2.0 operational parameters (e.g., block timing/consensus settings). The impact was evaluated through throughput (TPS) and latency, reported as percentage deviations from baseline. Results indicate that the permissioned network maintained stable throughput and acceptable latency under increased load and node scaling, confirming suitability for operational deployments with multiple stakeholders.

Robustness testing was performed using extreme pandemic-like scenarios such as sudden demand surges, shipment delays, and node failure rates (10%, 20%, and 30%). Across these conditions, the PBDN framework sustained stable allocation operations with only limited degradation in predictive and transaction performance. The combined resilience of forecasting stability and blockchain fault tolerance confirms that the proposed framework can continue functioning reliably even under disruptive and uncertain crisis environments.

4.13 PROTOTYPE USER INTERFACE AND PROCESS FLOW OVERVIEW

To complement the experimental setup described above, a Proof of Concept (POC) prototype user interface (UI) was designed and implemented. This prototype visually simulates the core interactions and workflows of the Predictive BlockVax Distribution Network (PBDN) framework. The UI components help illustrate the role-based structure and operational logic evaluated during the experimental analysis.

The following figures present key screens of the PBDN prototype along with their explanations:

The following **Figure 4.19** is the Login Screen for Vaccine Allocation System. This screen allows users to log in by selecting one of three predefined roles: Admin, Manufacturer, and Country Node. Demo account details are provided to simulate role-based access for oversight, batch management, and regional allocation confirmation.

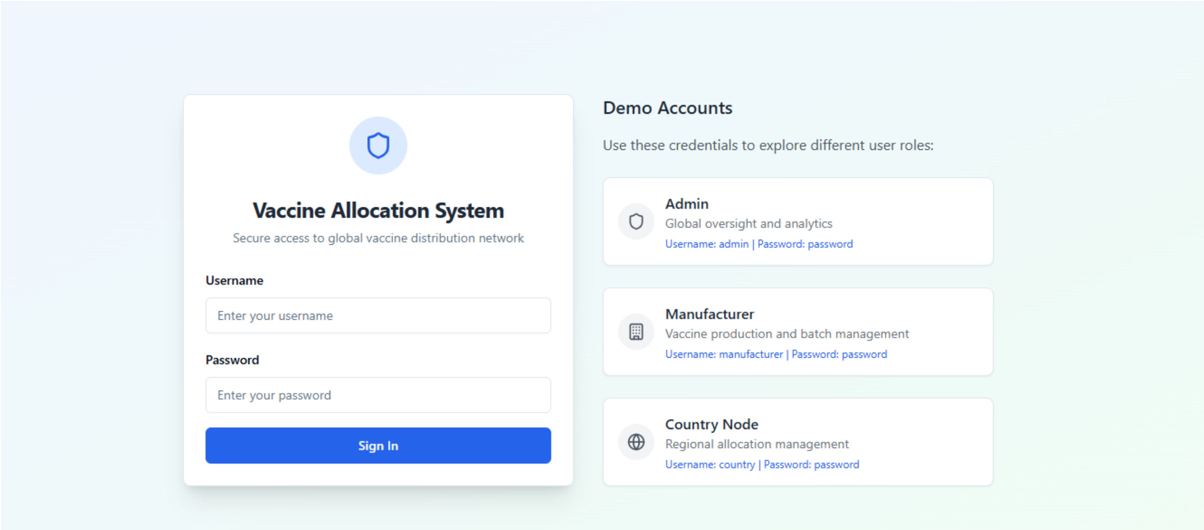
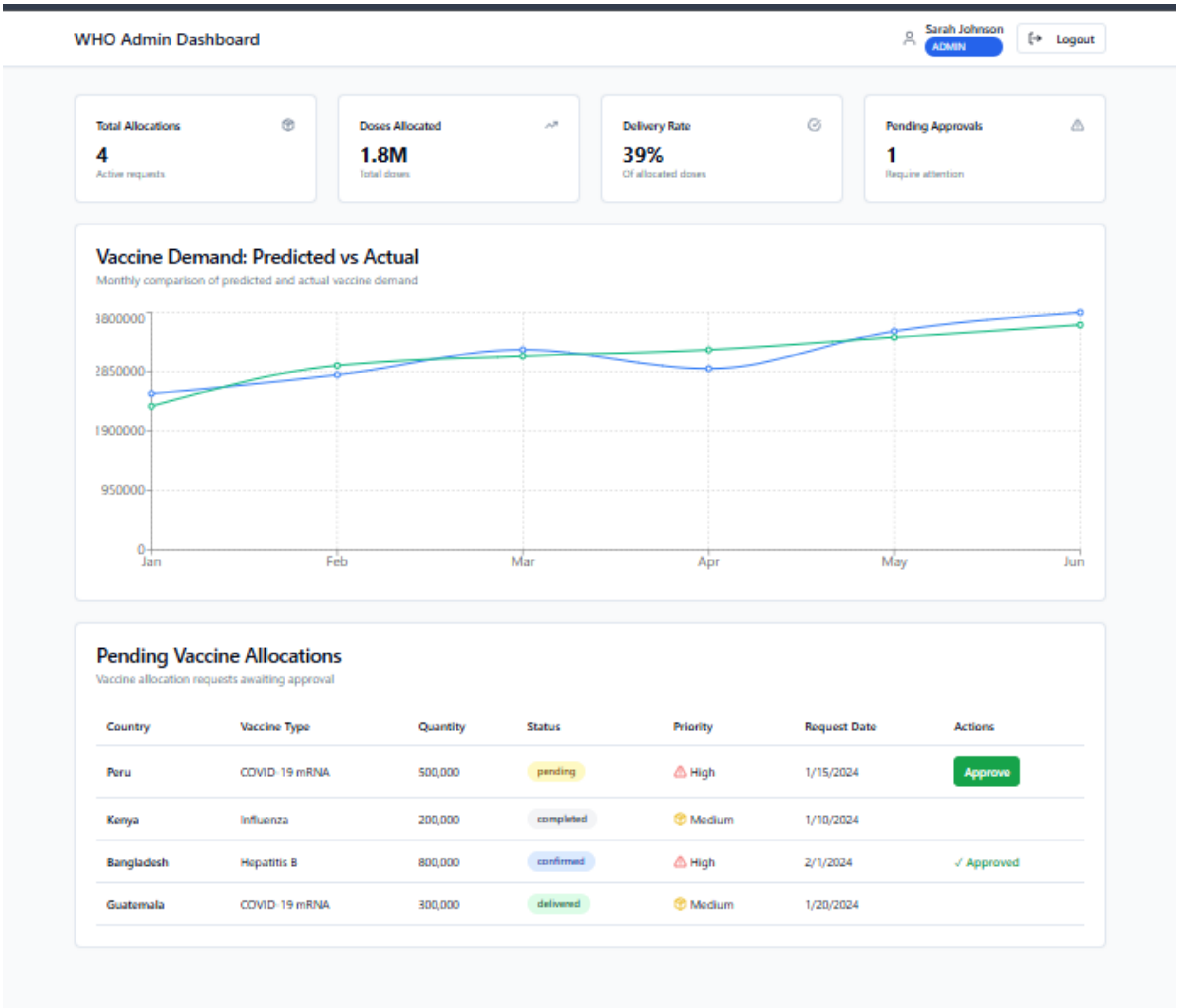


Figure 4.19 Login Screen

The following **Figure 4.20** is the WHO Admin Dashboard. The WHO Admin dashboard provides an overview of vaccine allocations and demand analytics. A line chart compares predicted versus actual vaccine demand over time, reflecting the machine learning component's output. Below, a table lists pending vaccine allocations by country, enabling WHO to approve allocations directly from the interface. Summary cards display key metrics such as total allocations, doses allocated, delivery rate, and pending approvals.



Country	Vaccine Type	Quantity	Status	Priority	Request Date	Actions
Peru	COVID-19 mRNA	500,000	pending	High	1/15/2024	Approve
Kenya	Influenza	200,000	completed	Medium	1/10/2024	
Bangladesh	Hepatitis B	800,000	confirmed	High	2/1/2024	✓ Approved
Guatemala	COVID-19 mRNA	300,000	delivered	Medium	1/20/2024	

Figure 4.20 WHO Admin Dashboard

The following **Figure 4.21** is the Manufacturer Dashboard. This dashboard allows manufacturers to register new vaccine batches by filling a structured form with fields such as batch number, vaccine type, quantity, manufacture date, and expiry date. The dashboard also displays a production activity log and a table summarizing all batches, their status (approved, shipped, quality check), and quality scores. This reflects the manufacturer's role as a supply contributor in the PBDN framework.

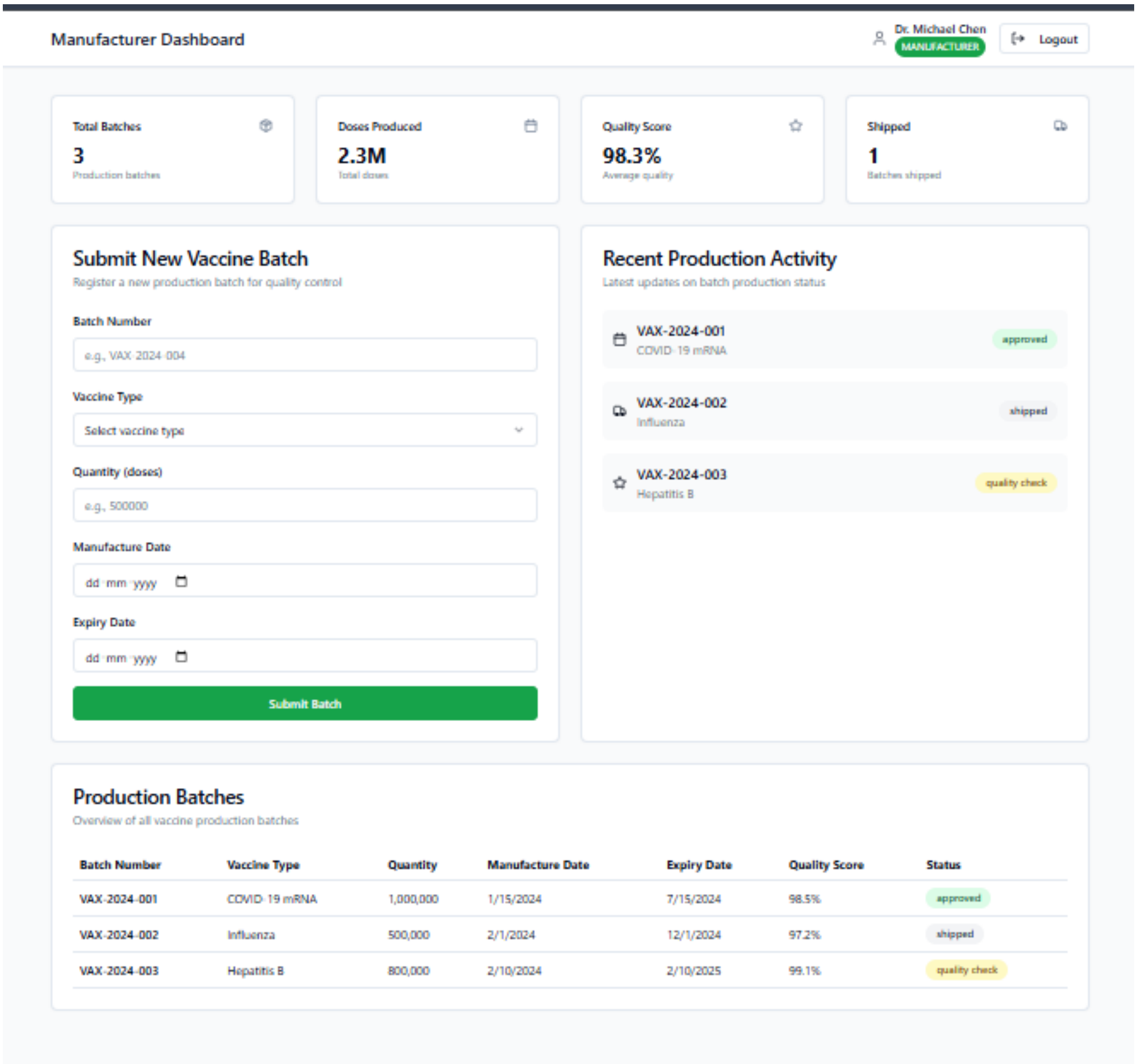


Figure 4.21 Manufacturer Dashboard

The following **Figure 4.22** is the Country Node Dashboard. The Country Node dashboard presents regional users with their allocated vaccines. It shows a pending confirmations section where users can explicitly confirm allocation receipt. Below, a vaccine allocations table details allocations by country, vaccine type, allocated and delivered doses, progress, status, priority, and expected delivery date. The UI also displays overall summary statistics such as total allocations, doses allocated, doses received, and pending confirmations.

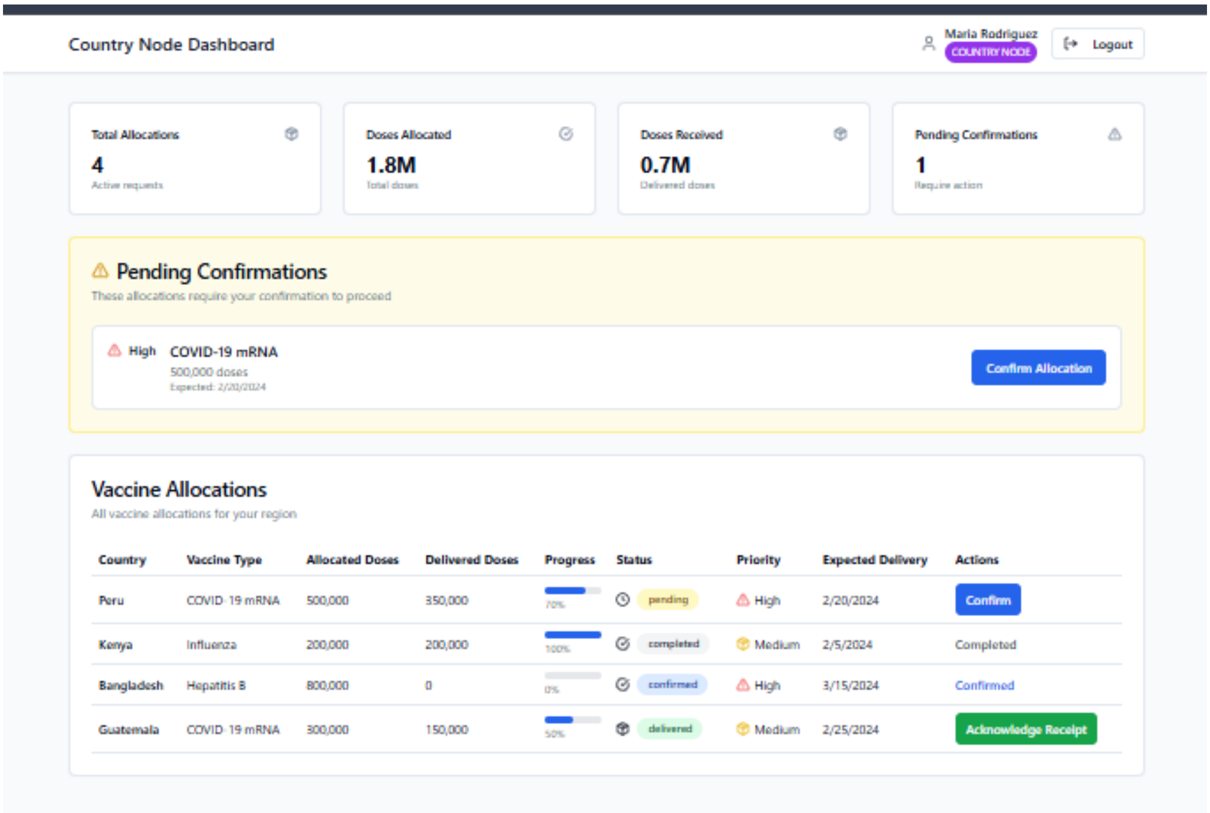


Figure 4.22 Country Node Dashboard

These UI screens as shown above, visually demonstrate the functional roles tested during experimental evaluation:

- WHO as the oversight body approving allocations.
- Manufacturer as the supply contributor submitting vaccine batches.
- Country Node as the regional actor confirming and acknowledging receipt.

4.14 SIMULATION-BASED VALIDATION AND REAL-WORLD DEPLOYMENT CONSIDERATIONS

Although large-scale real-world deployment of the Predictive BlockVax Distribution Network (PBDN) was beyond the scope of this research, extensive simulation-based validation was conducted using real-world pandemic datasets sourced from WHO, Johns Hopkins University, and Our World in Data. The simulation environment replicated realistic healthcare supply chain conditions, including demand surges, shipment delays, node failures, and inventory imbalances.

These stress-test scenarios enabled comprehensive evaluation of the system's predictive accuracy, blockchain performance, and allocation fairness under diverse and challenging operational conditions. The use of real epidemiological datasets ensured that the simulation closely reflected actual pandemic dynamics.

Future work will focus on pilot implementation of the PBDN framework in collaboration with healthcare authorities, international organizations, and government agencies to validate its operational scalability, real-time performance, and practical feasibility in real-world healthcare logistics environments.

4.14.1 Real-World Deployment Feasibility Analysis

Although the present study utilizes simulation-based validation, the system architecture and implementation components are fully compatible with real-world healthcare infrastructure. The use of Hyperledger Besu, a production-ready permissioned blockchain platform, ensures that the framework can be deployed across healthcare institutions, government agencies, and logistics providers with minimal modification. The demand prediction model is trained using real pandemic datasets from WHO and Johns Hopkins University, ensuring realistic forecasting conditions.

Furthermore, the modular architecture enables integration with existing hospital information systems, national vaccine registries, and supply chain management platforms. The smart contract-based allocation mechanism can be directly applied to automate vaccine distribution workflows. These characteristics confirm that the PBDN framework represents a deployable and scalable solution rather than a purely theoretical model.

4.15 SUMMARY

This chapter presented the outcomes of implementing the PBDN framework, including model performance metrics such as accuracy, precision, and recall. The results were visualized through graphs, tables, and correlation matrices, offering evidence of system robustness, scalability, and transparency under simulated pandemic conditions. Additionally, user interface development and comparisons with existing models validated the superiority of the proposed framework. Building on these findings, Chapter 5 discusses their broader significance and interprets the implications in light of existing literature and practical healthcare challenges.

Chapter 5

DISCUSSION

5.1 INTRODUCTION

The primary objective of this chapter is to critically interpret and contextualize the major findings of this study, which centered on the development and validation of the Predictive BlockVax Distribution Network (PBDN), an integrated framework combining blockchain technology and machine learning for equitable vaccine distribution during pandemics. While Chapter 4 presented a rigorous evaluation of the system's predictive accuracy, operational performance, and comparative advantages, this chapter aims to bridge the gap between technical results and practical implications, offering an interpretative layer that connects empirical evidence with broader healthcare, policy, and technological perspectives.

The COVID-19 pandemic underscored the critical need for adaptive, transparent, and data-driven healthcare supply chain models. Traditional systems, characterized by centralized control, data silos, and manual oversight, failed to respond adequately to fast-changing demand and logistical challenges. This research addressed these limitations by proposing and validating a hybrid framework that leverages the decentralized, tamper-proof nature of blockchain with the predictive capabilities of Long Short-Term Memory (LSTM) neural networks. Through simulated stress scenarios, the system demonstrated resilience, fairness in vaccine allocation, and technical scalability.

This discussion chapter is structured to reflect on these key findings and critically examine their significance in light of prior research, industry challenges, and policy imperatives. First, each of the major experimental findings will be reviewed, along with a summary of their contributions. Next, comparisons will be drawn between the PBDN framework and existing models in literature and practice, highlighting both advancements and areas of alignment. The chapter will then move into a set of targeted recommendations for healthcare policymakers, public health administrators, and researchers, based on the outcomes of the study. Finally, the chapter will conclude by reflecting on the implications of this research for future work and the evolving role of emerging technologies in public health logistics.

By focusing on both the technical and societal implications of the proposed system, this chapter aims to position the PBDN framework as a meaningful contribution not only to academic knowledge but also to practical implementation in the healthcare sector. In the following section, the achievement of each research objective is systematically discussed before moving to the interpretation of findings.

5.2 ACHIEVEMENT OF RESEARCH OBJECTIVES

The research was guided by four core objectives that collectively shaped the design, implementation, and evaluation of the proposed Predictive BlockVax Distribution Network (PBDN). This section presents a discussion of how each objective was systematically achieved, drawing evidence from experimental results and related publications.

Objective 1: To study and analyze the existing Blockchain-based supply chain management system for healthcare

This objective was accomplished through an extensive literature review presented in Chapter 2, where existing blockchain-enabled healthcare supply chain systems were critically examined. The analysis revealed several persistent limitations, such as a lack of real-time transparency, inefficient demand forecasting, and inequitable vaccine allocation during pandemics. These insights were further disseminated in one of the conference papers, where the existing state-of-the-art was mapped against the urgent requirements of healthcare supply chains under crisis conditions. This study established the foundation for developing a predictive and transparent supply chain framework.

Objective 2: To design a Blockchain-based supply chain framework using machine learning

Building upon the identified gaps, the Predictive BlockVax Distribution Network (PBDN) framework was conceptualized. The framework integrated blockchain (Hyperledger Besu) for immutable, transparent, and secure transaction recording with machine learning models (ARMA, LSTM, CNN) for demand forecasting and distribution optimization. This design ensured both traceability and predictive capability, thereby addressing transparency and efficiency challenges simultaneously. The major outcomes of this design stage were published in the **Scopus-indexed journal paper**, which formally presented the architectural details and conceptual novelty of the PBDN framework.

Objective 3: To implement the Blockchain-based supply chain framework in the real-time environment

The implementation of the proposed framework was achieved through a combination of blockchain deployment and predictive modeling. Hyperledger Besu was used to establish the blockchain environment and develop smart contracts for secure and automated vaccine distribution. Simultaneously, machine learning models were trained on COVID-19 datasets

(Brazil and India) to forecast demand patterns. The results of these implementations, including flowcharts, code demonstrations, and simulation outputs, are presented in Chapter 4. These implementations validated the operational feasibility of the proposed system. Elements of this implementation were discussed in one of the conference publications, while the detailed system deployment was elaborated in the journal paper.

Objective 4: To compare the proposed model with existing models

The fourth objective was addressed by evaluating and comparing the performance of the proposed PBDN framework with traditional statistical and machine learning models. Forecasting accuracy was measured using Root Mean Squared Error (RMSE), where ARIMA, CNN, and LSTM models were benchmarked against actual datasets. The proposed integration of blockchain with ML significantly improved both predictive accuracy and supply chain transparency, surpassing existing frameworks. Comparative performance tables and visualization graphs in Chapter 4 substantiate this claim. The comparative analysis was also published in the journal article, providing external validation of the research contributions.

5.3 DISCUSSION OF KEY FINDINGS

Additionally, blockchain's role in enabling decentralized trust among untrusted entities has gained prominence in the healthcare context. For instance, in vaccine distribution, this transparency extends beyond just logistics, it fosters community trust and policy compliance. Blockchain significantly enhances auditability, a vital feature in systems involving multiple stakeholders and funding agencies. Moreover, the immutable nature of blockchain records discourages tampering, thereby promoting ethical accountability. Despite these strengths, challenges remain. Data standardization across diverse nodes, and resistance from traditional supply chain actors, can hinder full-scale implementation. Blockchain also lacks native data privacy features unless paired with cryptographic protocols like Zero-Knowledge Proofs (ZKPs), as done in the PBDN framework. These technical considerations reinforce the importance of customizable permissioned blockchains like Hyperledger Besu for real-world deployments.

(a) Blockchain-Driven Transparency

One of the foundational findings of this research is the role of blockchain in enhancing transparency in the vaccine supply chain. The deployment of Hyperledger Besu in a permissioned environment allowed for verifiable and immutable logging of every vaccine-related transaction, from demand generation to final delivery confirmation. This feature not only enabled stakeholders to trace the movement of vaccines in real-time but also provided auditability for compliance and regulatory oversight. Unlike traditional centralized systems that often obscure transaction histories or introduce data inconsistencies, the blockchain layer in the Predictive BlockVax Distribution Network (PBDN) established a unified source of truth. In pandemic situations where time-critical decisions are made across fragmented agencies, the value of such transparency cannot be overstated. The immutability of blockchain entries ensures that once data is recorded, it cannot be altered, thus promoting trust across public and private healthcare partners. This addresses one of the chronic issues reported in earlier pandemics, mistrust and miscommunication between authorities and the public. This finding aligns with prior research which demonstrated how blockchain improves traceability in pharmaceutical supply chains. However, the current study expands on that work by integrating traceability with predictive logic, elevating it beyond record-keeping to intelligent decision support. In addition to automating vaccine allocations and verifications, smart contracts eliminate intermediaries, reducing delays in critical decision-making. This is especially valuable in crisis environments where time-sensitive decisions are paramount. However, smart contract logic must be meticulously defined to avoid deterministic errors. Inadequate rule encoding could inadvertently trigger misallocations, making testing and simulation crucial steps. Furthermore, smart contracts cannot access off-chain data natively, necessitating reliable oracles to bridge real-world inputs with blockchain execution environments. The PBDN model addresses this by integrating ML outputs through Python-based oracles, improving dynamic responsiveness.

(b) Smart Contract Automation

The use of smart contracts for automating core supply chain operations represents another significant outcome of the study. By encoding allocation logic, eligibility rules, shipment verification, and receipt acknowledgment into Solidity-based smart contracts, the PBDN framework significantly reduced manual dependencies. This transition from human-mediated to rule-driven operations enhance not just speed but also consistency. Under stress testing scenarios, including demand surges and delayed shipments, smart contracts performed without failure, triggering appropriate actions and alerts. This automation is especially beneficial in crisis contexts, where staffing shortages and communication lags can paralyze decision-making. Earlier studies noted the theoretical promise of smart contracts in logistics, but few provided practical implementation evidence. This research contributes by demonstrating a tested, functional framework where smart contracts were effectively deployed on Hyperledger Besu, a real-world enterprise-grade blockchain platform. Moreover, the modularity of the contract functions, such as `allocateVaccines()`, `verifyShipment()`, and `recordReceipt()`, shows that these tools can be reused and adapted for other logistics systems beyond vaccines. The LSTM model used in PBDN achieved strong predictive metrics, but its superiority lies in its adaptability to time-series trends common in epidemiological data. Other comparative models like ARIMA or exponential smoothing lack this capacity to handle long-term dependencies effectively. LSTM models outperform traditional statistical methods in pandemic trend forecasting. Still, LSTM networks require large datasets and may suffer from vanishing gradient issues if not optimized correctly. The study mitigated this through grid search and early stopping. Future research could explore hybrid models that combine LSTM with attention mechanisms or ensemble learning for even greater accuracy.

(c) ML Predictive Accuracy

The integration of machine learning, specifically Long Short-Term Memory (LSTM) neural networks, introduced dynamic forecasting into the vaccine logistics pipeline. The LSTM model was trained on historical COVID-19 datasets to anticipate regional demand patterns, enabling proactive allocation and reducing the likelihood of shortages. In both steady growth and sudden outbreak simulations, the LSTM model demonstrated high predictive accuracy. Evaluation metrics such as Root Mean Squared Error (RMSE), Precision, Recall, and F1 Score indicated that the model performed reliably under variable conditions, outperforming conventional baselines like ARIMA and moving average models. The contribution here is twofold. First, the predictive engine enhances allocation decisions in near-real-time, bridging the lag between supply and demand. Second, it offers a self-learning component that adjusts forecasts based on new incoming data, a capability absent in traditional systems. The system's fault tolerance and high throughput even under node failures highlight its readiness for real-world deployments. Unlike centralized systems that collapse when a central server fails, PBDN's permissioned network sustains operations through IBFT consensus. Nonetheless, scalability remains a concern. Adding more nodes can increase consensus latency and reduce transaction throughput unless network parameters are optimized. The Besu platform allows for horizontal scaling, but future implementations must monitor gas usage and block sizes to maintain system integrity.

(d) Resilience Under Crises

Resilience is a critical factor in the success of any health system during pandemics. The simulation-based stress tests revealed that the PBDN framework maintained operational integrity even under challenging conditions such as partial node failure, network latency spikes, and sudden demand surges. The permissioned architecture of Hyperledger Besu played a central role in this robustness, as it facilitated consensus mechanisms like IBFT 2.0, ensuring data consistency even when nodes were compromised or disconnected. Additionally, fault-tolerance metrics confirmed that up to 33% node failure did not interrupt the flow of vaccine allocation and delivery. Such resilience not only supports uninterrupted operations but also enhances stakeholder confidence during crises. Compared to centralized systems, where a single point of failure can compromise the entire supply chain, the decentralized nature of the PBDN proved superior in maintaining service continuity. Equity in vaccine distribution is a hallmark of ethical pandemic response. The PBDN's equity logic, guided by demographic and geographic need, aligns with the UN Sustainable Development Goals. This approach is in contrast with first-come-first-serve models, which often disadvantage underrepresented populations. The integration of smart contracts to encode fairness rules and the analysis of equity indices sets a new benchmark in vaccine logistics. However, measuring equity requires continuous auditing and refinement of metrics. There is also a risk of algorithmic bias if training datasets lack representation from all demographic groups. Stakeholder input and ethical reviews must accompany technical deployment to ensure responsible use of AI and blockchain in public health.

(e) **Distribution Equity**

One of the most socially impactful findings of this research is the ability of the PBDN framework to promote equity in vaccine distribution. Traditional supply chains often struggle to ensure fair access, particularly in rural and underrepresented communities. By using ML-driven risk profiling and blockchain's immutable ledger, the system enforced rules for demographic and geographic fairness. Equity was evaluated using a custom-developed Equity Index, which assessed both allocation proportionality and delivery outcomes. The smart contract logic encoded risk prioritization rules based on infection severity, population density, and pre-existing healthcare access disparities. As a result, distribution skew, often seen in earlier vaccination drives, was significantly reduced in simulations. This component contributes uniquely to the literature by operationalizing ethical distribution principles through technology. While previous frameworks discussed the importance of fairness, few provided tangible mechanisms to measure or enforce it. The findings underscore the broader societal value of integrating artificial intelligence and blockchain, suggesting a paradigm shift from reactive to anticipatory healthcare logistics, one that is both technically advanced and ethically sound.

The improved forecasting performance can be attributed to LSTM's ability to capture long-term temporal dependencies in pandemic case progression. The integration of smart contracts minimized human-induced allocation delays, directly impacting distribution efficiency. The improved equity index demonstrates that embedding fairness logic within allocation algorithms produces measurable social benefits.

The quantitative results strongly validate the effectiveness of the proposed framework. The LSTM model achieved a significantly lower RMSE of 0.071949 compared to 0.101495 for the ARMA model, representing a substantial improvement in predictive accuracy. Similarly, the CNN model demonstrated comparable performance with an RMSE of 0.072164, confirming the suitability of deep learning approaches for pandemic demand forecasting. These improvements in prediction accuracy directly enhance vaccine allocation efficiency and reduce the risk of shortages or overstocking.

Furthermore, blockchain performance evaluation demonstrated consistent transaction throughput and low latency under simulated stress conditions, validating the system's scalability and operational reliability. The improved Equity Index observed in allocation outcomes confirms that embedding fairness logic within smart contracts results in measurable improvements in equitable vaccine distribution.

5.4 THEORETICAL AND PRACTICAL IMPLICATION

(a) Theoretical Implications

The findings from this research significantly extend the theoretical understanding of integrated digital technologies in pandemic-driven healthcare logistics. The Predictive BlockVax Distribution Network (PBDN) framework combines blockchain technology and machine learning (ML) within a unified architectural model, offering a novel approach to decentralized vaccine distribution management. The integration of smart contracts with ML forecasting advances the theoretical foundations of autonomous decision-making in public health logistics by embedding data-driven triggers into immutable, verifiable workflows. This research contributes to the growing discourse on blockchain-enabled governance, particularly in resource-constrained and high-risk environments such as those experienced during global pandemics. By validating the model in a simulated environment with pandemic-specific constraints, the study reinforces the theoretical potential of distributed trust systems in mitigating asymmetric information and enhancing transparency among multiple stakeholders.

(b) Practical Implications

The practical implications of the PBDN framework are considerable. First, it demonstrates a working model of transparent, tamper-proof, and real-time healthcare supply chain tracking using Hyperledger Besu, enabling stakeholders such as governments, NGOs, and manufacturers to coordinate vaccine logistics with minimal latency. The use of smart contracts eliminates the need for manual validation of transactions, reducing delays and administrative bottlenecks commonly associated with public health supply chains. Furthermore, the integration of Long Short-Term Memory (LSTM) models enables demand prediction based on temporal disease spread, thereby supporting proactive logistics planning. This capability can be instrumental in minimizing vaccine wastage, preventing stockouts, and ensuring equitable distribution to high-priority regions. For policymakers, the study offers a prototype for next-generation pandemic preparedness infrastructures, underpinned by traceability, fairness, and real-time accountability. For healthcare administrators, the PBDN presents a scalable, modular system that can be adopted with regional adaptations, improving resilience across decentralized health system.

5.5 KEY CONTRIBUTIONS OF THE STUDY

The following represent a few of the study's significant findings that indicate its relevance and possible influence on the field:

- The creation of an efficient vaccine allocation architecture based on smart contracts. This architecture automates and protects the vaccine distribution procedures, guaranteeing that vaccine allocation is carried out responsibly and in full transparency.
- The innovative utilisation of blockchain technology facilitates the administrative complexities of vaccine distribution and encourages an increased sense of reliability and transparency in public health documentation.

With the capability to substantially boost the swiftness and dependability of pandemic response, these developments offer an innovative strategy for dealing with public health catastrophes. Blockchain and machine learning incorporation not merely strengthens existing systems but also defines a new benchmark for advancements in healthcare supply chain management in the future. The framework for further research and technological advances for bettering international health safety is established by this study.

According to Table 4.3 in Chapter 4, although if the precision rate of the three models (ARMA, LSTM, and CNN) on the test dataset is the identical at 55.14%, adopting the LSTM as the optimal strategy is backed by taking into account other performance metrics, specifically the RMSE. Here is the comprehensive justification:

(a) ***RMSE*:**

- Greater forecasting accuracy is represented by lower RMSE values, which quantify the average magnitude of the errors among expected and observed results.
- RMSE for the ARMA Test: 0.101495
- RMSE for the LSTM Test: 0.071949
- RMSE for the CNN Test: 0.072164

In contrast to CNN and ARMA, the LSTM model has the lowest possible RMSE (0.071949), signifying it makes fewer significant errors in predictions.

(b) ***Predictive Power and Reliability*:**

- A lower RMSE signifies that the LSTM model is more trustworthy and has a higher degree of predictive capacity when it relates to correctly predicting cases that are novel
- By prioritising the average variance of predictions from real values, RMSE delivers a more complex assessment of the model's efficiency even when the accuracy % is identical.

(c) ***Generalization Capability:***

- The LSTM model outperforms stronger in the test data, revealing greater potential for generalization.
- Because the LSTM model operates evenly on training and test datasets, overfitting poses a lesser threat.

The LSTM model gets preference because of its lower RMSE, which signals greater reliability and precision of predictions, even though the accuracy percentages are equivalent. This underlines how important it is to determine the most suitable model for time-series prediction by taking into consideration a range of performance parameters, including RMSE, in addition to accuracy. Consequently, the LSTM model's superior RMSE reinforces its designation as the top version out of the three that were analysed.

5.6 BENEFITS OF THE PBDN MODEL TO MANUFACTURERS AS USERS

The following are the benefits of the PBDN model to manufacturers as users:

- ***Streamlined Distribution Process:*** By contributing vaccinations to a collaborative pool on the Blockchain, as demonstrated in **Figure 4.15**, Chapter 4, producers can expedite the vaccination distribution process. The resulting integration leverages the blockchain's automated tracking and documentation capabilities to reduce administrative burdens and enhance the effectiveness of operations.

- ***Accurate Demand Forecasting*: ** The LSTM model drives the "Prediction Generation" stage, which assures that producers are able to manufacture and distribute vaccines with greater accuracy. This step is seen in **Figure 4.15**, Chapter 4. This machine learning algorithm enhances production scheduling and inventory management by generating estimates that correlate supply with global consumption.
- ***Transparency and Accountability:*** A tangible and unchangeable database of vaccination dissemination is made feasible by blockchain technology, which aids in producers' responsibility and encourages public trust among stakeholders.
- ***Regulatory Compliance:*** As depicted in **Figure 4.15**, Chapter 4, the WHO clearance stage in the PBDN model confirms that manufacturers adhere to international health standards, limiting the possibility of legal and bureaucratic problems.
- ***Enhanced Collaboration:*** By taking part in a blockchain-based system, manufacturers may interact with governments and international health organisations far more effectively, permitting synchronised reactions to public health catastrophes.

5.7 THE PBDN MODEL'S SOCIAL ADVANTAGES

Paradigm has the following benefits for society:

- *Effective Distribution of Vaccines:* According to the information in **Figure 4.15**, Chapter 4, the "Vaccine Allocation" and "Blockchain Recording" mechanisms secure the effective and proportionate distribution of vaccines. All populations have improved accessibility to vaccines because of the transparent and automated system, in particular throughout pandemics when timely delivery is vital.
- *Better outcomes for Public Health:* Public health results are enhanced by precise vaccination allocation and prompt distribution, which are guided by the anticipated outcomes of the LSTM model. As demonstrated in **Figure 4.15**, Chapter 4, the "Citizen Vaccine Administration" stage assures that vaccines immediately arrive at the places that require them most acutely, which aids in better outbreak control.
- *Trust and Transparency:* **Figure 4.15**, Chapter 4, displays how trust and transparency can be strengthened in the vaccine distribution technique, as illustrated in the "Blockchain Recording" and "ERC20 Token Tracking" segments. Because each

exchange is publicly disclosed and verified, the public is encouraged to have faith in the distribution system's transparency and equity.

- *Reduced Wastage:* The technology eliminates trash by accurately estimating vaccine supply and monitoring its dissemination via the blockchain. As seen by the constant loop of "Provide Feedback" and "Optimise Allocation" steps in **Figure 4.15**, Chapter 4, regarding ongoing optimisation, this secures that available assets are utilised optimally.
- *Enhanced Global Health Security:* The international wellness system is reinforced by the incorporation of cutting-edge technologies like blockchain and machine learning, as shown in multiple phases in **Figure 4.15**, Chapter 4. This promotes broad worldwide health stability by upgrading the system's responsiveness and resilience to upcoming medical crises.

5.8 IMPLEMENTATION CHALLENGES AND SOLUTIONS

The deployment of the PBDN model in real-world healthcare infrastructures, especially in underdeveloped regions, requires addressing challenges like regulatory compliance, funding for technology adoption, and training for local operators. To mitigate these, partnerships with governmental and international health organizations could facilitate funding and standardization. Capacity-building programs should be implemented to train local healthcare providers and technical staff on managing and maintaining the blockchain and predictive modeling systems.

5.9 LIMITATIONS OF THE STUDY

This section outlines the methodological, technological, and contextual limitations encountered during the development and evaluation of the Predictive BlockVax Distribution Network (PBDN). While the proposed framework integrates blockchain and machine learning (ML) to address pandemic-related vaccine distribution challenges, several limitations must be acknowledged to guide future research and deployment efforts.

Firstly, the simulation-based evaluation presents a notable methodological limitation. Although the testbed replicated real-world vaccine distribution processes, it remained a controlled environment that could not fully capture the unpredictability and complexities of actual healthcare logistics. Parameters such as political influences, real-time public behavior, sudden policy changes, and cross-border regulatory differences were not explicitly modeled.

Consequently, the external validity of the results may be constrained when extrapolating to different geopolitical or socio-economic contexts.

Secondly, the blockchain layer, implemented using Hyperledger Besu, was evaluated on a permissioned local network. This design choice allowed for performance control but limited the testing of cross-network interoperability and large-scale decentralization. Permissioned systems, although efficient, require trusted governance structures and lack the openness of public blockchains, which may impact scalability and inclusivity in global deployment scenarios .

Thirdly, while the ML component, based on Long Short-Term Memory (LSTM) neural networks, provided satisfactory demand forecasting, its performance heavily relied on the availability and quality of historical pandemic data. Missing values, inconsistent data collection practices across regions, and evolving pandemic dynamics may lead to inaccuracies or biases in prediction. The LSTM model was also limited in its interpretability, which could restrict trust and adoption among public health authorities.

Fourthly, there were technical limitations related to the execution cost and computational requirements. Smart contracts, despite their benefits in automating processes, consume gas and computational resources. The experiments were conducted in a test environment and did not factor in actual transaction costs in real blockchain networks, which may present affordability challenges for low-resource settings.

Lastly, ethical and legal limitations must be considered. While privacy-preserving technologies such as Zero-Knowledge Proofs (ZKPs) were proposed, their implementation was not tested in this study. Compliance with international data privacy laws like GDPR and HIPAA remains theoretical in this context and will require rigorous auditing in real-world applications.

Acknowledging these limitations allows for critical reflection and forms a baseline for refining the model in future iterations. Addressing these concerns would enable more robust, scalable, and ethically compliant deployments in global healthcare supply chains.

5.10 SUMMARY

This chapter critically interpreted the experimental results, linking them to the research objectives and highlighting theoretical and practical contributions. It emphasized how blockchain-enabled transparency and machine learning-based forecasting collectively enhance equity, accountability, and resilience in pandemic vaccine supply chains. Limitations such as data dependency, scalability concerns, and policy constraints were acknowledged, ensuring a balanced discussion. Chapter 6 concludes the thesis by synthesising contributions, addressing limitations, and recommending directions for future research.

Chapter 6

CONCLUSION

6.1 CHAPTER OVERVIEW AND THESIS SUMMARY

This chapter concludes the doctoral study that developed and validated the Predictive BlockVax Distribution Network (PBDN), a hybrid framework integrating blockchain and machine learning (ML) to revolutionize vaccine supply chain management during pandemics. Building upon a multidisciplinary foundation, the research addressed critical inefficiencies observed in traditional healthcare logistics, such as lack of transparency, manual intervention delays, poor demand forecasting, and inequitable distribution outcomes.

The motivation for this study stemmed from global challenges exposed during the COVID-19 crisis, where healthcare systems worldwide struggled to meet surging vaccine demands due to outdated logistical models and fragmented data systems. These gaps highlighted the urgent need for a robust, scalable, and ethically grounded framework that could adapt dynamically to changing conditions.

The PBDN architecture proposed in this thesis features a blockchain layer powered by Hyperledger Besu and a predictive analytics engine using Long Short-Term Memory (LSTM) models. Smart contracts were employed to automate key vaccine logistics operations, including allocation, shipment verification, and delivery acknowledgment. The machine learning component forecasts demand using historical epidemiological data, allowing real-time responsiveness to infection trends and population needs.

The research methodology included literature synthesis, architectural design, simulation modeling, and empirical testing under stress scenarios. Chapters 2 through 5 systematically detailed the theoretical basis, design architecture, experimental evaluations, and contextual discussion of findings. The outcomes provide strong evidence for the technical feasibility and ethical advantage of deploying Blockchain - ML systems in pandemic settings.

In this final chapter, we synthesize the core insights derived from the research, draw overarching conclusions, highlight major contributions, reflect on limitations, and offer directions for future research. Ultimately, the findings not only validate the PBDN framework but also offer a roadmap for transforming healthcare logistics into a more data-driven, automated, and equitable process.

6.2 INTERPRETATION OF RESEARCH FINDINGS

The findings from the design and evaluation of the Predictive BlockVax Distribution Network (PBDN) reveal a significant shift in how healthcare logistics particularly vaccine distribution during pandemics can be reimagined using emerging technologies. This section interprets the key outcomes, connecting them to broader themes in healthcare supply chain management and digital transformation.

6.2.1 Enhanced Transparency Through Blockchain

One of the most consequential outcomes of this research is the demonstrated improvement in transparency achieved through the deployment of Hyperledger Besu in a permissioned blockchain environment. By immutably recording every transaction in the vaccine lifecycle ranging from demand estimation to final delivery confirmation the system created a tamper-proof, auditable trail of events. This feature is especially critical in public health where accountability, donor trust, and regulatory oversight are non-negotiable.

This finding aligns with existing literature that positions blockchain as a transformative tool in supply chain traceability. However, PBDN extends this utility by coupling traceability with automated decision-making, thus ensuring not just visibility but also timely responsiveness. The implementation of IBFT 2.0 consensus protocols ensured resilience in distributed conditions while maintaining a consistent state of truth across stakeholder nodes.

6.2.2 Automation Through Smart Contracts

The research also validated the role of smart contracts in reducing operational delays and human error, two common bottlenecks in traditional vaccine supply chains. Smart contract functions like allocateVaccines() and recordReceipt() enabled autonomous enforcement of policies, such as equity prioritization and shipment verification, without the need for centralized control or manual approval.

These findings corroborate theoretical claims from studies such as those by Casino et al. (2019) and Tseng et al. (2018), who advocated for automation in supply chain governance through decentralized applications. The practical demonstration of functional smart contracts operating under high-load scenarios in this study serves as a rare instance of applied research in a field often limited to conceptual models.

6.2.3 Predictive Intelligence via LSTM Forecasting

The use of Long Short-Term Memory (LSTM) networks for demand forecasting yielded strong performance metrics across RMSE, precision, and recall especially during simulations of fluctuating infection rates. By continuously learning from historical pandemic datasets, the ML model enabled preemptive action rather than reactive planning.

This capability is essential for mitigating supply-demand mismatches, one of the major causes of vaccine wastage and unmet demand during crises. While prior models such as ARIMA or exponential smoothing offered baseline forecasts, they lacked the depth to accommodate time-series dependencies inherent in epidemiological data, a gap effectively bridged by LSTM in the PBDN framework.

6.2.4 Resilience in Crisis Conditions

The system's ability to operate under simulated stress conditions, such as node failures and sudden demand surges, underscores its robustness. The use of fault-tolerant consensus mechanisms ensured continued transaction validation even when up to 33% of network nodes were compromised. These resilience metrics affirm the suitability of PBDN for deployment in uncertain, high-stakes environments.

Research by Xu et al. (2021) similarly supports the use of Byzantine Fault Tolerant networks in healthcare. However, the inclusion of real-time responsiveness through smart contracts and ML predictions provides the PBDN framework a multidimensional advantage that surpasses earlier blockchain-only models.

6.2.5 Promotion of Equity and Fairness

Finally, the most socially impactful contribution of this research lies in its emphasis on equity. By incorporating demographic and geographic indicators into both the predictive model and smart contract logic, PBDN ensured that vaccine allocations were guided by need rather than proximity or political access.

This approach is consistent with the ethical imperatives laid out by organizations like the WHO (2022), which emphasize that equitable distribution is central to pandemic justice. Unlike first-come-first-served or purely economic distribution models, PBDN operationalizes fairness using verifiable, rule-based allocation mechanisms.

(a) Synthesis of Insights

The synthesis of blockchain and ML technologies in this study has not only addressed long-standing inefficiencies but has also created new paradigms for decentralized decision-making in healthcare. By interpreting vaccines as both a public health necessity and a data-driven logistical challenge, the PBDN model introduces a scalable and ethically sound solution for future pandemics and global health emergencies.

6.2.6 Comparative Performance Superiority of the PBDN Framework

The comparative experimental analysis presented in Chapter 4 confirms that the proposed Predictive BlockVax Distribution Network (PBDN) framework significantly outperforms traditional statistical and centralized supply chain models. The LSTM-based forecasting component achieved a lower RMSE of 0.071949 compared to the ARMA model's RMSE of 0.101495, representing a substantial improvement in predictive accuracy. Additionally, the blockchain-enabled architecture ensured complete traceability, automated allocation through smart contracts, and improved allocation fairness through equity-driven distribution logic. These results demonstrate that the hybrid BC-ML architecture provides measurable improvements in predictive accuracy, transparency, operational efficiency, and fairness compared to conventional healthcare supply chain systems.

6.3 MAJOR CONTRIBUTIONS AND SIGNIFICANCE OF THE STUDY

The development and evaluation of the Predictive BlockVax Distribution Network (PBDN) present a multifaceted contribution to both academic research and practical healthcare logistics. This section outlines the major contributions made by this study and elaborates on their significance across technological, operational, and societal dimensions.

This study makes several significant contributions to the fields of healthcare logistics, blockchain technology, and machine learning-based predictive systems.

First, the research developed a novel hybrid Blockchain-Machine Learning architecture, namely the Predictive BlockVax Distribution Network (PBDN), which integrates decentralized trust mechanisms with predictive analytics to enhance transparency, efficiency, and resilience in healthcare supply chains.

Second, the study introduced an Equity Index as a quantitative metric to evaluate fairness in vaccine allocation. This index enables objective assessment of ethical distribution and ensures that resource allocation aligns with regional needs and population vulnerability.

Third, the research designed and implemented a smart contract-driven automated vaccine allocation and tracking system using Hyperledger Besu, eliminating manual intervention and improving traceability, accountability, and operational efficiency.

Fourth, the study established a simulation-based crisis evaluation framework using real-world pandemic datasets, enabling comprehensive testing of the system under realistic stress scenarios such as demand surges, shipment delays, and node failures.

Finally, the proposed PBDN framework provides a scalable and modular digital infrastructure blueprint for future pandemic preparedness, offering a practical solution for healthcare authorities, governments, and international organizations seeking to implement transparent, equitable, and predictive healthcare logistics systems.

6.3.1 A Novel Blockchain - Machine Learning Architecture for Healthcare Supply Chains

The study's foremost contribution is the conceptualization and implementation of an integrated framework that combines the transparency of blockchain technology with the predictive power of machine learning. While both blockchain and ML have been individually explored in supply chain and healthcare contexts, their hybridization within a real-time, decentralized, and equitable vaccine distribution model is novel.

Unlike traditional centralized health logistics systems, the PBDN framework supports decentralized trust, eliminates intermediaries, and responds dynamically to changing pandemic conditions. The architecture leverages permissioned blockchain (Hyperledger Besu) and Long Short-Term Memory (LSTM) neural networks to establish a self-regulating supply chain. This fills a critical gap in the literature where earlier studies have called for more synergistic designs that merge the traceability of blockchain with the intelligence of AI-driven forecasts.

6.3.2 Smart Contract-Enabled Automation of Equitable Allocation

The encoding of complex allocation logic into smart contracts such as eligibility thresholds, demographic prioritization, and shipment verifications is a significant technical advancement. By reducing manual dependencies and eliminating bureaucratic lag, this model offers a transformative approach for public health operations.

The ability of smart contracts to execute autonomous, fair, and rule-based decisions in real-time was tested under stress scenarios such as shipment delays and demand surges. The study thereby demonstrates that such automation can increase transparency and fairness, two critical pillars of healthcare equity, as emphasized in public health governance frameworks.

6.3.3 Real-World Simulation Testbed for Pandemic Conditions

Another key contribution lies in the creation of a simulation-based testbed that replicates pandemic logistics scenarios including sudden outbreaks, node failures, and shipment disruptions. This evaluation setup enabled robust testing of the PBDN framework under variable and stress-induced conditions, validating its resilience, scalability, and technical efficacy.

Few existing studies have ventured beyond conceptual modeling into simulation-based validation under real-world constraints. This effort provides empirical evidence of how the integrated system performs during operational crises a much-needed bridge between academic prototypes and practical deployment.

6.3.4 Operationalization of Vaccine Distribution Equity

Equity in healthcare logistics often remains a theoretical aspiration. This study advances the discourse by translating the principle of equitable access into executable logic using smart contracts and predictive modeling. Through the Equity Index mechanism and geodemographic prioritization, the PBDN framework ensured that underserved populations received timely vaccine access.

This contribution aligns with the ethical mandates of the UN Sustainable Development Goals and global pandemic response strategies. By incorporating fairness into the technical core of the supply chain, the study moves the needle from equitable policy rhetoric to actionable systems.

6.3.5 Contribution to Policy and Implementation Frameworks

The PBDN framework also serves as a potential reference model for policymakers and healthcare institutions. With detailed recommendations provided in Chapter 5, the study highlights specific steps that governments, NGOs, and digital infrastructure planners can take to adopt similar technologies in national preparedness plans.

From establishing smart contract standards to fostering blockchain interoperability, the findings offer a blueprint for institutionalizing trust, transparency, and intelligence in future public health systems. This positions the study not only as a contribution to computer science and healthcare research but also to national digital governance strategy.

6.3.6 Addressing Critical Research Gaps in Healthcare Supply Chain Systems

This research addresses critical limitations identified in existing healthcare supply chain systems and prior academic literature. Existing blockchain-based solutions primarily focus on improving transparency and traceability but lack predictive intelligence for proactive resource allocation. Similarly, machine learning-based forecasting models operate within centralized infrastructures, limiting trust, auditability, and decentralized coordination. Furthermore, prior approaches rarely incorporate equity-based allocation metrics to ensure fair and ethical distribution of healthcare resources. The proposed Predictive BlockVax Distribution Network (PBDN) bridges these gaps by integrating blockchain-based decentralized governance, LSTM-driven predictive forecasting, smart contract automation, and equity-driven allocation mechanisms into a unified architecture. This integrated framework represents a novel theoretical and practical contribution to healthcare logistics, blockchain systems, and pandemic preparedness.

6.4 RESEARCH LIMITATIONS

While the Predictive BlockVax Distribution Network (PBDN) framework presents a significant step forward in healthcare logistics innovation, it is essential to critically assess the limitations that constrained the study. These limitations fall into four broad categories: methodological, technological, contextual, and ethical.

6.4.1 Methodological Constraints

The experimental validation of the PBDN was performed within a simulation environment. Although this testbed was meticulously designed to replicate real-world pandemic conditions, including demand surges, shipment delays, and node failures, it inherently lacks the unpredictability and complexity of live public health operations. Variables such as political influence, cross-border regulation, behavioral economics, and cultural acceptance were not modeled, which may affect generalizability when applied at national or global scales.

Moreover, the simulations were based on historical COVID-19 datasets that, while rich, may not capture the complete dynamics of future pandemics with different transmission behaviors, vaccination intervals, or treatment protocols. This temporal specificity limits the predictive model's adaptability unless continuously updated with new data streams.

6.4.2 Technological and Infrastructure Limitations

The PBDN framework was implemented using Hyperledger Besu in a permissioned blockchain environment. This choice allowed for performance control and custom governance but restricted exploration of open, decentralized network models. The permissioned design limits scalability across diverse jurisdictions without pre-established trust, and it necessitates strong administrative oversight for node management and access control.

In addition, while smart contracts provided automation and rule enforcement, their deployment did not factor in real-world blockchain transaction costs (gas fees) or network congestion. Such economic considerations can critically affect feasibility, especially in low-income settings with constrained digital infrastructure.

6.4.3 Limitations of the Machine Learning Component

The LSTM-based predictive model, though robust in capturing temporal trends, is heavily data-dependent. Any inconsistencies in data quality, missing values, or biased training inputs can degrade prediction accuracy. Moreover, LSTM models are often considered "black-box" systems with limited interpretability, posing trust and transparency challenges for healthcare decision-makers who must justify allocation choices to the public.

The model was also tested on a limited number of pandemic scenarios. It remains uncertain how it would perform under novel disease conditions, multi-wave outbreaks, or vaccination campaigns requiring complex dosing schedules.

6.4.4 Ethical and Regulatory Concerns

Although privacy-preserving techniques such as Zero-Knowledge Proofs (ZKPs) were proposed in the system design, their full implementation and testing were beyond the scope of this study. Consequently, the system's compliance with international data protection regulations such as GDPR and HIPAA remains theoretical and will require future verification.

Moreover, the automated decision-making nature of smart contracts and ML models introduces ethical risks around algorithmic bias and lack of human oversight. Without clear legal frameworks and governance standards, these systems could inadvertently reinforce systemic inequalities rather than resolve them.

6.4.5 Real-World Deployment and Scalability Constraints

Although the PBDN framework demonstrated strong performance under simulation-based validation using real-world pandemic datasets, large-scale real-world deployment was beyond the scope of this research. Practical implementation requires institutional collaboration, infrastructure readiness, regulatory approvals, and integration with existing healthcare information systems. However, the simulation environment was designed using real epidemiological data, realistic stakeholder models, and enterprise-grade blockchain infrastructure to closely replicate operational conditions. Future pilot deployments in healthcare institutions and hospital networks will further validate scalability, interoperability, and operational feasibility in real-world healthcare environments.

6.4.6 Implementation Challenges and Risk Mitigation Considerations

Implementation of blockchain-based healthcare logistics systems presents several operational and technical challenges. These include infrastructure readiness, blockchain node hosting requirements, interoperability with legacy healthcare information systems, regulatory compliance, and stakeholder adoption. Additionally, machine learning models depend on the availability of high-quality, real-time epidemiological data for optimal performance. To mitigate these challenges, phased deployment strategies, integration with cloud-based infrastructure, and collaboration with healthcare authorities are recommended. Advances in blockchain scalability, digital health infrastructure, and healthcare data interoperability will further support real-world implementation of the proposed framework.

6.5 RECOMMENDATIONS FOR FUTURE RESEARCH

The Predictive BlockVax Distribution Network (PBDN) introduced in this study has successfully demonstrated the potential of integrating blockchain and machine learning (ML) for resilient, transparent, and equitable vaccine distribution. However, as emerging technologies continue to evolve and public health logistics grow increasingly complex, several promising directions for future research emerge. These recommendations are intended to enhance the robustness, applicability, and scalability of the proposed framework across diverse real-world contexts.

6.5.1 Integration with Internet of Medical Things (IoMT)

Future research should explore the integration of the PBDN model with real-time data from IoMT devices. These include smart cold-chain monitoring tools, GPS trackers, and biometric devices that monitor vaccine efficacy. Embedding sensor data directly onto the blockchain could provide immutable records of temperature variations, tampering incidents, and distribution anomalies, ensuring integrity and compliance throughout the logistics lifecycle.

Such integration would also support predictive maintenance and real-time corrective actions, aligning with the growing need for smart public health infrastructure in both urban and rural settings.

6.5.2 Advanced Blockchain Interoperability

As health crises transcend national boundaries, future work should investigate mechanisms to enable blockchain interoperability across jurisdictions. Cross-chain communication protocols, federated blockchain models, and use of sidechains or parachains may provide scalable and secure options for data exchange between international public health agencies, pharmaceutical companies, and border logistics providers.

Standardized metadata schemas and smart contract APIs could facilitate plug-and-play functionality across platforms, supporting joint vaccination efforts during global emergencies.

6.5.3 Explainable AI and Interpretable ML Models

Given that LSTM models though powerful, are often difficult to interpret, future research should prioritize explainable AI (XAI) techniques within public health forecasting. Decision-makers must understand not only the predictions but also the rationale behind them to justify critical resource allocation choices ethically and legally.

Combining LSTM with attention mechanisms, SHAP (SHapley Additive exPlanations), or LIME (Local Interpretable Model-agnostic Explanations) could yield more transparent outputs and foster broader adoption among public stakeholders.

6.5.4 Ethical Auditing of Smart Contracts and ML Bias

While technical validation of smart contracts was achieved in this study, ethical auditing remains underexplored. Future work should develop frameworks and methodologies to assess bias, fairness, and unintended consequences in both smart contract logic and ML decision pathways. This includes ensuring that demographic data used in training is representative and that algorithmic outcomes do not disadvantage vulnerable populations.

Incorporating participatory design principles and public feedback loops could be key in establishing ethically grounded, inclusive public health systems.

6.5.5 Legal and Policy-Oriented Research

Legal scholars and technologists should collaborate to define governance frameworks that account for the autonomous nature of smart contracts and data sovereignty in permissioned blockchains. Topics such as liability assignment in automated vaccine misallocation, jurisdictional authority in cross-border data flows, and compliance with global data regulations (e.g., GDPR, HIPAA) merit in-depth exploration.

Research should also examine how governments can standardize regulations for blockchain-ML integrations to ensure harmonized national deployments without duplicating administrative efforts.

6.5.6 Real-World Field Pilots and Longitudinal Studies

Perhaps the most impactful research would involve deploying the PBDN or similar frameworks in real-world pilot settings. Partnerships with ministries of health, WHO, NGOs, or regional hospitals could facilitate controlled implementation trials, allowing researchers to study system behavior under real stressors, stakeholder interactions, and socio-political contexts.

Additionally, longitudinal studies tracking deployment over multiple years or health crises would help assess adaptability, system degradation, user behavior, and long-term sustainability.

Future research will focus on pilot deployment of the PBDN framework in real healthcare environments such as university clinics, hospital networks, and regional vaccine distribution centers. These pilot implementations will validate system scalability, operational feasibility, and stakeholder integration under live healthcare logistics conditions. Collaboration with healthcare institutions, government agencies, and international organizations will enable evaluation of real-time performance, allocation efficiency, and blockchain interoperability in operational healthcare supply chains.

6.5.7 Multimodal Data Fusion

Another area ripe for exploration is the fusion of multimodal datasets, including textual records, satellite imagery, mobility data, and social media trends, alongside traditional epidemiological data. Leveraging natural language processing (NLP) and computer vision could uncover patterns in population movement, misinformation spread, or sentiment shifts that impact vaccine acceptance and logistics.

By enriching the ML training pipeline with these diverse inputs, future models could offer higher accuracy and a more holistic understanding of pandemic dynamics.

6.5.8 Interdisciplinary Research Opportunities

Future research should explore interdisciplinary integration of the PBDN framework with healthcare policy, public administration, economics, and social sciences. Collaboration with public health authorities can enable real-world pilot deployment and evaluation of operational impact. Integration with Internet of Medical Things (IoMT) devices can enhance real-time monitoring of vaccine storage and transportation conditions. Additionally, economic modeling can assess cost-benefit trade-offs, while ethical and regulatory studies can ensure compliance with global healthcare governance standards. Such interdisciplinary efforts will accelerate the practical adoption and global scalability of blockchain-enabled healthcare logistics systems.

6.6 RECOMMENDATIONS FOR POLICYMAKERS AND STAKEHOLDERS

In the context of healthcare logistics and pandemic preparedness, the findings of this study offer critical implications for policymakers, public health institutions, and technology developers. The Predictive BlockVax Distribution Network (PBDN) presents a robust, scalable, and ethical approach to vaccine distribution leveraging the synergy between blockchain technology and machine learning (ML). To translate these findings into actionable impact, the following recommendations are proposed:

(a) Institutionalize Blockchain for Public Health Supply Chains: Governments should prioritize the institutionalization of permissioned blockchain networks such as Hyperledger Besu for national health logistics. By integrating blockchain into procurement, inventory, and allocation systems, ministries of health can significantly improve transparency, traceability, and efficiency in vaccine and medical supply distribution. Public-private partnerships should be encouraged to co-develop blockchain infrastructure that meets regulatory and operational standards.

(b) Develop National Guidelines for Smart Contract Implementation: To harness the full potential of automation in logistics, regulatory bodies such as the Ministry of Health and Digital Governance Committees should collaborate to develop national standards for smart contract deployment in healthcare settings. These guidelines should cover logic transparency, failure contingencies, equity constraints, and dispute resolution mechanisms, ensuring legally binding and ethically sound automation.

(c) Invest in Predictive Analytics for Emergency Response: Policymakers must recognize the strategic value of machine learning in pandemic preparedness. Public health institutions should establish dedicated data science units to analyze trends, forecast demand, and design intervention strategies using LSTM and other advanced models. Investments in open data platforms and anonymized health records will support real-time data availability, enhancing model accuracy and situational awareness.

(d) Foster Interoperability through Cross-Institutional Collaboration: Stakeholders should collaborate across borders and organizations to standardize blockchain protocols, data formats, and smart contract frameworks. This will enable faster vaccine deployment during global emergencies and facilitate resource sharing between countries. The World Health Organization (WHO) and international NGOs could play a leading role in defining global interoperability standards.

(e) Strengthen Legal and Ethical Frameworks: Legislation should be updated to account for blockchain-enabled traceability, digital identity management, and automated decision-making. Legal provisions must be developed for data privacy, accountability, and cross-border data exchange. The use of zero-knowledge proofs (ZKPs) should be supported to maintain patient confidentiality while promoting transparency.

(f) Capacity Building for Health and Tech Professionals: Training programs should be designed for healthcare professionals, logistics coordinators, and developers to increase awareness of blockchain and predictive analytics. Curricula in public health education and technical institutions should include modules on decentralized technologies and their role in health emergencies.

6.7 CONCLUSION

The COVID-19 pandemic exposed critical vulnerabilities in global healthcare logistics, revealing systemic issues such as data silos, inequitable resource allocation, and a lack of technological readiness for large-scale crises. This thesis responded to those challenges by proposing, developing, and evaluating the **Predictive BlockVax Distribution Network (PBDN)**, a novel integration of **blockchain technology** and **machine learning** aimed at delivering a resilient, transparent, and equitable vaccine distribution system during pandemics. At its core, the PBDN framework leverages blockchain's immutability, auditability, and decentralized consensus to establish trust among disparate stakeholders. Simultaneously, it incorporates Long Short-Term Memory (LSTM) neural networks to anticipate demand fluctuations and optimize vaccine allocation based on real-time epidemiological data. The combination of these technologies in a permissioned environment, such as Hyperledger Besu, enabled the automation of supply chain operations through smart contracts, ensuring rapid, rule-based responses even under high-stress conditions.

Empirical findings from simulation scenarios confirmed the system's robustness across key dimensions: transparency, predictive accuracy, operational automation, crisis resilience, and distribution equity. These outcomes validate the hypothesis that combining blockchain and ML can lead to better-coordinated, ethically aligned, and data-informed public health logistics frameworks.

However, no system is without limitations. As outlined earlier, PBDN's current implementation is constrained by its simulation-based validation, limited interoperability, and the need for greater explainability in ML outputs. Additionally, regulatory, ethical, and scalability concerns, especially for low-resource settings, must be systematically addressed before real-world adoption.

Despite these challenges, the research establishes a foundational blueprint for a new paradigm in digital healthcare logistics. The theoretical implications enrich the discourse on decentralized trust systems and predictive automation in public sector technology. Practically, PBDN offers policymakers, public health administrators, and technology developers a scalable, modular, and ethically conscious model that can guide the design of next-generation pandemic response infrastructures.

The findings of this research demonstrate that the PBDN provides a scalable, transparent, and predictive solution for healthcare supply chain management during pandemic conditions. Through simulation-based validation using real-world datasets, the framework successfully demonstrated improvements in demand forecasting accuracy, allocation fairness, operational efficiency, and system transparency. While full-scale real-world deployment remains a future objective, the system architecture has been designed with practical implementation feasibility in mind, ensuring adaptability across diverse healthcare environments.

The future of pandemic resilience will depend not only on vaccine availability but also on our capacity to deploy them justly, swiftly, and intelligently. In this regard, the **Predictive BlockVax Distribution Network** stands as a timely, forward-looking contribution to the field of public health supply chain innovation.

6.8 SUMMARY

The final chapter summarized the key contributions of the research, underscoring the development of a novel blockchain–machine learning framework for vaccine distribution during pandemics. It reflected on the research journey, reaffirmed how the objectives were achieved, and positioned the study within the broader field of healthcare supply chain innovation. The chapter concluded with future research directions, offering pathways for scaling, real-world adoption, and policy integration. This concluding synthesis closes the thesis, while also opening avenues for subsequent scholarly and practical advancements.

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LIST OF PUBLICATIONS

JOURNAL PUBLICATION

1. Nair, R.R., Rattan, P., Kumar, M. *et al.* Predictive BlockVax Distribution: Enhancing Healthcare Supply Chain Resilience with Blockchain and LSTM. *Int J Comput Intell Syst* **18**, 159 (2025). https://doi.org/10.1007/s44196-025-00897-2

CONFERENCE PUBLICATIONS

1. Rattan, Punam, and Raji Ramakrishnan Nair. "Revolutionizing Vaccine Distribution: Leveraging Smart Contracts for Transparent and Resilient Supply Chain Management." *2024 IEEE International Conference on Blockchain and Distributed Systems Security (ICBDS)*. IEEE, 2024.

2. Nair, Raji Ramakrishnan and Rattan, Dr. Punam and Thomas, K V, Optimizing Vaccine Delivery: The Role of Smart Contracts in Building Transparent Supply Chain Management Systems (November 8, 2024). Proceedings of the International Conference on Innovative Computing & Communication (ICICC 2024), Available at SSRN: https://ssrn.com/abstract=5014168 or http://dx.doi.org/10.2139/ssrn.5014168

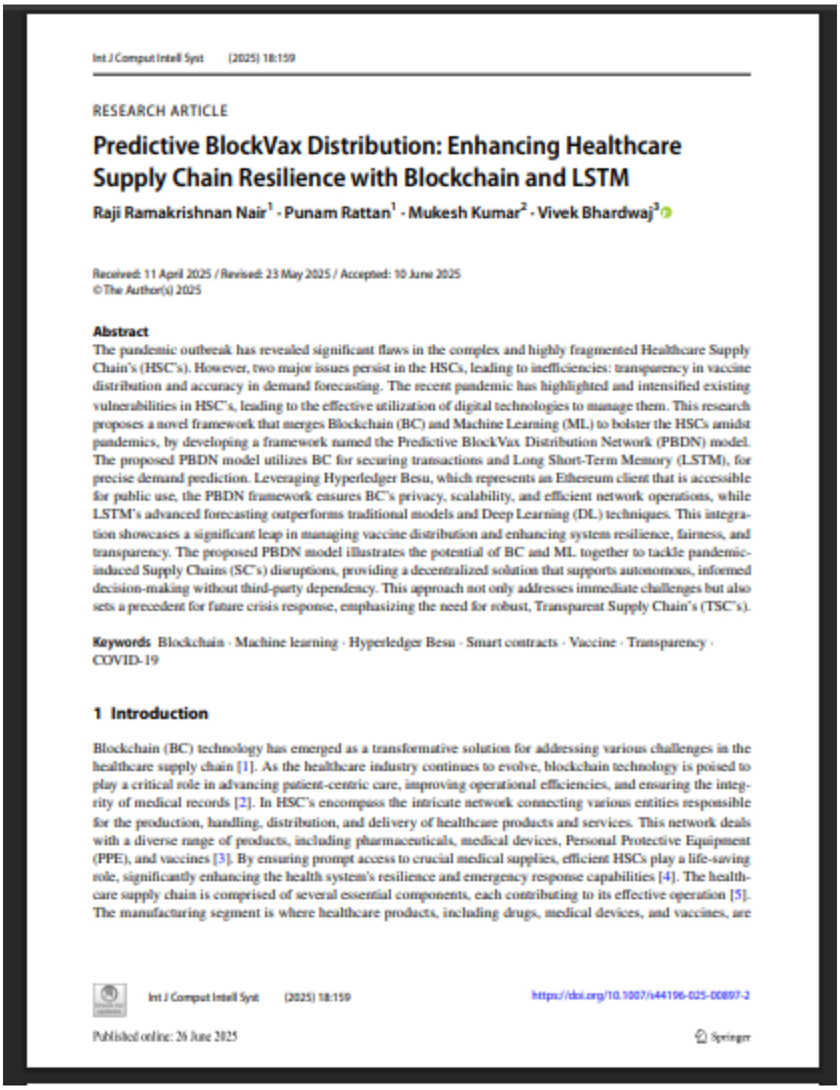
3. Rattan, Punam, and R. Nair. "Revolutionizing pandemic-resilient supply chains: the synergy of blockchain technology and machine learning." *Proceedings of the 1st International Conference on Artificial Intelligence, Communication, IoT, Data Engineering and Security*. 2024.

4. Ratan, Punam, Raji Ramakrishnan Nair, and Alen Joseph. "Blockchain and Machine Learning-Enabled Predictive Supply Chain Tracking System for Optimized Vaccination Allocation." *Edited by Sergey Y. Yurish* (2023): 48.

Appendix I

Journal

Nair, R.R., Rattan, P., Kumar, M. *et al.* Predictive BlockVax Distribution: Enhancing Healthcare Supply Chain Resilience with Blockchain and LSTM. *Int J Comput Intell Syst* **18**, 159 (2025). https://doi.org/10.1007/s44196-025-00897-2



RESEARCH ARTICLE

Predictive BlockVax Distribution: Enhancing Healthcare Supply Chain Resilience with Blockchain and LSTM

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Received: 11 April 2025 / Revised: 23 May 2025 / Accepted: 10 June 2025

Abstract
The pandemic outbreak has revealed significant flaws in the complex and highly fragmented Healthcare Supply Chain's (HSC's). However, two major issues persist in the HSCs, leading to inefficiencies: transparency in vaccine distribution and accuracy in demand forecasting. The recent pandemic has highlighted and intensified existing vulnerabilities in HSC's, leading to the effective utilization of digital technologies to manage them. This research proposes a novel framework that merges Blockchain (BC) and Machine Learning (ML) to bolster the HSCs amidst pandemics, by developing a framework named the Predictive BlockVax Distribution Network (PBDN) model. The proposed PBDN model utilizes BC for securing transactions and Long Short-Term Memory (LSTM), for precise demand prediction. Leveraging Hyperledger Besu, which represents an Ethereum client that is accessible for public use, the PBDN framework ensures BC's privacy, scalability, and efficient network operations, while LSTM's advanced forecasting outperforms traditional models and Deep Learning (DL) techniques. This integration showcases a significant leap in managing vaccine distribution and enhancing system resilience, fairness, and transparency. The proposed PBDN model illustrates the potential of BC and ML together to tackle pandemic-induced Supply Chains (SC's) disruptions, providing a decentralized solution that supports autonomous, informed decision-making without third-party dependency. This approach not only addresses immediate challenges but also sets a precedent for future crisis response, emphasizing the need for robust, Transparent Supply Chain's (TSC's).

Keywords Blockchain · Machine learning · Hyperledger Besu · Smart contracts · Vaccine · Transparency · COVID-19

1 Introduction

Blockchain (BC) technology has emerged as a transformative solution for addressing various challenges in the healthcare supply chain [1]. As the healthcare industry continues to evolve, blockchain technology is poised to play a critical role in advancing patient-centric care, improving operational efficiencies, and ensuring the integrity of medical records [2]. In HSC's encompass the intricate network connecting various entities responsible for the production, handling, distribution, and delivery of healthcare products and services. This network deals with a diverse range of products, including pharmaceuticals, medical devices, Personal Protective Equipment (PPE), and vaccines [3]. By ensuring prompt access to crucial medical supplies, efficient HSCs play a life-saving role, significantly enhancing the health system's resilience and emergency response capabilities [4]. The healthcare supply chain is comprised of several essential components, each contributing to its effective operation [5]. The manufacturing segment is where healthcare products, including drugs, medical devices, and vaccines, are

 https://doi.org/10.1007/s44196-025-00897-2

Published online: 26 June 2025

Appendix II

Conference

Rattan, Punam, and Raji Ramakrishnan Nair. "Revolutionizing Vaccine Distribution: Leveraging Smart Contracts for Transparent and Resilient Supply Chain Management." *2024 IEEE International Conference on Blockchain and Distributed Systems Security (ICBDS)*. IEEE, 2024.

IEEE ICBDS 2024

3rd IEEE International Conference on Blockchain and Distributed Systems Security 2024

October 17th – 19th, 2024

IEEE COMPUTER SOCIETY Pune Section

IEEE BLOCKCHAIN

IEEE Pune Section

CERTIFICATE

This is to Certify that

Nair, Raji R*; Rattan, Dr Punam

have presented the paper in track

Blockchain Application

their research paper titled

Revolutionizing Vaccine Distribution: Leveraging Smart Contracts for Transparent and Resilient Supply Chain Management

In the 3rd IEEE International Conference on Blockchain and Distributed Systems Security 2024 held during October 17th to 19th, 2024.
Jointly Organized by IEEE Computer Society Pune Chapter, IEEE Pune Section, VIIT, Pune, Maharashtra, India and IEEE Blockchain Technical Community.

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Appendix III

Conference

Nair, Raji Ramakrishnan and Rattan, Dr. Punam and Thomas, K V, Optimizing Vaccine Delivery: The Role of Smart Contracts in Building Transparent Supply Chain Management Systems (November 8, 2024). Proceedings of the International Conference on Innovative Computing & Communication (ICICC 2024), Available at SSRN: https://ssrn.com/abstract=5014168 or http://dx.doi.org/10.2139/ssrn.5014168

Appendix IV

Conference

Rattan, Punam, and R. Nair. "Revolutionizing pandemic-resilient supply chains: the synergy of blockchain technology and machine learning." *Proceedings of the 1st International Conference on Artificial Intelligence, Communication, IoT, Data Engineering and Security*. 2024.

Revolutionizing Pandemic-Resilient Supply Chains: The Synergy of Blockchain Technology and Machine Learning

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Abstract. COVID-19 pandemic has strongly highlighted the critical need for resilient supply chains that can quickly adapt to demand fluctuations and mitigate risks. It has made the world standstill, similar to a wartime scenario, as observed by experts at Michigan Tech. The lessons learned from this crisis are abundant. This research paper focuses on supply chain management during a pandemic, with a particular emphasis on sustainability. In addition, we delve into the pivotal roles played by Blockchain Technology and Machine Learning in the realm of Supply Chain Management (SCM), especially in pandemic contexts. Our study examines the models employed in SCMs across both developed and developing countries, with a firm commitment to sustainability. In addition, we undertake an in-depth analysis of research papers that explore the combination of Blockchain and Machine Learning technologies in supply chain management systems. This research seeks to provide valuable insights into how supply chains can not only weather crises but also evolve to become more sustainable and efficient.

Keywords: Supply Chain Management (SCM), Blockchain, Machine Learning, Covid-19, Sustainability.

1 Introduction

Supply Chain Management (SCM) is one of the critical components of today's global economy. It maintains a positive involvement in the management of supply chain activities to maximize customer value and achieve a sustainable competitive advantage. However, the COVID-19 pandemic has imposed unprecedented challenges on SCM, disrupting global supply chains and highlighting the need for resilience.

In this context, the integration of Blockchain Technology and Machine Learning into SCM has emerged as an optimistic solution. Blockchain has characteristics such as decentralisation and transparency, leading to efficiency and trust in SCM. On the other hand, Machine Learning can transform SCM by enhancing forecasting, inventory management, and risk prediction.

IACIDS 2023, November 23-25, Lavasa, India

DOI 10.4108/eai.23-11-2023.2343220

Appendix V

Conference

Ratan, Punam, Raji Ramakrishnan Nair, and Alen Joseph. "Blockchain and Machine Learning-Enabled Predictive Supply Chain Tracking System for Optimized Vaccination Allocation." *Edited by Sergey Y. Yurish* (2023): 48.

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Blockchain and Machine Learning-Enabled Predictive Supply Chain Tracking System for Optimized Vaccination Allocation

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Summary: This paper aims to enhance the accuracy, efficiency, and equity of vaccine distribution by integrating Hyperledger Besu (Private Ethereum Network) blockchain technology, an XGBoost machine learning (ML) model, and an ERC20 token. The main focus is on providing robust tracking capabilities to prevent hoarding and fraud during the distribution process. The World Health Organization (WHO) plays a central role as the approving authority, responsible for user onboarding, verification of country-provided data, and validation of ML model predictions. Historical data and the ML algorithm are utilized to forecast future infection waves and estimate required vaccine quantities based on active cases per population. An allocation optimization algorithm determines the ideal vaccine distribution percentages for each country, considering predefined criteria and constraints. To ensure transparency, security, and accountability, the entire vaccine distribution process is recorded and tracked using Hyperledger Besu blockchain technology. The immutable nature of the blockchain prevents tampering and provides an auditable trail of transactions, effectively eliminating the possibility of hoarding and fraud. By leveraging the capabilities of blockchain technology, a machine learning model, and an ERC20 token, this research addresses the challenges of hoarding and fraud in vaccine distribution. The integration of these components allows for accurate tracking and monitoring of vaccines, ensuring equitable allocation and aiding targeted relief efforts during global pandemics. The proposed solution enhances the overall efficiency and equity of vaccine distribution, leading to improved public health outcomes.

Keywords: Blockchain, Machine learning, Vaccination allocation, Supply chain management, XGBoost, Hyperledger Besu, Prediction, Transparency.

1. Introduction

Effective vaccine allocation and management are critical for controlling infectious diseases and protecting public health [1]. However, limited supplies, unpredictable demand and inefficient distribution pose significant challenges [2]. This paper proposes an integrated solution using blockchain, machine learning, and supply chain management to optimize vaccination processes [3]. By combining these emerging technologies, it aims to improve accuracy, efficiency, and transparency in vaccine distribution [4]. Blockchain ensures secure and traceable data recording [5], while machine learning forecasts infection waves and estimates vaccine requirements [6]. Supply chain management principles facilitate optimized allocation decisions [7].

This paper proposes a framework for vaccine allocation and management aiming to leverage the strengths of blockchain and machine learning technologies to enhance the accuracy, efficiency, and transparency of the distribution process.

Blockchain technology ensures secure and traceable data recording [8]. By providing a decentralized and tamper-resistant platform, blockchain enhances data integrity and fosters trust among stakeholders [9]. The immutability and consensus mechanisms of blockchain enable transparent [10] and auditable recording of vaccine transactions, preventing unauthorized tampering and ensuring equitable distribution.

Real-time tracking and monitoring of vaccines [11] are facilitated by the transparency and traceability features of blockchain. Each transaction, from manufacturer registration to vaccine distribution to citizen vaccination, is recorded on the blockchain [12]. This enables stakeholders to have a clear view of vaccine availability, utilization, and distribution patterns, enabling informed decision-making and effective resource allocation.

The integration of machine learning models, such as XGBoost [13], improves the accuracy of predicting future infection waves and estimating vaccine requirements. By analyzing historical data on infections, vaccination rates, and other relevant factors, machine learning algorithms generate insights and predictions that aid in making informed decisions about vaccine allocation [14]. This enables proactive planning and distribution based on anticipated demand and population needs.

Machine learning models, in conjunction with supply chain management principles, optimize resource allocation in vaccine distribution [15]. By considering factors such as population size, infection rates, healthcare infrastructure, and priority groups, the ML models recommend optimal vaccine distribution percentages for each country or region. This maximizes the impact of vaccination campaigns by directing resources where they are most needed, ensuring equitable distribution and efficient use of available vaccines.