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Blockchain-based solution for COVID-19 vaccine waste reduction
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ABSTRACT
Coronavirus 2019 (COVID-19) vaccines have been produced on a large scale since 2020. However, large-scale vaccine production has led to two forms of waste; namely, overproduction and underutilization. Most of today’s systems and technologies used to manage waste data related to COVID-19 vaccines fall short of providing transparency, traceability, accountability, trust, and security features. In this paper, we address the problem of COVID-19 vaccines waste due to their overproduction and underutilization. We propose a blockchain-based solution that is composed of five phases: registration, commitment, production and delivery, consumption; and waste assessment. These phases make up the complete life cycle of a COVID-19 vaccine, and they are governed by several smart contracts to ensure accountability of all the actions taken by the involved entities and reduce any excessive waste caused by overproduction, overordering, or underconsumption. We ensure security, traceability, and data provenance by recording all actions through smart contracts in the form of events on an immutable ledger. We utilize decentralized storage such as the InterPlanetary File System (IPFS) to reduce the costs posed by large-sized file storage when stored on-chain. We present algorithms that describe the logic behind our developed smart contracts. We test and validate the functionalities of our proposed solution. We conduct security, cost, and scalability analyses to show that our solution is affordable, scalable, and secure. We compare our solution with the existing blockchain-based solutions to show its novelty and superiority. The smart contract code is made publicly available on GitHub.

1. Introduction

In recent years, unprecedented vaccination efforts have been carried out to deal with the Coronavirus 2019 (COVID-19) pandemic. As of Jan 25, 2022, the total number of people around the world that are fully vaccinated against COVID-19 is 4.11 billion, and it involves around 9.93 billion COVID-19 vaccine doses. Furthermore, the total number of unvaccinated people is 3.09 billion, which means around 6.18 billion vaccine doses are needed to fully vaccinate them (Ritchie et al., 2020). Producing such a large number of vaccine doses within a relatively short time can have a detrimental effect on the environment and public health especially that supply chains in general and in the health industry in particular are becoming increasingly complex (Müüßigmann et al., 2020). Vaccine wastage can be divided into opened, unopened, and partially used vials. The wastage of opened and partially used vials is usually caused by the inability of the healthcare worker to draw the correct amount for each dose from the vial. On the other hand, the wastage of closed vials is usually caused by the manufacturer when vaccine doses are overproduced or by the healthcare center when they either overorder vaccine doses or underconsume them (Hasija et al., 2021).

Extensive efforts have been put into improving the Healthcare Waste Management (HCWM) system to reduce the impact of COVID-19 waste on the environment and public health. In this regard, the World Health Organization (WHO) provided a Standard Operating Procedure (SOP) that should be followed by all workers (World Health Organization, 2021; Hosseini Bamakan et al., 2022). Preventive steps must be taken, though, because of the speed at which COVID-19 vaccines have been produced on a large scale. Necessary actions must be taken to avoid vaccines waste caused by their overproduction, overordering, or underutilization. Additionally, Industry 4.0 technologies can be utilized and implemented to further improve the current state of the HCWM system such as Internet of Medical Things (IoMT) devices to reduce the impact of COVID-19 waste as well as any other kind of waste that might be generated (Balasubramanian et al., 2021; Hrouga et al., 2022).

Fig. 1 represents a typical life cycle of COVID-19 vaccines. First, the manufacturer will send a request to the Food and Drug Administration...
(FDA) to start producing COVID-19 vaccines. If approval is granted, the manufacturer will start producing COVID-19 vaccines in lots based on orders received from healthcare centers. Second, a local regulator will permit local entities such as the COVID-19 vaccines cold-storage unit, distributor, and healthcare centers to perform their respective tasks. Third, the produced COVID-19 vaccine lot will be stored in the large-scale COVID-19 vaccine cold storage unit to preserve the vaccines. Fourth, the distributor will pick up the COVID-19 vaccine lots and deliver them to healthcare centers based on their placed orders. Fifth, healthcare centers will either store COVID-19 vaccines in a local storage unit or administer them immediately to patients. Finally, the manufacturer, large-scale cold storage unit, and healthcare centers might decide to dispose of unused or expired COVID-19 vaccines according to predefined guidelines in their respective countries (Analytics et al., 2020; Central Coordinating Office, 2018; Hosseini Bamakan et al., 2021).

Preventing unnecessary COVID-19 vaccines waste is extremely challenging because it involves many parties, and it requires overcoming some hurdles such as accountability, transparency, traceability, and data provenance. Fig. 2 summarizes the followed methodology of our work which is based on the DSR framework. First, the problem is identified based on the issues of the existing COVID-19 vaccine waste management system. Second, the main objectives and the scope of the paper are defined. Third, the design of the proposed solution is envisioned, planned, and developed. Fourth, the developed solution is demonstrated and tested. Fifth, the proposed solution is evaluated. Finally, the process is iterated based on the outcome of the evaluation step, and the objectives and design are updated accordingly. The main contributions of the paper are as follows.

- We propose a blockchain-based solution to reduce COVID-19 vaccine waste, which is caused by its overproduction and underutilization, in a manner that is decentralized, transparent, traceable, auditable, reliable, secure, and trustworthy.
- We make a theoretical contribution by explaining the process by which COVID-19 vaccines are overproduced or underutilized, and that helped in defining the main factors that contribute to COVID-19 vaccines waste.
- We integrate the Ethereum blockchain with the decentralized storage of the InterPlanetary File System (IPFS) to handle the large amount of data. We present five phases of the proposed solution, which are registration, commitment; production and delivery; consumption, and waste assessment, by using the system architecture, sequence diagrams, entity-relationship diagram, and six algorithms.
- We develop smart contracts to automate the functionality and represent the logic behind each phase of the proposed solution. We implement, test, and validate the smart contracts using REMIX IDE and KOVAN Testnet. Smart contracts code is made publicly available.¹
- We perform security and cost analyses and provide general guidelines for how it can be applied to other applications.

The remainder of this paper is structured as follows. Section 2 presents the related work focused on COVID-19 waste assessment and management. Section 3 describes the proposed blockchain-based solution for COVID-19 vaccine waste reduction. Section 4 describes implementation details. Section 5 presents testing and validation details of the smart contracts. Section 6 presents the discussion and analysis of the proposed solution. Finally, Section 7 concludes the paper by summarizing our contributions along with outlining future work directions.

2. Related work

In this section, we present the existing blockchain and non-blockchain-based solutions proposed for medical waste management and reduction.

2.1. Non-blockchain-based solutions

The authors in Al-Omran et al. (2021) provided an estimation of the amount of medical waste generated by the COVID-19 pandemic in the

¹ https://github.com/DrugTraceability/WasteAssessment/blob/main/Code.
The study conducted in Hasan and Habibur Rahman (2018) presents a comprehensive analysis of healthcare waste management (HCWM) practices and the possible technological alternatives. The case study was conducted in Khulna, a city in Bangladesh, by using a questionnaire survey and field investigations to evaluate the current status of HCWM. Moreover, the Sustainability Assessment of Technologies (SAT) methodology was used to improve the efficiency of treating medical waste. The authors concluded that the lack of training of workers and the lack of safety equipment while treating medical waste were the main issues. Finally, they provided guidelines for the hospitals in Khulna city to improve their HCWM systems.

The researchers in Hasija et al. (2022) provided an overview of the COVID-19 vaccine waste management system and the unforeseen impact that it can have on the environment. Additionally, the study provides an assessment of the waste generated during COVID-19 vaccination campaigns. The authors encourage community cooperation when it comes to following the existing rules for waste management and provide guidelines for better waste management. The main findings of this work are the categorization of the main types of COVID-19 vaccine waste, the effects of COVID-19 vaccine waste on the environment, and the potential COVID-19 vaccine waste management and treatments.

All the aforementioned solutions and guidelines have mainly focused on dealing with the issue of COVID-19 waste after it occurred, by improving the waste treatment technologies and providing workers with high-level training to improve waste treatment efficiency.

### 2.2. Blockchain-based solutions

Ahmad et al. (2021) proposed a decentralized blockchain-based solution to automate forward supply chain processes for COVID-19 medical equipment. The written smart contracts were deployed on the Ethereum blockchain, where they were tested and validated. Overall, the solution enables data provenance for COVID-19 medical equipment and their waste disposal, and it imposes penalties on actors that commit violations. The main contribution of this work is the development of a smart contracts that are reside on the Ethereum blockchain, which are capable of tracking and tracing COVID-19 medical equipment and waste, however, the proposed solution does not implement any measures for reducing the generated waste.

Douladiris et al. (2020) proposed a blockchain framework for reverse logistics of used medical equipment. More specifically, the proposed solution enables traceability for medical equipment based on blockchain technology and smart contracts. Moreover, the solution provides irrefutable proof-of-identity for all transactions. The written smart contracts were compiled and deployed using Ganache-CLI and Truffle. The novelty of this work is that it is the first study to utilize blockchain technology to introduce a viable solution for a refurbishing channels for medical equipment while taking regulations into consideration.

Pelonero et al. (2020) proposed a blockchain-based solution for waste recycling where users are incentivized for proper waste recycling. The solution is built on Ethereum PoW test network called Ropsten. The proposed solution allows municipalities to keep track of what people do, which can help them come up with better strategies in the future. The main contribution of this work is the use of Tokens to reward users based on the amount of recycled material provided which can be an incentive for citizens to recycle their own waste.

Mondal and Kulkarni (2022) utilized the public Ethereum blockchain to develop a transparent framework for plastic waste management. The proposed solution enables traceability of all transactions that occur in the system. Moreover, a query/response model is used among the participants. Finally, participants are incentivized by tokens (non-monetary) that can be later used for discounts and other related purposes. The contribution of this work is the utilization of blockchain technology to track and trace plastic waste, and to create an incentive framework for users to reduce plastic waste.

Dua et al. (2020) proposed a blockchain-based e-waste management technique. The solution tracks the generated e-waste and provides an incentive layer where participants are encouraged to utilize government-regulated agencies for e-waste disposal. The proposed solution was deployed and tested using a private Ethereum blockchain, and the DApp was built using Visual Studio Code (VS Code). The novelty of this work lies in the linkage between the public and private participants where all the participants in the chain get a share of the allocated incentives.

Patari et al. (2021) used blockchain and the Internet of Things (IoT) to develop a smart waste management system which simplifies waste segregation with the aid of smart bins. Moreover, the proposed solution distributes rewards to participants that properly dispose of waste into the smart bins. The authors used different blockchain networks such as Ropsten testnet, Matic network, and Binance Smart Chain (BSC) to compare the performance of their proposed solution with different
network configurations. The main contribution of this work is that it implements a decentralized incentives framework to reward all participants and establish trust since there is no central authority that controls the incentives and their distribution.

Gupta and Bedi (2018) proposed an Ethereum blockchain-based solution for e-waste management in India. The proposed solution incentivizes and penalizes participants based on predefined rules in the smart contracts. Moreover, all interactions among the participants are recorded and stored on an immutable ledger to ensure traceability. The main contribution of this work is the use of blockchain and smart contracts to track and trace E-waste while ensuring that no inappropriate or malicious actions happen throughout the chain.

Farizi and Sari (2021) used the Hyperledger Fabric blockchain to implement an e-waste management solution. The proposed solution ensures security because data stored on blockchain cannot be altered. Moreover, the authors developed a scoring system that rewards participants based on how they handle waste. The blockchain technology ensures integrity and authenticity of the scoring system. The main finding of this paper is that blockchain technology should be used to store necessary data only since it is very slow compared to traditional databases such as MySQL. Moreover, the main contribution of this work lies in the use of a scoring system that incentivizes participants to handle the electronic waste properly.

In summary, the aforementioned blockchain-based solutions have mainly focused on using blockchain technology for tracking purposes, where the trackable resource unit (TRU) is the medical equipment. Traceability in general helps in verifying the origin of the TRU and how it is handled throughout its life cycle. However, one issue that remains unsolved is identifying entities that are not fulfilling their commitments. For example, a healthcare center cannot deny being the source of some medical waste. However, it can still accuse other entities, such as the manufacturer, who caused overproduction. Therefore, commitment details need to be kept on the blockchain so that no one can make bogus acquisitions.

### 3. The proposed blockchain-based solution details

In this section, we propose a blockchain-based solution for critical issues in the pharmaceutical supply chain in general and the COVID-19 vaccine supply chain in particular. The main focus is on providing a solution that reduces COVID-19 waste and ensures accountability. Fig. 3 represents the high-level system architecture of the proposed solution, which consists of three main components. The first component is the actors who will be accessing smart contracts through a DApp. The second component is the front-end, which is mainly the DApp that links the actors to the smart contracts. The third component is the back-end, which consists of the APIs, smart contracts, decentralized storage, and the Ethereum distributed ledger, and this is where data is transmitted from the actors to the Ethereum distributed ledger and vice versa. The details of each component are explained further below.

- **Actors:** The main actors in our proposed solution are the local regulator, the COVID-19 vaccine manufacturer, the COVID-19 vaccine distributor, the healthcare centers, and the Timer Oracles. Each actor has different roles and responsibilities. Therefore, they are only granted access to specific functions in different smart contracts to perform their respective tasks.

- **DApp:** The actors in the proposed solution use the DApp to access smart contracts in an easy and seamless way. To create a truly decentralized application, a number of elements must be included, which are: a web3 provider such as Infura to allow the DApp to relay it to the blockchain; and finally, hosting the DApp on a decentralized storage such as IPFS to avoid centralization problems that might occur by hosting the DApp on a centralized storage.

- **Off-Chain Storage:** Storing information on the blockchain can be expensive. Therefore, using decentralized storage such as IPFS can mitigate this issue (Biswas et al., 2020). IPFS is a distributed file system for storing and accessing data in peer-to-peer network (IPFS, 2022).

- **Smart Contracts:** A smart contract is a program that runs on the Ethereum blockchain and represents a certain logic defined by the developer. Smart contracts are written in a high-level language called Solidity and executed by the Ethereum Virtual Machine (EVM). The proposed solution has Registration, Commitment, Production, Consumption, and Waste Assessment smart contracts.

- **Ethereum Distributed Ledger:** All logs, transactions, and events are stored on the Ethereum distributed ledger permanently. This element is key to the success of the proposed solution because it allows it to achieve traceability, accountability, and transparency.

#### 3.1. Actors interactions

- **Distributor Commitment Phase:** All interactions among the actors during the distributor commitment phase are illustrated in
Fig. 4. The manufacturer deploys the commitment smart contract and specifies the name of the vaccine, the maximum/minimum vaccine boxes within the Lot, and the commitment duration for both the distributors and bidders. Once the smart contract is deployed, the Timer Oracle starts monitoring the triggering condition under which the commitment window is closed. This phase has two potential scenarios. The first scenario is when a distributor successfully commits to delivering the vaccine lot and the distributor gets approved by the smart contract. The second scenario is when none of the distributors commits to delivering the vaccine, which leads to the denial of the production of the vaccine lot by the smart contract.

- **Bidders Commitment Phase**: If a distributor successfully commits to delivering the vaccine lot, then the bidders’ commitment phase can begin. Fig. 5 illustrates the interactions among the actors during the bidders’ commitment phase. Each bidder (or healthcare center) will place a bid that represents the number of boxes it is willing to commit to, which is aggregated by the commitment smart contract. This phase has three potential scenarios. The first scenario is when the maximum capacity of the manufacturer is reached before the end of the commitment time window, which leads the production smart contract to approve production and announce all the relevant details. The second scenario is when the Timer Oracle triggers the end of the commitment phase and the aggregated bids exceed the minimum threshold. Therefore, the production smart contract approves production and announces all the relevant details. The third scenario is when the Timer Oracle signals the end of the commitment phase and the aggregated bids do not exceed the minimum threshold. Therefore, the production smart contract denies production.

The proposed solution goes through different phases, and each phase involves different interactions among the actors. Figs. 4–7
show these interactions, and they are segregated into four phases as described below.

- **Production and Consumption Phase:** If the commitment smart contract approves production, the manufacturer starts producing the vaccine lot. Fig. 6 illustrates the interactions among the actors during the production and consumption phases. The smart contract announces the details of the manufactured vaccine lot, such as the vaccine lot EA, number of boxes, and the expiry date. The committed distributor is responsible for delivering vaccine boxes to the committed healthcare centers. In order for the production phase to be over, the committed distributor and committed healthcare centers must confirm the delivery and reception of vaccine boxes, respectively. In the consumption phase, the committed healthcare centers will start consuming the vaccine boxes. In the proposed solution, it is assumed that a healthcare center will either use the vaccine boxes by administering them to patients or dispose of them once they are no longer wanted, and in both cases, the consumption smart contract will announce the details of each event.

- **Waste Assessment Phase:** Once the expiry date of the vaccine lot is reached, the Timer Oracle will trigger the Waste Assessment smart contract. Fig. 7 illustrates the interactions among the actors during the waste assessment phase. This phase has four potential scenarios. The first scenario occurs when none of the actors violate any rules and an event is emitted indicating that the vaccine lot was properly produced, delivered, and consumed. The second scenario is when the manufacturer overproduces, and an event is emitted announcing that the manufacturer has committed a violation along with the excess amount. The third scenario is when a distributor commits a violation by failing to deliver the correct amount to healthcare centers, and an event is emitted announcing that the distributor has committed a violation along with the missing amount. The fourth and final scenario occurs when a healthcare facility wastes vaccine boxes, and an event is emitted announcing the healthcare facility(s) that committed the violation as well as the amount wasted.

4. Implementation details

In this section, the setup, implementation details, and algorithms of the proposed solution are described. The proposed solution consists of five smart contracts which are written in Solidity language, compiled using REMIX IDE, and tested on the KOVAN test network, which is a Proof-of-Authority Testnet for the Ethereum Mainnet that does not require mining, which reduces the likelihood of Denial-of-Service attacks (DDoS attacks). Choosing the most appropriate configuration for the blockchain network is critical to ensure that it meets the required security, scalability, and decentralization by the solution (Farshidi et al., 2020). Moreover, the KOVAN Testnet allows rapid deployment and testing because it has a shorter block time and low maintenance costs since it does not involve intense mining (Mandiri, 2017). In addition to that, Chainlink keepers network is available on KOVAN Testnet for development and testing purposes, which is utilized in our solution to set up Timer Oracles.

The smart contracts are written and compiled using the REMIX IDE, which is a development environment for writing and executing smart contracts. After that, smart contracts are deployed on KOVAN Testnet.
with the required parameters by the designated actors. Moreover, the Chainlink Keepers Network, which provides users with a decentralized network of nodes that are incentivized to perform all registered tasks (referred to as Upkeeps) without competing with each other, is utilized.
to trigger specific functions based on predefined conditions. Fig. 8 represents the entity-relationship diagram where interactions among the smart contracts, their relationships, and attributes are illustrated.

The Registration smart contract is deployed by a local regulator who is responsible for registering manufacturers, distributors, and healthcare centers by executing the different functions illustrated in the figure. Furthermore, each vaccine lot will have a unique commitment, production, and consumption smart contract. Therefore, the relationship between the registration smart contract and these smart contracts will be 1 to n.

The commitment smart contract is deployed by the manufacturer, who will not produce the vaccine lot unless the other actors commit to it. A distributor needs to commit to delivering the vaccine lot via the DistributorCommitment function. Moreover, each healthcare center needs to declare the distributor with which it is affiliated through the PlaceBid function before placing any bids through the PlaceBid function. Finally, the Timer Oracle will trigger the PerformUpkeep function when the commitment duration expires.

The production smart contract is deployed by the manufacturer, who is also responsible for providing the details of the produced vaccine lot via the ProduceVaccineLot function. Moreover, the committed distributor will have to start the delivery process by executing the startDelivery function and confirm the delivery of vaccine boxes via the ProofofDelivery function. Finally, each committed healthcare center will have to confirm receiving the vaccine boxes via the ProofofReception function.

The Consumption smart contract is deployed by the local regulator, and each healthcare center is required to execute the UseVaccineBoxes and DisposeVaccineBoxes whenever it uses or disposes of vaccine boxes, respectively. The commitment, production, and consumption smart contracts have a 1 to 1 relationship with each other because they represent a single vaccine lot only.

The Waste Assessment smart contract is deployed by the local regulator, and it has one main purpose, which is to identify any violations that occur during the production and consumption phases. The timer oracle is responsible for triggering the performUpkeep function when the vaccine lot expiry date is reached. The waste assessment smart contract has a 1 to 1 relationship with the commitment, production, and consumption smart contracts because it can be associated with only one vaccine lot at a time.

4.1. Algorithms

Each smart contract is written to implement a certain logic in the proposed solution. For further clarification of the logic behind each one of the smart contracts, detailed algorithms are presented. The main algorithms of the proposed solution are described below.

Algorithm 1 represents the registration phase. The deployer of the Registration smart contract automatically becomes authorized to execute the different registration functions within the smart contract. In our solution, the local regulator deploys the registration smart contract and becomes responsible for registering actors according to their respective roles. To authorize manufacturers, the local regulator will add the Ethereum address of the manufacturer to a mapping called manufacturer. Similarly, to authorize distributors and healthcare centers, the local regulator will add the Ethereum addresses of the distributors and healthcare centers to distributor and healthcarecenter mappings, respectively. An event is also emitted with registration details after every successful registration function execution.

Algorithm 2 represents the distributor commitment phase. During this phase, a distributor can opt to deliver the vaccine lot. If the execution is successful, the distributor status is updated to “Committed”, and all the relevant details are stored in the form of an event on the blockchain so that other entities, especially the affiliated healthcare centers, are made aware of it.
Algorithm 3: Bidder Commitment

Input: CommitmentDuration, vaccineName, MaxVaccineBoxes, MinThreshold, StartingTime, Bidders, PlacedBid
Output: Events declaring the commitment details of the Bidders

initialization;
if caller == healthcarecenter ∧
   ExecutionTime ≤
   StartingTime + CommitmentDuration ∧
   PlacedBid + CurrentBids ≤
   MaxVaccineBoxes then
   Add healthcarecenter to Bidders list
   Update healthcarecenter status to committed
   Update CurrentBids by adding the PlacedBid
   if CurrentBids == MaxVaccineBoxes then
      Emit an event declaring the EA of both the
         healthcarecenter and the vaccine Lot along
         with the amount of PlacedBid
      Emit an event declaring the end of the
         commitment window
      Emit an event declaring that the vaccine Lot
         production is approved along with its EA and
         committed bids amount
   else
      Emit an event declaring the EA of both the
         healthcarecenter and the vaccine Lot along
         with the PlacedBid
   else
      Revert bidder commitment process and show an error.
   /* Bidder commitment process is complete */
if caller == TimerOracle ∧ ExecutionTime >
   StartingTime + CommitmentDuration ∧
   CommitWindowClosed == false then
   if CurrentBids ≥ MinThreshold then
      Update Production permission to true
      Update CommitWindowClosed to true
      Emit an event declaring production approval, the end of the commitment window, and the details of the approved vaccine Lot
   else
      Update CommitWindowClosed to true
      Emit an event declaring that production of the
         vaccine Lot is denied
   else
      Revert bidder commitment state and show an error.
   /* The commitment phase is complete */

Algorithm 4: Production and Delivery

Input: VaccineLotExpirationDate, ProducedBoxes, DeliveryDuration, Lotstate, ReceptionConfirmation, ReceivedBoxes, BidderCommitted, TotalBids, TotalDeliveredBoxes
Output: Events declaring the state of the vaccine Lot initialization:

if caller == manufacturer ∧
   Lotstate == NotManufactured ∧
   VaccineLotExpirationDate ∧
   ProducedBoxes, DeliveryDuration, IPFSHash
   Update Lotstate to "Manufactured"
   Emit an event declaring the end of the manufacturing process with the details of the vaccine Lot
else
   /* Revert contract state and show an error.
      Manufacturing process is complete */
   if caller == distributor ∧
      Lotstate == Manufactured ∧
      Update Lotstate to EnRoute
      Emit an event declaring the start of the delivery process
else
   /* Revert contract state and show an error.
      if caller == healthcarecenter ∧
      Lotstate == EnRoute ∧ BidderCommitted[caller]
      == true ∧ ReceivedBoxes == PlacedBid[caller]
      then
      Update ReceptionConfirmation status to true
      Emit an event declaring the details of the received vaccine boxes
else
   /* Revert contract state and show an error.
      if caller == distributor ∧ Lotstate == EnRoute
      ∧ ReceptionConfirmation == true then
      Update TotalDeliveredBoxes by the delivered amount
      if TotalDeliveredBoxes == TotalBids then
         Emit an event declaring the details of the delivered vaccine boxes to the healthcare center
         Emit an event declaring the end of the delivery process
   else
      Emit an event declaring the details of the delivered vaccine boxes to the healthcare center
   else
      Emit an event declaring the details of the delivered vaccine boxes to the healthcare center
else
   /* Revert contract state and show an error.
      The delivery process is complete */

Algorithm 3 represents the bidders’ commitment phase. During this phase, a bidder that has an affiliated distributor that is committed to delivering the vaccine Lot can place a bid as long as the total number of the submitted bids does not exceed the maximum capacity of the manufacturer. If the execution is successful, the healthcarecenter EA status is updated to “Committed”, the total number of placed bids is updated, and an event is emitted declaring the details of the placed bid. Moreover, if the placed bid results in achieving the maximum capacity of the manufacturer, two additional events are emitted, declaring that the vaccine lot production is approved, and the commitment phase is over. Finally, when the commitment phase deadline is reached, the Timer Oracle will trigger the Commitment smart contract to announce the final decision. If the total number of placed bids exceeds the minimum threshold set by the manufacturer, an event will be released declaring that vaccine lot production is approved. Otherwise, vaccine lot production is denied.
Algorithm 4 represents the Production and Delivery phase. During this phase, the manufacturer will produce the vaccine lot, the smart contract will store all the necessary details on the blockchain, and an event will be emitted to declare that it is ready for delivery. The distributor will then initiate the delivery process by updating the state of the vaccine lot to "EnRoute" which indicates that it is out for delivery. Finally, both the distributor and healthcare centers will have to confirm delivering and receiving the vaccine boxes, respectively, and events are emitted to declare the details of the delivery and reception of the vaccine boxes.

Algorithm 5 represents the consumption phase. During this phase, healthcare centers can either use or dispose of vaccine boxes, and the details of either case are stored on the blockchain in the form of an event. The consumption details are important for the waste assessment process, where healthcare centers can be held accountable for any waste they cause.

Algorithm 6 represents the waste assessment phase. During this phase, the Timer Oracle will trigger the Waste Assessment smart contract once the vaccine lot reaches its expiration date. If the manufacturer overproduces, an event is emitted declaring that the manufacturer has committed a violation. Moreover, if the distributor fails to deliver the correct number of vaccine boxes, an event is emitted declaring that the distributor has committed a violation. Furthermore, if a healthcare center fails to use or dispose of any vaccine boxes, an event is emitted declaring that the healthcare center has committed a violation. Finally, if the violation counter is equal to zero, then an event is emitted declaring that no violations were committed.

5. Testing and validation

In this section, the functionality and logic of our developed smart contracts are tested and validated. The REMIX IDE is used to write, compile, and deploy the smart contracts, and Etherscan is used to execute functions and view the emitted and stored events. Table 1 contains a list of all participants as well as their Ethereum addresses, whereas Table 2 contains a list of smart contracts as well as their addresses.

The proposed solution is tested by an example where a COVID-19 Pfizer vaccine lot is supposed to be produced if all participants agree to fully commit to their respective roles. Waste accountability and assessment are determined based on the decisions made by the participants during the commitment, production, and consumption phases. In the commitment phase, the manufacturer is assumed to have a maximum capacity of 100 boxes within the vaccine lot and a minimum threshold of 80 boxes. Moreover, the distributor is assumed to commit to delivering the vaccine lot; healthcare center A places a 50-box bid, and healthcare center B places a 40-box bid. In the production phase, it is assumed that the manufacturer produces 95 boxes instead of 90. Furthermore, the distributor is assumed to deliver the correct quantities to healthcare centers A and B. In the consumption phase, it is assumed that healthcare center A uses 45 boxes and disposes of 5 boxes, whereas healthcare center B manages to use all 40 boxes that it initially committed to. Finally, a short period of time was used for the commitment duration and vaccine expiration for simplicity and time-saving during the testing phase. Moreover, the same image was
uploaded to the IPFS during the different phases for simplicity, which explains the similarity among the IPFS hashes in the different events.

Fig. 9. The emitted events during the registration phase.

Fig. 9 summarizes the events of the registration phase, in which the manufacturer, distributor, and healthcare centers are registered. The emitted events contain information such as the Ethereum address of the registered users and the registrar.

The distributor commitment events are depicted in Fig. 10. There are two main events. The first is CommitmentDetails which records the details of the vaccine Lot, and the second is DistributorCommitmentDetails which records the Ethereum address of the committed distributor.

Fig. 11 summarizes the events during the bidders’ commitment phase and the final decision on the production of the vaccine lot. The HealthcareCenterCommitmentDetails event records all the necessary details of the committed healthcare center, the ProductionApproved event is only emitted when the conditions of the manufacturer are met, and the ProductionDenied event is emitted if any of the conditions is not met.

Fig. 12 illustrates the emitted events during the production process and the start of delivery. In the former, the VaccineLotProduced event is emitted where the details of the produced vaccine lot are announced, whereas in the latter, an event named EnRoute is emitted by the production smart contract when the distributor starts the delivery process.

Figs. 13 and 14 show the events where healthcare centers A and B confirm the reception of the vaccine boxes and the distributor confirms delivering them. The ConfirmReception event emits all the related details to the reception process. On the other hand, the ConfirmDelivery event is used to emit the details of the delivered vaccine boxes from the distributor side. Finally, the EndDelivery event is emitted when all the vaccine boxes have been successfully delivered.

Fig. 15 illustrates the Consumption Phase details where healthcare centers can either use or dispose of vaccine boxes. The VaccineBoxesDisposed event emits the details of the disposed vaccine boxes. Similarly, the VaccineBoxesUsed event emits the details of the used vaccine boxes.

Fig. 16 depicts the events that occur during the waste assessment phase. In this example, there are two violations. The first violation is committed by the manufacturer when it produces five additional vaccine boxes. Therefore, the ManufacturerViolation event emits the details of the violation. The second violation is committed by Healthcare Center A where 5 vaccine boxes were disposed of instead of being used, therefore, the HealthcareCenterViolation event is emitted with all the necessary details.

6. Discussion

In this section, we perform analyses in terms of security and cost to assess different aspects of the proposed solution. Moreover, the proposed solution is compared with existing solutions. Finally, guidelines on how the proposed solution can be generalized and extended are provided.

6.1. Security analysis

Different security metrics of the proposed solution must be examined and assessed to ensure that they comply with the standards of the healthcare industry. The main security metrics that are being examined are integrity, data privacy, accountability and non-repudiation, availability and reliability, and preventing Man-in-the-middle (MITM) and distributed Denial-of-Service (DDoS) attacks.

Integrity is achieved because blockchain ensures that any stored information is immutable by design, and in our proposed solution, information is stored in the form of an event where some attributes of the event are indexed to make it easier for the user to query and fetch information.

Data privacy is important to ensure that no personal information is stored permanently on-chain. In our proposed solution, all participants are identified by an Ethereum address instead of their real information. Therefore, their personal details remain private and off-chain.

Table 2

| Smart contract | Contract address |
|----------------|------------------|
| Registration   | 0 × 59e0369A0Bf415B85f788447C55658f00DC585 |
| Commitment     | 0 × 3be7283f1bbe3737ca101a695fa54ea0df65211 |
| Production     | 0 × 1e3602B39aD2f769EcFedf13A74b4604091eb1B |
| Consumption    | 0 × 7e59d0e0Ed482B3174C5D343F2d1944A136dcD |
| Waste assessment| 0 × b0E7Ce5bd8BaB8324AE535F6e65ac7f72d114A69E91 |

In this section, we perform analyses in terms of security and cost to assess different aspects of the proposed solution. Moreover, the proposed solution is compared with existing solutions. Finally, guidelines on how the proposed solution can be generalized and extended are provided.

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The third security metric is “accountability and non-repudiation”, which is achieved by utilizing the “Modifier” feature in the Solidity language. In the proposed solution, all participants are allowed to execute their designated functions by authorizing their assigned Ethereum addresses. Therefore, any execution they perform is stored permanently on an immutable ledger, and they are held accountable for their actions.

The fourth security metric is “availability and reliability”. The former refers to the ability of the proposed solution to work when needed, whereas the latter refers to the period of time during which the proposed solution can operate without failure. Therefore, this is highly dependent on the quality of the nodes operating the blockchain network. If the proposed solution is implemented by using the mainnet of Ethereum, then it would provide it with high availability and reliability because it has many nodes. However, if a private Ethereum blockchain is used, then it will be highly dependent on the quality of operating nodes and the consensus algorithm used.

The fifth security metric is “MITM and DDoS attack prevention”. The former refers to an attack where an intruder manipulates the data of a transaction before it reaches its destination. However, in a blockchain, all transactions are signed by the sender’s private key before they are sent, and they cannot be changed or cancelled without the private key. Therefore, the intruder cannot manipulate the transaction without the private key, which is extremely difficult to access or guess unless the sender willingly or mistakenly hands it over. The latter refers to attacks that target the blockchain itself by spamming it with transactions to slow it down. In the mainnet of Ethereum, such attacks are extremely unlikely because they cost ETH, which is the currency used in the Ethereum network to pay for transactions. Therefore, the attacker or spammer needs to spend an enormous amount of ETH to succeed. However, in a Proof-of-Work (PoW) private Ethereum blockchain, an attacker can mine a lot of ETH with relatively low hashing power, which the attacker can use to initiate an attack. In our
proposed solution, the KOVAN Testnet uses Proof-of-Authority (PoA), where nodes or validators put their reputation on the line to validate transactions. Therefore, if a validator decides to spam the network, other validators can vote to kick it out.

### 6.2. Smart contracts security analysis

Smart contracts are susceptible to different vulnerabilities such as integer overflow, integer underflow, parity multisig bug, call-stack depth attack, transaction-ordering dependence (TOD), timestamp dependency, and re-entrancy. The tool used to carry out the security analysis is called “Oyente”, which is a tool specialized in conducting security analysis on smart contracts to identify any vulnerabilities (Shigemura et al., 2019). Fig. 17 summarizes all the results obtained by applying the Oyente tool to the written smart contracts. The results indicate that none of the smart contracts are suffering from any of the common vulnerabilities, which implies that the written smart contracts are secure.

### 6.3. Cost analysis

Cost analysis is important to understand the costs associated with executing functions in the proposed solution, which helps in deciding the feasibility of implementing it on Ethereum’s mainnet. Any taken action has a transaction and gas usage associated with it, and each unit of gas has a cost. Table 3 summarizes the amount of gas used in each smart contract deployment and function execution, along with the cost in USD. An average gas price of 120 GWEI and the Ethereum price of 2450 USD were used according to the ETH gas station (Eth Gas Station, 2022) which was accessed on Jan 25, 2022. From the table, it can be concluded that deploying smart contracts is the most costly operation in the proposed solution, and given that each vaccine
lot is represented by a smart contract, it is not practical to deploy the smart contracts on Ethereum’s mainnet. Therefore, it would make more sense to build the proposed solution on a private Ethereum blockchain to avoid the high gas costs. Alternatively, a layer 2 solution such as Polygon Network can be used to process transactions on a side-chain to reduce gas fees (Jaynti et al., 2022).

Using the PoA consensus algorithm in a private Ethereum blockchain requires setting up validators manually, which can be quite costly and complex. Therefore, Layer 2 scaling solutions such as Polygon Network can be used to avoid the high setup costs and still achieve high scalability. The Polygon network works by processing and executing transactions on side-chains, which are secondary blockchains that interface with the main blockchain to submit aggregated blocks every now and then (Jaynti et al., 2022). Other scaling solutions include Optimistic Rollups and zkRollups. The main objective of Layer

Fig. 14. The emitted events when distributor confirms and ends delivery.

Fig. 15. The emitted events during the consumption phase.
2 solutions is to take transaction execution off-chain while keeping transaction data only on-chain.

6.4. Comparison with the existing solutions

Our solution is compared with other existing blockchain-based solutions to show the novelty and main contributions of our work. The comparison is done based on various criteria. First, the application type which is the specific area each solution is addressing. Second, the type of waste which specifies the category or the material the waste is made of. Third, the blockchain platform that is used in each proposed solution. Third, the mode of operation is used to show whether a solution is public or private. Fourth, the consensus algorithm indicates how the blockchain nodes reach consensus in each proposed solution. Fifth, off-chain storage indicates if a solution is utilizing external storage to handle large-sized data. Sixth, waste reduction which implies if a proposed solution has a mechanism to reduce waste. Seventh, transactions fees and throughput are used as an indicator of the performance of the utilized blockchain and its configuration. Finally, the DApp indicates if a proposed solution has fully functional DApp or not.

Ahmad et al. (2021) provided a solution for medical equipment supply chain traceability and waste management where shippers are penalized for any committed violations. Our solution differs from this solution by making each entity in the supply chain commit to their role and demands in the supply chain, rather than just penalizing workers who are responsible for treating the medical waste. Moreover, the penalty system proposed in Ahmad et al. (2021) can be expanded to include participants who do not fully commit to their actions. From a technical perspective, our solution uses a private Ethereum blockchain with the PoA consensus algorithm, which makes our proposed solution more scalable and more cost-efficient compared to the public PoW Ethereum blockchain used by the authors.

Douladiris et al. (2020) proposed a blockchain framework for reverse logistics of used medical equipment, which is similar to the concept of Ahmad et al. (2021) but with fewer details. Therefore, our solution differs from this one by including preventive measures rather than just handling waste. Moreover, from a technical perspective, both solutions used the private Ethereum blockchain with decentralized storage (IPFS) to avoid storing large-sized data on-chain. However, our solution uses the PoA consensus algorithm, which can make the network more scalable. The other solution, on the other hand, uses PoW, which makes the network more vulnerable to DDoS attacks.

In Pelonero et al. (2020), the authors proposed a blockchain-based solution that incentivizes users to properly handle general waste by implementing a reward system. Similarly, solution (Paturi et al., 2021) aims to address the issue of general waste management by utilizing blockchain technology. The main difference between our solution and Pelonero et al. (2020), Paturi et al. (2021) is that our solution includes a commitment phase where all participants declare the quantity of the produced items that they are willing to commit to, thus preventing excess waste from the beginning. Additionally, our solution ensures waste reduction instead of just managing it after it occurs. From a technical perspective, our solution uses a private network that validates transactions based on the PoA consensus algorithm, which eliminates gas fees and increases throughput significantly. Moreover, our solution utilizes off-chain storage for large-sized files. On the other hand, Pelonero et al. (2020) is built on a public PoW Ethereum network, which can be quite costly when the network is congested and the throughput is relatively low. Paturi et al. (2021) is built and tested on three different networks, namely, Ethereum, Matic, and BSC, to compare performances. The authors concluded that the Matic network is the most efficient because it has the highest throughput and low gas fees.

The authors in Mondal and Kulkarni (2022) proposed a blockchain-based solution for plastic waste management. The solution utilized a query/response model among the participants to enable traceability of...
all transactions. The solution also provides non-monetary incentives represented in the form of tokens that can be later used for discounts. The solution only addresses the issue of plastic waste after it happens, rather than preventing it from the beginning, which is one of the main differences compared to our solution. From a technical perspective, our solution has better overall performance for the same reasons explained in the comparison with solution (Peloner et al., 2020).

The solutions proposed in Dua et al. (2020), Gupta and Bedi (2018), and Farizi and Sari (2021) aim to address the issue of e-waste management by utilizing blockchain technology. All solutions use an incentive layer to encourage participants to manage waste properly. Moreover, all solutions ensure the traceability of the transactions that take place. Although the main application of our solution is different, our approach is different because it aims to reduce and prevent waste from the
beginning by ensuring the commitment of all participants. From a technical perspective, Gupta and Bedi (2018) is expected to have the worst performance because it uses the public PoW Ethereum blockchain, which can be quite costly and slow. Dua et al. (2020) uses a private PoW Ethereum network, which can benefit from the low transaction fees, but it might face issues with scalability since the PoW consensus algorithm can slow things down. Farizi and Sari (2021) is built on the Hyperledger-Fabric blockchain, which is a private blockchain with no transaction fees involved and can reach high throughput. Moreover, it can allow private and confidential transactions among participants. Hyperledger-Fabric has no cryptocurrency; therefore, incentivizing validators in the network can be challenging and usually leads to expensive infrastructure to maintain the network. Finally, our solution utilizes Private PoA Ethereum, which has low transaction fees, high throughput, and relatively low infrastructure costs, hence creating a good balance among the important characteristics of a blockchain network.

The most significant difference between our solution and other solutions is the implementation of the commitment smart contract, where participants need to commit to their roles and demands, which they can be held accountable for if they commit any violations. However, other solutions are mainly focused on handling medical waste after it happens rather than preventing it. From a technical perspective, our solution relies on using a private PoA Ethereum blockchain configuration that leads to cost efficiency and scalability. Table 4 summarizes the differences between our solution and other blockchain-based solutions.

### 6.5. Generalisation

The proposed solution targets waste prevention and accountability of COVID-19 vaccines, which is one application that can leverage the use of the logic behind the written smart contracts. Other applications within the healthcare industry or other industries can utilize the proposed solution to ensure accountability and waste prevention in their respective applications. This can be achieved by customizing the smart contracts according to their needs.

Assuming that other applications are needed by private enterprises, it would still be recommended to use a blockchain network that is sustained by distributed nodes that reach consensus by using the PoA consensus algorithm. Moreover, other applications might require the items to be tracked in real time to ensure that they do not get damaged because of a certain entity mishandling them, such applications will require including Internet of Medical Things (IoMT) devices that must be managed by blockchain as well to prevent counterfeiting (Akkaoui, 2021; Meng et al., 2020). This modification can be implemented by adding a new entity such as a container that continuously tracks the conditions of the transported items and triggers the respective smart contract whenever a violation is detected.

Figs. 3–7 can be used as a guide to connect the required application with our proposed solution. The interactions among the participants might be different, but the smart contracts can still be applied to other applications as long as they have the logic.

### 7. Practical implications and limitations

This paper studies the positive impact of blockchain technology on COVID-19 waste reduction. The proposed solution specifically contributes to the healthcare industry by ensuring very high security and trust for all the transactions that occur within the pharmaceutical supply chain. Moreover, the proposed solution has a unique smart contract that represents the commitment phase, where all participants have to declare all the products they are willing to commit to. This part of the solution represents a unique contribution for the industry and its people who are interested in blockchain technology because it addresses the overproduction and underutilization problems in the healthcare industry. Furthermore, the proposed solution contributes to the professionals in Industry 4.0 by introducing the emerging blockchain technology in a way that allows them to mitigate some of the most persistent problems, such as traceability and accountability. Additionally, the proposed solution can be further extended and built upon by other scholars and academics who are interested in blockchain technology. For example, other scholars and academics might be interested in applying blockchain technology in a field that requires traceability and accountability.
accountability other than healthcare. Therefore, following the same logic of the smart contracts, the proposed solution can be extended to address similar problems in different industries.

Although the proposed solution brings many beneficial features to the table, there are still many challenges. The following are some of the challenges that may interfere with large-scale adoption and implementation of our proposed solution and blockchain solutions in general.

- **Blockchain Limitations:** The use of blockchain has some inherent limitations, such as high power consumption in the case of using the PoW consensus algorithm. Moreover, the scalability of the blockchain is highly dependent on the consensus algorithm, block size, and block verification time. Therefore, configuring these factors properly can be very tricky.

- **Lack of Industry 4.0 Experts:** The use of blockchain technology will require the use of many Industry 4.0 technologies, such as IoT devices. The lack of experts in this field will be a real challenge for the long-term success of blockchain technology in the healthcare industry (Meng et al., 2020).

- **Privacy and Data Security:** Although transparency can be a beneficial feature in some cases, like traceability, it can raise concerns regarding the privacy of sensitive data that is stored on the blockchain (Menon and Jain, 2021). This issue can disincentivize users from storing sensitive data on-chain to prevent malicious users from misusing them. Another issue with on-chain data is that it requires all users and IoT devices to feed data into the blockchain. Any missing data would hinder traceability and auditability.

- **Interoperability with Legacy Systems:** To effectively implement blockchain technology as a solution for the existing healthcare infrastructure, it has to be interoperable with legacy systems. If this challenge is not met, it will be very difficult to ensure end-to-end traceability.

8. Conclusion and future work

In this paper, we have proposed a blockchain-based solution for COVID-19 vaccine waste reduction, which is caused by its overproduction and underutilization, in a manner that is decentralized, secure, accountable, traceable, transparent, auditible, and trustworthy. We developed Ethereum smart contracts to ensure that participants are always accountable for any generated waste. The proposed solution utilized decentralized storage such as IPFS to allow participants to store large-sized data off-chain to reduce costs which were posed by storing data locally on the blockchain network. We designed and presented a high-level system architecture, sequence diagrams, and algorithms. We implemented, tested, and validated the smart contracts by using the REMIX IDE platform and KOVAN Testnet. We justified the use of a private Ethereum network by performing a cost analysis to demonstrate the costs associated with using a public Ethereum network. We presented different approaches that can be used to make the proposed solution scalable, such as Ethereum layer 2 solutions. By performing security analysis on the smart contracts, we showed that our solution is invulnerable to common exploits. We compared our solution with the existing blockchain-based solutions to show its novelty and superiority. The comparison with existing solutions showed that our solution overcomes some existing limitations such as large-sized data storage which is handled by off-chain storage, higher throughput which is achieved by using the PoA consensus algorithm, better data privacy by using a private permissioned Ethereum blockchain rather than a public permissionless one, and waste reduction by including the commitment smart contract which ensures that every entity is accountable for any waste they generate. We discussed how our proposed solution can be generalized and extended to other applications that require accountability and waste prevention. We make a theoretical contribution by thoroughly explaining the process of producing, consuming, and disposing COVID-19 vaccines, which showed how multiple participants can contribute in the unnecessary waste that is caused by either overproduction or underutilization. Finally, we introduced the commitment phase which can act as cornerstone in a regulatory framework that is concerned with COVID-19 vaccines waste since it ensures accountability among all the participants in the COVID-19 vaccine supply chain. The following are the main findings of our work:

- The use of a commitment phase ensures that all participants are accountable for the COVID-19 vaccines they request and handle without the need for the introduction of an incentive framework
- The use of a private-permissioned blockchain can allow regulators to customize the blockchain configuration according to their needs while also utilizing the smart contracts to facilitate all the required functions without the need for centralized authorities
- It is necessary to have a clear framework that includes all the participants and all aspects of the supply chain to ensure and enforce accountability, which allows regulators to easily spot the source of the waste

For future research, although blockchain technology offers a lot of attractive and beneficial features, there are still some concerns that should be taken into consideration. For example, the immutability feature of blockchain means any stored information cannot be changed or altered. Therefore, any human error cannot be corrected. Moreover, the current interoperability limitations in blockchains necessitate the use of the same blockchain type if the solution is adopted at a large scale. Additionally, integrating the blockchain solution with legacy systems can be very challenging due to the different nature of both systems. Another major aspect that must be further investigated is the practicality of the proposed solution and how it will perform in a real healthcare ecosystem, therefore, a pilot project should be setup with a sample of users within COVID-19 vaccines supply chain. Furthermore, the solution must comply with patient privacy laws, and it should be customizable for other regions that impose different laws. Finally, we plan to further improve the efficiency of the COVID-19 vaccine supply chain by adding real-time tracking of vaccine lots to the proposed solution so that we can make sure they are handled properly at every step.

CRediT authorship contribution statement

Ahmad Musamih: Conceptualization, Methodology, Investigation, Writing – original draft. Khaled Salah: Conceptualization, Methodology, Project administration. Raja Jayaraman: Conceptualization, Validation, Writing – review & editing, Supervision. Ibrar Yaqoob: Conceptualization, Validation, Writing – review & editing. Yousuf Al-Hammadi: Validation, Writing – review & editing. Jiju Antony: Writing – review & editing.

Data availability

No data was used for the research described in the article.

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Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.
