

Trustworthy Vaccine Distribution backed by Blockchain Technology

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ABSTRACT

India encountered multiple difficulties in the distribution of vaccines during the COVID-19 pandemic. The manufacturers encountered challenges such as the distribution of counterfeit vaccines, inadequate data sharing, supply chain complexities, and transparency-related issues. It was difficult to make sure that the vaccines were genuine and functional. Traditional systems are not capable enough for the purpose of monitoring vaccines from the point of origin till administration. The proper storage of vaccines and its distribution is another concern for the manufacturers. Blockchain technology is a good solution to overcome these issues related to vaccine distribution. It uses a decentralized system that is immutable in nature and is transparent. This ensures the safety of records, the tracking of vaccines, and the trust of all parties involved in the process. The study examines the primary obstacles to vaccine distribution in India and the factors that influence vaccine quality. These features might include the capacity to monitor vaccinations, clear information, security, cooperation with varied groups, and the use of emerging technologies like AI and IoT. Blockchain technology enables secure storage and verification of vaccine data by a variety of stakeholders such as manufacturers, distributors, healthcare professionals, and government officials. This may build trust by allowing all parties to observe the situation in real time. The study also touches some existing blockchain-based frameworks and pilot projects like VaccineLedger, StaTwig and other models designed for Indian needs. The results indicate that the blockchain has the potential to address trust issues, prevention of counterfeit vaccines into the system, and ensure that all individuals receive safe vaccines. Finally, the investigation demonstrates how blockchain technology can revolutionize the functioning of India's health system by enhancing the efficiency and dependability of vaccine distribution.

Keywords: Blockchain Technology, Supply Chain Management, Vaccine Distribution, Vaccine Ledger

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1. INTRODUCTION

Vaccination is a life-threatening public health involvement that comprises the management of vaccines to inspire an individual's immune system to develop adaptive invulnerability to pathogens, thereby preventing infectious viruses (1). Vaccines contain deteriorated or unplugged parts of a certain organism (antigen) that trigger a resistant response within the body. Through this process, the body learns to recognize and fight the actual pathogen if it is encountered in the future, significantly reducing the risk of illness and its spread within the community (2).

1.1. Importance of Vaccination

- a) **Disease Prevention:** One of the best methods for preventing infectious diseases is vaccination, reducing morbidity and mortality rates worldwide (1).
- b) **Herd Immunity:** A high vaccination rate in a population indirectly protects the unvaccinated by reducing the overall incidence of the disease (2).

- c) **Cost-Effectiveness:** Vaccination campaigns held on different terms reduce medical costs associated with treating illnesses that immunisation can prevent (3).

- d) **Global Health:** Vaccines are essential for disease control on a worldwide basis supporting global health stability and security (3).

1.2. Vaccination Distribution

Vaccination distribution systematic process of ensuring vaccines are delivered from manufacturers to the end recipients efficiently, safely, and equitably (4). This complex process is divided into several stages:

- a) **Manufacturing and Quality Control:** The vaccines production using the facilities of pharmaceutical is a highly regulated and meticulous process that go through several stages to ensure the highest standards of safety and efficacy. The research and development is the beginning phase for the vaccine to design and test in laboratory settings (5). Identified candidate undergoes clinical trials to evaluate its safety and effectiveness in humans. The vaccine is manufactured in sterile environments using precise protocols to

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maintain consistency and prevent contamination. The final product is tested based on Quality control measures at every step including the testing of raw materials as well as monitoring of production processes. The above mentioned measures ensure that each batch of vaccine strictly meets regulatory standards before it is approved for the public use against infectious diseases (6).

- b) **Storage and Handling:** To ensure effectiveness of vaccines stored under the cold chain conditions are crucial to preserving vaccine. The cold chain is a actually a temperature-controlled supply chain that starts from vaccines manufacturing until they are administered to patients. Vaccines are very sensitive to their predefined temperature range. Most of the vaccines needs to be stored at refrigerated temperatures (2°C to 8°C). Some may require freezing or ultra-low or negative temperatures. Cold chain is managed using specialized refrigeration equipment with insulated packaging and real-time temperature monitoring systems during transportation and storage. If the cold chain fails to maintain the defined measures may lead to the vaccines becoming ineffective or unsafe. It is essential to follow the defined cold chain protocols to ensure that vaccines remain strong and can provide the intended protection against diseases (7). These protocols include techniques related to the use of refined and updated equipment as well as cleanroom standards. To minimize the risk of infection the personnel must undergo severe training in hygiene practices and proper handling procedures. Most of the vaccines are handled in controlled environments with HEPA (High Efficiency Particulate Air) filtration systems to maintain air purity. All types of contact surfaces and tools are sanitized on a regular basis. The components used once are employed wherever possible to reduce infection risks (4,5).
- c) **Transportation and Logistics:** Transportation networks play a vital role in distributing vaccines from manufacturers to distribution centres and healthcare facilities. Maintaining the required cold chain and timely delivery is also ensured during this process. These networks covers transportation through air, road, and sea. As per vaccine needs the required temperature is maintained during vaccines delivery. Managing supply and demand across different regions is possible through effective coordination of logistics. This coordination ensures that vaccines reach their destinations without delay also preventing shortages in high-demand areas and minimizing waste in others (5).
- d) **Distribution Centers and Inventory Management:** Central and regional warehouses play a vital role in the vaccine distribution chain by storing vaccines securely before they are dispatched to local healthcare providers. These warehouses are maintained and equipped with dedicated refrigeration units to maintain the predefined and required cold chain to ensure the vaccines remain operative. There are advanced

inventory management systems implemented to keep track of vaccine stocks and also monitor the expiry dates as per distribution schedules. These inventory management systems provide real-time data enabling efficient allocation of vaccines based on current needs and preventing shortage and wastage of vaccines. These systems maintains optimal inventory levels and ensuring timely replacement and distribution of vaccines to the healthcare providers effectively (8).

- e) **Healthcare Delivery:** The final stage of vaccine distribution is to deliver vaccines to healthcare facilities such as hospitals, clinics, and community health centers. The trained healthcare professionals control vaccines to individuals in the community to immunize based on the given facilities. Efficiency is maintained by delivering the vaccines in optimal condition. Healthcare professionals are responsible for storing vaccines, managing patient records and sticking to the protocols for safe management and also responsible to ensures that each individual receives the correct dosage and is monitored for any adverse reactions (3).
- f) **Monitoring and Reporting:** Monitoring of vaccine and its safety is tracked with the help of Surveillance Systems by collecting data on vaccination rates, its effectiveness and any side effects caused after vaccination. The reports generated by these systems becomes crucial for identifying such areas where low vaccine uptake was reported with safety concerns and ensuring that vaccines are reaching the intended populations. Vaccination programs run by the government and public health authorities are successful based on the data collection and reporting mechanisms supporting to take decisions and strategies to improve vaccination programs. The data provided by these systems are used to analyzing and help policymakers to adjust distribution plans by enhancing public awareness campaigns. This process ensures that vaccines are managed efficiently and safely to protect public health (3,6).

1.3. Overview of Vaccination Distribution Challenges

The distribution of vaccination go through several challenges related to the equitable access, maintaining the supply chain integrity and managing logistics. In many underdeveloped and remote regions face challenges like shortages of vaccines, storage facilities inappropriate and transportation difficulties. These challenges become more complex when there is a need to provide proper cold-chain storage for vaccines with a specific temperature ranges. Another challenge is to track vaccine deliveries and prevent counterfeit vaccines as well as ensuring timely and accurate data on vaccine availability and immunization coverage. These challenges highlight the requirement for providing more efficient systems to ensure vaccines reach all populations safely and effectively (9).

1.3.1. Logistics

- a) **Cold Chain Requirements:** The temperature of the storage is essential to keep as per specification to keep the vaccines active. The challenge is to maintain the temperature of the cold chain as per specification from manufacturing to administering due to inadequate infrastructure. Breakdowns in the cold chain may cause spoilage and wastage of vaccines (7).
- b) **Transportation:** One of the most important part of the transportation is to ensure that the vaccines are delivered on time before their expiry. This may be challenging due to poor roads with limited transportation options and coverage of long distances in a very short period of time (5).
- c) **Inventory Management:** The vaccines should be tracked through the entire supply chain at each checkpoint to prevent overstocking and stockouts. This entails strong inventory management systems which are scarce (hard-to-reach) (6).
- d) **Coordination:** The need for the coordination between the manufacturers, distributors, healthcare providers and directive body for an uninterrupted distribution process. Without proper communication and coordination things can be delayed and ineffective (4).

1.3.2. Tracking

- a) **Traceability:** The ability to identify what vaccine a patient receives, where it is produced, verify the quality, and ensure against delays and diversion. Existing tracking systems are still disparate and inconsistent.
- b) **Data Management:** It is essential to collect and manage data regarding the distribution of vaccinations as well as administration in order to assess progress and make sound decisions. Data systems are insufficient or nonexistent in much of the world.
- c) **Verification:** Checking the authenticity and integrity of vaccines during various stages of the supply chain is essential to avoid the spread of fake vaccines. Verification usually has weak mechanisms (5).

1.3.3. Fraud

- a) **Counterfeit Vaccines:** The spread of fake vaccines can be massively harmful to public health. Detecting and blocking fake vaccines from getting distributed is the primary problem (10).
- b) **Diversion:** Vaccines intended for a given destination end up being diverted and illegally sold or used elsewhere (11).
- c) **Corruption:** Corruption in the supply chain may lead to selling vaccines on the black market, diversion, or inaccurate allocation of supplies all affecting equitable and fully effective distribution (12).

1.3.4. Accessibility

- a) **Geographical Barriers:** Most of the remotes and rural regions experience a challenge in reaching to healthcare facilities making it difficult for vaccine carriers to deliver vaccines to these areas (6).
- b) **Socioeconomic Barriers:** Socioeconomic factors associated with poverty and lack of education can hamper the vaccine access. Vaccination may not be affordable or prioritized by people in low-income communities (13).
- c) **Health Infrastructure:** Poor healthcare infrastructure means shortage of healthcare workers and facilities limits the effective distribution and administration of vaccines (14).
- d) **Public Awareness and Acceptance:** Low uptake of vaccination due to misinformation, cultural beliefs, and vaccine hesitancy. It is difficult to increase public awareness and acceptance based on these initiatives (14).

1.4. Introduction to Blockchain Technology

It was first proposed by an unidentified individual or group claiming to be "Satoshi Nakamoto" in 2008 and forms the backbone of the Bitcoin (15). At its most basic form, blockchain is a decentralized and local digital record that records communications among many computers in such a way that the data cannot be altered afterwards. That doesn't changeability, combined with transparency and safety, is this technology of the block chain attractive for additional applications so as not to cover cryptocurrencies (16).

1.5. Key Features of Blockchain Technology

- a) **Regionalization:** Unlike traditional centralized databases and systems, which have a central organization running the database, a blockchain is run by a P2P (point-to-point) network. Each participant (called a node) maintains its own copy of the entire blockchain, ensuring that there can be no single point of failure (17).
- b) **Fixity:** Once data is documented in a blockchain, it is tremendously hard to amend. This is because each block contains a cryptographic hash of the previous block, along with a timestamp and transaction data. Any attempt made to change the data in a block requires modifications at all subsequent blocks which is practically infeasible in a large network (18).
- c) **Transparency:** The transactions are visible to all parties on a public blockchain which generates accountability and trust. This transparency guarantees that every action can be tracked down and verified. (19).
- d) **Safety:** Through its use of advanced cryptographical techniques, blockchain secures data and mediates access. Moreover, since the technology is regionalized, it is not subject to malicious attacks, such as hacking or fraud (16).

- e) **Consensus Mechanisms:** Having consensus systems like Proof of Work (PoW) and Proof of Stake (PoS) blockchain confirms connections and adds them to the ledger. It means that all the nodes within the grid are in contract to the state of the blockchain (15).

1.5.1. Applications of Blockchain Technology

While blockchain technology gained initial popularity through cryptocurrencies, its potential applications are vast and varied, including:

Cryptocurrency is one of the most popular application of blockchain technology. It has the potential to cover almost every sector. Some of the sectors are listed below:

- a) **Finance:** Blockchain is not just about crypto it can be used for much quicker and safer financial transfers outside of crypto such as cross-border payments and remittance (20).
- b) **Supply Chain Management:** It can help verify the authenticity of products and reduce fraud by expanding the traceability and transparency of supply chains (8).
- c) **Healthcare:** Blockchain can also be introduced to health information systems in order to enhance their security and interoperability to ensure that the right patient data is available for treatment without sacrificing privacy (9).
- d) **Voting Systems:** Utilizing blockchain-based voting system can offer a secure and transparent way to conduct partiality-free elections to lower down fraud risk and increase voter trust (21).
- e) **Smart Contracts:** Provisions of these smart contracts are coded directly into the code allowing for automatic and reliable contract enforcement without the involvement of third parties (22).
- f) **Identity Verification:** It can offer a safe and controlled way to deal with multiple identities using Blockchain when no one person needs to hold that responsibility to get rid of identity theft and fraud (23).

1.5.2. Challenges and Future Directions

Despite its potential, blockchain technology faces several challenges:

- a) **Scalability:** Most of the existing blockchain networks especially with PoW require a long time to process heavy traffic on transactions (9).
- b) **Energy Consumption:** PoW consensus mechanism use extensive computational resources which results in high energy consumption (9).
- c) **Regulatory and Legal Issues:** Several countries have already imposed regulations and rules regarding blockchain and cryptocurrency. These regulations are continuously developing (22).
- d) **Interoperability:** The coordination of multiple blockchains into more acceptable big picture data is a challenge (9).

The future of blockchain will probably continue innovating to solve these puzzle and also mass adoption across multiple sectors. New approaches to consensus systems such as Proof of Stake and other alternatives are designed specifically to increase scalability while lowering energy consumption (9). While some uses have accrued a bad name recently there is strong belief that as the technology matures it has potential to change many industries for the better by providing secure and transparent means of managing digital transactions and data (20,23).

1.5.3. The probability of blockchain to address the encounters related to Vaccine Distribution

With the capability to enhance transparent security and efficiency by solving a large number of problems associated with vaccination delivery (23). Here are some key areas where blockchain can make a substantial impact:

1.5.3.1. Supply Chain Transparency and Traceability

- a) **Tracking Vaccine Origins and Movements:** Blockchain can create an indisputable record of every point in time and all processes of the vaccination supply chain from engineering to delivery and administration. This may record each step in the journey on the blockchain as one verifiable and accountable record of events related to vaccine passage (5).
- b) **Preventing Counterfeiting:** Blockchain potentially has ability to stop fake vaccines from entering the market by providing a publicly accessible and immutable audit trail of vaccine batches. Blockchain records can allow healthcare providers and patients to check the validity of vaccines (10).

1.5.3.2. Improving Data Integrity and Security

- a) **Immutable Records:** Blockchain has distributed and permanent nature of record keeping. This nature of blockchain restrict the records to be changed or modified. This process reinforces the accuracy and reliability of records concerning vaccine manufacturing, storage, and distribution (6).
- b) **Enhanced Security:** Sensitive information is protected from unauthorized access by using cryptographic techniques. This is vital for maintaining the confidentiality and protection of patient details and vaccine information (3).

1.5.3.3. Optimizing Logistics and Inventory Management

- a) **Real-Time Tracking:** All parties involved in the distribution process can access up-to-date information by implementing real-time monitoring system of blockchain on vaccine shipments regarding the location and status of vaccine batches (4).
- b) **Automated Inventory Management:** Smart contracts are coded by blockchain to automate the inventory management tasks by reordering supplies when stock

levels drop below a predefined point. The shortages and replacement of vaccines can be reduced (7).

1.5.3.4. Ensuring Cold Chain Compliance

- a) **Temperature Monitoring:** Mostly vaccines are stored as per predefined temperature regulations. Blockchain can make the use of IoT sensors to keep logs of temperature data during the supply chain. These logs may be securely stored on the blockchain by offering a trustworthy record that can be audited to verify whether cold chain standards are maintained (7).
- b) **Automated Alerts:** Once again smart contracts can be used to generate automatic alerts when temperature limits exceed or drops by taking immediate corrective measures to prevent spoilage and maintain vaccine effectiveness (5).

1.5.3.5. Streamlining Regulatory Compliance

- a) **Simplifying Audits:** The audits can be easily executed by regulatory agencies due to the clear and unchangeable characteristics of blockchain records. All required documents and compliance evidence can be accessed effortlessly on the blockchain during the audit (17).
- b) **Reducing Administrative Burden:** Blockchain can reduce administrative workload by automating documentation and reporting so that healthcare professionals may concentrate more on patient care (16).

1.5.3.6. Enhancing Collaboration and Coordination

- a) **Interoperability:** The vaccine distribution chain involves multiple parties like manufacturers, distributors, healthcare providers and regulatory agencies. Blockchain collaborates and share data with various participants during vaccine distribution chain (15).
- b) **Unified Platform:** A blockchain-based system guarantees a unified platform for all participants by reducing the possibilities of discrepancies and ensuring that everyone has access to the same data (22).

1.5.3.7. Ensuring Equitable Distribution

- a) **Transparent Allocation:** The vaccine distribution process should be transparent and can be achieved by using blockchain. This transparency during distribution builds public trust and ensures that vaccines reach the populations who require them the most (23).
- b) **Preventing Hoarding and Fraud:** To prevent hoarding and fraud during distribution the transparency feature of blockchain can help reduce misdirection of vaccine supplies. Any inconsistencies in the distribution process can be swiftly detected and rectified (22).

2. LITERATURE REVIEW

Namasudra S and K Akkaya (19) in their paper presented a detailed description of blockchain technology being used in various sectors like finance, healthcare, insurance etc. by covering its advantages like data integrity, verifiability, decentralization and traceability. Authors stated that the blockchain technology has the limitations of network robustness, scalability, immaturity, time-consuming and storage. The paper describes the blockchain application for international payments called Santander One Pay FX, Axoni for capital markets. The implementation of blockchain faces the challenges of cyberattack, high energy consumption and data compression.

Pathak R et al. (10) states that counterfeit has become a global issue requiring some special attention and measures to overcome with it. There is a need of some new steps to tackle the vaccine counterfeit problem. This review paper suggests consumers to be proactive and react against the recognized difference in the vaccine. It also suggests to educate consumers to identify original and fake vaccine. However, the scope of the study is limited to suggesting the policymakers to work on appropriate laws to reduce counterfeit.

Lim J et al. (5) states a problem of vaccine distribution which is not cost efficient and requires temperature-controlled environment to distribute vaccines. Authors proposed an approach to redesign the vaccine distribution chain. The proposed model was not able to reduce the wastage of vaccines due to power failure. The proposed model is programmed to work on stable population and may fail if the population increases and require change in network structure if the new vaccine is introduced.

Kamenivskyy Y et al. (24) identified the key challenges associated with security issues and lack of production capacity in the vaccine distribution chain using direct interviews. A framework is proposed by the authors to improve communication between stakeholders, simplify vaccine inventory and increase supply chain security. The smart contract is used to automate the inventory and QR Code with vaccine dose ID is cross-referenced for validation. The proposed solution was not able to improve miscommunication between stakeholders. Blockchain cannot increase the number of production industries or manufacturers and cannot force the manufacturers to pack one dose per vial. So, the proposed model is not able to address a solution to overcome this challenge. It is also limited to store patient's medical record and unable to handle organizational physical challenges like power failure and insufficient staff or technical assistance.

Das D, Ruj S et al. (25) proposed a Blockchain-enabled Secure Vaccine Passport System using the power of smart contract. Vaccine Passport is a documentary proof of being vaccinated. The prototype is built on Ethereum platform deployed on Sepolia Test Network for evaluating and validating the effectiveness of the system. The future scope of the system is to focus on scalability and performance to handle large volume of transactions.

P. Saliou, Q. Duteil et al. (26) focused on fake vaccine trafficking during COVID-19 pandemic. This study states the seriousness and means of falsification by suggesting the need of coordination between all involved actors to tackle this problem. The study describes a detailed history of fake vaccines in developing and developed countries. Authors stated the need of regulatory and political support to initiate some necessary actions to overcome the challenge of falsification.

Park A, H Li (27) focused on blockchain technology and operation management in supply chain management especially in airport industry aiming sustainable performance. The manuscript mentions about the Airport Collaborative Decision Making (A-CDS) platform adopted by Italian airports which is a blockchain-based application to promote cooperation between aviation industry and air traffic controllers to reduce fragmentations and inefficiency. However, it is still not possible to identify high sustainability issues in Italian airports. The application platform was implemented on the Italian airports but can be extended to airports in different countries by making some advancements in blockchain technology.

Meghla T, Rahman M et al. (28) performed demand forecasting for COVID-19 vaccines according to geographical area and storage facilities. The study describes the necessity of blockchain and machine learning in supply chain management with demand forecasting of COVID-19 vaccines. The proposed model is limited to the forecasting based on geographical area and storage facility, but not the efficacy of the vaccine. Further study may include collection of huge vaccine distribution dataset to check its effectiveness.

Musamih A, Jayaraman R, Salah K et al. (29) addresses important issues of COVID-19 vaccine distribution related to tracking, tracing, and monitoring. The paper proposed a Ethereum blockchain-based solution for managing data related to vaccine distribution during COVID-19 pandemic. This solution uses smart contract to automate the traceability of vaccine distribution. The proposed model is not able to describe the use of permissioned Ethereum which require Ether (a native cryptocurrency of Ethereum blockchain) to execute functions. Further advancement of Quorum platform can be used to make sure that the transactions are accessed by the authorized personnel.

Verma A, Bhattacharya P, M Zuhair (30) proposed a scheme called VaCoChain. The article illustrates the benefits of UAVs integrated with 5G-TI (5G-Tactile Internet) for distributing vaccines during pandemics. This 5G-TI enabled UAV is monitored through ground controller stations as it supports real-time dense connectivity. This connectivity has <1 milliseconds round trip-time (RTT) and high availability of 99.99999%. This proposed technology is limited to infrastructure cost, weather impact, data traceability and UAV performance. In future, the proposed model may involve private and secure communication between healthcare professionals by integrating quantum based key distribution.

Angraal S, Krumholz H, Schulz W (23) described current and future applications of blockchain technology within healthcare industry. The article states the technical limitations like blockchain data is encrypted which can be potentially compromised. The speed and scalability of blockchain technology in the field of health care is already arisen in smaller blockchain-based applications. The bitcoin network is able to validate 7 transactions per second which could limit the throughput of large blockchain networks. It is yet to be proven that the large volume of data has cost-effectiveness. The study suggests more research in the field with large-scale production deployments and advancements because applications in health care are yet to be established.

The article of **Rathee G, Garg S and G Kaddoum** (31) aims to provide a secure COVID-19 vaccine distribution system using IoT. The article states the challenges and issues that need to be focused before integrating smart-systems. These challenges include verification delay of any new block before adding it to existing blockchain. The network scalability should be flexible which may be increased or decreased according to the requirements of the application. The proposed phenomenon may be further enhanced by verifying each block by maintaining ledger's time required to verify in future communication.

2.1. Improving Vaccine Distribution Systems using Blockchain

Vaccine distribution systems can be improved by increasing transparency, safety, and productivity across the supply chain by using blockchain. It provides real-time tracking of vaccines from the distributor to the end-user by keeping log of each transaction and movement in a ledger of immutable nature. This tracking system ensures that vaccines are not lost and allows all participants to verify their validity and origin. By using cryptographic techniques and distributed nature of blockchain makes it secure from tampering and fraud. It also ensures that data related to distribution is secure and cannot be altered without detection (32). All participants of distribution system has access to a unified platform based on blockchain to ensure vaccines are delivered on time and track the entire route plan reducing any diversion. Blockchain can collaborate with IoT devices to monitor the temperature and condition of vaccines during transit. The IoT sensors alert participants if there are any ups and downs in the predefined temperature ranges to prevent the wastage of vaccines (25). Blockchain can maintain accurate inventory records to prevent overstocking or shortages and support in the effective allocation of vaccines. Transparent nature of blockchain and immutability help stakeholders to prevent fraud and misuse of vaccines by ensuring that each dose reaches the intended recipient. Blockchain also simplifies regulatory compliance by generating automated reports and providing reliable data helping in reducing the administrative burden on healthcare providers (24). Blockchain ensures transparent and equitable distribution in the regions where there are limited or low resources available and also tracks that vaccine allocation is done on priority (33).

2.2. Evaluating the Blockchain-based Model

It is a strong requirement for evaluating a blockchain-based model, especially in the context of blockchain-based solutions (34). However, depending on the specific requirements of our proposed model, we may consider the following tools:

- i. **Hyperledger Caliper:** When it comes to evaluate the performance of any blockchain-based solution then Hyperledger Caliper is the best choice. This open-source blockchain benchmarking tool allows us to test performance based on metrics such as operation throughput, expectancy, resource consumption, and scalability. Hyperledger Caliper is a native tool within the Hyperledger ecosystem and it is well-integrated with Hyperledger Fabric and other Hyperledger projects which makes it perfect for a detailed performance analysis of our proposed model (35–37). It supports multiple blockchain frameworks such as Hyperledger Fabric, Ethereum, and Quorum (38).
- ii. **Quebec Framework:** The evaluation of any model is tested based on some metrics. Quebec Framework provides a structured approach to evaluate blockchain solutions which focuses on metrics like decentralization, security, and scalability. It is a comprehensive framework that not only focuses on just performance but, also consider the broader context of blockchain application. In the vaccine distribution evaluation based on the performance, scalability, security and decentralization are important and can be identified through this framework (39).
- iii. **BlockSim:** It is yet another open-source discrete-event simulation tool for blockchain systems. It can simulate blockchain protocols and evaluate performance metrics like transaction throughput, delay, and block propagation times (40).

Hyperledger Caliper is likely the best choice because it is specifically designed for evaluating Hyperledger-based models that offer comprehensive performance testing and align it with the objectives of our research. It will allow us to accurately assess how well our proposed model meets the demands of vaccine distribution in terms of robustness, scalability, efficiency, throughput and security (38).

3. JUSTIFICATION OF RESEARCH

The global healthcare systems faced many challenges during the COVID-19 pandemic inspired to conduct research on Vaccine distribution using blockchain. This study is justified by the pressing need for secure, transparent, and efficient vaccine distribution mechanisms which blockchain technology promises to address effectively.

3.1. Addressing the Challenges in Vaccine Distribution

There are challenges faced by the vaccine distribution networks such as counterfeiting, logistical inefficiencies, and lack of transparency. Pathak et al. (10) and Musamih et al. (29) highlight the issue of fake drugs within the medical supply chain, especially in vaccine distribution. It is challenging to track and trace vaccines from producers to

end users due to the complexity and dispersion of global supply chains where counterfeiters may take advantage of creating weaknesses. This damages public confidence and presents serious health hazards. Research by Boeck et al. (6) highlights the deficiencies in vaccination supply chains in low- and middle-income (LMIC) nations where logistical issues are most visible.

These issues can be solved through blockchain due to its inherent features of transparency, immutability, and traceability. Blockchain is capable enough to provide end-to-end visibility in the supply chain, as discussed by Antal et al. (41). It can significantly reduce the risk of counterfeiting and ensure that vaccines are sourced from authentic manufacturers and delivered through the appropriate channels.

3.2. Enhancing Supply Chain Efficiency and Transparency

The COVID-19 pandemic illustrated severe vulnerabilities of the global vaccine distribution network and demanded new thinking about existing systems. As suggested in the studies by Lim et al. (5) and Kamenivskyy et al. (24) the standing is that vaccine dispersal networks should be redesigned to tackle the special obstacles of pandemics. Blockchain technology is not a revolution that will change the world it is simply another tool that can be combined with other technologies— such as the Internet of Things (IoT) or Machine Learning (ML) — can make these networks more effective and transparent.

The work of Verma et al. (30) on VaCoChain system reveals that combining blockchain with emerging technologies like 5G and unmanned aerial vehicles (UAVs) to build a responsive and resilient vaccine distribution system. This approach will improve the speed and accuracy of vaccine delivery to ensure that the entire process is transparent and verifiable to boost public confidence in the vaccination process.

3.3. Facilitating Data-Driven Decision-Making

Blockchain has the ability to provide a decentralized and guaranteed record of transactions with the support of data-driven decision-making in vaccine distribution. Meghla et al. (28) proposed a Blockchain-ML based model that leverages data to forecast vaccine demand and optimize supply chain operations. This integration ensures that vaccines are distributed equitably and efficiently to healthcare providers and policymakers to take decisions about resource allocation.

3.4. Supporting Public Health Initiatives

The logistics of vaccine distribution is not where blockchain play role in promoting public health initiatives. Research by Singh et al. (16) and Rotbi et al. (42) shows that blockchain could further be used in order to assist in the monitoring and documenting any adverse effects after vaccination to improve vaccine safety and efficiency. Blockchain can enable better public health outcomes by allowing better collaboration among healthcare stakeholders by data sharing.

3.5. Addressing the Problem of Counterfeit Vaccines

In 2020, counterfeit COVID-19 vaccines were reported in multiple countries, including Russia, Mexico and Ecuador, during the early stages of the pandemic(43–45). Meningitis counterfeit vaccines were identified in Cameroon (2019), China (2016) and Niger (2015). Counterfeit Cholera vaccines were found in Bangladesh, particularly in areas affected by floods in 2019 (46)(26).

4. RESEARCH GAPS

- i. Complete vaccination coverage for children is delayed by logistical challenges, unfair healthcare access, unreliable data, and vaccine uncertainty. Current systems lack efficiency and transparency (9,18)(47)(48).
- ii. Vaccine distribution is compromised by pilferage, leading to financial losses. Traditional methods lack real-time monitoring and verification (4,5,49,50)(51).
- iii. Duplicate and counterfeit vaccines threaten public health and minimizes trust in vaccination programs. Existing tracking systems lack real-time visibility (10,11,26,46).

5. RESEARCH OBJECTIVES

The research gaps reported in the previous section lead this research work to a set of objectives listed below:

- i. To study the contemporary models and technology for vaccine management.
- ii. To propose a blockchain-based model for an optimized vaccine distribution system.
- iii. To evaluate the proposed blockchain-based model against the identified key parameters.

6. RESEARCH METHODOLOGY

The study consists of three distinct goals that are coupled to one another and proposed to be accomplished in the order that they have been laid out. The methods to be used to accomplish each aim will vary, though, because each one has a unique task that must be completed as a stand-alone activity. To achieve the first research objective, the focus will be on understanding the existing technology being used for vaccine distribution in India. This will involve a detailed review of existing literature on vaccination distribution practices, particularly technological solutions already in use, especially within India. The researchers proposed different types of models and phenomenon ideas to solve different types of problem in various sectors since the inception of blockchain technology. Every research article has some limitations and future suggestions to upgrade the proposed model. Exploring published journal articles, government reports, and case studies to clearly understand the current infrastructure, its challenges, and areas where improvements are needed. Additionally, it explores how emerging technology blockchain can be integrated into vaccine distribution to make the process more efficient, robust and scalable.

The second research objective would require studying the probable role of blockchain data on vaccine distribution occurring in India, and the utility of this data in vaccine distribution. The existing literature on blockchain technology is reviewed for supply chain transparency, and vaccine distribution will be conducted to identify key challenges and opportunities. A blockchain-based model will address transparency and traceability from source to consumer within the vaccine supply chain based on these insights. The evaluation of the proposed model is based on some key parameters such as data integrity, real-time tracking, cost-efficiency, scalability, robustness, throughput, security, and interoperability.

The third objective shall evaluate the proposed model based on identified key parameters proposed in objective 2 above. The proposed model will next be validation process by using a benchmarking tool within a controlled setup. Transaction volumes and network loads will be used to test the performance of model against the identified key parameters. This process enables a comprehensive evaluation of its feasibility and potential impact on vaccine distribution. The generated outcomes will be analysed to identify any bottlenecks or areas for improvement and findings will be compared against existing vaccine distribution techniques to validate the advantages of the proposed model.

7. EXPECTED OUTCOME

The projected outcomes of this research are multi-layered and aim to significantly enhance vaccine distribution systems in India. It starts by thoroughly understanding the current technology and infrastructure being used. The research will then identify existing challenges and areas that need improvement by providing a foundation for integrating emerging technologies like Blockchain, IoT, and AI. This combination is expected to address critical inefficiencies, increase transparency, and improve the scalability of vaccine distribution. The second outcome will comprise the proposal of blockchain-based model which will be personalized as per Indian context using Hyperledger technology. This model is expected to offer a more secure, reliable, and efficient system for managing vaccine distribution data as well as addressing the limitations of existing systems. Finally, the proposed model will be validated through the identified key parameters. These parameters will ensure that the evaluated model is successful based on performance, scalability, security and robustness. These outcomes will not only contribute to the academic understanding of blockchain applications in healthcare but also offer practical solutions for enhancing vaccine distribution in India.

Conflicts of Interest

“The author(s) declare(s) that there is no conflict of interest regarding the publication of this paper.”

Statements and Declarations

Competing Interests

The authors declare that they have no competing interests.

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Author Contributions

Author Name	Contribution
Kamal Kumar	Conceptualization, Literature review, blockchain model design, implementation, manuscript writing
Dr. Preetinder Brar	Supervision, review, and editing

Data Availability

No datasets were generated or analyzed during the current study.

Research Involving Human Participants and/or Animals

This article does not contain any studies involving human participants or animals performed by any of the authors.

INFORMED CONSENT

Informed consent was not required as this study did not involve human participants.

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REFERENCES

1. Ada G. Overview of Vaccines and Vaccination. *Mol Biotechnol.* 2005 Mar;29(3):255–71.
2. SA Plotkin. Vaccines, Vaccination, and Vaccinology. *Perspective.* 2003; 187:1349–59.
3. Lombard M, Pastoret P, AM Moulin. A Brief History of Vaccines and Vaccination. *Rev Sci Tech.* 2007;26(1):29–48.
4. Medlock J, AP Galvani. Optimizing Influenza Vaccine Distribution. *Science (1979).* 2009;325(5948):1705–8.
5. Lim J, Norman B, J Rajgopal. Redesign of Vaccine Distribution Networks. *Wiley Online Library.* 2022;29(1):200–25.
6. Boeck K De, Decouttere C, N Vandaele. Vaccine Distribution Chains in Low-and Middle-income Countries: A Literature Review. *Elsevier.* 2020; 97:102097–135.
7. Pelliccia M, Andreozzi P, Paulose J, D'alicarnasso M, Cagno V, Donalisio M, et al. Additives for vaccine storage to improve thermal stability of adenoviruses from hours to months. *nature.com [Internet].* 2016 [cited 2024 Jul 12];7. Available from: <https://www.nature.com/articles/ncomms13520>
8. Boschi AA, Borin R, Raimundo JC, Batocchio A. An Exploration of Blockchain Technology in Supply Chain Management. *22nd Cambridge International Manufacturing Symposium.* 2018;
9. Siyal A, Junejo A, Zawish M, Ahmed K, A Khalil. Applications of Blockchain Technology in Medicine and Healthcare: Challenges and Future Perspectives. *Cryptography.* 2019;3(3).
10. Pathak R, Gaur V, Sankrityayan H, J Gogtay. Tackling Counterfeit Drugs: The Challenges and Possibilities. *Springer.* 2023 Jul 1;37(4):281–90.
11. Chauhan H, Gupta D, Gupta S, Singh A, Aljahdali HM, Goyal N, et al. Blockchain Enabled Transparent and Anti-counterfeiting Supply of COVID-19 Vaccine Vials. *Vaccines (Basel).* 2021;9(1239):1–18.
12. NF Siahaan. The Fake Vaccine and in Terms of Civil Law Theory (Commercial Law) That Related to Consumer Protection and Organized Crime. *International Joint Conference on Arts and Humanities.* 2021; 618:697–700.
13. Ryan Lomondot Diamla M, Mukattil N, Ryan Diamla ML, Carl Mejia PG, Joel Breboneria BL, Rajan JK, et al. Public Health Nurses' Demographic Factors and Level of Awareness as Determinants to Safe Vaccine Administration. *International Journal of Advanced and Applied Sciences.* 2020;7(6):103–9.
14. Ahiakpa ID JK, Cosmas ID NT, Anyiam ID FE, Enalume KO, Lawan I, Gabriel IB, et al. COVID-19 Vaccines Uptake: Public Knowledge, Awareness, Perception and Acceptance among Adult Africans. *PLoS One.* 2022 Jun 1;17(6 June):1–21.
15. Sahani A, Singh P, Kumar A. Introduction to Blockchain. *Springer.* 2020;01(4):1–9.
16. Singh G, Garg V, P Tiwari. Introduction to Blockchain Technology. *Springer.* 2021;1–235.
17. Laurence T. Introduction to Blockchain Technology. Vol. 1. 2019.
18. MA Engelhardt. Hitching Healthcare to the Chain: An Introduction to Blockchain Technology in the Healthcare Sector. *Technology Innovation Management Review.* 2017;7(10):22–34.
19. Namasudra S, K Akkaya. Introduction to Blockchain Technology. *Springer.* 2023; 119:1–28.
20. Laroija C, Saxena D, C Komalavalli. Applications of Blockchain Technology. *Elsevier.* 2020;
21. Wu J, NK Tran. Application of Blockchain Technology in Sustainable Energy Systems: An Overview. *Sustainability.* 2018;10(3067).
22. Miraz MH, Ali M. Applications of Blockchain Technology Beyond Cryptocurrency. *Annals of Emerging Technologies in Computing.* 2018 Jan 1;2(1):1–6.

23. Angraal S, Krumholz HM, Schulz WL. Blockchain Technology: Applications in Health Care. *Circ Cardiovasc Qual Outcomes*. 2017 Jun 1;10(9).
24. Kamenivskyy Y, Palisetti A, L Hamze. A Blockchain-based Solution for COVID-19 Vaccine Distribution. *IEEE Engineering Management Review*. 2022;50(1):43–53.
25. Das D, Ruj S, Maitra S. SecureVAX: A Blockchain-Enabled Secure Vaccine Passport System. *Cryptography and Security*. 2024 Jul 18;
26. Saliou P, Duteil Q, Plotkin SA, Gentilini M. The Scourge of Vaccine Falsification. Vol. 40, *Vaccine*. Elsevier Ltd; 2022. p. 2126–8.
27. Park A, H Li. The Effect of Blockchain Technology on Supply Chain Sustainability Performances. *Sustainability*. 2021;13(4):1726.
28. Meghla TI, Rahman MM, Biswas AA, Hossain JT, Khatun T, Amin Biswas A. Supply Chain Management with Demand Forecasting of Covid-19 Vaccine using Blockchain and Machine Learning. 12th International Conference on Computing Communication and Networking Technologies (ICCCNT). 2021;
29. Musamih A, Jayaraman R, Salah K, HR Hasan. Blockchain-based Solution for Distribution and Delivery of COVID-19 Vaccines. *IEEE Access*. 2021; 9:71372–87.
30. Verma A, Bhattacharya P, M Zuhair. VaCoChain: Blockchain-Based 5G-Assisted UAV Vaccine Distribution Scheme for Future Pandemics. *IEEE J Biomed Health Inform*. 2021;26(5):1997–2007.
31. Rathee G, Garg S, G Kaddoum. An IoT-based Secure Vaccine Distribution System through a Blockchain Network. *IEEE Xplore*. 2021;10–5.
32. Priyanka MrsR, Sreeram DrG. Protecting Vaccine Safety: An Improved, Blockchain-Based, Storage-Efficient Scheme. *Educational Administration: Theory and Practice*. 2024 Jun 4;30(6):887–96.
33. S Saranya. Go-win: Covid-19 Vaccine Supply Chain Smart Management System using Blockchain, IoT and Cloud Technologies. *Turkish Journal of Computer and Mathematics Education*. 2021;12(12):1460–4.
34. Scherer M. Performance and Scalability of Blockchain Networks and Smart Contracts. *Digitala Vetenskapliga Arkivet*. 2017;1–46.
35. Androulaki Artem Barger Vita Bortnikov E, Cachin Konstantinos Christidis Angelo De Caro David Enyeart C, Ferris Gennady Laventman Yacov Manevich C, Muralidharan S, Murthy C, Nguyen B, et al. Hyperledger Fabric: A Distributed Operating System for Permissioned Blockchains. *EuroSys*. 2018 Apr 23; 18:1–15.
36. Nasir Q, Qasse I, M Abu Talib. Performance Analysis of Hyperledger Fabric Platforms. *Wiley Online Library*. 2018; 2018:1–14.
37. Nguyen MQ, Loghin D, Dinh TTA. Understanding the Scalability of Hyperledger Fabric. 2021 Jul 21;
38. Nguyen MQ, Loghin D, Tuan T, Dinh A. Performance and Scalability Analysis of Ethereum and Hyperledger Fabric. *IEEE Access*. 2023; 11:67156–67.
39. Chembessi C, Beaurain C, G Cloutier. Analyzing Technical and Organizational Changes in Circular Economy (CE) Implementation with a TOE Framework: Insights from a CE Project of Kamouraska (Quebec). *Springer*. 2022 Sep 1;2(3):915–36.
40. Alharby M, van Moorsel A. BlockSim: An Extensible Simulation Tool for Blockchain Systems. *Frontiers in Blockchain*. 2020;3(28):1–16.
41. Antal C, Cioara T, M Antal. Blockchain Platform for COVID-19 Vaccine Supply Management. *IEEE Open Journal of the Computer Society*. 2021; 2:164–78.
42. Rotbi M, S Motahhir. Blockchain Technology for a Safe and Transparent Covid-19 Vaccination. *Journal of ICT Standardization*. 2022;10(2):125–44.
43. Actualités | MesVaccins [Internet]. [cited 2024 Nov 13]. Available from: <https://www.mesvaccins.net/web/news/18018-contrefacon-de-vaccins-et-d-antiviraux-contre-la-covid-19>
44. Ecuador Clinic Injected Thousands with Fake COVID-19 Shots | TIME [Internet]. [cited 2024 Nov 13]. Available from: <https://time.com/5933689/ecuador-covid-19-vaccine-scam/>
45. Medical Product Alert N°2/2021: Falsified COVID-19 Vaccine BNT162b2 [Internet]. [cited 2024 Nov 13]. Available from: <https://www.who.int/news/item/26-03-2021-medical-product-alert-n-2-2021-falsified-covid-19-vaccine-bnt162b2>
46. Jarrett S, Wilmansyah T, Bramanti Y, Alitamsar H, Alamsyah D, Krishnamurthy KR, et al. The Role of Manufacturers in the Implementation of Global Traceability Standards in the Supply Chain to Combat Vaccine Counterfeiting and Enhance Safety Monitoring. *Vaccine*. 2020 Dec 14;38(52):8318–25.
47. Sarker A, Akram R, Ali N, Chowdhury Z, M Sultana. Coverage and Determinants of Full Immunization: Vaccination Coverage among Senegalese Children. *Medicina (B Aires)*. 2019;55(480).
48. Khan J, Shil A, R Prakash. Exploring the Spatial Heterogeneity in Different Doses of Vaccination Coverage in India. *PLoS One*. 2018 Nov 1;13(11).
49. Musamih A, Jayaraman R, Salah K, HR Hasan. Blockchain-based Solution for Distribution and

- Delivery of COVID-19 Vaccines. IEEE Access. 2021; 9:71372–87.
50. Muckstadt JA, Klein MG, Jackson PL, Gougelet RM, Hupert N. Efficient and Effective Large-Scale Vaccine Distribution. Int J Prod Econ. 2023 Aug 1;262.
51. Samad A, AS Abdul Ghani. The Golden Liquid and Criminal Opportunity. Malaysian Journal of Law & Society. 2022; 30:91–8.