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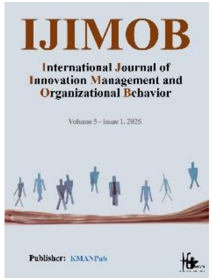

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Designing an Intelligent System for Vaccine Supply Chain Management Based on Blockchain Using Machine Learning Algorithms

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A B S T R A C T

Objective: The objective of this study is to design and evaluate an intelligent vaccine supply chain management system (VSC) based on blockchain technology, integrating machine learning algorithms and Internet of Things (IoT) devices.

Methodology: The research employs a multifaceted approach, incorporating blockchain technology to ensure data immutability and transparency, machine learning models for predictive analytics, and IoT devices for real-time monitoring. Key methodologies include the implementation of a hybrid LSTM-CNN model for credibility assessment, an SVM-based intelligent inoculation module, and sharding for improving blockchain scalability. Data for model training and evaluation were sourced from existing vaccine supply chain records and simulated scenarios to ensure robust testing of the system's components.

Findings: The study demonstrates that integrating blockchain with machine learning significantly enhances the management of vaccine supply chains. The hybrid LSTM-CNN model effectively assesses the credibility of vaccine manufacturers, while the SVM model accurately predicts the need for vaccinations. Sharding improves the system's scalability, allowing for efficient processing of large transaction volumes. The system also ensures that expired vaccines are promptly detected and removed from the supply chain, thereby maintaining vaccine quality and safety.

Conclusion: This research highlights the transformative potential of combining blockchain technology, IoT, and machine learning in vaccine supply chain management. The proposed system not only improves efficiency, transparency, and security but also addresses the scalability challenges inherent in global immunization efforts.

Keywords: *Vaccine, Blockchain, Machine Learning, Supply Chain*.

1 Introduction

The global effort to eradicate infectious diseases heavily relies on the efficient and secure distribution of vaccines. However, the complexity of the vaccine supply chain often results in inefficiencies, leading to resource wastage, delivery delays, and reduced potency. Furthermore, the lack of transparency and accountability within the supply chain can lead to counterfeit products, posing a significant threat to public health. To address these challenges, recent advancements in blockchain technology and machine learning offer a promising solution. By establishing blockchain as a foundational infrastructure, information related to the production, distribution, transportation, and storage of vaccines can become accessible and transparent. This transparency not only empowers stakeholders with real-time insights but also acts as a significant deterrent against fraudulent activities and unauthorized interactions. A key issue addressed in this research is the reduction of fraud (Persad & Largent, 2022).

Vaccine quality refers to various aspects, including authenticity, safety, potency, and efficacy. Unfortunately, counterfeit, defective, expired, and substandard vaccines are prevalent worldwide. Designing an intelligent system for vaccine supply chain management based on blockchain and machine learning is a relatively new concept developed in response to the challenges faced by vaccine supply chains. Traditional vaccine supply chain management faces multiple challenges, including limited visibility, data silos, and the risk of counterfeit products entering the market. These challenges can lead to storage issues, wastage, and reduced effectiveness of immunization programs. The integration of blockchain technology and machine learning algorithms can address these challenges by providing a transparent and secure platform for tracking inventory and vaccine distribution. While studies have been conducted on the use of blockchain technology in the vaccine supply chain, the integration of machine learning algorithms is a relatively new concept. The combination of these technologies has the potential to revolutionize vaccine supply chain management (Felgendreff et al., 2023; Persad & Largent, 2022; Rimmer, 2021; Shakeel et al., 2019; Weeks et al., 2023).

Blockchain enables the tracking of goods at every stage of the supply chain, providing an accurate history of product movement. Blockchain's ability to reduce reliance on intermediaries not only streamlines processes but also lowers transaction costs, making supply chains more efficient and cost-effective (Hastig & Sodhi, 2020; Haughton et al., 2022). The application of blockchain in complex global supply chains has been explored by researchers who emphasized the potential of blockchain technology to address long-standing challenges such as counterfeiting and lack of transparency in the supply chain. The integration of blockchain technology into cold supply chains signifies a shift in the operation and management of supply chain data, with profound implications for efficiency, transparency, and security. The decentralized nature of blockchain offers a robust framework for data sharing and collaboration among various stakeholders in the cold supply chain (Hastig & Sodhi, 2020; Haughton et al., 2022; Kaur et al., 2022; Khamenehmohammadi, 2021; Khanfar et al., 2021).

Given the aforementioned points, the objective of this research is to design an intelligent system that seamlessly integrates blockchain technology and machine learning algorithms to optimize vaccine supply chain management. This includes evaluating the effectiveness of real-time monitoring through Internet of Things (IoT) devices in improving vaccine quality, assessing the performance, efficiency, and reliability of the developed intelligent system in managing vaccine supply chains, including data transparency, traceability, and accountability, and examining the relationships between various components of the intelligent system to understand how blockchain and machine learning complement each other to improve vaccine supply chain operations.

2 Methods and Materials

This study employed a Design Science Research (DSR) methodology, focusing on the practical application of blockchain-based and machine learning-based systems for Vaccine Supply Chain (VSC) management. The process began with the identification and engagement of key stakeholders, including government entities, manufacturers, distributors, vaccination centers, and inspection organizations. The deployment of IoT infrastructure utilized smart vaccine containers equipped with RFID technology to facilitate real-time data collection. The system architecture was designed to ensure minimal latency and high availability for data transmission from IoT devices to the blockchain network, emphasizing the importance of data validation processes to ensure the accuracy and integrity of the collected data before uploading to the blockchain. The development of smart contracts involved automating and executing agreements within the supply chain, such as

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storage and transportation conditions. Decentralized applications (dApps) were created to provide a user-friendly interface for interacting with the blockchain, offering stakeholders real-time access to data and analytics. Finally, the integration of machine learning algorithms aimed to predict vaccine demand and conduct sentiment analysis based on the data collected and stored on the blockchain, highlighting an iterative design process that allows for continuous refinement and adaptation of the system based on feedback and evaluation.

The steps in designing the intelligent supply chain system are as follows:

System Initiation and Stakeholder Engagement: Identifying and engaging key stakeholders, including government entities, manufacturers, distributors, vaccination centers, and inspection organizations.

Establishment of Oversight Scope and Review Authority: Establishing the scope of oversight and review authority for entities such as the FDA and government health organizations.

Deployment of IoT Infrastructure: Utilizing IoT devices equipped with RFID technology in smart vaccine containers to enable real-time data collection.

Design and Implementation of Protocols for IoT Devices: Monitoring critical parameters such as temperature, location, and container integrity.

Data Collection and Transmission: Setting up a secure and reliable method for data transmission from IoT devices to the blockchain network, ensuring minimal latency and high availability.

Execution of Data Validation Processes: Verifying the accuracy and integrity of the collected data before uploading it to the blockchain.

Blockchain Network Configuration: Constructing the blockchain infrastructure with a focus on scalability, security, and interoperability with existing systems and platforms.

Development of Smart Contracts: Developing smart contracts to automate and enforce agreements in the supply chain, such as vaccine storage and transportation conditions.

Development of Decentralized Applications (dApps): Creating a user-friendly application interface for interacting with the blockchain, providing stakeholders with real-time access to data and analytics.

Machine Learning Integration: Designing and integrating ML algorithms to predict vaccine demand and conduct sentiment analysis based on the data collected and stored on the blockchain.

3 Findings and Results

3.1 Operational Design of the Vaccine Blockchain System for the Intelligent System

The vaccine blockchain consists of three components: the GMP chain, the distribution chain, and the immunization chain. These three chains are maintained by three institutions within the vaccine supply chain: vaccine manufacturing companies, the aggregate release agency, and the CDC. Generally, vaccines flow through these three institutions sequentially before being administered to consumers for immunization. These institutions use smart contracts to add or query vaccine records. These smart contracts are deployed on the vaccine blockchain and executed in the Ethereum Virtual Machine (EVM).

At the top of Figure 1 is the "Government" flow, representing the comprehensive regulatory body that oversees the vaccine distribution system. This level of oversight is critical to ensuring the fair and efficient distribution of vaccines. The government interacts with two main entities: the Company and the CDC. The Company likely represents pharmaceutical companies responsible for the production and supply of vaccines. In contrast, the CDC (Centers for Disease Control and Prevention) might oversee the public health aspect and manage vaccine distribution and administration guidelines. A crucial part of this interaction is the "batch release," which likely refers to the regulatory approval process that each vaccine batch must undergo before being released for public use. The role of the government is to facilitate coordination between production (the Company) and public health management (CDC) to ensure vaccine accessibility and compliance with safety standards.

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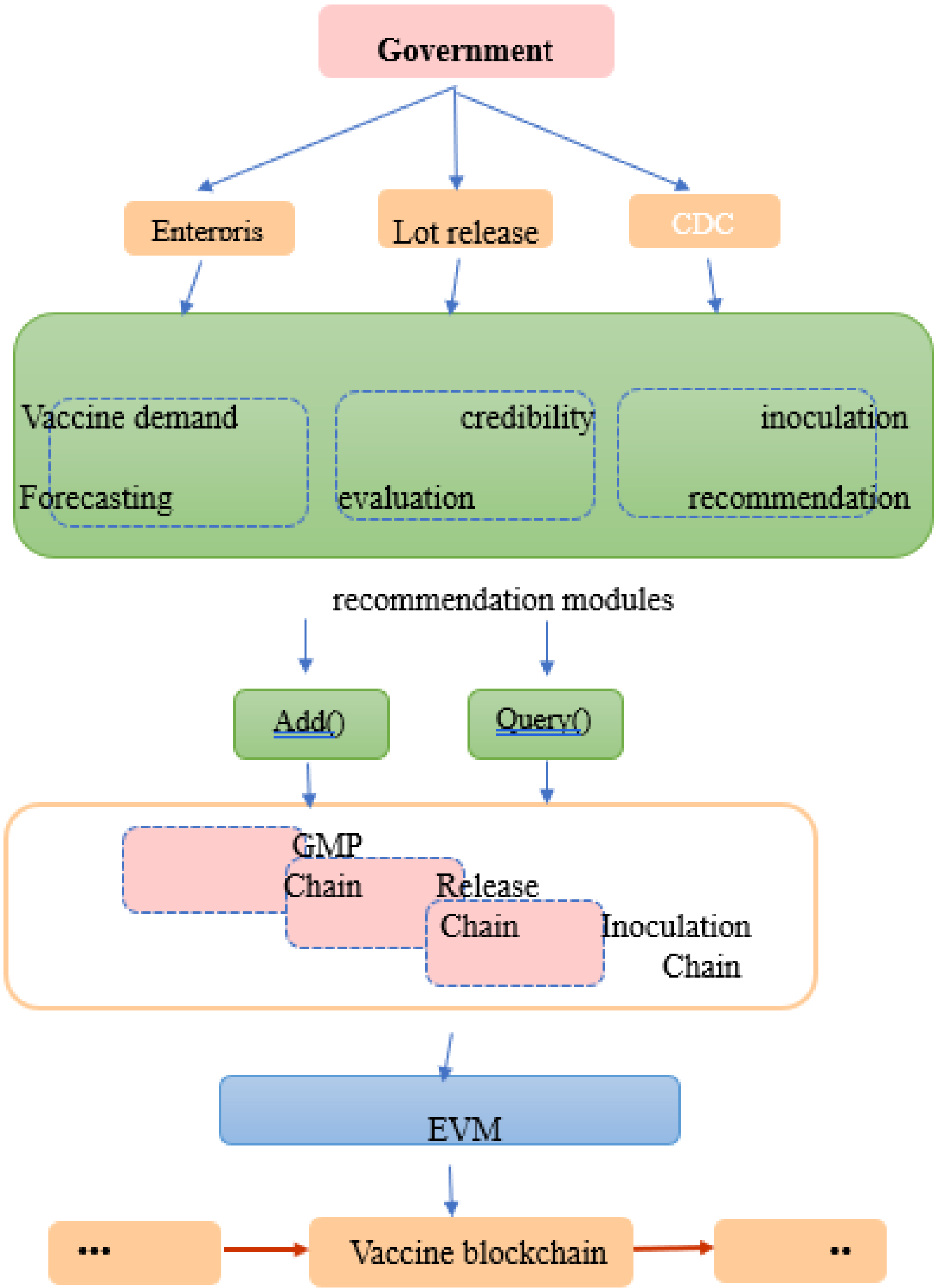
Figure 1

Architecture of the Vaccine Blockchain System



3.2 GMP Chain

The Good Manufacturing Practice (GMP) chain is a critical component of the pharmaceutical industry, especially in the vaccine supply chain, where it acts as a set of regulations and standards designed to ensure that products are produced and controlled according to quality standards. This includes all aspects of production, from raw materials, premises, and equipment to staff training and personal hygiene. Detailed, written procedures for every process that could affect the quality of the final product are essential. There must be systems in place to provide documented proof that correct procedures are consistently followed at every step in the manufacturing process—every time a product is made. In the context of blockchain integration, the GMP chain becomes part of a larger, immutable ledger, ensuring that not only are these practices adhered to, but they are also

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recorded and made transparent for audit and regulatory review. This blockchain-based approach to the GMP chain ensures that any deviation from established practices is immediately noticeable and traceable to its source, thereby enhancing accountability and the integrity of the vaccine manufacturing process. By leveraging the tamper-proof nature of blockchain, the GMP chain ensures that data related to the manufacturing environment, personnel credentials, validation, and cleaning procedures remain unaltered once entered into the system. The integrity of GMP in blockchain is crucial for regulatory compliance and maintaining public trust in the safety and efficacy of vaccines.

3.3 Distribution Chain

The aggregate release process for vaccines, particularly for those produced by companies with Good Manufacturing Practice (GMP) certification, is a critical and comprehensive protocol designed to ensure vaccine safety and efficacy before their market release. This meticulous process, structured into a series of ten distinct steps, covers all aspects from initial production to final approval by regulatory authorities.

The process begins with vaccine production, where manufacturers adhere to stringent GMP quality standards. These guidelines are essential to ensure that vaccines are produced in a controlled environment and maintain the highest levels of safety and quality. After production, the next critical step is self-testing, where manufacturers conduct rigorous internal testing of the vaccines. This self-assessment is crucial to ensure that the vaccine meets all necessary specifications and efficacy criteria. Successful completion of this stage is mandatory before moving forward in the aggregate release process.

Following internal testing, the next step involves applying for GMP certification from the Drug Administration. This certification is a formal acknowledgment that the vaccine has been produced according to the required safety and quality standards. Once GMP certification is obtained, companies proceed to gather the necessary documentation and complete the application form for vaccine release. These documents include detailed information about the vaccine, such as manufacturing processes, internal testing results, and quality assurance measures.

The stage of verifying the quantity of vaccines involves confirming the accuracy of the information provided against the actual quantity of vaccines produced. Ensuring the accuracy of this data is critical for maintaining transparency and precision in the vaccine supply chain. After verification, manufacturers submit a request for the aggregate release of vaccines. This request is a formal application to regulatory authorities for the authorization to market the vaccine, pending approval.

The subsequent stages of this process involve significant involvement from regulatory bodies, such as the State Food and Drug Administration (SFDA). Upon receiving the application, the SFDA conducts spot sampling at the production sites, ensuring an unbiased and representative selection of vaccine samples. These samples are then sealed and sent to the National Inspection Agency. The sealing process is vital to maintain the integrity of the samples during their transfer to the inspection center.

The final and determining stage of the aggregate release process is the inspection and verification of vaccine samples by the National Inspection Agency. This stage involves a thorough examination of the vaccine samples to confirm that they meet all required safety and efficacy standards. If the samples pass inspection, the vaccine is approved for market release. This final approval signifies that the vaccine has met all regulatory requirements and is ready for distribution to the public.

The aggregate release process is a testament to the stringent safety and quality standards upheld in the vaccine manufacturing and distribution industry. It is a multilayered procedure that ensures only safe and effective vaccines are made available on the market, playing a crucial role in protecting public health. Every stage of the process, from production to final inspection, is meticulously designed to verify the quality and safety of vaccines, ensuring they meet the stringent requirements set by health authorities. This comprehensive approach to vaccine release is essential for maintaining public trust in vaccination programs and ensuring the effectiveness of public health initiatives.

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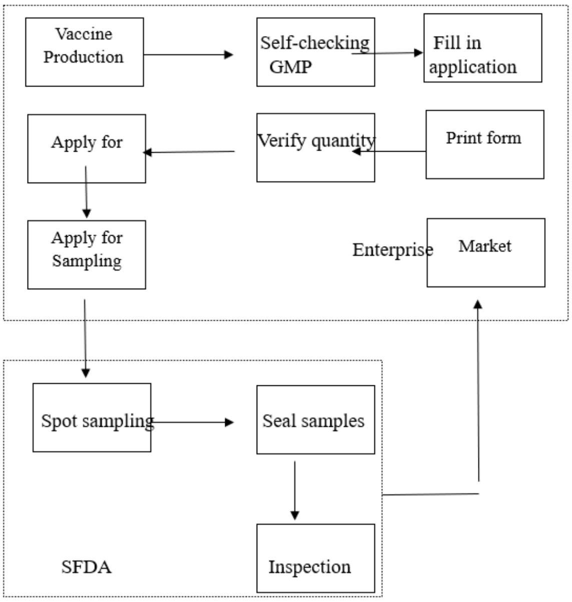
Figure 2

Vaccine Release Process



Throughout the entire process mentioned here, vaccine manufacturing records provided by companies are logged in the GMP chain. Inspection records, added by the aggregate release agency, must also be recorded in the distribution chain. After the aggregate release process, vaccines are sent to the CDC to be administered to vaccine recipients. When a user requires vaccination, they submit a vaccination request to the CDC, and then they are vaccinated at the CDC. Meanwhile, the immunization record is sent to the immunization chain.

3.4 Immunization Chain

The immunization chain is used to store immunization records. The main information in this chain includes basic information about vaccine recipients, the immunization department, the administering physician, and so forth. Thus, the immunization chain is also crucial to the system (Yong et al., 2020).

Implementing a blockchain-based immunization chain for storing vaccination records introduces advanced technical features that significantly enhance the efficiency, security, and privacy of vaccine distribution systems. The immunization chain primarily stores essential information about vaccine recipients, such as basic personal details, the vaccination department, and the administering physician, while carefully omitting sensitive personal information to protect privacy. The identity of the vaccine recipient is securely retained by the recipient and used to query personal vaccination information. This approach is critical for maintaining the confidentiality and integrity of personal health data, a vital aspect of any medical record system.

The architecture of the immunization chain allows for the integration of smart contracts, which are crucial in developing an intelligent vaccination model. This model can utilize vaccination records to generate intelligent vaccination recommendations for users. By analyzing stored data, the system can provide personalized vaccine recommendations, manage schedules, and more effectively track vaccination outcomes. This capability is not only useful for individual health management but also plays a significant role in public health monitoring and planning.

Blocks in the vaccine blockchain system are used to store all relevant vaccine information, as shown in Figure 3. In the design presented in this paper, each block primarily consists of three types of transactions uploaded by the companies, the aggregate release agency, and the CDC. These transactions comprise five data fields: timestamp, sender, receiver, quantity, and record content. The timestamp records the transaction time. The sender indicates the initiator of a transaction, typically one of the three institutions. For the vaccine blockchain, the receiver and quantity fields are set to zero, and the records are stored in the "data" field. Records are organized as a hash table structure, which is a dictionary-like set of unique keys and their values. The keys of these hash tables represent record categories, such as "production," "inspection," or "immunization." The values

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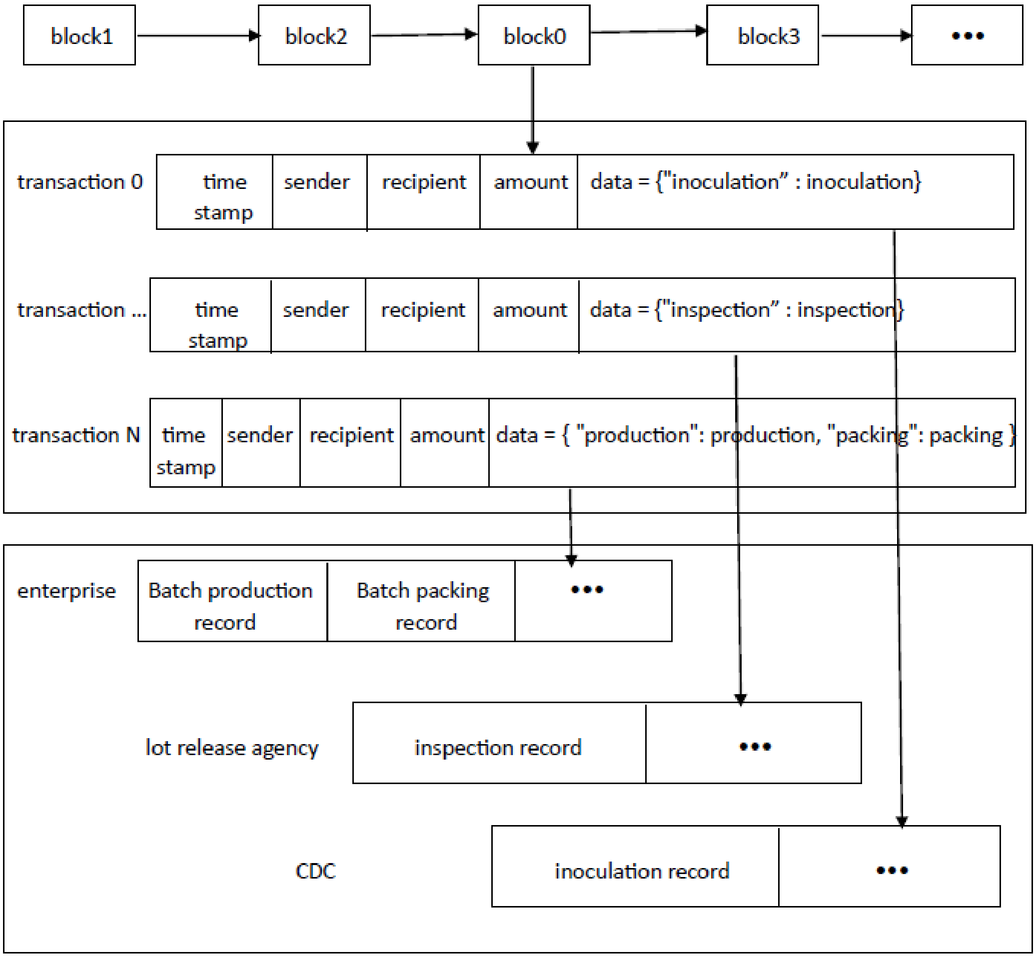
in these hash tables exist as an object containing record information and even other nested objects. With the hash table format, records, once stored on the blockchain, can be unstructured.

Figure 3

Block Structure Information for Vaccine Blockchain



3.5 Reference Control

If companies, the aggregate release agency, or the CDC wish to upload their records, they must request accounts (including a public key and a private key) from the government. Additionally, the government maintains an account for these institutions. Institutions upload records by signing them with their private key, and the signature is verified by the vaccine blockchain system to ensure that the records are correctly submitted by the respective institutions. Accordingly, the government regularly reviews the records uploaded by these institutions. If any issues are found in the records, the relevant entities are investigated and potentially prosecuted.

The use of vaccination records stored in the distribution chain extends beyond mere registration; it plays a crucial role in enhancing the efficiency and effectiveness of the vaccination process through intelligent modeling. These records form the foundational data set for developing an intelligent vaccination model. By analyzing this data, the system can learn and identify patterns, which can then be used to generate intelligent vaccination recommendations for users. This aspect of the distribution chain highlights its importance not only as a data repository but also as a dynamic tool that contributes to the advancement of intelligent vaccination strategies. The intelligent vaccination model utilizes the rich data within the distribution chain to provide tailored recommendations, potentially improving vaccination coverage, optimizing vaccine distribution, and enhancing the overall public health response to vaccine-preventable diseases.

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Therefore, the vaccination chain is not merely a passive record of vaccination events but a pivotal element in the broader vaccine management ecosystem. It supports the development of intelligent systems that can adapt to and respond to various public health needs. By leveraging the power of data analysis and machine learning, the intelligent vaccination model can offer insights and recommendations that make the vaccination process more efficient and user-centered. This integration of data-driven intelligence into the vaccination process represents a significant step forward in public health management, where informed decisions can lead to better health outcomes and more effective disease prevention strategies. In summary, the role of the distribution chain in storing, protecting, and intelligently utilizing immunization data makes it an essential component of a modern, efficient, and responsive vaccine supply chain management system.

3.6 Smart Contracts for the Vaccine Supply Chain

The integration of smart contracts into the vaccine blockchain, as highlighted in the research by Grishchenko et al. (2018), represents a pivotal advancement in realizing the monitoring functions of vaccine distribution. These smart contracts are intricately designed within the Ethereum blockchain framework, a technology known for its decentralization and robustness. As described by Wood (2014), Ethereum is an open-source blockchain platform that facilitates the creation and use of decentralized applications (dApps). The inherent features of this platform make it an ideal foundation for developing a vaccine distribution system that is both secure and efficient.

Ethereum's capability to support smart contracts is particularly noteworthy. Smart contracts are essentially programs that execute precisely as programmed, without the risks of operational failures, censorship, fraudulent activities, or interference from external parties, as explained by Christidis and Devetsikiotis (2016). This level of reliability and independence in execution is critical in the context of vaccine supply chains. In this system, smart contracts can be programmed to monitor and verify various stages of the vaccine journey, from production to delivery. They ensure that each stage of the distribution process adheres to predefined conditions, such as maintaining proper storage temperatures or verifying the accuracy of vaccine batches. This automated oversight provided by smart contracts not only streamlines supply chain processes but also significantly reduces the risk of human error and manipulation.

Furthermore, the Ethereum platform's support for decentralized applications (dApps) that run on the Ethereum Virtual Machine (EVM) provides a flexible and powerful environment for developers. The EVM is a specialized runtime environment that facilitates the execution of code written in smart contracts. This environment is crucial for the smooth operation of dApps, which can range from tracking applications that provide real-time updates on vaccine shipments to systems that manage inventory levels and facilitate communication between various stakeholders in the supply chain. Ethereum's ability to offer a reliable and dedicated runtime for these smart contracts and dApps ensures that operations in the vaccine supply chain are not only automated but also timely and predictable.

3.7 Detection of Expired Vaccines

Using the vaccine blockchain designed in this study, along with smart contracts, this issue can be effectively controlled. As shown in Figure 4(a), before inoculation, the CDC must execute a detect() function, which is called in the web middleware. The detect() function queries the production date and the quality assurance period of the vaccines to determine whether they have expired. If the vaccines are expired, the sendExpiration() function is called to send the information about the expired vaccines to the blockchain system, and all institutions receive the expiration information. Meanwhile, the inoculate() function is not executed, and the add() function is not used to add the inoculation record. Additionally, the system does not execute the pay() function to process payment to the CDC. In this way, information about expired vaccines is disseminated throughout the entire vaccine supply chain as a reminder to the relevant institutions, and the inoculation institution receives no reward for administering expired vaccines. Furthermore, companies that supply expired vaccines do not profit from them.

The integration of blockchain technology and smart contracts in vaccine management introduces a deep level of transparency and accountability into the supply chain. If the detect() function identifies expired vaccines in the system, the automated nature of smart contracts ensures that all stakeholders are immediately informed, and the necessary checks and balances are put in place. This not only prevents the use of expired vaccines but also creates a trustless system where data integrity is paramount. The blockchain ledger

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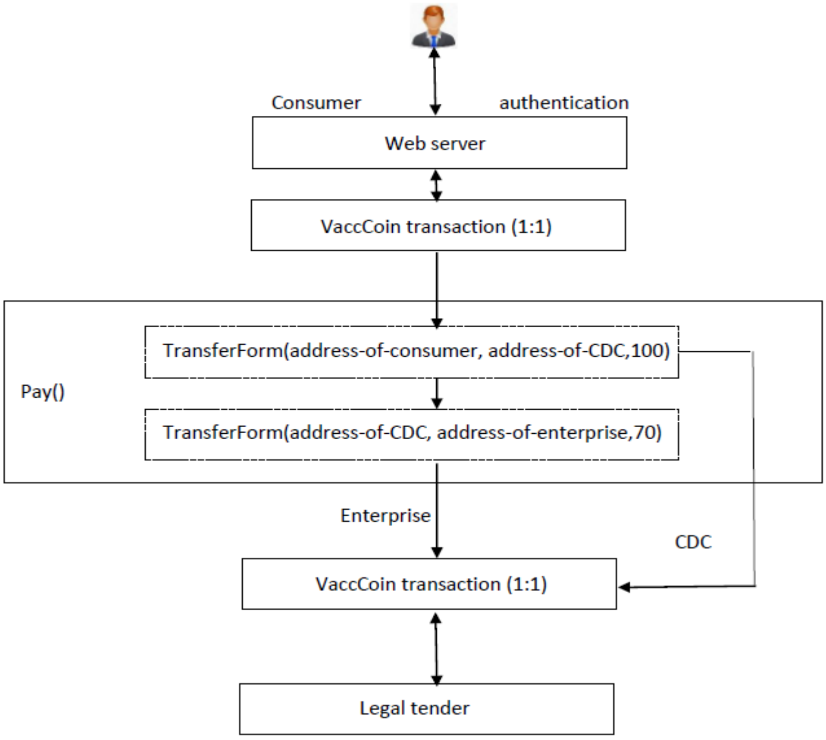
acts as an immutable record, ensuring that once the sendExpiration function is triggered, the information about expired vaccines cannot be altered or deleted. This process builds trust in the system among both consumers and regulatory bodies.

Moreover, the vaccine blockchain system discourages the distribution of expired vaccines by preventing payment through the pay() function, as there is no incentive to administer such vaccines. As a result, the financial flow within the vaccine supply chain is directly tied to compliance with safety standards (Rai, 2023). This approach not only reduces the risk of administering expired vaccines but also promotes responsible behavior among vaccine providers. Consequently, the vaccine blockchain not only serves as a tool for enforcing health standards but also acts as a mechanism for economic regulation. The distribution network thus becomes a self-regulating ecosystem where compliance is coded into the structure of transactional operations. This is a system where ethical compliance is not only morally right but also economically sound.

Figure 4

Vaccine Payment Flowchart



3.8 *Vaccine Information Query*

When an incident necessitates the need for a vaccine, the vaccine blockchain is used to trace the entire process of vaccine circulation for investigating and assigning responsibility for the incident. As shown above, the vaccine blockchain system prepares vaccine query functions, which are also executed by smart contracts. Smart contracts are initiated by message calls provided by the Ethereum platform. Query parameters are stored in the data field of the message. The system then judges the identity through the parameters. Generally, two types of vaccine records are queryable: one type is the inoculation record, which is referenced by vaccine recipients. The other type is the vaccine circulation record, which can be created by any of the three vaccine institutions (vaccine manufacturing companies, the aggregate release agency, and the CDC). The flow chart in Figure 5(b) details this process.

For personal inoculation record requests from consumers, the blockchain system calls the query(ID) function, where the input parameter ID is the consumer's identification. This function traverses the inoculation chain in the vaccine blockchain to find the consumer's information and returns the results of all the consumer's inoculation records. For vaccine circulation queries initiated by institutions, the blockchain system executes another function, queryVaccine(batch number), where the input argument or parameter is the vaccine batch number. In this case, the

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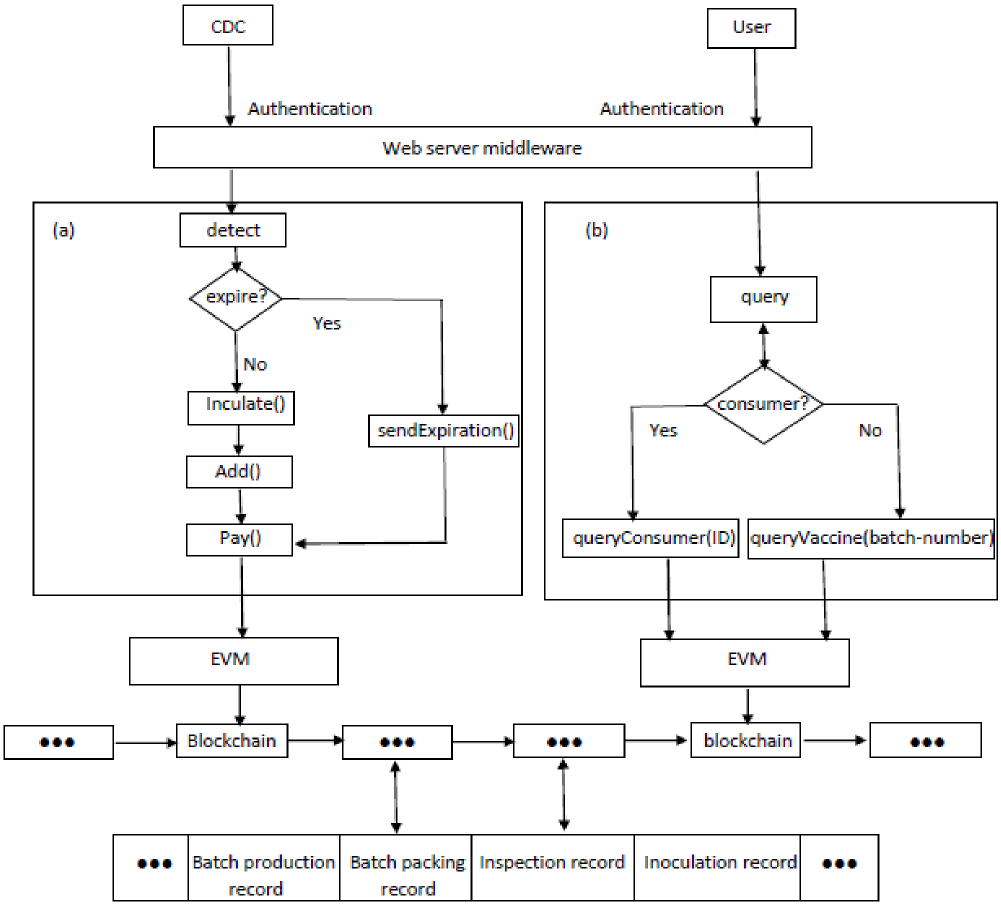
function traverses the GMP chain and the distribution chain to find the vaccine information, and the query results are returned.

Figure 5

(a) Expired Vaccine Detection Flowchart, (b) Vaccine Query Flowchart



3.9 VaccCoin

To facilitate value exchange throughout the blockchain supply chain, a virtual currency system like a payment system is required. The ERC20 token standard describes the functions and events that an Ethereum token contract needs to implement. The functions and events in the ERC20 standard are shown in Figure 5, with parameters omitted in this article. Traditionally, the CDC (or a hospital) purchases vaccines from companies, and consumers pay cash to the CDC in exchange for vaccination. In this case, cash transactions occur between companies and the CDCs and between the CDCs and consumers. However, with the ERC20 interface, we can implement a cryptographic payment system to transfer token balances. In our design, VaccCoin is issued to replace cash transactions between companies and the CDC and between the CDC and consumers. VaccCoin is always specified to have a 1:1 conversion ratio with fiat currency. Therefore, the value of VaccCoin is equal to the value of fiat currency.

As shown in Figure 4, consumers (vaccine recipients) first log into the web middleware and purchase the required amount of VaccCoin. After a successful vaccination (as shown in Figure 4), the vaccine blockchain system calls the pay() function to complete the transaction. The pay() function first calls the transferFrom() function to transfer VaccCoins from the consumer's address to the CDC's address with the amount of VaccCoins equivalent to the vaccine sale price (e.g., 100 VaccCoins). Then, the transferFrom() function is called once more to transfer VaccCoins from the CDC's address to the company's address. This time, the amount of VaccCoins is the sale price minus the CDC's revenue (e.g., 30 VaccCoins), and the

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company's revenue is the remaining VaccCoins (e.g., 70 VaccCoins).

In fact, the VaccCoin mechanism can be effectively used to monitor vaccine quality. Problematic or expired vaccines generate no revenue, encouraging these institutions to produce high-quality vaccines and sell them before their expiration date.

3.10 *Intelligent Recommendation Modules Based on Machine Learning Algorithms*

This section introduces the intelligent recommendation modules used in the vaccine blockchain system. It mainly consists of three modules: the vaccine demand forecasting module for companies, the credibility assessment module for the aggregate release agency, and the intelligent inoculation module for the CDC. According to Khan et al. (2010), traditional machine learning models for credibility prediction include Decision Trees (DT), Naive Bayes (NB), Random Forest (RF), k-Nearest Neighbors (KNN), and Support Vector Machines (SVM). As Lecan et al. (2015) stated, a Convolutional Neural Network (CNN) is a widely used deep learning model that can capture certain features regardless of spatial location (convolution refers to a fusion of features). As explained by Li et al. (2017), a Long Short-Term Memory (LSTM) network is another commonly used deep learning model that is adept at time series forecasting.

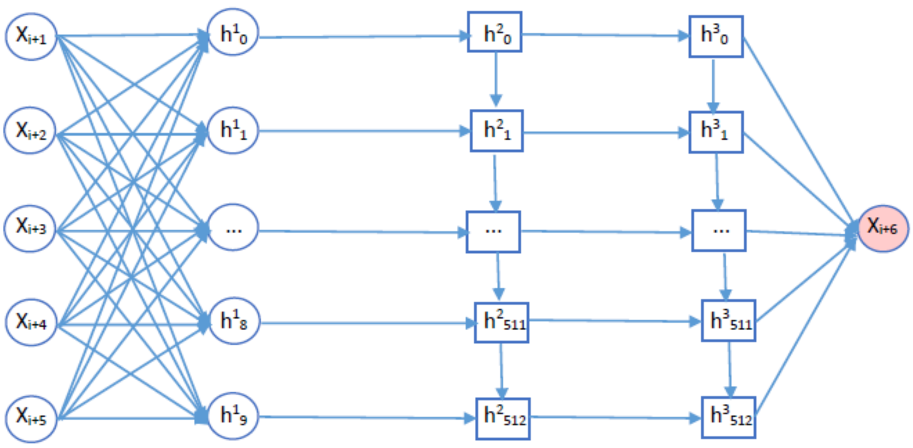
3.11 *Vaccine Demand Forecasting Module*

One of the main reasons for vaccine expiration is the inaccurate estimation of vaccine demand. Therefore, a model that can accurately predict vaccine demand is crucial for vaccine production planning. The records stored in the vaccine blockchain system can provide the total annual vaccine doses consumed, which can be used to predict vaccine demand for the upcoming year.

As shown in Figure 6, an LSTM-based deep learning model is designed to predict vaccine demand. To make the model sensitive to input data, a fully connected (FC) layer with 10 hidden nodes is placed before the LSTM layer. This layer can effectively map the input series to a new vector space, allowing for better preprocessing of raw series data. Two LSTM layers with 512 gate units are designed after the FC layer and are used to learn internal features. In the design presented in this article, we use five consecutive sets of demand data to predict the next value. Thus, the deep model is designed with five input nodes and one output node.

Figure 6

LSTM Model for Vaccine Demand Forecasting



3.12 *Credibility Assessment Module*

Generally, credibility information is crucial for many aggregate release agencies in determining the quality of companies' vaccines. Machine learning models and Deep Neural Network (DNN) technologies are widely used for sentiment analysis (Deepika & Senthil, 2019; Feng et al., 2021) and can be utilized to indicate company credibility assessments and establish a credibility evaluation system to assist regulators in conducting company credibility reviews. In the vaccine blockchain system, we employ traditional machine learning models and DNN models to predict the credibility of companies, thereby assisting the aggregate release agency in evaluating vaccine companies.

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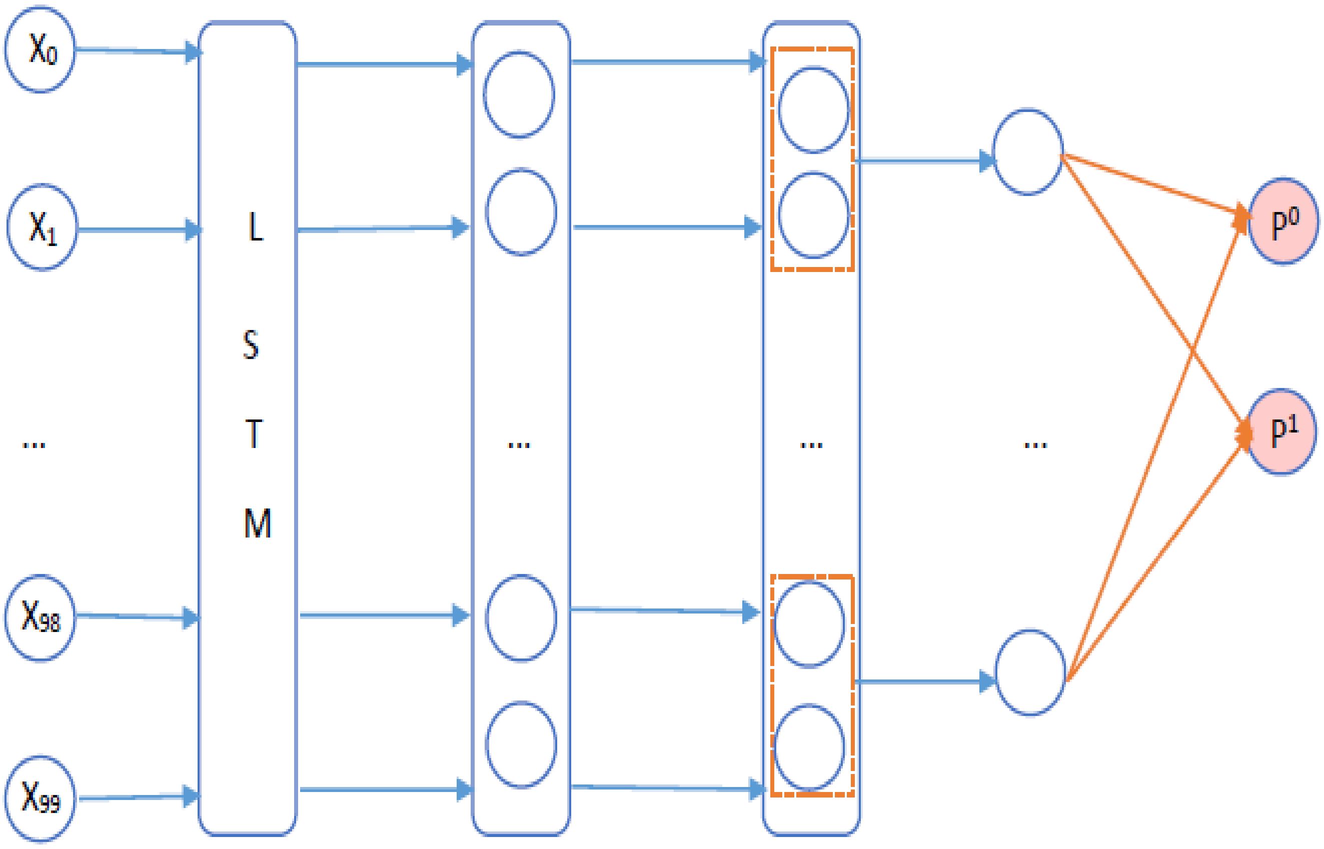
Figure 7

Deep LSTM-CNN Model for Credibility Assessment



A Convolutional Neural Network (CNN) can be used to capture negative expressions and reflect vaccine users' evaluations. In the system presented in this research, both CNN and LSTM were tested. Meanwhile, a hybrid deep model (denoted as Mixed), which incorporates the advantages of both CNN and LSTM, was designed for the organizational assessment of vaccines. As shown in Figure 7, the hybrid model consists of both an LSTM module and a CNN module (including a convolutional layer and a max-pooling layer). Thus, the hybrid model is designed to capture both position-independent negative expressions and contextual relationships. Message samples are encoded using the word embedding method. Therefore, each sentence is represented by a vector of length 200, which serves as the input vector in the deep learning models. The output of the deep model is configured as a SoftMax function with two nodes representing the probability of positive or negative sentiment.

3.13 Intelligent Inoculation Module

As mentioned above, immunization information in the vaccine blockchain can be used for intelligent inoculation, implemented by an SVM model with a radial basis function (RBF) kernel. In the design presented in this research, four features related to influenza were selected to evaluate the likelihood of influenza. The vaccine system then reminds the user, based on the prediction result of the trained SVM model, whether they need to be vaccinated.

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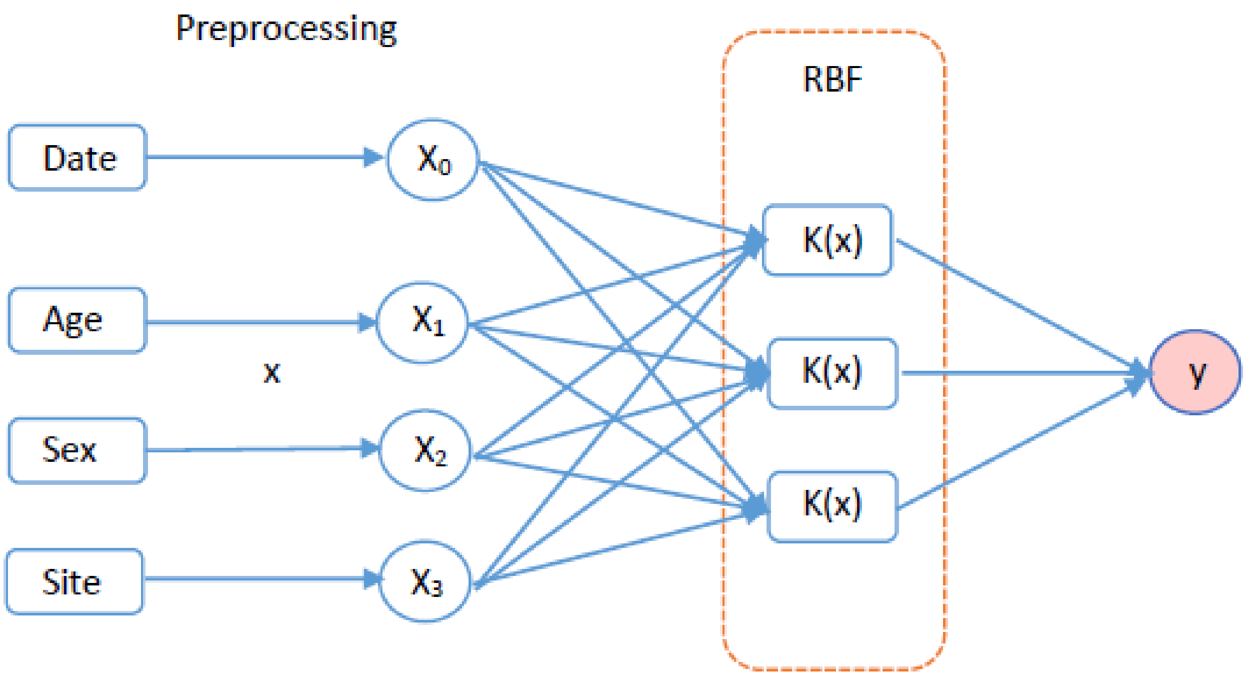
Figure 8

SVM Model for Intelligent Inoculation Module



As shown in Figure 8, four features are used as the input vector for the SVM model, which includes the date, age, gender, and recipient site. These four features constitute a vaccination sample. The date represents the time of vaccination, and the age field represents the recipient's age in years. Gender information is represented by the gender field, and the site field indicates the location of the vaccination. These four features are first preprocessed as floating-point numbers: the date is digitally converted and represented as one of four numbers indicating the four seasons. Age is digitally represented as a numerical value in years; gender is digitally represented as one of two numbers. The site is digitally represented according to the postal code of the location. Meanwhile, the result of whether the user is infected or not is used as the output of the SVM model. That is, if the user is infected, the output probability is 1; otherwise, it is 0.

3.14 Blockchain Scalability in the Intelligent Vaccine Supply Chain System

Blockchain scalability is crucial to ensuring that an intelligent vaccine supply chain can manage the vast amount of transaction data generated by global immunization efforts. Sharding is a promising solution to blockchain scalability issues. This method involves dividing the blockchain network into smaller, more manageable segments or "shards" that can process transactions in parallel. By distributing the responsibility for processing transactions among multiple shards, the overall network capacity can be significantly increased. Each shard processes only a portion of the network's transactions, allowing for parallel processing and significantly reducing the load on individual nodes. This division can also increase transaction throughput by preventing network congestion through load distribution. Additionally, sharding can help reduce latency, ensuring that transactions are confirmed more quickly, which is particularly important in vaccine supply chains where delays can compromise vaccine quality and effectiveness (Khanfar et al., 2021; Persad & Largent, 2022).

Implementing sharding has profound implications for data storage on blockchain networks. By splitting the network into shards, each containing only a portion of the blockchain's total data, the storage and computational burden on individual nodes is significantly reduced. This state-splitting approach allows each shard to maintain an independent state, optimizing data retrieval and processing within the shard. Layer 2 solutions, also known as off-chain solutions, are pivotal in enhancing blockchain scalability and are particularly critical in complex systems like vaccine supply chains. These solutions work by managing transactions off the main blockchain, significantly improving scalability and transaction speed.

4 Discussion and Conclusion

This research presented a multifaceted approach essential for designing an intelligent system for Vaccine Supply Chain (VSC) management based on blockchain technology. The theoretical foundations of blockchain and the Internet of Things (IoT) in the supply chain were thoroughly explored, highlighting their critical roles in enhancing supply chain efficiency. The complexities of the vaccine and pharmaceutical supply chains were examined, emphasizing the necessity of smart contracts and applications in managing these intricate systems. A focal point of this study was the transformative impact of machine learning on optimizing and designing VSC systems, demonstrating its essential role in modern supply chain strategies. The principles of intelligent system design in VSC, including the integration of real-time data processing and architecture and data flow within intelligent systems, were meticulously analyzed. This comprehensive analysis clarifies how these advanced technologies can improve vaccine supply chains and significantly contribute to their efficiency, security, and resilience, particularly in responding to global healthcare challenges. It is worth noting that further research is needed on implementing blockchain technology in various health information systems and the associated benefits. This study contributes to the knowledge of how blockchain and machine learning can optimize vaccine supply chain management, ultimately supporting global vaccination efforts and improving public health outcomes. Given the complexity and innovative approach of integrating blockchain technology, IoT, and machine learning algorithms to enhance vaccine supply chain management, several nuanced limitations must be considered. Firstly, the technological infrastructure required for such integration is significant and necessitates a high level of digital literacy among its users. Secondly, the success of this integrated system heavily relies on the willingness of all stakeholders in the vaccine supply chain to actively participate and share data. The decentralized nature of blockchain technology, while offering security and transparency benefits, also presents challenges regarding data privacy, ownership, and control. Finally, the use of machine learning algorithms in this system introduces the need for large volumes of accurate and timely data to effectively train these models. The quality of predictions and insights generated by machine learning is directly linked to the quality of the input data.

Authors' Contributions

All authors have contributed significantly to the research process and the development of the manuscript.

Declaration

In order to correct and improve the academic writing of our paper, we have used the language model ChatGPT.

Transparency Statement

Data are available for research purposes upon reasonable request to the corresponding author.

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Declaration of Interest

The authors report no conflict of interest.

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Ethical Considerations

In this research, ethical standards including obtaining informed consent, ensuring privacy and confidentiality were observed.

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