# Supply Chain Management with Demand Forecasting of Covid-19 Vaccine using Blockchain and Machine Learning

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*Abstract*—Vaccination of the global population against COVID-19 is one of the challenging tasks in supply chain management that humanity has ever faced. The rapid roll-out of the COVID-19 vaccine is a must for making the worldwide immunization campaign successful, but its effectiveness depends on the availability of an operational and transparent distribution chain that can be audited by all related stakeholders. In this paper, the necessity of Blockchain and Machine Learning in supply-chain management with demand forecasting of the COVID-19 vaccine has been presented. The aim is to understand how the convergence of Blockchain technology and ML monitor the prerequisite of vaccine distribution with demand forecasting. Here, we have proposed an approach consists of Blockchain and Machine Learning which will be used to ensure the seamless COVID-19 vaccine distribution with transparency, data integrity, and end-to-end traceability for reducing risk, assuring the safety, and also immutability. Besides this, we have performed demand forecasting for appropriate COVID-19 vaccines according to the geographical area and the storage facilities. Lastly, we have discussed research challenges and also mentioning the limitations with future directions.

*Index Terms*—Blockchain, Machine Learning, Vaccine distribution, COVID-19, Pandemic, AI, Forecasting, Supply-chain.

## I. INTRODUCTION

COVID-19 virus, a member of the coronavirus ribonucleic acid virus family [1], has caused a worldwide pandemic, putting a strain on the healthcare system and societal levels. It spread rapidly through community transmission to about 124,535,520 confirmed cases of COVID-19, including 2,738,876 deaths, reported to WHO up to 25 March 2021 [2] after its identification in Wuhan City, China in December 2019 [3]. While substantial attempts have been made to tackle the pandemic, it has only decreased the transmission rate of the virus. There are also restrictions in many countries to ensure that hospitals and medical centers are not affected [4].

Therefore, the rapid rollout of the covid vaccine conducting global vaccination program is vital for the management of the pandemic [5]. From the start of the pandemic, pharmaceutical industries have focused on producing a vaccine in record time to ensure COVID-19 containment [6].

More than two hundred novel coronavirus vaccine candidates are under development, as of March 2021, more than 50 are in clinical trials worldwide testing potential vaccines and 13 candidate vaccines now have been approved around the globe [7] [8]. If the following aspects are not handled properly, the effectiveness of the COVID-19 immunization program is likely to suffer:

1) Some COVID-19 vaccine especially messenger ribonucleic acid (mRNA) vaccine types, may need ultra-low temperature (ULT) storage to maintain potency, posing additional challenges to cold chain storage and transport, particularly in remote areas, away from refrigeration facilities, major transportation links, and places with unstable power supply [9]. TABLE I below displays the storage criteria of the most possible vaccine candidates as they got approval for use:

2) Ensuring the proper tracking, safety, efficacy, reporting of vaccine utilization, and quality of COVID-19 vaccines throughout the supply chain.

3) Developing and mobilizing resources to address the vaccine roll-out strategy, countries will need to compile information from government agencies and the private sector on the available cold chain capacity, including surge capacity.

4) Ultra-low temperature cold chain (UCC) profile vaccines present many problems for low- and middle-income countries (LMIC) due to insufficient UCC facilities

TABLE I
STORAGE CRITERIA OF VACCINE.

| Vaccine manufacturer | Freezer temperature | Refrigerator temperature | Max storage days |
|---|---|---|---|
| Pfizer-BioNTech [10] | -70 ℃ | -80 ℃ to -60 ℃ | 30 days after opening the freezer |
| ModernaTx [10] | -20 ℃ | -25 ℃ to -15 ℃. | 30 days in the refrigerator |
| Oxford-AstraZeneca [10] | Do not freeze | +2 ℃ to 8 ℃ | 6 months in the refrigerator |
| Gam-COVID-Vac(Sputnik V) [12] | N/A | +2 ℃ to 8 ℃ | 2 months |
| Bharat Biotech(COVAXIN) [11] | N/A | +2 ℃ to 8 ℃ | 4 months |

within their health system. Countries receiving an ultra-low temperature (ULT) COVID-19 vaccine should have a deployment plan of the UCC equipment based on vaccine profile to ensure vaccination strategy. They should also think about potential alternatives, in case the UCC profile vaccines don't work in the country.

5) Accuracy and transparency of the list of citizens to be vaccinated to register and maintain. These data are not only sensitive personal information but also require accuracy, prevention of impersonation, protection of privacy, and immutability.

6) In order to prevent the possibility of diversion and falsification, traceability should be ensured across the COVID-19 vaccines supply chain. Otherwise, public trust will be disrupted.

7) Safety follow-up of a large number of vaccinated people to analyze whether a side effect is likely to be caused by the vaccine and to report suspected adverse reactions to the vaccine.

Traditional vaccine monitor systems are mostly handled by the government authorities, such as several release agencies which require random sampling tests to ensure the safety of the vaccine. Nevertheless, there is a huge possibility to tamper with the vaccine information. Therefore, this method is not viable to ensure vaccine quality as well as vaccine expiration [13]. The economic order quantity (EOQ) model was applied to find an optimal vaccine replenishment time to address the risk of vaccine expiration, however, this model also couldn't solve the problem in the international vaccine supply chain [14].

As COVID-19 is a global problem, tackling COVID-19 will require a decentralized and immutable database that can help to be stored and handled the global distribution of a vaccine properly. Blockchain and Machine Learning approach could be the perfect platform for vaccine supply chain management and demand forecasting.

COVID-19 vaccine distribution can be more effective and transparent due to Blockchain, which guarantees traceability and a comprehensive audit of storage, cold chain, and delivery conditions. In our point of view, Blockchain technologies have the potential to provide a truly integrated application of data transparency and provenance monitoring in vaccine distribution, allowing the convergence of various information silos owned and operated by various categories of stakeholders such as WHO, suppliers, manufacturers, distributors, and medical personnel in the vaccine distribution chain. Blockchain

can record the adherence to critical quality requirements and manufacturing process parameters from the production line to the clinical site across the full product lifecycle. Accurately forecasting demand for the vaccine is another important issue to consider. As the number of vaccines is limited, we cannot afford to waste any single dose of vaccine. The ability to trace each stage of the product lifecycle and the provenance of materials enables suppliers to predict demand and medical facilities to track when shipments are arriving or delayed. Machine learning can be used to analyze these vast amounts of data from the blockchain and anticipate the demand for a particular vaccine in a region. Furthermore, Blockchain is immutable; that's why the Blockchain network peers can ensure that vaccines are stored and managed with no tempered data.

This work attempts to find solution on the following research questions:

**RQ1:** How many vaccines to ship where and when?

**RQ2:** Which vaccine is to supply where and when?

**RQ3:** How to ensure seamless COVID-19 vaccines distribution through Blockchain-based supply chain management?

## II. RELATED WORK

Effective distribution of COVID-19 vaccine to all over the world is a very challenging task due to many factors such as temperature, storage, and so on. Therefore, the distribution of the lifesaving COVID-19 vaccine by assuring safety and efficacy are notably complex and hard to deal with. This makes it essential to ensure the spontaneous exposure and quick notification of supply chain disruptions in delivering life-saving vaccines. In this section, we have thoroughly investigated the existing research work for proposing a better solution in this aspect by finding out the actual research gap.

Chen et al. [15] have performed a rapid review on AI technology to understand its significance for combating the COVID-19 virus. They have included 11 papers for the review and found that AI could be applied in 4 ranges named public health, diagnosis, clinical decision making, and therapeutics. They distinguished many of the shortcomings in this aspect and concluded that AI technology could be explored in other four areas. They mentioned that there is a necessity for efficient methods to manage the COVID-19 pandemic. Though they also mentioned that supply shortage could be an issue because of massive demand and limited production initially, but they did not suggest any of the particular solutions to mitigate the issue.

Khurshid et al. [16] discussed the application of Blockchain technology for addressing the crisis of trust during the outbreak. The work's primary intention is to explain Blockchain mitigates the data-related trust problems. They have noted their observation of major supply chain failures for PPE and lifesaving ventilators in clinics and hospitals during the pandemic. They explained how Blockchain technology mitigates this issue. They did not suggest any particular direction on how Blockchain can reduce the supply chain failures when vaccines need to be distributed across all over the world to save many lives.

Abd-alrazaq et al. [17] presented Blockchain technologies to alleviate the challenges of the COVID-19 pandemic. To identify the related work, they explored 11 bibliographic databases. They found that most of the Blockchain-related research work was not sophisticated enough to exhibit the desired impact in fighting against the COVID-19. They mentioned that additional investigations are needed to assess the performance of Blockchain for fighting COVID-19 in terms of scalability, transaction cost, and so on.

Marbouh et al. [18] explored several Blockchain applications and opportunities to combat the COVID-19 pandemic and developed a tracking system to collect COVID-19 data from various sources. They discussed how Blockchain could play a significant role in the medical supply chain but they did not particularly discuss how Blockchain can be used in the effective and safe distribution of the life-saving vaccine.

Sodhi et al. [19] presented the broad challenges along with a few of the responses and listed the research opportunities for supply chain management in case of extreme conditions. They only mentioned the capability of Blockchain technology to track-and-trace products along the supply chain.

Chamola et al. [20] explored the use of technologies to reduce to alleviate the influence of the COVID-19 outbreak. They discussed two Blockchain-based applications that are developed to combat against with the COVID-19 pandemic. They noted that vaccines can take a longer time to bring the COVID-19 pandemic to the end, but did not specify what can be the way of proper distribution of these lifesaving vaccines.

Kalla et al. [21] highlighted the usual difficulties that have appeared in the time of the COVID-19 outbreak. Next, to weigh the Blockchain application, they identified possible use-cases to meet prevailing demands. For each of the use-cases, they presented an upper-level view of how Blockchain can be leveraged and address the required performance. They noted that Blockchain-enabled cloud-controlled manufacturing ecosystems can be used to manufacture COVID-19 vaccines and medicines globally manufactured but did not specify the possible way of lifesaving vaccine storages and distributions.

Ricci et al. [22] discussed some of the striking use of Blockchain technology to alleviate the consequences of COVID-19 in case of contact tracing and vaccine passport support. The study aims are to point that only a precise aggregate of blockchain technology with high-level cryptographic techniques can ensure security and privacy-preserving aid to combat the virus. However, in their work, they did not specify any of the specific detailed solutions for the global distribution of life-saving vaccines using technology. They have just proposed the Blockchain-based COVID-19 certifications.

Sharma et al. [23] presented a Blockchain-based platform to fight the Covid-19 pandemic. They have also distinguished and addressed 09 notable Blockchain applications in resolving the difficulty resulting from the Covid-19 outbreak. They concluded that human beings require a technology-empowered solution to combat the COVID-19 crisis. They also discussed a blockchain-based platform named VeChain that is developed to observe vaccine production in China. In VeChain, all actions associated with vaccine manufacturing are recorded and filed on distributed ledgers, which helps to diminish the risk of possible modifications to vaccine information. But they did not address any of the feasible solutions regarding COVID-19 vaccine distribution all over the world using Blockchain technology.

Manoj et al. [24] used Blockchain technology to propose an incentive-based strategy for COVID-19 planning. Kumar et al. [25] identified the hurdles encountered by healthcare divisions to deal with the pandemic and presented possible solutions with modern techniques like IoT and AI. Nguyen et al. [26] introduced a distinct conceptual architecture that combines blockchain and AI-specific to fight against COVID-19. Especially, they highlighted the fundamental solutions to fight the COVID-19 outbreak using Blockchain and AI. Mashamba-Thompson et al. [27] recommended a low-cost self-testing and tracking system to fight the COVID-19 pandemic based on Blockchain and AI. Bhaskar et al. [28] proposed a model that profiled decisive stockpiles and improved efficiency of production through blockchain and advanced analytics.

From the above analysis of the related work, we observed that most of the researchers used Blockchain technology to fight the COVID-19 pandemic. Our prime concern is to propose a Blockchain technology-based solution for the effective supply chain management. Adopting Blockchain technology in supply chain management has several advantages over the other technology such as eliminating fraud and errors, ensuring advanced inventory management, reducing costs, minimizing delays in paperwork, identifying any issue faster, building consumer and participant trust. In most of the research work, authors have mentioned that Blockchain technology can be used to track vaccine production, PPE distribution, and other essential drug distribution including vaccines. However, they did not specify any of the solution for the lifesaving COVID-19 vaccine distribution across all over the world by ensuring the maintenance of the proper temperature, storage, and other important issues related to the vaccines.

## III. RESEARCH METHODOLOGY

The existing vaccine supply chain model is not enough transparent and failed to gain the trust of the people. The current vaccine distribution chain is failed to include drug manufacturers, distributors, hospitals, and pharmacies, national and local level vaccine stores, and even various branches of

government in the same platform. Therefore, a global vaccine distribution platform is needed to deploy for rapid vaccine roll-out. The proposed Blockchain-ML approach for transparent COVID-19 vaccine supply chain management with demand forecasting is presented in Figure 1. The proposed vaccine Blockchain-ML approach can be divided into two modules: blockchain for the trustworthy data records for vaccine trace-ability in the vaccine supply chain and machine learning for demand forecasting.

### A. Blockchain in Covid-19 Vaccine Distribution

Blockchain is a distributed ledger technology with an immutable, decentralized database. It can assure all agents that the information of vaccine supplies is being stored and handled rightly. COVID-19 vaccine rollout involves the fol-lowing stakeholders: WHO, Supplier, Manufacturer, Distribu-tor, National Vaccine Store, Local Store, Doctor & Hospital, Pharmacy, and Individual.

The main stakeholders in the proposed model act as peer network nodes. The vaccine information is stored in the block and block links to the one before it and after it. The vaccines need to be stored at frigid temperatures to be effective. When a vaccine gets approval from the WHO, the manufacturers of the vaccine will collect raw materials from the supplier and after production, manufacturers start supplying the vaccine to the distributor.

A block is generated when a transaction happens. Here, sending and receiving information can be considered as trans-actions. The first block is generated when a vaccine manufac-turer company gets approval from the WHO. The block in the vaccine blockchain system is used to store all vaccine-related information such as a timestamp, the Sender, receiver, vaccine data records content, and cold chain temperatures. The time-stamp records the transaction time. The sender and receiver represent the initiator of a transaction, which is usually one of the stakeholders. When the block is generated it doesn't append to the chain rather it waits for approval in the mining pool. When a block gets approved, only then it can be added to the chain. Each block is chained to the other by the cryptographic hash function. When a block is added to the chain, it cannot be tempered. Blockchain ensures the following things:

1) Manufacturers can monitor whether shipments are de-livered to the right destinations on time.
2) Distributors would give a higher effective delivery track-ing platform, including storage essentials verifications, and would be the beginning to know and report if things go incorrect.
3) National and local level vaccine stores can also verify the vaccine is stored at the right temperature or not throughout the vaccine life cycle.
4) Hospitals and doctors can competently handle their stocks, demand constraints, and lessening supply. Be-sides, they would get guarantees concerning vaccine authenticity and precise storage conditions.

5) Individuals would have an identical guarantee for the particular vaccine they take and after-effects of the vac-cinated individuals are stored in the immutable database and privacy is assured

### B. Machine learning in demand forecasting of Covid-19 vac-cine

Machine learning algorithms can be used to forecast vacci-nation demand and the most appropriate vaccine for the partic-ular geographical area. The number of vaccines is limited and the vaccine is expensive. Therefore, the wastage of vaccines should be carefully addressed. Moreover, the vaccine supply chain should be seamless so the dosages don't get stuck for the storage facility or unexpectedly delayed. Selecting the right vaccine according to the geographical area is also a critical issue. For example, BioNTech's vaccine needs the coldest temperature minus 70°C (minus 94°F) that should not be supplied to regions where temperature cannot be maintained. The data set can be extracted from the Blockchain for anal-ysis. The data set contains attributes such as country, region, infection rate, region temperature, population by age, vaccine manufacturer, vaccine batch, freezer temperature, refrigerator temperature, max storage days, side effects among the number of vaccinated people, available logistic service capacity of ultra-low temperature by region, number of the dose received by the individual, and other information related to the logistics. First of all, the data from the Blockchain will be preprocessed. Secondly, the feature will be extracted and then the models will be trained. In the proposed model, two different types of machine learning techniques have been used: ML Regression has been used for demand forecasting and ML Classification has been used to select appropriate vaccines.

### IV. OPEN RESEARCH CHALLENGES

TABLE II represents the requirements and opportunities of Blockchain-ML technology to handle use cases related to COVID-19 vaccine distribution and demand forecasting.

Here we have analyzed the challenges that we may face to implement the proposed model. Integration of Blockchain and ML in the vaccine supply chain is still in its infancy. Different batches of the covid vaccine may be produced by different contract manufacturers at different facilities, resulting in variations among them, and there may be further issues around the storage of individual lots of vials from within each batch. Keeping track of exactly which lot and batch was used to vaccinate each individual may be critical to tracking any safety issues with the vaccine. Most of the data is subjected to privacy policies and local regulations such as vaccine development and GDPR. Therefore, most of the data is not easily accessible. Furthermore, for gathering the data, it will require a special kind of permission from Govt agencies and vaccine manufacturers. The majority of the software applications for the supply chain were intended for use within a specific organization. For the proposed model, we need to keep track of every activity as well as participants of the network manufacturers, distributors, hospitals, pharmacies,
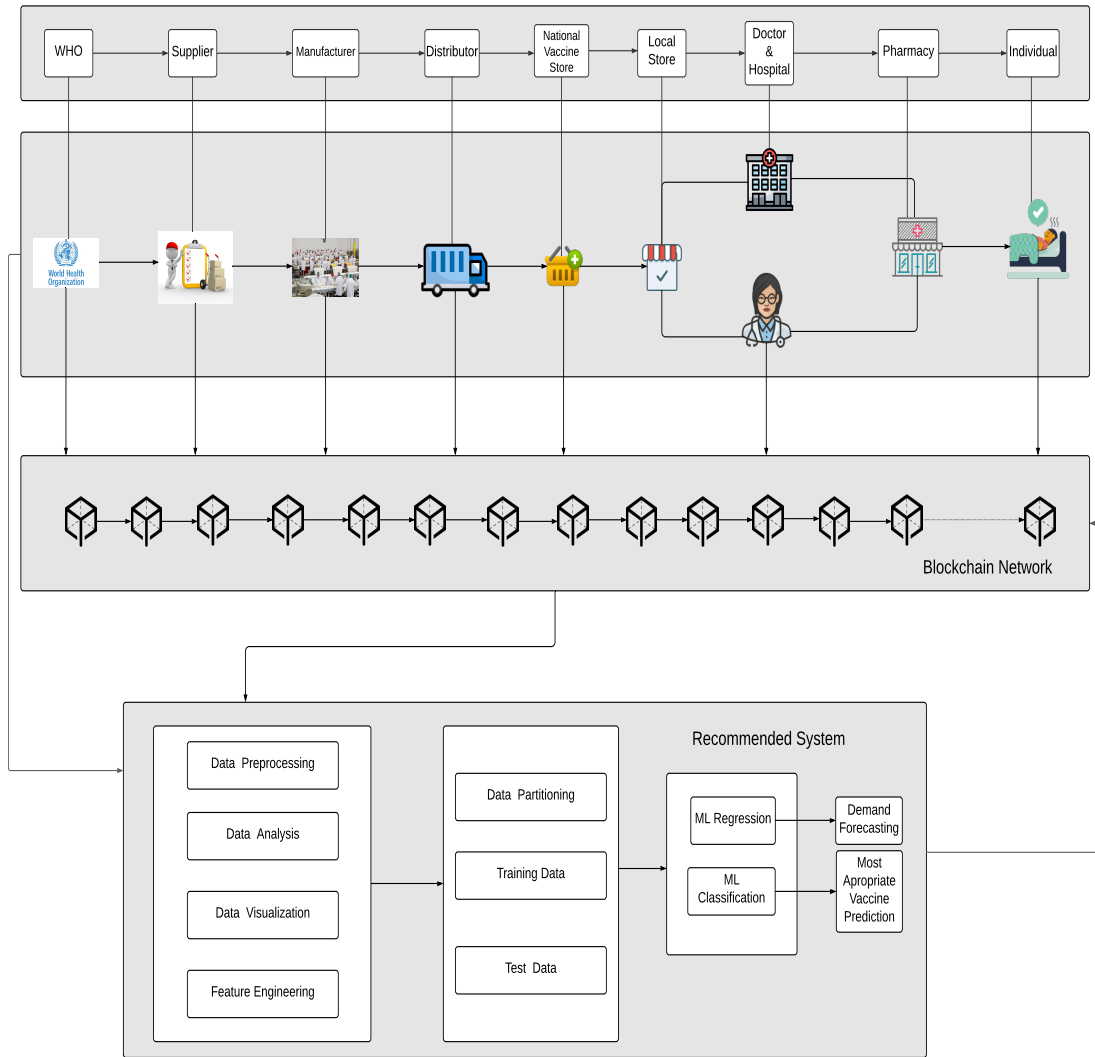
Fig. 1. A functional prototype of the proposed system.

etc. All participants may not use the same system right now. Moreover, some of these participants are competitors of each other that are usually resistant to share data, or they may be incapable to share data easily owing to security, regulatory, and compliance concerns. Building a unique platform to include all the participants/stakeholders in vaccine distribution and demand forecasting is costly and time-consuming.

## V. LIMITATIONS AND FUTURE RESEARCH DIRECTIONS

In this paper, initial demand forecasting performance can be low because of limited data in the Blockchain network. But it will overcome after getting the vast amount of data in the Blockchain network. The proposed model only focuses on the most appropriate vaccine forecasting in terms of geographical areas and storage facilities but not the efficacy of the vaccines. But, while a significant number of people get vaccines then this data can be used for efficacy prediction for the particular vaccine. Our proposed model needs to be implemented with

a comparative analysis of machine learning algorithms for demand forecasting. Therefore, our future work is to focused on collecting COVID-19 vaccine distribution datasets and implement the proposed model for the verification of the model's effectiveness.

## VI. CONCLUSION

In this paper, Blockchain-ML based model has been proposed for the transparent tracing of COVID-19 vaccine distribution with demand forecasting. Here, Blockchain technology is used to verify the vaccine distribution process and chain of custody from manufacturing to end-users. Besides the seamless vaccine distribution, it is essential to ensure the most appropriate vaccine to the people based on the geographical areas and storage capacity. For this, we have applied the Machine Learning model to forecast the most appropriate COVID-19 vaccine based on the available data. Machine learning techniques: ML Regression and ML Classification can analyze the dataset from the blockchain and predict the

TABLE II
THE REQUIREMENTS AND OPPORTUNITIES OF BLOCKCHAIN-ML TECHNOLOGY

| Participants | Requirements | Blockchain-ML opportunities | Remarks |
|---|---|---|---|
| WHO | Monitor vaccine development and approvals, Verification of genuinity of vaccine, Availability of provenance data about vaccine | Complete trace of vaccine manufacturing history, Verification of authenticity of vaccine | The reputational score of each vaccine producer can be calculated with transparent blockchain-ML based supply chain |
| Supplier & Manufacturer | Supply pharmaceutical formulations and Ingredients, Availability of provenance data about demand, Manufacturing Vaccine according to demand, Supply vaccine to country level distributor | Transparent and fast payment settlements, Protection of trade documentations, Demand forecasting of a particular vaccine of a particular location | Monitoring the conditions of shipment of vaccines in a cold chain and knowledge in compliance with COVID-19 and storage conditions in real time |
| Distributor | Guarantee of vaccine procurement from an authorized manufacturer, Supply vaccine to country level distributor, Availability of provenance data about available cold storage | Transparency of vaccine logistics operations, Establishing data provenance of substandard vaccine | Temperature and cold storage capacity monitoring before supplying vaccine to any particular place |
| National Vaccine Store | Availability of provenance data about available cold storage, Availability of provenance data about demand, Available information of vaccinated people, Data regarding population, Available logistic service capacity | Establishing data provenance of substandard vaccine, Assure the traceability and rigorous audit of the storage and delivery conditions | Blockchain-ML data can further help to calculate data of population with number of doses |
| Local Store | Available logistic service capacity | Complete traceability of the COVID-19 vaccine supply chain and cold-chain cycle | Tracking the vaccine distribution against the defined handling and storage rules |
| Doctor and Hospital | Available information about storage conditions,manufacturing date,manufacturer, QR code and/or Website and cold-chain lifecycle to verify vaccine genuinity | Access to complete medical history of an individual | Reporting side-effects of vaccinated people for further research |
| Pharmacy | Authorized by doctor and hospital, Available capacity for storing vaccine, Permission from National Health Authority | Maintaining tamper-resistant records, Proof of the delivery chain | Blockchain-ML based supply chain help buying genuine vaccines from reputed organizations |
| Individual | Verify genuinity of vaccine, Update after-effects of vaccine | The immunization information in the vaccine blockchain can be used for intelligent inoculation | Helping people to view, verify, and validate COVID-19 vaccine, Tamper-proof self-reporting of side effects |

number of vaccines required in a particular place and suggest particular vaccines according to the storage facilities.

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