A Scoping Review on the Application of Blockchain During COVID-19 Pandemic : focusing on digital vaccination certificate

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Abbreviation and Acronyms

Abbreviation / Acronyms	Definition
AI	Artificial Intelligence
CDC	Centers for Disease Control and Prevention
COVID-19	Coronavirus disease 2019
Dapps	Decentralized applications
DVC	Digital Vaccination Certificate
FDA	Food and Drug Administration
GDP	Gross Domestic Product
IoT	Internet of Things
ML	Machine Learning
PHEIC	Public Health Emergency of International Concern
PoS	Proof of Stake
PoW	Proof of Work
PRISMA	Preferred Reporting Items for Systematic Review and Meta-Analysis
SARS-CoV-2	Severe Acute Respiratory Syndrome Coronavirus 2
SVC	Smart Vaccination Certificate
TPS	Transactions Per Second
UAVs	Unmanned Aerial Vehicles
WHO	World Health Organization

Abstract

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This study involves a scoping review to look into the specific attributes of blockchain and to examine various cases where digital vaccination certificates have been implemented or proposed during the COVID-19 pandemic. After applying the eligibility criteria, 54 studies were deemed suitable for full-text review. Among these, 20 studies met the inclusion criteria for this scoping review. Studies in the form of journals were

the most common and most studies were published in the 'Technology' category. The highest number of cases are found in Asia followed by Europe. The most common type and platform is public blockchain and Ethereum. Most of the studies utilize smart contracts. The included studies presented a summary of the blockchain technologies utilized in the proposed solutions. This study summarized the potential benefits and limitations of blockchain technology in digital vaccine certificates in response to COVID-19. Despite blockchain's benefits like decentralization and transparency, limitations in scalability, cost-effectiveness, and ethical considerations have hindered its widespread adoption. The study highlights the need for further research to address these challenges and suggests exploring the integration of other technologies and policies with blockchain. The aim is to provide a foundation for future research on the effective use of digital vaccine certificates in crises like the COVID-19 pandemic.

Key words: blockchain, COVID-19, SARS-CoV-2, coronavirus disease 2019, vaccine, certification

I. Introduction

1. Background

Research from the McKinsey Technology Council(2022) suggests that by 2027, up to 10 percent of global Gross Domestic Product (GDP) could be associated with blockchain-enabled transactions. With 61% of companies ranking digital transformation as a top priority, blockchain is becoming an essential technology in achieving that objective by providing means of sharing data and exchanging value securely between organizations. The application of blockchain technology is witnessing a rapid expansion, driven by its distinctive features. As a result, the global market for blockchain is anticipated to reach US$1.76 trillion by 2030. Furthermore, it is predicted that blockchain technology could significantly contribute to the creation of employment opportunities worldwide by the same year, as indicated in PwC's report(PwC, 2020).

Due to its ability to revolutionize established systems through decentralization, transparency, and immutability, blockchain technology has attracted a lot of interest from a variety of businesses(Marbouh et al., 2020). Given the increasing allure of blockchain technology and its integration into various organizations and industries, the healthcare sector has emerged as a substantial domain where numerous use cases have been pinpointed for blockchain application(Agbo, Mahmoud and Eklund, 2019). Furthermore, blockchain holds the potential to become an integral component of the global response to pandemics.

This is underscored by an official document of the European Parliament (Turino, Rinaldi and Macchiaroli, 2022), which acknowledges blockchain as one of the ten key technologies in the battle against COVID-19 (KRITIKOS, 2020; Turino, Rinaldi and Macchiaroli, 2022).

Highly contagious viruses like COVID-19 make it urgent to discover suitable remedies, from hastening the identification of virus carriers to slowing the spread of the virus to developing a vaccine(KRITIKOS, 2020). The current era's technological progress stands as one of the key strengths that may offer potential solutions to the multifaceted challenges presented by COVID-19(Kalla et al., 2020). Innovative technologies, including blockchain, machine Learning (ML) and artificial intelligence (AI), the internet of things (IoT), three-dimensional printing, unmanned aerial vehicles (UAVs), robotics, nanotechnology, and synthetic biology, along with 5G communications, big data and edge computing and cloud, harbor the potential to be harnessed in the creation of intelligent emergency management strategies tailored to address the complexities of the COVID-19 pandemic(Kalla et al., 2020). Therefore, these new technologies may be useful in combating COVID-19 and the subsequent pandemic. In particular, blockchain technology that has the potential to transform a variety of industries, including finance, supply chain, and healthcare could be the key to combat the crisis(Marbouh et al., 2020). Amidst the backdrop of the persistent COVID-19 pandemic and other infectious disease crises, the application of blockchain technology presents a promising avenue for tackling critical challenges and fortifying response mechanisms. In the current COVID-19 pandemic scenario, blockchain holds the potential to play a pivotal role in the global response to the coronavirus. It can achieve this

by tracking the transmission of the disease, facilitating the implementation of digital vaccination certificates, and ensuring the resilience of medical supply chains(KRITIKOS, 2020).

During the COVID-19 pandemic, there is no doubt that the area that has mainly suffered the fallout of the crisis is that of healthcare infrastructures. National systems were struggling to perform an accurate prediction of the pandemic course, mainly due to the widespread lack of automation in data sharing between different healthcare structures(Ricci et al., 2021). In the context of COVID-19 and similar pandemics, blockchain technology can be a vital tool. It enables effective solutions for tracking and monitoring, fosters transparent product and information exchange, and upholds data security with robust encryption, ensuring data integrity and network durability(Turino, Rinaldi and Macchiaroli, 2022). Creating a blockchain network for epidemic data sharing would enhance openness, accessibility, and transparency. This approach reduces potential data discrepancies between different entities like healthcare facilities and government bodies. Additionally, making vaccine data widely accessible through such a network is likely to increase public engagement in vaccination efforts(Marbouh et al., 2020; Rashid et al., 2022). Notwithstanding the potential of blockchain technology, its adoption within the domains of healthcare and infectious disease management remains deficient in terms of policies and substantiated cases. While blockchain technology represents a promising innovation, the availability of policies and empirical cases for its application in healthcare and infectious disease contexts is rather limited. Particularly in the context of a global health challenge

like a pandemic, the lack of uniformity in policies and implementation across different countries makes it challenging to achieve worldwide consistency in blockchain adoption(Gartner, 2021).

Due to the fact that blockchain technology is still relatively new and has been the subject of much hype in both the press and grey publications, there is a lot of false information, speculation, and uncertainty regarding blockchain's potential applications in the healthcare sector.(Agbo, Mahmoud and Eklund, 2019). In addition, there were more related studies that placed a greater emphasis on technical viewpoints than from the perspective of healthcare experts. This can be attributed to the fact that the adoption of blockchain technology in the healthcare and infectious diseases sectors is still in the early stages(Qiu and Zhu, 2021). Hence, a comprehensive understanding of blockchain's characteristics is essential to maximize its applicability in combating infectious diseases like COVID-19. Furthermore, it is necessary to explore how blockchain technology can be effectively employed from a public health perspective during epidemic outbreaks, identifying trends and creating foundational resources for future research by analyzing existing studies.

Amidst the COVID-19 pandemic, blockchain technology's utility is expanding, with a particular focus on vaccination certificates(Bansal, Garg and Padappayil, 2020). The advent of COVID-19 vaccines in December 2020 ushered in a wave of changes and impacts across various sectors. Initially, countries responded to the pandemic by implementing border closures and imposing strict travel restrictions. However, as global vaccination rates increased, presenting vaccination certificates became a means to alleviate social and travel

constraints(WHO,2021) Taking the United States as an example, on October 25, 2021, the U.S. Presidential Proclamation came into effect, resuming international travel while imposing restrictions on non-immigrant air travelers who had not completed their COVID-19 vaccinations(CDC, 2021). Approximately two years later, it was announced that noncitizen nonimmigrant air passengers would no longer be required to present documentation of full COVID-19 vaccination to board flights to the United States, effective May 12, 2023(CDC,2023).

Presently, according to the Centers for Disease Control and Prevention **(**CDC)(2023), apart from COVID-19 vaccines, pre-travel vaccine recommendations are provided for travelers, and certain vaccines, such as yellow fever, are officially managed with certificates. While international travel requirements for COVID-19 vaccines have been adapting to the evolving pandemic situation, it is plausible that, as we transition into a more sustainable management framework, international travel requirements and recommendations for COVID-19 vaccines could be internationally standardized, taking into account factors like age, timing, and dosing. If such requirements are established, the significance of vaccination certificates in ensuring compliance would become more pronounced. Digital proof of vaccination could serve as a mechanism not only to facilitate international travel during pandemic situations characterized by concerns about virus transmission but also to stimulate economic recovery and foster global job creation(Mithani et al., 2022).

From the initial outbreak through the pandemic, with the introduction of vaccines and

the cycle of restrictions and relaxations, the Director-General of WHO came to the conclusion that COVID-19 is a recognized and continuous health issue rather than a public health emergency of international concern (PHEIC) at WHO's 15th meeting on May 5th, 2023(WHO, 2023). Throughout the COVID-19 pandemic, a multitude of studies emerged, covering a range of topics, including vaccine efficacy and distribution. However, research on digital vaccination certificates and related technologies remains relatively underdeveloped, often with an emphasis on technical aspects.

Notably, there is a shortage of comprehensive reviews that highlight and summarize key blockchain solutions related to digital vaccination certificates, a vital aspect of bolstering public health efforts since WHO declared that COVID-19 is no longer classified as a PHEIC. Many pandemic-related restrictions have been eased, and long-term management strategies are now in progress. Nevertheless, it has not been officially declared endemic, and the possibility of resurgence and future pandemics remains ever-present. At this critical juncture, this study seeks to identify blockchain technologies proposed or implemented for COVID-19 pandemic management, with a central emphasis on digital vaccination certificates. It is anticipated that this research will contribute to the formulation of policies and guidelines for the application of blockchain technology in future pandemic crisis management. Given that approximately four years have transpired since the initial discovery of the COVID-19 virus, the findings from this current research hold significance not only for mitigating COVID-19 but also as foundational knowledge for the future application of blockchain technology in addressing forthcoming pandemics.

2. Purpose of this Study

This study involved a scoping review to investigate the specific attributes of blockchain and to examine various cases where digital vaccination certificates have been implemented or proposed in the COVID-19 pandemic. This study then analyzed the practicality and limitations of using blockchain-based digital vaccination certificates. The goal is to provide essential groundwork for future research, which will aim to create clear guidelines for the effective use of blockchain-based digital vaccination certificates during situations like the COVID-19 pandemic crisis.

II. Methodology

1. Scoping Review

1.1. Indications for scoping reviews

Scoping reviews, as the name implies, offer a great method for evaluating the extent or inclusiveness of the literature pertaining to a specific topic. They also offer a distinct insight into the volume of existing literature and research and deliver an extensive and comprehensive overview of their key findings. When the potential for specific research questions remains uncertain and a more targeted systematic review may not yet be feasible, scoping studies serve as valuable tools for examining emerging literature(Munn et al., 2018).

The overarching objective of a scoping review is to create a conceptual map of the key themes within a specific research area, along with identifying the primary sources and types of evidence accessible(Tricco et al., 2016). These reviews aim to offer a broad overview of the existing literature, although the depth of analysis may vary. The extent of coverage is influenced by its intended purpose(Arksey and O'Malley, 2005).

For conducting the scoping review, Arksey and O'Malley(2005) outlined using the framework and guiding principles outlined. They listed specific reasons for conduction scoping review in In their study established a methodology for scoping reviews(Arksey and

O'Malley, 2005). Afterward, some following studies have provided additional guidance and extended this original framework(Munn et al., 2018; Pham et al., 2014; Tricco et al., 2016). There are the suggested purposes for doing a scoping review based on the previously described indications(Munn et al., 2018). Indications for scoping reviews are as follows: to identify the types of available evidence in a given field, to clarify key concepts/ definitions in the literature, to examine how research is conducted on a certain topic or field, to identify key characteristics or factors related to a concept, as a precursor to a systematic review, and to identify and analyze knowledge gaps(Munn et al., 2018).

1.2. Systematic review or scoping review

Depending on their question and goal, authors should choose the scoping review or the systematic review approach. The most important factor is whether the review aims to answer clinically meaningful questions or inform practice(Munn et al., 2018). When it comes to issues of viability, appropriateness, meaningfulness, or efficacy, a systematic review is most useful(Pearson, 2004). If the study is primarily concerned with the identification of particular traits or concepts, as well as the mapping, reporting, or discussion of these traits or concepts, a scoping review is a better choice(Munn et al., 2018). Instead of offering a carefully considered, synthesized conclusion or solution to a particular issue, scoping reviews aim to present an overview or map of the evidence(Arksey and O'Malley, 2005). Because of this, it's typical not to consider methodological limitations or bias risk associated with the data utilized in a scoping review(Peters et al., 2015).

1.3. Scoping review for this study

The application of blockchain technology, especially in the form of digital vaccination certificates for the COVID-19 pandemic and other infectious diseases, represents a relatively uncharted domain. Recognizing this novelty, the scoping review methodology was chosen for this study due to its aptitude in illuminating the breadth of such emerging subjects. Given the diverse potential of blockchain in addressing pandemic-related challenges, it becomes crucial to first map the extant literature comprehensively. Such an exploration not only aids in grasping the current state of knowledge but also pinpoints areas of deficiency, paving the way for subsequent, more detailed research. Ultimately, this study seeks to lay the groundwork for deeper inquiries into the role of blockchain during COVID-19 and potential future pandemics.

The framework and guiding principles provided by Arksey and O'Malley (2005), along with additional suggestions and guidelines from other studies, served as the foundation for this scoping review(Munn et al., 2018; Peters et al., 2015; Pham et al., 2014; Tricco et al., 2016). This study covers the five steps including identifying the research question, identifying relevant studies, studying the selection, charting the data, and summarizing and reporting the findings(Arksey and O'Malley, 2005). The 'consultation exercise' that Arskey and O'Malley(2005) suggested as an optional step was not conducted.

2. Research Question

The research questions for this study are as follows:

First, what are the key features and characteristics of blockchain that make it suitable for the implementation of digital vaccination certificates during infectious disease crises like COVID-19?

Second, what are the existing or proposed use cases of digital vaccination certificates powered by blockchain in the management of the COVID-19 pandemic?

Third, what are the potential benefits of blockchain in digital vaccination certificate and primary challenges and limitations in the context of COVID-19 pandemic?

Fourth, What lessons can be learned from the adoption or proposal of blockchain- based digital vaccination certificates during the COVID-19 pandemic, and how can these insights inform the development of guidelines for the application and utilization in future infectious disease crises?

3. Search Strategy

A comprehensive literature search was carried out utilizing databases such as PubMed, Embase, and Web of Science and was last updated as of Dec 1st, 2023. The complete search was performed using a combination of keywords, including 'Blockchain,' 'COVID-19,' and 'vaccine certification'. The specific search terms are shown in **Table 1.**

Table 1. Search strategy

#	**PubMed** (2020-03-11 ~ 2023-05-05)
1	“Blockchain”[MeSH Terms] OR blockchain[All Fields] OR blockchains[All Fields]
2	"COVID-19"[Mesh] OR "SARS-CoV-2"[Mesh] OR "COVID-19"[All Fields] OR "SARS-CoV-2"[All Fields] OR COVID[All Fields] OR coronavirus[All Fields]
3	(immunity OR vaccine OR vaccination) AND (certificate OR certification OR documentation OR passport)
4	2 or 3
5	1 and 4
#	**Embase** (2020-03-11 ~ 2023-05-05)
1	'blockchain'/exp OR 'blockchain' OR blockchain*
2	'coronavirus disease 2019'/exp AND 'covid-19' OR 'sars-cov-2' OR covid OR coronavirus
3	(immunity OR vaccine OR vaccination) AND (certificate OR certification OR documentation OR passport)
4	2 or 3
5	1 and 4
#	**Web of Science** (2020-03-11 ~ 2023-05-05)
1	ALL=(blockchain OR blockchains)
2	ALL=(sars cov 2 OR covid OR covid 19)
3	ALL=((Immunity OR vaccine OR vaccination) AND (certificate OR certification OR documentation OR passport))
4	2 or 3
5	1 and 4

4. Eligibility Criteria

To be included, studies had to focus on the implementation or proposal of blockchain technology for purposes related to digital vaccination certificates during the COVID-19 pandemic. Research on topics that are not related to digital vaccination certificates were excluded. Studies that reviewed or discussed the theoretical possibilities of blockchain were excluded. The studies conducted before the declaration of the COVID-19 PHEIC or after the declaration of the end of the COVID-19 PHEIC have been excluded. Studies published in languages other than English were not included. There were no limitations placed on the study's design, measured outcomes, or publication country.

5. Study Selection and Data Extraction

EndNote X9 was employed to facilitate the literature search and organization. Initially, the process involved a comprehensive search for relevant studies. Following this, Microsoft Excel 2016 and Word 2016 were utilized to identify and eliminate duplicate studies. To select studies for inclusion, the eligibility criteria was considered. The primary screening phase involved assessing the titles and abstracts of the identified studies. This initial screening allowed for the exclusion of studies that did not align with the defined eligibility criteria. Subsequently, studies that met these initial criteria progressed to the next stage, where a more in-depth review of the full texts was conducted.

A total of 1,236 studies were obtained from various databases, comprising 258 from

PubMed, 168 from Embase, and 810 from Web of Science, following the removal of 124 duplicate studies. After applying the eligibility criteria, 54 studies were deemed suitable for full-text review. Among these, 20 studies met the inclusion criteria for this scoping review. A Preferred Reporting Items for Systematic Review and Meta-Analysis(PRISMA) flow chart of the study selection process is shown in **Figure 1.**

6. Data Analysis

In this study, we summarized the characteristics of blockchain-based digital vaccination certificates in ascending order by topic, including author, research area, publication information, blockchain technology-related summaries, limitations, and more, utilizing tables and charts as the primary data sources. All data has been recorded in accordance with the references provided in the literature. Publication dates are based on the dates registered in Endnote X9, and research areas are recorded as the regions affiliated with the first author's institution.

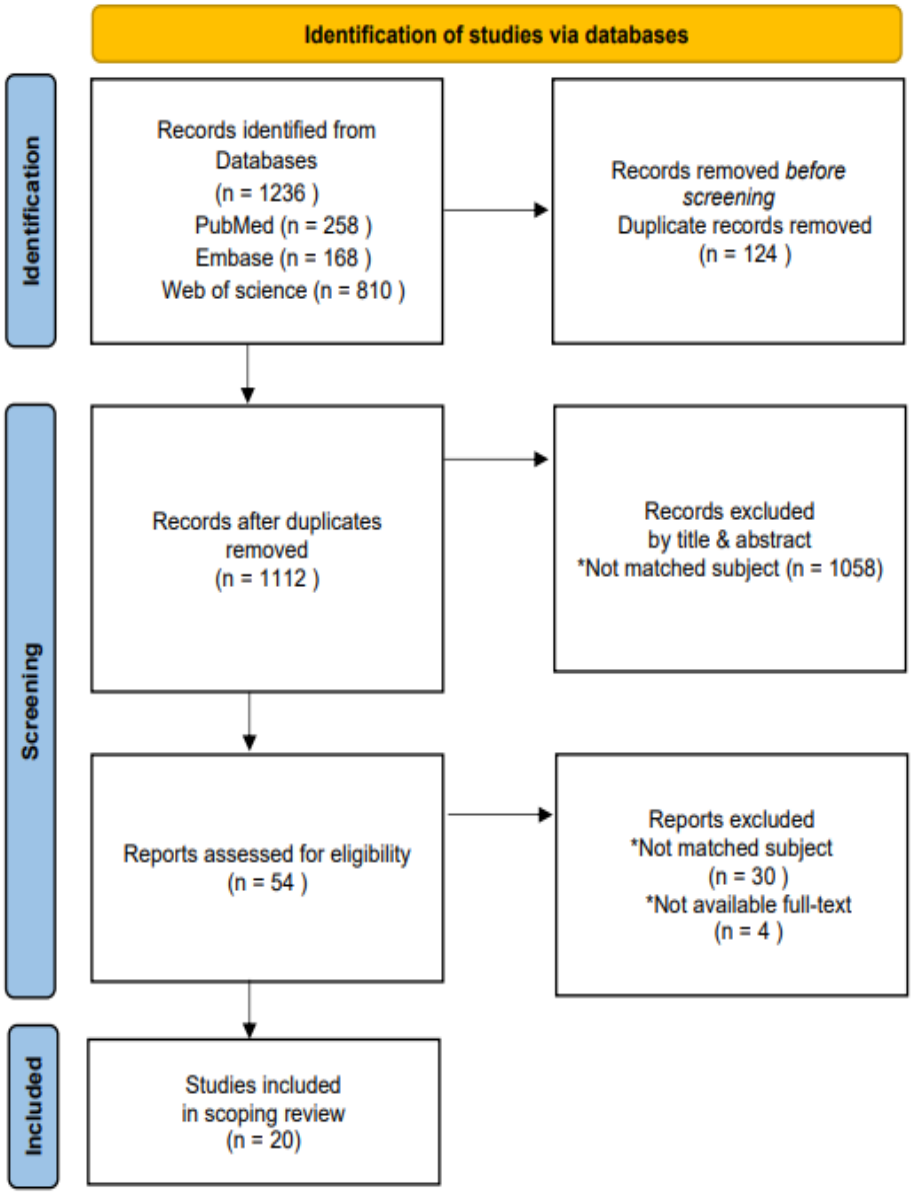


Figure 1. PRISMA flow chart.

III. Blockchain Technology

1. History of blockchain

1.1. Conceptual Foundations

The conceptual foundations of blockchain were laid with discussions on distributed ledgers in the 1970s. In 1976, a paper titled "New Directions in Cryptography" introduced the idea of a distributed ledger. The subsequent proposal by Stuart Haber and Scott Stornetta in 1991 emphasized timestamping data rather than the medium, a concept that would prove essential to blockchain's integrity. Additionally, in 1979, Ralph Merkle's 'Hash tree' or 'Merkle tree' introduced a secure mechanism for data storage and verification, setting the stage for blockchain's data integrity(Laurent L, 2018).

In the 1990s, the notion of "Electronic cash" or "Digital Currency," originally proposed by David Chaum, made substantial contributions to the concept of blockchain. Protocols like e-cash schemes were introduced to tackle the challenge of double-spending. In 1997, Adam Back's "hashcash" played a pivotal role in countering spam emails, which led to the development of "b-money" by Wei Dai, based on peer-to-peer network principles(Laurent L, 2018).

1.2. The Emergence of Bitcoin

Satoshi Nakamoto is widely recognized as the inventor of blockchain technology when

he published a groundbreaking paper in 2008 titled "Bitcoin: A Peer-to-Peer Electronic Cash System."(Nakamoto, 2008). Nakamoto's paper introduced a novel electronic payment system based on cryptographic principles. It solved the long-standing issue of double-spending, ensuring that digital currency cannot be duplicated, thus enabling secure and transparent transactions. This paper outlined the concept of a public ledger that traces and confirms transaction history, preventing double-spending issues(Nakamoto, 2008).

Nakamoto's work led to the release of open-source software to implement the Bitcoin system, and in early 2009, the first Bitcoin network was established. While Nakamoto's identity remains undisclosed, Bitcoin garnered immense attention for its ability to maintain user anonymity and its transparency, setting the stage for a new era of cryptocurrencies (Nakamoto, 2008).

1.3. Evolution of Blockchain

The advent of Bitcoin marked the beginning of the blockchain journey. Bitcoin not only demonstrated the potential of blockchain but also paved the way for its evolution into different generations. Blockchain 1.0 primarily focused on creating virtual currencies like Bitcoin and reducing costs associated with traditional physical currencies. It included digital currencies such as Bitcoin, Monero, Dash, and Litecoin, which were used for various purposes, including small-value payments, foreign exchange, and gambling(Xu, Chen and Kou, 2019).

Blockchain 2.0 broadened the technology's horizons by introducing the concept of smart

properties and smart contracts. Platforms like Ethereum, Ethereum Classic, NEO, and QTUM brought these concepts to life, facilitating applications beyond virtual currencies(Liu, 2021). This generation delved into areas such as securities trading, supply chain finance, and payment clearing, focusing on security and data integrity through the integration of blockchain and smart contracts(Kim, 2020).

Blockchain 3.0 further expanded the scope of blockchain into non-financial domains, including government, healthcare, science, culture, and the arts. This generation aims to popularize the technology and emphasizes decentralization and the integration of tokens for various validations. Blockchain's integration with tokens is poised to bring about significant societal transformation(Maesa and Mori, 2020).

In conclusion, the history of blockchain is a story of conceptual evolution, marked by key developments from distributed ledger concepts to the emergence of Bitcoin and the subsequent generations of blockchain technology. It has reshaped the way we think about data management, security, and transactions, ushering in a new era of decentralized, secure, and transparent digital innovation(Xu, Chen and Kou, 2019).

2. Principle of Blockchain

Blockchain is a distributed ledger technology in which ledger data containing transaction records is collectively owned and verified by all participants within a peer-to-peer network. Each new transaction is sequentially added to the ledger, and there is no risk

of arbitrary alteration or deletion of past transaction records. Transactions are grouped into blocks, and these blocks are linked together like a chain. This decentralized ledger operates continuously, recording transaction history in chronological order, and requires approval from all participants through a real-time verification system (consensus mechanism). This ensures that transaction records cannot be tampered with or hacked(Kim, 2020)

Additionally, transaction records and data are transparently and securely transmitted and stored over the internet without relying on central servers. Consequently, blockchain enables peer-to-peer transactions without the involvement of central trusted third-party institutions, such as government or banks, allowing for the automation of transactions. Ultimately, blockchain acts as a trust network that enables direct peer-to-peer transactions without the need for intermediaries, offering endless utility in various fields beyond cryptocurrencies(Kim, 2020).

Some key underlying technologies and concepts that drive blockchain include type of blockchain, notable platforms such as Ethereum and Hyperledger Fabric, hash functions, mining, and smart contracts. Understanding these specific technologies is essential for comprehending and exploring the potential applications of blockchain(Laurent L, 2018).

2.1. Type of blockchain

2.1.1. Private

A private blockchain, also known as a permissioned blockchain, is a type of blockchain

network where access and participation are restricted to a select group of entities or individuals(Liu, 2021). These participants are typically known and trusted, and they are given specific permissions to interact with the blockchain. Private blockchains are often used in situations where privacy, control, and regulatory compliance are essential. They are commonly employed by businesses and organizations for various purposes, such as supply chain management, internal record-keeping, or confidential transactions. Examples of private blockchains include Hyperledger Fabric and Corda(Liu, 2021; Yaga et al., 2019).

2.1.2. Public

A public blockchain, also referred to as a permissionless blockchain, is a decentralized network where anyone can join, participate, and validate transactions without needing approval or permission(Liu, 2021). These blockchains are open to the public and often operate on a trustless and transparent basis. Participants in a public blockchain network follow a set of consensus rules, and transactions are recorded on a public ledger. The most well-known example of a public blockchain is Bitcoin, but there are many others, including Ethereum and Litecoin. Public blockchains are often used for cryptocurrency transactions and various Decentralized Applications (DApps)(Yaga et al., 2019).

2.1.3 Consortium

In the context of blockchain technology, a consortium is a collaborative effort involving multiple organizations, often from the same industry or sector, to establish and operate a shared blockchain network(Liu, 2021). These organizations come together to jointly

govern and maintain the blockchain, sharing the responsibilities and resources required for its operation. Consortium blockchains offer a middle ground between private and public blockchains. They are semi-private networks, where access is limited to a predefined group of participants, but the control and governance of the blockchain are distributed among the members of the consortium. This type of blockchain is useful for scenarios where several organizations want to collaborate and share data or processes, such as supply chain management, financial services, or healthcare. One prominent example of a consortium blockchain is R3 Corda's network, which is used by financial institutions(Liu, 2021; Yaga et al., 2019).

2.2. Hash Function

A chain of blocks connected to one another makes up a blockchain. A block typically comprises the following information: data; a nonce, which stands for "number only used once"; the hash of the previous block, which is an encrypted string with a certain length; and the hash of the block itself. The reason a block is termed a blockchain is because it forms a chain structure, with each new block always containing the hash of the previous block(Spencer-Hicken, 2022; Yaga et al., 2019). Cryptographic hash functions generate hashes. Any information can be put into a cryptographic hash algorithm, which outputs a unique 64-digit hexadecimal number. Any information can be hashed with ease in an ideal hash function, but it is challenging to extract inputs from the hash. Furthermore, even slight modifications to the inputs will have a substantial and seemingly unrelated impact on the final hash. Because of this, it is simple to confirm that the hash is generated from the known

inputs, but it is computationally costly to find the inputs that generate a known hash(Zhou and Kraft, 2022)

2.3. Mining

Mining is the essential process in blockchain that confirms and integrates new transactions into the public ledger. This process is vital for maintaining the overall security and trustworthiness of the blockchain network. Mining primarily takes two forms: Proof of Work (PoW) and Proof of Stake (PoS). In PoW, miners solve complex mathematical puzzles, while in PoS, validators stake cryptocurrency to validate transactions. Mining serves several crucial functions in the blockchain network, such as security, decentralization, consensus, and incentives. Through mining, blockchain realizes its potential as a trustless and tamper-resistant system for recording and verifying digital transactions(Laurent L, 2018).

2.4. Notable Platforms - Ethereum and Hyperledger Fabric

Ethereum is an open-source, decentralized platform designed for creating and deploying smart contracts and decentralized applications (DApps). Distinct from Bitcoin, which primarily serves as a cryptocurrency, Ethereum employs its Ethereum Virtual Machine (EVM) for executing programmable scripts. Ether (ETH) is its native cryptocurrency, facilitating transactions and rewarding participant nodes. As a public, permissionless platform, Ethereum is favored for its broad accessibility. Its established ecosystem, combined with ERC standards, streamlines the development of tokens and smart contracts.

This, along with its pioneering status in smart contract platforms, has cemented its credibility in the blockchain sphere.

Hyperledger Fabric, developed by the Linux Foundation under the Hyperledger project, is an open-source blockchain tailored for enterprise solutions. Contrasting public blockchains, Fabric operates in permissioned environments where participants' identities are known. This design ensures data privacy and suits businesses seeking regulatory compliance. With a modular architecture, Fabric can be customized for various industries like finance and supply chain. It employs "chain codes" for smart contract functionalities, akin to Ethereum but fine-tuned for enterprise requirements. The platform's controlled nature often results in enhanced transaction speeds, making it ideal for enterprises valuing performance, privacy, and regulatory alignment.

2.5. Smart Contract

A smart contract is a self-executing and programmable digital agreement that operates within a blockchain network. It is essentially a piece of code that defines the terms and conditions of a contract. When specific predefined conditions are met, the smart contract automatically enforces and executes these terms(Vacca et al., 2021). This automation eliminates the need for intermediaries or trusted third parties to oversee and verify transactions, as trust is established through the inherent features of the underlying blockchain technology(Spencer-Hicken, 2022).

Smart contracts have a broad range of applications across various industries. They are

utilized in financial services for automated payment processing, in supply chain management for tracking and verifying the origin of products, and in many other use cases. Particularly in situations where security, transparency, and efficiency are critical, smart contracts offer a means to reduce the risk of errors and fraud while simplifying processes and lowering costs(Vacca et al., 2021).

3. Characteristics of Blockchain

3.1. Decentralization

Traditional databases, such as SQL databases, are centralized. In contrast, on a blockchain, every participant (nodes/computers) on the network has access to the entire database and the complete history of all transactions. This means that the information on the blockchain isn't stored in any single location, and no centralized version of this information exists for a hacker to corrupt. By distributing its operations across many nodes, blockchain reduces risks associated with centralized control, such as manipulation, censorship, and single points of failure. Furthermore, this decentralized nature ensures that blockchain networks remain operational even if parts of the network fail(Zheng et al., 2017).

3.2. Transparency

Transactions on the blockchain are transparent and can be viewed by all participants on the network, thanks to the open-source nature of blockchain technology. While individuals have unique blockchain addresses, and their direct identity isn’t tied to these addresses,

transactions can be traced back to them. For blockchain implementations like Bitcoin, this is an intentional feature, ensuring every transaction's openness. Such transparency fosters accountability and trust among participants, ensuring that each transaction is conducted transparently and reduces the potential for fraudulent activities(Saberi et al., 2019).

3.3. Immutability

In the context of blockchain, immutability implies that once a transaction has been added to the blockchain, it cannot be altered or deleted. This property is achieved through cryptographic hash functions. Each block in the blockchain possesses a unique code, known as a 'hash', which contains the hash of the preceding block, thus creating a linked chain. Any attempt to alter information within a block would change its hash, disrupting the link with subsequent blocks and notifying the network of the discrepancy. This feature safeguards the integrity of data, ensuring that once information is written to the blockchain, it remains trustworthy and protected against tampering(Zheng et al., 2017).

The characteristics of blockchain can be utilized in various aspects of pandemic management. Blockchain can transparently record the entire process from the production of vaccines to their delivery, storage, and vaccination. This allows for real-time identification and response to the authenticity of vaccines and issues in the distribution process. And blockchain supports secure data sharing between medical institutions. Research data related to COVID-19, patient information, etc., can be transparently shared

while also protecting personal information. Also, through a blockchain-based digital health certification system, individuals can securely store and share their vaccination status and COVID-19 test results. This can be used for entry restrictions in travel, event participation, etc(Abd-Alrazaq et al., 2021).

Building on the core principles of blockchain technology, namely decentralization, transparency, and immutability, it becomes evident that blockchain offers a groundbreaking approach to data management and upholding data integrity. In practical scenarios, such as the management of a pandemic. the application of blockchain technology can be transformative. Blockchain can facilitate processes that are transparent, secure, and efficient, ranging from the distribution of vaccines to the secure sharing of medical data and the management of digital health certifications. Such applications not only highlight the versatility of blockchain technology but also its potential to significantly improve and secure processes in critical sectors like healthcare and supply chain management(Abd-Alrazaq et al., 2021).

IV. Digital vaccination certificate during COVID-19

1. Vaccination Certificate in Pandemic

After the COVID-19 vaccine was first approved for use in December 2020, social and travel restrictions began to ease as vaccination rates increased worldwide. In a pandemic like COVID-19, rapid patient tracing and vaccination emerge as pivotal elements in crisis management. With the growing recognition of the importance of vaccines, the role of vaccination certificates, which serve as tools for confirming vaccination status or immunity, has gained prominence. Vaccination certificates play a big role in cross-border movement(Mithani et al., 2022).

In 1933, the International Sanitary Convention for Aerial Navigation introduced the first International Certificate of Inoculation and Vaccination to prevent the spread of infectious diseases across borders. Beyond safeguarding travelers, vaccination laws aim to protect specific populations, contain outbreaks or epidemics, reduce mortality, and potentially eliminate diseases(Pavli and Maltezou, 2022).

WHO approves internationally recognized certificates, along with proof of vaccination, for entry into specific countries in the case of diseases like yellow fever(Mithani et al., 2022). More requirements for proof of vaccination before traveling may be implemented in the case of a global public health emergency that poses a threat to human populations'

health. (Pavli and Maltezou, 2021). Certificates can come in diverse forms, such as paper certificates, QR codes, mobile apps, and more. As technology advances, authentication methods continue to diversify and become more sophisticated(WHO,2021). In this research, our specific focus is on blockchain-based digital vaccination certificates among these varied formats.

2. Digital Vaccination Certificate and Its Challenges

Various terms are used to refer to this concept, including digital vaccination certificate, digital vaccine passport, immunity passport, and vaccine passport. In this study, instead of meticulously distinguishing each term, we predominantly use the term "digital vaccination certificate" to encompass the broader concept of a digital proof of vaccination or immunity.

A vaccination certificate is a health record that specifies a vaccination that a person has received. Traditionally, this record was on a paper card with important information about the person getting the vaccination, the date it was given, and other information from the core data set.(Rashid et al., 2022). A digital vaccination certificate is an electronic version of the vaccination record that can be accessed by the recipient and authorized healthcare providers. It functions similarly to a paper certificate in terms of ensuring continuity of care or serving as documentation of vaccination(WHO, 2021).

3. Characteristics of Blockchain for Digital Vaccination Certificate

3.1. Decentralization

Blockchain technology employs a distributed ledger system to record transactions, eliminating reliance on centralized servers or clients. This decentralized approach is facilitated by nodes in the blockchain communicating directly with each other. Such a structure is instrumental in addressing challenges like cross-border digital vaccination certificate authentication. This decentralized nature not only contributes to the robustness of the system but also to its scalability and accessibility across different regions(Vanderslott and Marks, 2021).

3.2. Transparency

The interconnected blocks in the blockchain ledger, each containing its hash and the hash of the previous block, allow for swift integrity checks. This transparency in data linkage ensures that any participant in the network can verify the authenticity of the information. The transparent nature of blockchain technology thus plays a crucial role in maintaining a clear and verifiable record of transactions, vital for applications such as digital vaccination certificates(Koyama et al., 2023).

3.3. Immutability

A key feature of blockchain is its immutable nature. Once recorded, the data spread across computers globally cannot be altered or deleted. This immutability ensures the authenticity and reliability of the stored data, making blockchain an ideal solution for storing sensitive information like vaccination certificates(Koyama et al., 2023). The system's trustworthiness is further cemented through the use of asymmetric encryption. The immutable nature of blockchain thus ensures that the data is genuine and tamper-proof, enhancing the overall reliability of the digital vaccination certificate system(Medina et al., 2023).

The characteristics of decentralization, transparency, and immutability inherent in blockchain technology can make it a highly reliable and efficient system for managing digital vaccination certificates. The decentralized nature ensures a wide and equitable distribution of data, transparency allows for easy verification and integrity checks, and immutability guarantees the security and authenticity of the stored information.

4. Challenges of Digital Vaccination Certificate

Existing vaccination information systems face issues and challenges due to inconsistent progress in the digitalization of immunization programs between nations. The absence of

a structured process for record-keeping by responsible parties during vaccine distribution and administration complicates the verification of data authenticity. Traditional centralized vaccine management systems often face issues of limited data accessibility and are susceptible to single-point breakdown, making it challenging to guarantee information sharing and the availability of third-party verification services.(Zhao and Ma, 2022). Limiting who is allowed to engage in social and professional activities through immunity licenses would promote forgeries and push people to seek infection.(Bansal, Garg and Padappayil, 2020).

V. Results

The complete search was performed using a combination of keywords, including 'Blockchain,' 'COVID-19,' and 'vaccine certification'. 258 from PubMed, 168 from Embase, and 810 from Web of Science, following the removal of 124 duplicate studies. After applying the eligibility criteria, 54 studies were deemed suitable for full-text review. Among these, 20 studies met the inclusion criteria for this scoping review.

1. Characteristics of included studies

Table 2 summarizes the general characteristics of included studies. When looking at the publication type of each reported study, the form of journals was the most common. The publications are broadly divided into two categories: Technology and Health. And most of studies are published in Technology categories. The countries of the first authors of the reported studies were from 15 countries. China and UK appear as the leading country. Most of studies conducted in a single country alone, and other studies conducted in collaboration with two or more countries. Also, it shows a notable concentration in Asia and Europe continent.

Table 2. Characteristics of the included studies

Id.	Author	1st author	Co-author	Year	Title	Publication	Type	Article
#1	A. Koyama et al	Japan	Japan, Vietnam	2023	A Decentralized COVID-19 Vaccine Tracking System Using Blockchain Technology(Koyama et al., 2023)	CRYPTOGRAPHY	Journal	Article
#2	M. B. Barati et al	UK	UK	2021	A Privacy-Preserving Distributed Platform for COVID-19 Vaccine Passports(Barati et al., 2021)	IEEE/ACM 14th International Conference on Utility and Cloud Computing	Proceeding	Proceeding
#3	H. C. J. Gao et al	China	China	2022	An Immunity Passport Scheme Based on the Dual-Blockchain Architecture for International Travel(Gao et al., 2022)	Wireless Communications & Mobile Computing	Journal	Article
#4	D. H. S. Shih et al	Taiwan	Taiwan, USA	2022	An International Federal Hyperledger Fabric Verification Framework for Digital COVID-19 Vaccine Passport(Shih et al., 2022)	Healthcare	Journal	Article
#5	A. M. Razzaq et al	China	China, Pakista, Saudi Arabia, Egypt	2022	Blockchain in Healthcare: A Decentralized Platform for Digital Health Passport of COVID-19 Based on Vaccination and Immunity Certificates(Razzaq et al., 2022)	Healthcare	Journal	Article
#6	M. Abubakar et al	UK	UK	2021	Blockchain-based Platform for Secure Sharing and Validation of Vaccination Certificates(Abubakar et al., 2021)	IEEE/2021 14th International Conference on Security of Information and Networks (SIN)	Proceeding	Proceeding

Table 2. Characteristics of the included studies – continued

#7	Y. Cao et al	China	China	2022	Blockchain-Based Privacy-Preserving Vaccine Passport System(Cao, Chen and Cao, 2022)	SECURITY AND COMMUNICATION NETWORKS	Journal	Article
#8	H. R. S. Hasan et al	UAE	UAE, UK	2020	Blockchain-Based Solution for COVID-19 Digital Medical Passports and Immunity Certificates(Hasan et al., 2020)	IEEE Access	Journal	Rapid Review
#9	R. M. P et al	Korea	Korea	2022	Block-HPCT: Blockchain Enabled Digital Health Passports and Contact Tracing of Infectious Diseases like COVID-19(Rashid et al., 2022)	Sensors	Journal	Article
#10	M. K. Sharma et al	India	India	2022	BLOCKVAC: A Universally Acceptable and Ideal Vaccination System on Blockchain(Sharma, Kothapalli and Gujar, 2022)	IEEE/5th IEEE International Conference on Blockchain (Blockchain)	Proceeding	Proceeding
#11	A. A. S. Abuhashim et al	USA	Saudi Arabia	2021	Block-VC: A Blockchain-Based Global Vaccination Certification(Abuhashim, Shafei and Tan, 2021)	IEEE/4th IEEE International Conference on Blockchain (Blockchain)	Proceeding	Proceeding
#12	M. R. Eisenstadt et al	UK	UK	2020	COVID-19 Antibody Test/Vaccination Certification: There's an App for That(Eisenstadt et al., 2020)	IEEE Open Journal of Engineering in Medicine and Biology	Journal	Article
#13	V. A. Kamjula et al	Canada	Canada, Kuwait	2022	Covid-19 Contact Tracing and Vaccine Validation Using Blockchain Technology(Kamjula et al., 2022)	IEEE/4th International Conference on Blockchain Computing and Applications	Proceeding	Proceeding

Table 2. Characteristics of the included studies – continued

#14	S. A. Ait Bennacer et al	Morocco	Morocco, Portugal	2022	Design and implementation of a New Blockchain-based digital health passport: A Moroccan case study(Bennacer et al., 2022)	Inform. Med. Unlocked	Journal	Article
#15	H. A. W. Lee et al	Taiwan	Taiwan, India, Thailand, Pilippines	2022	Design of a Vaccine Passport Validation System Using Blockchain-based Architecture: Development Study(Lee et al., 2022)	Jmir Public Health and Surveillance	Journal	Article
#16	M. K. Nehme et al	Switzerland	Switzerland	2021	Digital COVID Credentials: An Implementation Process(Nehme et al., 2021)	Frontiers in Digital Health	Journal	Editorial Material
#17	R.-P. Pericàs-Gornals et al	Spain	Spain	2022	Highly private blockchain-based management system for digital COVID-19 certificates(Pericàs-Gornals, Mut-Puigserver and Payeras-Capellà, 2022)	INTERNATIONAL JOURNAL OF INFORMATION SECURITY	Journal	Article
#18	A. C. Abid et al	Tunisia	Tunisia	2021	NovidChain: Blockchain-based privacy-preserving platform for COVID-19 test/vaccine certificates(Abid et al., 2022)	Software-Practice & Experience	Journal	Article
#19	J. L. K. Hernández-Ramos et al	Italy	Italy	2021	Sharing Pandemic Vaccination Certificates through Blockchain: Case Study and Performance Evaluation(HERNANDEZ et al.)	Wireless Communications & Mobile Computing	Journal	Article
#20	A. B. N. Haque et al	Finland	Finland	2021	Towards a GDPR-Compliant Blockchain-Based COVID Vaccination Passport(Haque et al., 2021)	Applied Sciences-Basel	Journal	Article

Table 3. Publication trend over time

year	n	Percentage (%)
2020	2	10
2021	7	35
2022	10	50
2023	1	5
Total	20	100

The distribution of publication years from 2020 to 2023 for the 20 included studies that utilized blockchain technology for digital vaccination certificate in COVID-19 pandemic is shown in **Table 3**. In 2020 and 2021, when vaccine development and vaccination began, the number of publications was n=2 and n=7, respectively. In 2022, when vaccinations were finalized, there were n=10, the highest percentage of the period at 48%, and There is only one study in 2023 until May 5, when the end of COVID PHEIC was declared.

2. Characteristics of Blockchain technology in the Included Studies

Table 4. Characteristics of blockchain technologies by the included studies

Id.	Year	type	platform	Smart contract
#1	2023	Consortium	Substrate	Yes
#2	2021	Public	Ethereum	Yes
#3	2022	Consortium	Domestic Blockchain	N/A
#4	2022	Private	Hyperledger Fabric	Yes
#5	2022	Public	Ethereum	Yes
#6	2021	Public	Ethereum	Yes
#7	2022	Dual (Public, Consortium)	N/A	N/A
#8	2020	Public	Ethereum	Yes
#9	2022	Dual (Private, Public)	Hyperledger Fabric	Yes
#10	2022	N/A	Ethereum	Yes
#11	2021	Public	Ethereum	Yes
#12	2020	Consortium	OpenEthereum	Yes
#13	2022	Consortium	Ethereum-based	Yes
#14	2022	Public	Ethereum	Yes
#15	2022	Public	Ethereum	Yes
#16	2021	N/A	N/A	N/A
#17	2022	Public	Ethereum	Yes
#18	2021	Private	NovidChain	Yes
#19	2021	N/A	N/A	N/A
#20	2021	Public	N/A	Yes

The Characteristics of blockchain technologies as stated by the included studies are summarized in **Table 4**. The most common type and platform is public blockchain and Ethereum. This indicates a preference for the transparency and decentralized nature of public blockchains. Also, the high preference for Ethereum can be attributed to its versatile functionalities and a broad user base. Most of the studies are utilizing smart contracts. This

indicates the potential of smart contracts, with their automated execution capabilities, to play a pivotal role in the management and issuance of digital vaccination certificates related to COVID-19.

Table 5. Overview of the technical features applied to the vaccination certificate

Id.	**Technology**	**Key factor of blockchain technology**
#1	Vacchain	-Rust language as the foundation for the Substrate platform. -SYS-MAN, consensus on vaccine ownership, and implementation of vaccine passports.
#2	Blockchain-based platform for the creation of online COVID-19 vaccine certificates	-Utilizes Ethereum blockchain smart contracts for user consent in vaccine passport data handling. -Access contract on Ethereum blockchain monitors IPFS-stored vaccine passport data.
#3	immunity passport scheme based on the dual-blockchain architecture	-Immunity passport scenarios supported by a dual-blockchain structure. -Ensures privacy with searchable encryption and anonymous authentication techniques. -Security analysis demonstrates efficiency and effectiveness over other authentication systems.

Table 5. Overview of the technical features applied to the vaccine - continued

#4	Federated Identity Management(FIM) Architecture	-Federated Identity Management for secure resource sharing among partners. -Global inspectors validate the DVP of travelers using the system.
#5	decentralized framework for storing and distributing COVID-19 Digital Health Passport Certificates	-Blockchain solution with conscience identity, encryption, and IPFS for decentralized storage. -Ethereum contracts manage DHP, ensuring prompt responses from health authorities.
#6	blockchain-based solution for the creation and validation of vaccination certificates	-Combines self-sovereignty, smart contracts, and IPFS in a hybrid approach. -Removes central management, allowing direct vaccination record storage on mobile devices.
#7	Blockchain-Based Privacy-Preserving Vaccine Passport System	-Dual-chain framework in the blockchain system for enhanced security. -Vaccine passport validation using anonymous credentials and zero-knowledge protocols. -Threshold signature to prevent collusion in vaccine approval.
#8	Blockchain-Based Solution for COVID-19 Digital Medical Passports and Immunity Certificates	-Incorporates self-sovereign identity, re-encryption proxies, and IPFS. -Proxy Re-encryption Scheme for confidential, multi-party access.

Table 5. Overview of the technical features applied to the vaccine - continued

#9	Block-HPCT System	-Security through smart contracts, IPFS, and Hyperledger Fabric. -Linking on-chain and off-chain data with encrypted trusted oracles.
#10	BLOCKVAC System	-Implements the Universally Acceptable and Ideal Vaccination System. -Combines Ethereum smart contracts with Python for data management.
#11	Block-VC System	-Ethereum blockchain test network for a global vaccination certification system. -System focused on certificate issuance, verification, and vaccine management. -Efficient, private user information retrieval. -Smart contracts for streamlined data indexing and querying.
#12	App for COVID-19 Antibody Test/Vaccination Certification	-Mobile application paired with a decentralized server framework. -Adheres to W3C's Verifiable Credentials, Solid platform, and Consortium Ethereum blockchain. -Prioritizes user control over personal information storage and presentation.

Table 5. Overview of the technical features applied to the vaccine - continued

#13	COVID-19 Contact Tracing and Vaccine Validation System	-Blockchain-based healthcare system for contact tracing and vaccine certification. -Blockchain ensures secure, decentralized, and unalterable patient data storage. -Ethereum blockchain manages health pass data with a mix of on-chain and off-chain storage.
#14	Moroccan Digital Health Passport	-Ethereum blockchain framework safeguards health pass info, using smart contracts for access control and combining on-chain (Data Hashes) and off-chain (IFPS) data storage.
#15	Vaccine Passport Validation System	-Multiple parties interact through blockchain smart contracts. -Utilizes public chain alongside Ethereum's protocol.
#16	Digital COVID Credentials	-Blockchain-timestamped digital seal secures data integrity, containing only metadata for privacy.
#17	Highly Private Blockchain-based Digital COVID-19 Certificates	-High-privacy protocol for managing COVID-19 certificates with data sovereignty focus. -Combines proxy re-encryption with blockchain for enhanced security. -Hierarchical structure for efficient data sharing.

Table 5. Overview of the technical features applied to the vaccine - continued

#18	NovidChain	-Emphasizes Self-Sovereign Identity and robust encryption. -Adheres to the Verifiable Credentials Standard with options for selective disclosure. -Operates on a Private Permissioned Blockchain for controlled access. -Employs IPFS for off-chain user data storage, with only hashes stored on-chain.
#19	Sharing Pandemic Vaccination Certificates through Blockchain	-Encrypted certificates stored off-chain (e.g., in IPFS).
#20	GDPR-Compliant Blockchain-Based COVID Vaccination Passport	-Decentralized architecture reinforced by smart contracts. -QR code scanning involved in the verification process.

Table 5 presents a summary of the features of blockchain technologies utilized in the proposed solutions. These solutions aim to provide secure and efficient implementations for digital COVID-19 vaccination certificates. The diverse blockchain solutions for digital vaccination certificate highlight a trend towards decentralized, secure, and privacy-centric approaches. Decentralization and self-sovereignty are emphasized in solutions like Hybrid blockchain solution(Abubakar et al., 2021), NovidChain(Abid et al., 2022), and Digital Medical Passports(Hasan et al., 2020). Ethereum platforms and smart contracts play a crucial role in Ethereum-based platform(Barati et al., 2021), BLOCKVAC System(Sharma,

Kothapalli and Gujar, 2022), and Block-VC System(Abuhashim, Shafei and Tan, 2021). Privacy and security are pivotal in Privacy-Preserving Passport System(Cao, Chen and Cao, 2022), Highly Private Blockchain-based Certificates(Pericàs-Gornals, Mut-Puigserver and Payeras-Capellà, 2022), and Federated Identity Management(Shih et al., 2022). Lastly, hybrid systems in Immunity passport scheme(Gao et al., 2022)and Moroccan Digital Health Passport(Bennacer et al., 2022) show blockchain's potential in managing health data efficiently. Additionally, various technologies are utilized including on-chain and off-chain data linkage using symmetric key encryption oracles(Rashid et al., 2022), and the utilization of digital security seals with timestamps on the blockchain(Nehme et al., 2021).

3. Potential Benefits, Limitation, and Challenges of Blockchain in the Included Studies

This section summarized the potential benefits of introducing and utilizing blockchain technology-based vaccination certificates or digital passports in response to COVID19. It can be used as data for proactive response or management of global public health, such as various types of pandemic situations that may occur in the future. In addition, this section summarized the challenges and limitations for more efficient and stable use of technologies such as vaccine tracking using blockchain technology in pandemic situations such as COVID-19.

Table 6. the potential benefits

Id.	**System**	**Potential benefits**
#1	Vacchiain	- Counterfeit vaccine prevention. - Improved data security and reliability. - Enhanced vaccine distribution and inventory management. - Streamlined vaccine passport verification. - Increased trust in vaccination processes. - Enhanced trust and privacy for users.
#2	Inter Planetary File System (IPFS)	- Enhanced trust and privacy for users. - Creation of tamper-proof records. - Efficient data sharing mechanisms. - User consent and data control - Data accountability - Scalability and performance
#3	immunity passport scheme based on the dual-blockchain architecture	- Privacy Preservation - Traceability and Nonrepudiation - Stigmatization Solution - Feasibility and Reliability
#4	Federated Identity Management(FIM) Architecture	- Privacy Protection and Anti-Tampering - Global Verification and Accessibility - Efficiency in Vaccine Passport Management

Table 6. the potential benefits **-** continued

#5	decentralized framework for storing and distributing COVID-19 Digital Health Passport Certificates	- Enhanced Security and Privacy - User Autonomy and Control - Decentralized Access and Validation
#6	blockchain-based solution for the creation and validation of vaccination certificates	- Enhanced privacy and security for users - Decentralization of data storage - Elimination of reliance on third-party entities for data governance
#7	Blockchain-Based Privacy-Preserving Vaccine Passport System	-Transparent vaccine logistics. -Improved individual privacy. - Blockchain and IoT Integration - Verification for Travel and Disease Control - Prevention of Manipulation in Vaccine Approval
#8	Blockchain-Based Solution for COVID-19 Digital Medical Passports and Immunity Certificates	- Effective Pandemic Response - Reduced Response Time - Enhanced Privacy and Security - Integrity and Trustworthiness
#9	Block-HPCT System	- Enhanced data security and privacy. - Efficient management of COVID-19 information, vaccination, and testing data. - Cost-effective storage solution using IPFS and Hyperledger Fabric. - Adaptable for various contact tracing applications.

Table 6. the potential benefits - continued

#10	BLOCKVAC System	- Enhanced data privacy, scalability, and universal acceptability. - Secure and immutable vaccination records. - Modular, cost-effective, tracks individual and family vaccination histories. - Suitable for large population countries.
#11	Block-VC System	- Global, secure, and privacy-preserving platform for vaccination certification. - Tamper-proof and secure information. - Rapid and reliable cross-border verification.
#12	App for COVID-19 Antibody Test/Vaccination Certification	- Privacy-preserving, tamper-proof, scalable certification mechanism. - Secure personal information control. - Additional security and trust through Consortium blockchain
#13	COVID-19 Contact Tracing and Vaccine Validation System	- Enhanced security and privacy for patient data. - Authenticity and security in data storage and communication. - Flexible and transparent with various types of blockchain integration.

Table 6. the potential benefits - continued

#14	Moroccan Digital Health Passport	- Enhanced Privacy and Security - Controlled Access and Transparency - Data Integrity and Traceability - Reduced Fraud and Information Asymmetry
#15	Vaccine Passport Validation System	-Cost effective -Interoperability -Security -Verifiability -Transparency and Data Accuracy
#16	Digital COVID Credentials	-Decentralized Information and Privacy -Security and Accessibility
#17	Highly Private Blockchain-based Digital COVID-19 Certificates	-High Privacy and Security -Forgery Avoidance and Easy Verification -Controlled Sharing
#18	NovidChain	- Privacy Preservation - GDPR and KYC Compliance - Self-Sovereignty and Control - Integrity Verification - Effective Management of the Pandemic - Security and Traceability
#19	Sharing Pandemic Vaccination Certificates through Blockchain	-Enhanced Privacy and Security -Global Interoperability -Decentralization and Transparency -Reduced Fraud -Empowered Citizens

Table 6. the potential benefits - continued

#20	VacciFi	-Trust and Verifiability -Data Integrity and Security -Compliance with GDPR -Scalability

Table 6 provides an overview of the potential benefits that can be derived from the proposed solutions for each research study. The application of digital passports or certificates within the realm of public health offers a wide array of advantages and potential applications beyond the typical technical benefits associated with blockchain technology. It demonstrates a focused approach on enhanced privacy and security, as seen in Vacchain(Koyama et al., 2023), Inter Planetary File System(Barati et al., 2021) and Immunity Passport Scheme(Gao et al., 2022), and decentralized data management with the prevention of forgery and tampering and transparency emphasized in solutions like Decentralized framework(Razzaq et al., 2022), Blockchain-based solution(Abubakar et al., 2021), and NovidChain(Abid et al., 2022). Moreover, it highlights the efficiency in handling pandemic data, exemplified by Blockchain-Based Solution for COVID-19 Digital Medical Passports(Hasan et al., 2020) and Block-HPCT System(Rashid et al., 2022), and global interoperability for wider adoption as seen in Digital COVID Credentials(Nehme et al., 2021), Sharing Pandemic Vaccination Certificates(HERNANDEZ et al.). Furthermore, these solutions are advocated for their potential to bring about extended benefits, such as efficient data sharing and reduced response times(Hasan et al., 2020), cost-effective

modular tracking of individual and family vaccination histories(Sharma, Kothapalli and Gujar, 2022). They also serve as viable solutions to address issues related to data protection and customer verification, as stipulated by GDPR and KYC compliance(Abid et al., 2022; Haque et al., 2021).

Table 7. challenges or limitations

Id.	System	Challenges / Limitation
#1	Vacchiain	- Traceability - Data reliability - Vaccine ownership transfer - Privacy and security
#2	Inter Planetary File System (IPFS)	- Lack of user consent - Data accountability - Right to be forgotten - Scalability and performance - Centralized infrastructure
#3	immunity passport scheme based on the dual-blockchain architecture	- Falsification of Traditional Passports - Stigmatization of vaccination - Privacy risks for vaccinators - Legitimacy of inspectors
#4	Federated Identity Management(FIM) Architecture	- Data privacy concerns - Cybersecurity threats - Implementation complexity

Table 7. challenges or limitations - continued

#5	decentralized framework for storing and distributing COVID-19 Digital Health Passport Certificates	- Design complexity and implementation challenges - Technical and operational constraints
#6	blockchain-based solution for the creation and validation of vaccination certificates	- High cost and complexity - Security concerns: Man-in-the-Middle (MITM) attacks and Denial-of-Service (DoS) attacks - Transaction costs and scalability issues
#7	Blockchain-Based Privacy-Preserving Vaccine Passport System	- Interoperability & Integration - Cybersecurity - Resource Intensiveness - Using a consortium blockchain enhances privacy but may reduce transparency compared to a public blockchain
#8	Blockchain-Based Solution for COVID-19 Digital Medical Passports and Immunity Certificates	- Scalability and cost-effectiveness - Smart contract vulnerabilities - Privacy and confidentiality concerns

Table 7. challenges or limitations - continued

#9	Block-HPCT System	- Scalability and interoperability in real-world settings. - Complexity in integrating various technologies. - Compliance with data protection regulations. - Ongoing cost, transaction, and security analysis.
#10	BLOCKVAC System	- Scalability for populous countries. - Maintaining cost-effectiveness. - Managing on-chain and off-chain data storage. - Accessibility and usability across diverse regions.
#11	Block-VC System	- Gas consumption and Smart Contract execution costs - Blockchain query limitations - Dependence on network availability - Complexity of smart contracts implementation - Integration with existing systems - Privacy concerns - Adoption and standardization

Table 7. challenges or limitations - continued

#12	App for COVID-19 Antibody Test/Vaccination Certification	- Deployment and integration complexity - Ethical concerns: discrimination -Uncertainties in biological aspects of immunity
#13	COVID-19 Contact Tracing and Vaccine Validation System	- Scalability and interoperability with existing healthcare systems. - User-friendliness for all stakeholders.
#14	Moroccan Digital Health Passport	- Privacy concerns - Implementation complexity - Technical challenges - Cost and feasibility
#15	Vaccine Passport Validation System	- Transparency and confidentiality - Need for further study and development
#16	Digital COVID Credentials	X
#17	Highly Private Blockchain-based Digital COVID-19 Certificates	- Scalability - User Adoption -Cost-efficiency
#18	NovidChain	- Scalability - Complexity of implementation - User adoption - Privacy vs. public health needs
#19	Sharing Pandemic Vaccination Certificates through Blockchain	-Scalability concerns -Network bandwidth and response time -Resource utilization -System saturation

Table 7. challenges or limitations - continued

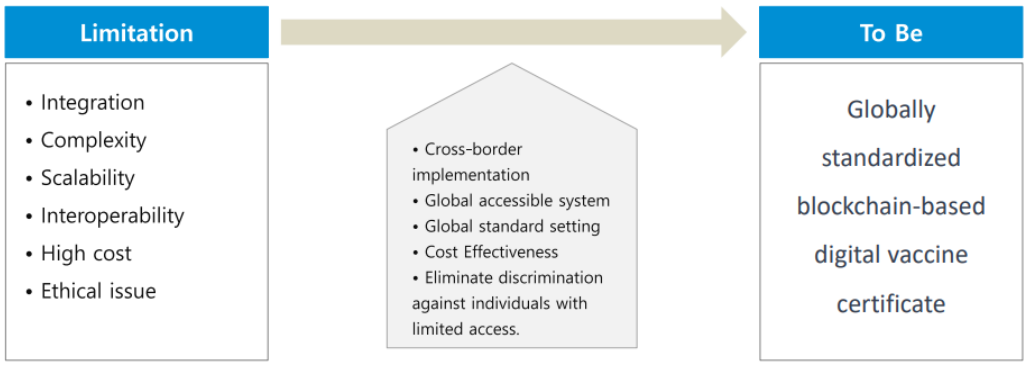
#20	GDPR-Compliant Blockchain-Based COVID Vaccination Passport	-Conceptual framework -Flexibility in design -Potential for insider attacks -GDPR compliance concerns

Table 7 provides summary of the challenges and limitations in implementing blockchain solutions for digital vaccination certificate in COVID-19. Integration challenges, such as those faced by Federated Identity Management(Shih et al., 2022) and Block-VC System(Abuhashim, Shafei and Tan, 2021), highlight difficulties in harmonizing blockchain with existing systems, especially when involving multiple blockchain frameworks, poses a major integration challenge with current health and government systems(Nehme et al., 2021). This complexity is further compounded by the need to balance privacy with the transparent sharing of health data, a task made more difficult by diverse regulatory frameworks(Abid et al., 2022; Haque et al., 2021; Pericàs-Gornals, Mut-Puigserver and Payeras-Capellà, 2022). Additionally, scalability is a critical concern; public health solutions require broad, cross-border implementation, yet achieving scalability and interoperability with existing systems remains a major hurdle(Abid et al., 2022; Abubakar et al., 2021; Barati et al., 2021; Haque et al., 2021; Hasan et al., 2020; HERNANDEZ et al.; Koyama et al., 2023; Rashid et al., 2022; Sharma, Kothapalli and Gujar, 2022). Another significant challenge is establishing globally accessible systems that are both affordable and practical in countries with varying healthcare systems and

technological capabilities(Lee et al., 2022; Sharma, Kothapalli and Gujar, 2022). The high cost and complex deployment processes of solutions like the blockchain-based system for vaccination certificates(Abubakar et al., 2021) and BLOCKVAC System(Sharma, Kothapalli and Gujar, 2022) pose significant barriers to widespread adoption. Moreover, ethical issues arise, particularly the risk of excluding individuals who either lack access or do not pass certification tests. There's also a concern that such systems could enable discrimination based on arbitrary factors like immunity status(Eisenstadt et al., 2020).

Figure 2 represents a flowchart illustrating the current limitations and expected outcomes achievable through improvements.

Figure 2. As-is To-be flowchart.



VI. Discussion

A comprehensive literature search was carried out utilizing databases such as PubMed, Embase, and Web of Science and was last updated as December 1st, 2023. The complete search was performed using a combination of keywords, including 'Blockchain,' 'COVID-19,' and 'vaccine certification'. 258 from PubMed, 168 from Embase, and 810 from Web of Science, following the removal of 124 duplicate studies. After applying the eligibility criteria, 54 studies were deemed suitable for full-text review. Among these, 20 studies met the inclusion criteria for this scoping review.

In this study a breakdown of the research cases in which blockchain technology was utilized for digital vaccination certificate in COVID-19 pandemic. The studies in the form of journals were the most common. And most of studies are published in Technology categories. When looking at the continental distribution of research cases where blockchain technology was utilized for digital vaccination certificate in COVID-19 pandemic, the highest number of cases was found in Asia followed by Europe.

The most common type and platform is public blockchain and Ethereum. This indicates a preference for the transparency and decentralized nature of public blockchains. And the high preference for Ethereum can be attributed to its versatile functionalities and a broad user base. Most of the studies are utilizing smart contracts. This indicates the potential of smart contracts, with their automated execution capabilities, to play a pivotal role in the management and issuance of digital vaccination certificates related to COVID-19.

Included studies presented a summary of the blockchain technologies utilized in the proposed solutions. These solutions aimed to provide secure and efficient implementations for digital vaccination certificate. Diverse blockchain emphasizes decentralization and self-sovereignty and highlights a trend towards secure, and privacy-centric approaches. They leverage various technologies, including hybrid systems managing health data efficiently, on-chain and off-chain data linkage using symmetric key encryption oracles, and the utilization of digital security seals with timestamps on the blockchain and so on.

This study summarized the potential benefits of introducing and utilizing blockchain technology-based vaccination certificates or digital passports in response to COVID19. These benefits encompass the prevention of forgery and tempering in vaccine distribution data, enhanced transparency, global interoperability, and efficient data sharing. Also, this study summarized the challenges and limitations for more efficient and stable use of technologies such as vaccine tracking using blockchain technology in pandemic crisis such as COVID-19. There are many challenges and limitations including integration, complexity, scalability, interoperability, high cost, ethical issue about discrimination This shows that despite the presence of potential benefits, there are still many challenges and limitations that cannot be solved.

The depth of analysis offered an understanding of the potential use of blockchain in this context. This in-depth exploration aids readers, policymakers, health system leaders, and

informaticians in considering the use of blockchain technology to respond to infectious diseases like COVID-19.

The research stands out for its analysis of literature not just from a technical standpoint but also considering public health perspectives. This dual approach enables a more holistic understanding of the benefits and limitations of blockchain technology in the context of public health emergencies. By focusing on digital vaccination certificates, the study addresses a critical component of pandemic response strategies. This focus is particularly pertinent considering the ongoing shifts in public health strategies and the increasing need for secure, verifiable vaccination records, highlighting the timeliness and relevance of the research.

The application of blockchain in healthcare is still in its early stages, resulting in a lack of long-term empirical research. This limitation is reflected in the depth and breadth of the literature, potentially impacting the comprehensiveness of the study. This research revealed a tendency in the existing literature to emphasize the technical aspects of blockchain in healthcare environments, rather than its practical implementation. This biased focus could limit the possibility of directly applying our research findings to public health policies and practices. The generalizability of our research findings is problematic due to the absence of a standardized approach to blockchain technology across various countries. This variability could affect the potential for implementing blockchain-based solutions

uniformly worldwide.

It was restricted to the COVID pandemic period, excluding subsequent studies published thereafter. Additionally, our study did not include grey literature, representing another limitation.

Some characteristics of blockchain technology for digital vaccination certificates (e.g., type, platform, smart contracts) were reported in some studies, but there were also unreported aspects in the literature, which we were unable to adequately describe and discuss.

Enhanced cross-border health data sharing through secure blockchain can streamline pandemic responses and global health monitoring. Developing standardized blockchain-based systems could improve vaccine data management and access across countries. This approach is crucial in developing countries with less advanced systems, potentially reducing global health disparities. Reliable international records will inform data-driven public health policies. However, current blockchain limitations like scalability and interoperability need addressing. Overcoming these is vital for global implementation, enhancing blockchain's benefits, and improving global health outcomes.

VII. Conclusion

This study involved a scoping review to investigate the specific attributes of blockchain and to examine various cases where digital vaccination certificates have been implemented or proposed in the COVID-19 pandemic. The application of blockchain technology, especially in the form of digital vaccination certificates for the COVID-19 pandemic and other infectious diseases, represents a relatively uncharted domain. Recognizing this novelty, the scoping review methodology was chosen for this study due to its aptitude in illuminating the breadth of such emerging subjects.

Integrating blockchain technology into vaccine certification offers significant improvements in data security and privacy, mitigating risks related to unauthorized access and data manipulation. This technology can also make the vaccine distribution and passport verification processes more efficient and reliable. However, blockchain solutions face challenges with scalability and interoperability, especially in terms of integrating with existing healthcare systems and ensuring broad implementation across countries. Balancing privacy with public health requirements is crucial, particularly in light of different regulatory frameworks. Ethical concerns also arise, such as the potential discrimination against individuals who lack access or fail authentication tests in a blockchain-based system.

Despite the potential benefits, applying blockchain to digital vaccination certificates presents several limitations and challenges, particularly in scalability, cost-effectiveness, and ethical aspects. These challenges have hindered the global expansion of this technology.

While blockchain's decentralization, transparency, and immutability offer promise for revolutionizing digital vaccination certificates, studies have shown that practical limitations often overshadow these benefits. The need for further research is clear, especially in addressing scalability, cost-effectiveness, and ethical issues. Future studies should also explore integrating other technologies and policies with blockchain to overcome its inherent challenges.

This study aims to provide insights into the potential benefits of blockchain in digital vaccination certificates and the primary challenges and limitations in the context of the COVID-19 pandemic, which can be helpful for consideration in future systematic literature reviews. It is hoped that this will lay the essential groundwork for future research regarding the effective use of digital vaccination certificates in crisis situations such as the COVID-19 pandemic.

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