

A Blockchain – Based Framework For Transparent, Immutable, And Secure Vaccine Supply Chains

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Abstract:

The effectiveness of the large-scale vaccination initiatives relies on the secure and transparent supply chains to ensure the authenticity, safety, and adequate treatment of the vaccines. The classic centralized systems are usually characterized by counterfeiting and data modification, fragmented records, and failure to monitor cold-chain conditions appropriately. These problems may jeopardize the quality of vaccines, diminish the confidence of the population and disrupt the successful process of immunization. This framework suggests the implementation of the blockchain-based system to develop transparent, immutable, and secure vaccine supply chain. The framework uses a permissioned blockchain network whereby the parties who are verified to be the authorized stakeholders, such as the manufacturers, logistics providers, healthcare facilities, and regulators have the capability to record and verify every step of the vaccine movement. Examples of critical operations that are automated by smart contracts include transfer of custody, compliance checks in cold-chain, and recall management. The IoT-powered sensors to monitor temperature, storage conditions in real-time are verified by anchoring the data to the blockchain where it is stored. Large datasets are provided with off-chain storage, whereas cryptographic approaches provide privacy and security to sensitive data. The proposed system offers end to end traceability; automated compliance checks and record audits, thereby boosting the confidence of stakeholders and improving resilience against fraud and inefficiencies. Finally, this is one way of delivering vaccines safely and contribute to the success of immunization efforts in the world.

Keywords: Pharmaceutical Supply Chain, Smart Contracts, Data Provenance, immutability, Authentication, Blockchain, Drug Traceability, Decentralized storage, Counterfeit Prevention, Supply chain Transparency, Pharmaceutical Supply Chain

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1. INTRODUCTION

Vaccines are still one of the most useful tools in the medical field and they have helped the population to prevent threatening diseases and avert the outbreak of epidemics on a massive scale. The successfulness of the vaccination programs however, is not just a question of science breakthrough or capability of creating vaccines. To a great degree it will be dependent on the efficiency, reliability, and security of the vaccine supply chain. There is no doubt that since it is manufactured to administration, it is obligatory that vaccines be kept, transported, and manipulated in well regulated environment particularly in cold chain where any slight deviation in temperature can render the vaccination ineffective and the patient susceptible. The conventional-based supply chains in the case of vaccines have a number of issues. The fake vaccines and unapproved diversion do not only threaten the health of the people, but also make people lose confidence in the healthcare systems. The nature of separate and centralized record-keeping systems makes it near possible to have a comprehensive view of the supply chain which translates to errors, time wastes and frauds. Due to the inability to monitor and audit in

real-time, the danger of failures in the supply chain increases. Furthermore, information management is even more complex due to regulations and data privacy needs that have to be met. Providing a decentralized, clear, and unmodifiable registry that can store all the transactions associated with vaccines digitally and in an immutable manner is one of the most appealing concepts brought out by Blockchain. In addition to that, once equipped with smart contracts, IoT-based solutions, and non-chain data storage, blockchain can address the most critical issues in the supply chain, including the need to make sure that provenance is ensured, that traceability can be conducted in real time, and that confidential data should be safeguarded. The suggested work offers a blockchain-related framework, which is supposed to enhance supply chains in the vaccine distribution industry in terms of clarity, impeccability, and security. The framework offers the characteristics of recording the manufacturing of vaccines, custody modifications, and cold-chain management and ensures compliance with regulations and maintenance of privacy simultaneously. The offered platform, the essence of which, in its turn, is aimed at the promotion of trust among all stakeholders, i.e., manufacturers, regulators, logistics providers,

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healthcare facilities, and patients, thus, the proposed platform aims at the alleviation of fraud, raising accountability, and providing safe and timely vaccines all over the world.

Role of Blockchain in Secure Vaccine Supply Chain

The blockchain technology has a number of distinct characteristics, among them being decentralization, immutability, transparency, and security, which render blockchain highly appropriate in managing vaccine supply chains. Its usefulness is explained by the following points:

1. Tamper-Proof Records

- All the transactions (production, storage, transportation, and administration) are recorded in an immutable ledger.
- Data is not editable and it cannot be deleted and this eliminates fraud, manipulation and forgeries.

2. End-to-End Traceability

- Vaccine batches receive a digital identity on the blockchain.
- Stakeholders are in a position to understand the path which the vaccine follows up to the patient making sure that it is authentic and accountable.

3. Cold Chain Monitoring

- IoT-based sensors monitor storage and transportation conditions like temperature and humidity.
- The blockchain secures such logs making it real-time to alert when there might be any exposure of the vaccines to deplorable conditions.

4. Secure Custody Transfers

- Smart contracts automatically authenticate and document the handovers of vaccines among manufacturers, distributors, and providers of healthcare.
- This eradicates controversies and provides a provable chain of custody.

5. Anti-False Fraud and Counterfeiting.

- Blockchain will eliminate the possibility of counterfeit vaccines getting into the system as the provenance of each unit can be verified.
- QR codes can be scanned by patients and healthcare providers to ensure that they are authentic.

6. . Regulatory Compliance and Auditing.

- Supply chain data is availed to regulators in a transparent manner.
- Recalls, compliance checks and audit are quicker, more secure and less expensive.

7. Data Security and Privacy

- Through it, sensitive information like patient information or company information is secured.

- Cryptography and off-chain storage are also available and yet can be accessible by authorization.

2. LITERATURE REVIEW

To support secure and transparent vaccine supply chain management, Xiong, Zhang, and Li (2023) come up with a blockchain-driven framework. They combined IoT sensors and smart contracts to track all the specifics of the supply chain beginning with production up to administration. The system consisted of a permissioned blockchain (Hyperledger Fabric) where the IoT devices monitored the temperature and humidity at all times and smart contracts would handle custody transfers as well as provide an intimation in case there was any cold-chain violation. The suggested architecture demonstrated that it was able to execute data sharing in a secure and very low delay way. The immutable records, real-time cold chain temperature monitoring, increased trust among stakeholders, and a highly strong recall audit feature are some of the features that are mandatory in the structure. Regrettably, the system is facing scalability issues to be implemented at the national scale, the cost of IoT and blockchain infrastructure is relatively high, and there are certain concerns about the privacy of the health and logistics data [1].

Through this, Yadav (2023) has set out a pioneer study by which he mainly concentrated on blockchain and IoT application in the vaccine supply chains and the status of India. To interpret the data in the framework of the Technology Organization environment Technology-Organization-Environment (TOE) framework and to handle the Delphi method and the DEMATEL methods were applied. The primary purpose of the research was to identify social and technical barriers and conditions that enable the implementation of new technologies that, in turn, give policy implications and suggestions regarding the healthcare ecosystem in India. The paper is an important addition to the knowledge of readiness in terms of organization and technology. However, it does not provide the demonstration of an actual technical implementation combined with its performance consequently restrict the engineering input [2].

The Vacledder proposed by Munasinghe et al. (2023) is a private permissioned blockchain system that detects counterfeit and tracks the vaccines. The system consisted of the four smart contracts addressing the regulatory compliance, the vaccine registration, the stock piling, and the location-based tracking. Its advantages lie in the fact that the modules of regulatory smart-contracts are well organized and the focus on counterfeit detection is very clear. Regrettably, being a prototype, it has not been implemented much with the national systems and IoT networks [3].

The BlockColdChain plan focuses on blockchain-based cold-chain traceability to store short sensor data in the chain whilst the entire sensor history is kept off-chain to enhance transparency and data provenance.

The strength of this piece of work is that it dwells upon the integrity of the cold-chain and the effective integration of the off-chain storage. Nonetheless, not many details are provided on the implementation and large scale performance testing is absent [4].

Kamenivskyy et al. (2022) developed a blockchain system architecture of the COVID-19 vaccine distribution and delivery, including a permissioned blockchain used, smart contracts to simplify the process of vaccine registration, creation of cold-chain alerts, transfer of custody, use of automated recalls. The article also throws some light on the issue of governance and the role of regulatory bodies. Despite being feasible and grounded in architecture, the architecture lacks any performance measurement in the case of a high-volume national-level deployment [5].

Antal, Cioară, and others (2021) introduced VacChain, a blockchain application with the goal of vaccine traceability, which consists of smart contracts, QR-code verification, and connections to the existing health information systems. The system is innovative both in terms of workflow and initial working prototype and therefore the stakeholders and the patients themselves can approve of the authenticity with the help of QR codes. However, the only thing on the prototype level is satisfactory and issues like scaling and high cost of integration and requirement of IoT infrastructure still has to be looked into [6].

One of the very first researchers to propose a blockchain-based system to distribute vaccines in a safe way, Yong et al. (2020) proposed using smart contracts to automate recalls, trace the origin, and grant transparency of the vaccines moving. The architecture of the system depends largely on the traceability and safety. The latter also, though, presupposes that the deployment of IoT devices is largely spread and that all interested parties are prepared, which may not be true in less developed regions [7].

Chen et al. (2022) developed a system that operates through the blockchain to record the vaccination and share the information in which the vaccination information of the patient was in the blockchain using smart contracts that managed access and sharing authorization. The old issues such as losing the vaccination notebooks and enhancing integrity of

records are sorted out by the new system and the portability of data is made easier. However, the issues of patient privacy and the regulations (e.g. GDPR/HIPAA) demand high-level encryption and off-chain, which is proposed but not wholly achieved [8].

Ai et al. (2022) developed a vaccine supply management system based on IoT and partnered with smart contracts and off-chain storage. The research project includes prototyping tasks on sensor data anchoring and shows a highly structured process of engineering. However, there is little reference to the dependability of the sensor network, or the issue of cost when rolling it out on a large-scale basis [9].

The elongated Vacledder paper by Munasinghe et al. (2023) outlines how smart contracts can be used to authorize the border, implement compliance and counterfeit detection along with tracking of stocks in cross-border vaccine supply chains. The article provides certain implementation specifics as well as compliance automation design. However, the inter-jurisdictional coordination of governance is hard to achieve and this makes it very difficult to implement it on a global basis [10].

Shiri et al. (2024) developed a multi-channel vaccine distribution model that included blockchain to enhance transparency and at the same time optimization of cost and efficiency. The evaluation of the trade-offs is based on the mathematical optimization of the study and, therefore, is highly useful in the planning on the policy level. However, the blockchain component is represented in an abstract way and integration problems of systems in the real world like latency and deployment challenges have not been tested empirically [11].

Boas et al. (2025) developed a high-tech also national tracking cold-chain technology, ColdNet that integrates blockchain and IoT. The study reflects the current technological trend of engineering by using IoT gateways and Hyperledger Fabric as data anchoring and monitoring tools, which can be adopted by the current cold-chain infrastructure. Yet, similar to most proposals with an engineering focus, it is still possible to perform a detailed cost analysis and establish governance structures at the national levels to handle the big scale project [12].

Table 1 Summary Table of literature Review

Sr No.	Concept	Contribution	Gaps Identified
1	Blockchain-Based Framework for Secure and Transparent Vaccine Supply Chain Management (2023)	IoT sensors + smart contracts on permissioned blockchain (Hyperledger Fabric) for end-to-end vaccine traceability.	Scalability issues, high IoT infrastructure costs, privacy concerns.
2	Blockchain technology and vaccine supply chain (2023)	Explores blockchain IoT adoption in Indian context using TOE and Delphi/DEMATEL; identifies barriers and enablers.	No technical implementation or performance benchmarks.
3	Vacledder: Supply chain traceability and counterfeit detection of COVID-19 vaccines (2023)	Private blockchain with smart contracts for compliance, vaccine registration, counterfeit detection, and traceability.	Prototype scope; IoT and national system integration limited.

4	BlockColdChain: Vaccine cold-chain traceability using blockchain (Preprint)	Anchors IoT sensor data on-chain, stores detailed logs off-chain for transparency.	Limited performance results and implementation evaluation.
5	A Blockchain-Based Solution for COVID-19 Vaccine Distribution and Delivery (2022)	Permissioned blockchain with smart contracts for custody transfers, recalls, and cold-chain alerts.	No scalability benchmarks for large-scale national rollouts.
6	Blockchain Platform for COVID-19 Vaccine Supply Chain (VacChain) (2021)	Blockchain + QR verification for vaccine traceability and integration with silos.	Prototype-level; scalability and IoT cost challenges.
7	An intelligent blockchain-based system for safe vaccine distribution (2020)	Blockchain + smart contracts for traceability, provenance, and recalls.	Assumes IoT ubiquity; less feasible in low-resource settings.
8	A Traceable Blockchain-Based Vaccination Record Storage and Sharing System (2022)	Anchors vaccination records on blockchain; smart contracts for secure sharing and portability.	Privacy and GDPR/HIPAA compliance challenges remain.
9	A Traceable Vaccine Supply Management System (2022)	IoT sensor anchoring + blockchain with off-chain storage; tested prototype.	Sensor network reliability and deployment costs not fully quantified.
10	Vacledger (Extended): Counterfeit detection and supply chain traceability (2023)	Extended Vacledger with compliance-focused smart contracts for cross-border tracking.	Governance and legal harmonization across jurisdictions remain unresolved.
11	An integrated blockchain-enabled multi-channel vaccine supply chain (2024)	Mathematical model + blockchain to balance transparency and cost efficiency.	Modeled only; lacks empirical deployment validation.
12	Coldnet: Blockchain-IoT vaccine logistics tracking (2025)	Recent Hyperledger Fabric + IoT gateways for cold-chain monitoring.	Large-scale cost, governance, and deployment challenges persist.

Research Gaps

Having read the literature about the blockchain technology in the vaccine supply chain, one can identify the gaps in research in this topic. The first one that will arise is the issue regarding the scalability of the project and its performance. In fact, the majority of the current systems have been trial-tested on the small-scale level or prototype and it remains unclear whether they will be as efficient in the national or global supply chains. Secondly, there is the issue of excessive infrastructure and operational expenses - i.e. the expenses that is associated with the implementation of IoT devices, maintenance of blockchain, and integration with the current logistics systems - that inhibits the widespread implementation of the technology, especially in resource-less regions. And thirdly, there is the problem of privacy and security, which has not been fully studied yet because many solutions retain sensitive health and logistic data on-chain, therefore, necessitating high levels of encryption, access control, and regulation, including GDPR and HIPAA. Fourth, the contact of mixed systems, including current healthcare databases, regulatory agencies, and supply chains in the different countries is often poorly addressed, thus leading to troubles with cross-border traceability and control. Fifthly, despite the references of others to the application of smart contracts in automatic operations and detection of counterfeits, there exist little reports of such attributes in practice in various circumstances of networks and their interruptions. Finally, the

empirical measurement models of the real benefits of blockchain on transparency, cold-chain integrity, cost-efficiency, and trust of the stakeholders remain inadequate. Sealing these gaps will lead to having more secure, scalable, and reliable vaccine supply chains using blockchain technology.

3. PROPOSED SYSTEM

The proposed system has a blockchain-based structure that is integrated with smart contracts to ensure such attributes as transparency, security, and traceability to the vaccine supply chain. This procedure incorporates key points in the following-way:

1. **Vaccine Registration:**
 - Every vaccine batch is registered on the blockchain by the manufacturer.
 - A unique digital identity (hash/transaction ID) is assigned to each batch.
2. **Stakeholder Onboarding:**
 - All participants in the supply chain—manufacturers, distributors, logistics providers, healthcare centers, and regulators—are registered on the permissioned blockchain network.
3. **Custody Transfer via Smart Contracts:**
 - When vaccines move from one stakeholder to another, a smart contract validates the transaction.

- Custody is transferred only when predefined rules (e.g., verified sender/receiver, digital signatures) are met.

4. Traceability and Transparency:

- Every transaction is immutably recorded on the blockchain.
- Regulators and stakeholders can trace the complete history of a vaccine batch to prevent counterfeit distribution.

5. Audit and Recall Management:

- In case of faulty or expired vaccines, smart contracts allow automated recalls.
- Immutable records ensure accountability and audit readiness.

6. Access Control:

- Patients and healthcare providers can verify vaccine authenticity using blockchain records.
- Role-based permissions ensure sensitive data is only accessible to authorized parties.

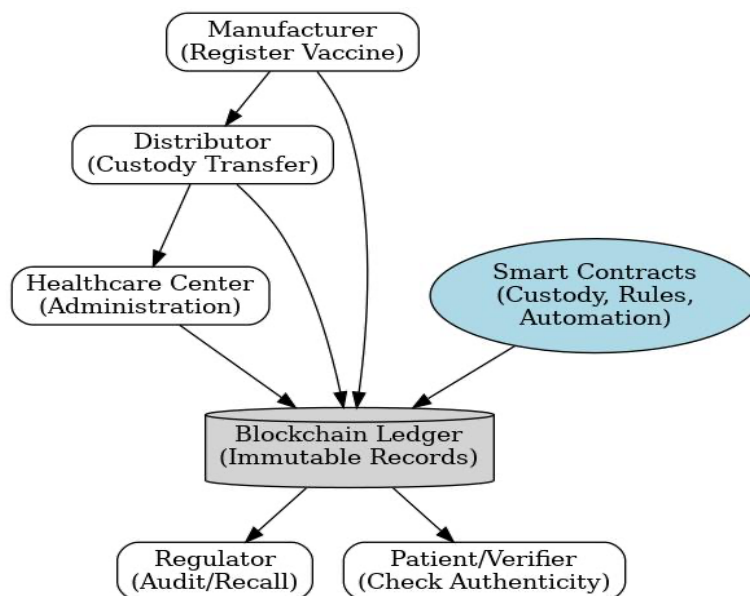


Fig. 1. Proposed System Architecture

Vaccine Registration:

Vaccine registration is the first block of the supply chain when all batches of vaccines of the manufacturer are registered in the blockchain. Each batch is assigned a unique digital identity in the blockchain, e.g. a hash or transaction ID, and therefore cannot be copied or modified. This forms an impeccable foundation of vaccine traceability at the very source of the supply chain.

Stakeholder Onboarding:

Under permissioned blockchain network, every character of the supply chain, manufacturers, distributors, logistics providers, healthcare centers, and regulatory authorities, etc. are on boarded. The system only allows access to known stakeholders and hence, transactions are conducted in a secure setting in the system, therefore, unauthorized parties cannot tamper with or access sensitive data

Custody Transfer via Smart Contracts:

The smart contracts are implemented whenever the drugs are delivered to another stakeholder to verify the transaction. The regulations are held within the agreements already existing like verifying the validity of the sender and receiver or checking the digital signatures. In this case, the new owner is only given the custody of the bunch of vaccines under these circumstances. This type of mechanization reduces the

potential of human error, the degree of responsibility, and prevents at the same time counterfeit diversion of vaccines.

Traceability and Transparency:

Any change of ownership and dealings remain permanent in the blockchain. That leads to open and detailed records of the journey of the vaccine since its development up to delivery, but also regulators, medical centers, and other accredited parties have access to such a history, therefore, full traceability is ensured, and the threat of counterfeit medications entering the supply chains is minimized.

Audit and Recall Management:

In the example of the defective vaccines, expired shelf life, or a response to the contamination of the vaccines, the smart contracts will simply cause the recall process to take place. First, non-modifiable records that include time stamps dictate the batches that were impacted to those who are able to offload them off the shelves, which in this case are the regulators. Besides this, it is an excellent feature to employ in regards to preparing the system against regulatory audit and compliance audits.

Access Control:

The framework fulfills role based access controls, which are role based and whose purpose is to

safeguard sensitive logistics and health information. The authorized parties should only be allowed to peep look at the data or adjust it. Concurrently, this process has been developed in such a way that it lets the patients and the physicians access the information on

whether the vaccine is genuine or not without invading on the privacy. The image of openness and privacy, therefore, creates the trust between the entire stakeholders.

4. RESULT AND DISCUSSION

1. Ganache Terminal

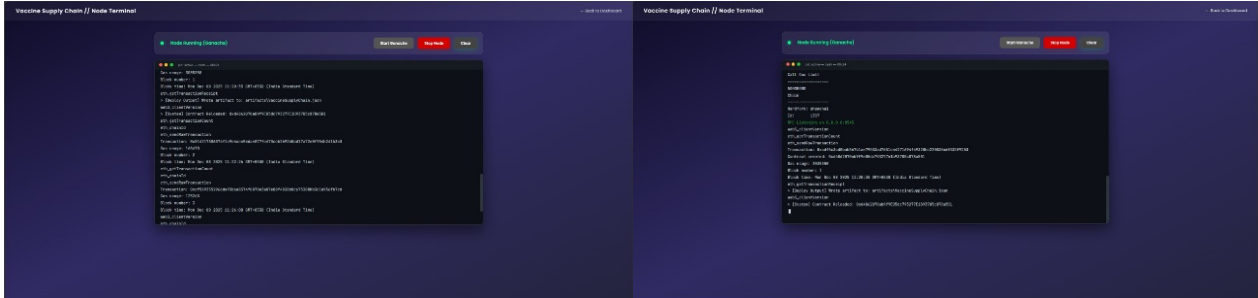


Fig 2 Ganache Terminal

The screen of the "Vaccine Supply Chain // Node Terminal" is presented in the following fig 2. One can see the activity of the Ganache (an Ethereum simulator) node that is identified by the name Node Running (Ganache) and a green light. The dark themed center console output displays the information of the blockchain such as Gas Limit, Chain ID, Hardfork, and RPC Listening on, Block Number (1), and successful Deployment Output of the VaccineSupplyChain.json smart contract in a particular address.

2. Create Vaccine Batch

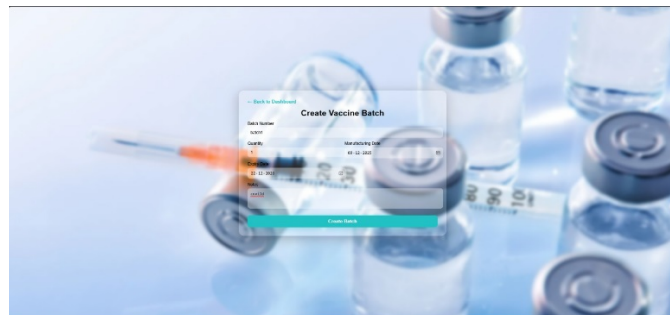


Fig 3. Create Vaccine Batch

The above figure 3, and it represents the pop-up or the shape of Create Vaccine Batch. The user is required to key Batch Number, Quantity, and Date of manufacturing, Date of expiration and Notes (e.g. storage, batch) field which is optional. The form can be submitted with the help of a Create Batch button.

3. Manufacturer Dashboard

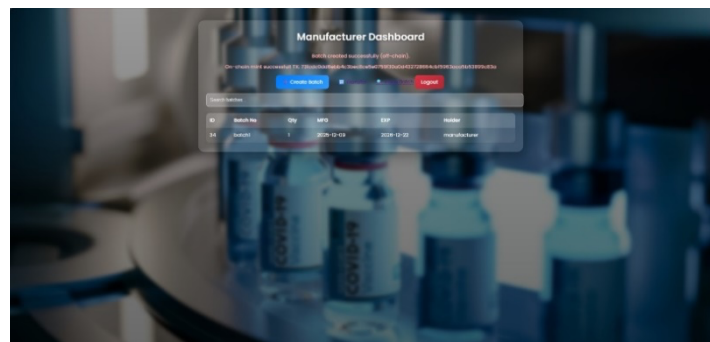


Fig 4. Manufacturer Dashboard

The above fig 4 reveals the Manufacturer Dashboard that is in essence a control panel of the manufacturer. It has clickable buttons of Create Batch, Transfer Batch and Trace, Trace Batch and Transfer Batch, as well as Logout. A table that is showing batches of the vaccine occupies the center part of the page. There are not over two batches with the

following details in the table ID 33, Batch No. batch29, and Quantity 1. Along with this, there is also the page of the Manufacturing (MFG), Expiration (EXP), and the manufacturer of the present Holder in 2025-12-10, 2026-04-23, and the manufacturer respectively.

4. Transfer Vaccine Batch

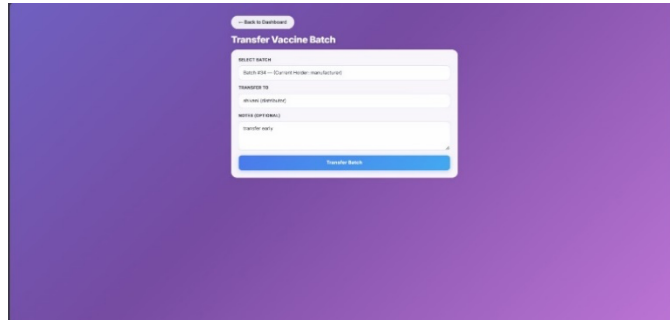


Fig 5. Transfer Vaccine Batch

The above figure 5 that denotes Transfer Vaccine Batch form. The user is choosing the batch in which he/she wants to transfer (Batch #33 - Current Holder: manufacturer). Transfer To field contains the name of a recipient shivani (distributor). The words transfer are typed into the optional Notes box. It is a screen through which the transaction is prepared and then actual transaction takes place.

5. Trace Vaccine Batch

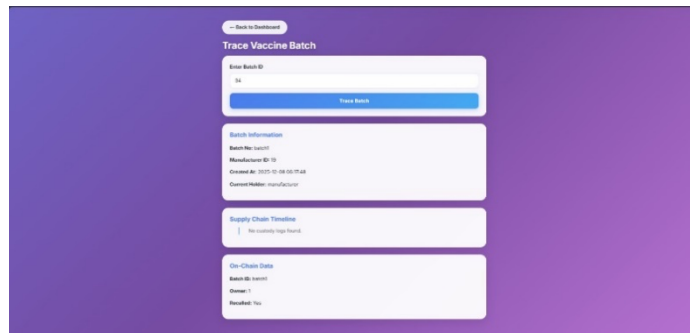


Fig 6. Trace Vaccine Batch

The above fig 6 indicates the findings of a Trace Vaccine Batch question of batch29. It gives: Batch Details: Batch No., Manufacturer ID, Creation date and Current Holder: distributor. Supply Chains Timeline: Transfer between the distributor and the manufacturer only on 2025-12-08. On-Chain Data: Shows the Owner: 1 and most strikingly, recalled: Yes, which means that the batch is recorded as having been listed as a recall on the blockchain.

6. Add Regulator

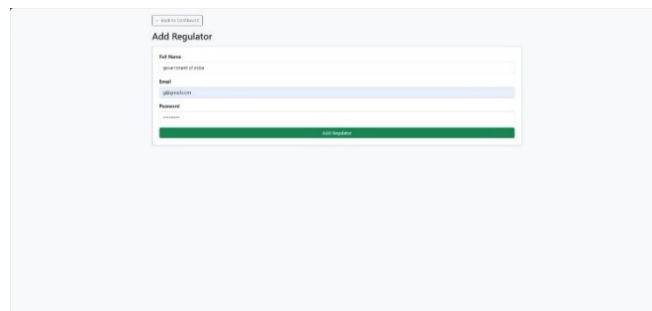


Fig 7. Add Regulator

The above fig represents shape adopted to incorporate Regulator to the system is shown in this fig 6. The fields are filled with the account of a new regulator, Full Name of the government of India, Email of the gmail.com, and Password (covered). It is done by clicking on the Add Regulator.

7. Recall Batch

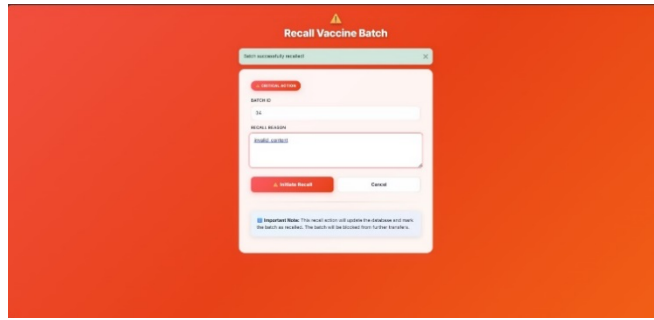


Fig 8. Recall Batch

The above fig 8 represents depicts the profile of Recall Vaccine Batch. The reason and Batch ID 33 were typed in as invalid content by the user. It possesses an Initiate Recall button. On the bottommost level, one will find a small point which lets one know that the default set up is to update the database with the recall but can be modified to be a call to the on-chain recalling function.

8. Trace Vaccine Batch

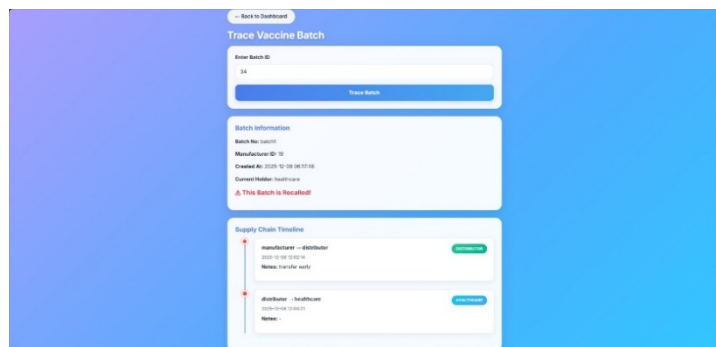


Fig 9. Trace Vaccine Batch

The above fig 9 represents output given by a Trace Vaccine Batch request is presented in this fig 8. It gives the information of Batch No: batch 1. Batch Information The distributor is currently. Most importantly, however, there is a huge caution: Supply Chain Timeline: It only takes one step: a transfer between manufacturer and distributor On-Chain Data: It also supports the status of the recall with Recalled.

9. Visual Analytics Dashboard



Fig 10. Visual Analytics Dashboard

The above fig 10 shows two graphs of the usage and the distribution of inventory of the system. User Roles Distribution donut chart is used to display the number of users in relation with all users including the Manufacturer, Distributor and Healthcare, Regulator and Admin.

10. Activity and Recall Log

Recent Transfer Activity

BATCH ID	BATCH NO	FROM	TO	TIMESTAMP
#36	batch1	MANUFACTURER	DISTRIBUTOR	2025-12-08 12:29:08
#34	batch1	DISTRIBUTOR	HEALTHCARE	2025-12-08 12:03:21
#34	batch1	MANUFACTURER	DISTRIBUTOR	2025-12-08 12:02:14

Recalled Batches

BATCH ID	BATCH NO	REASON	RECALLED AT
#37	batch1	Invalid content	2025-12-08 07:34:10
#36	batch1	dd	2025-12-08 06:58:48
#34	batch1	Invalid content	2025-12-08 06:17:48
#34	batch1	Invalid content	2025-12-08 06:17:48

Fig 11. Activity and Recall Log

The above fig 11 represents demonstrates the activity of the vaccine supply chain system of the recent past and divided into two tables. Recent Transfer Activity table entails three moves whereby two batches were transferred between Manufacturer and Distributor and one transfer between Distributor and Healthcare. Recalled batches table will be having 4 batches recalls with batch 37, 36 and two batches recalls with reason one of them being invalid content.

11. Bar graph



Fig 12. Bar graph

The above fig 12 represents bar chart that is adjacent to the fig 12, Batches by Current Holder Role, shows that Current Holder Role, the Manufacturer is currently holding 2 batches, compared to the Distributor and position of Healthcare, which has one batch each.

5. CONCLUSION

The proposed web 3.0 application proposed in this article is a safe and open system to the vaccine supply chain management. Combining blockchain with smart contracts, the system ensures that the history of the distribution of vaccines cannot be changed, is not fake, and the distributor is responsible. The use of PBFT consensus, SHA-256 hashing and digital signatures are able not only to boost the confidence of the stakeholders but also to prevent the development of counterfeit vaccines and consent of custody without authorization. The model has the strength to regulate control and enable traceability in real-time to ensure that the manufacturers, distributors, healthcare providers, and patients can be sure of vaccine authenticity. Programmes such as custody transfer and recall management that are automated reduce the errors, the time constraint, and the use of manual intervention hence, rendering the supply chain more

efficient and reliable. In spite of such issues like scalability and infrastructure costs, the framework opens the way to the secure management of vaccines. It plays a crucial role in providing safer distribution of vaccines and introduces opportunities in using blockchain in healthcare supply chains in the future by increasing transparency, trust, and auditability.

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