Decision Analytics Journal 9 (2023) 100344

Contents lists available at ScienceDirect

Decision Analytics Journal

journal homepage: www.elsevier.com/locate/dajour

A comprehensive review of blockchain technology: Underlying principles and historical background with future challenges

Gautami Tripathi [a,*], Mohd Abdul Ahad [a], Gabriella Casalino [b]

[a] Department of Computer Science and Engineering, Jamia Hamdard, New Delhi, India
[b] Department of Computer Science, University of Bari Aldo Moro, Italy

ARTICLE INFO

Keywords:
Blockchain technology
Consensus algorithms
Decentralized distributed ledger
Immutability
Cryptography
Transparency

ABSTRACT

Blockchain is a distributed digital ledger technology that has revolutionized businesses, industries, and commerce by eliminating the need for a central storage and control authority. Blockchain presents time-stamped and immutable blocks of data that are not owned by any single entity but rather managed by a group of nodes or computers where each block is secured and linked using cryptographic principles. The immutable and decentralized nature of blockchain has redefined trust, ownership, identity, and financial systems by providing a secure, fast, transparent, and pseudo-anonymous solution. This paper provides a comprehensive review of blockchain technology focusing on the historical background, underlying principles, and the sudden rise in the popularity of blockchain technology. The paper also discusses the various consensus algorithms of blockchain technology. Next, the paper focuses on the various application areas and prospective use cases of blockchain technology with the underlying challenges and issues. Further, the paper presents some unconventional use cases of blockchain technology. The study also reviews state-of-the-art articles to provide a comprehensive overview of the various aspects of blockchain technology in varied domains. The comparison between traditional database systems and blockchain technology is presented, and the appropriate scenarios where blockchain-based solutions may or may not provide the best solutions are also discussed. Further, it discusses some of the most infamous security breaches that impacted the blockchain industry in the recent past.

Contents

* Corresponding author.
E-mail addresses: gautami1489@gmail.com (G. Tripathi), itsmeahad@gmail.com (M.A. Ahad), gabriella.casalino@uniba.it (G. Casalino).

https://doi.org/10.1016/j.dajour.2023.100344
Received 20 March 2023; Received in revised form 17 October 2023; Accepted 18 October 2023
Available online 20 October 2023

1. Introduction

Blockchain technology has revolutionized the digital transformation of contracts, transactions, and records which form the defining structure of the economic, political, social, and legal systems that govern this world. The first generation of blockchain technology started with the introduction of bitcoin by the pseudonym Satoshi Nakamoto in the year 2008 [1], which introduced the concept of blockchain and marked the deployment of cryptocurrencies in financial applications involving cash, like digital payment systems. The second-generation blockchain was marked with the introduction of smart contracts that provided functionality beyond cash transactions like stocks, loans, and smart property. The third-generation blockchain had a broader application area that introduced blockchain-based solutions for applications beyond banking and finance and provides services in the areas of healthcare, government, science, etc. In less than a decade, blockchain technology has already seen three generations and is paving the way to enter the fourth generation with Artificial Intelligence (AI) and digital intelligence. The sudden popularity and growth of the technology can be estimated from the fact that in the year 2010 Laszlo Hanyecz, ordered two Papa John's pizzas worth approximately 30$ for 10,000 bitcoins. In the year 2018, the same bitcoins were estimated to be over $80 million [2]. This shows the exponential growth in technology and cryptocurrencies.

Blockchain has the potential to digitally transform the way the world transacts by allowing the contracts to be digitally embedded in databases that are transparent and provide security against tampering. This key attribute of blockchain technology eliminates the need for third parties and intermediaries like banks, lawyers, etc. Although the potential of blockchain is immense, there are some issues and challenges that need to be resolved for its widespread adoption.

1.1. Brief timeline of blockchain and related technologies

Blockchain is a digital distributed ledger that secures and links the digital records called "blocks" using cryptographic techniques. Although the term blockchain gained popularity in the year 2008 with the introduction of Bitcoin cryptocurrency [1], its underlying principles and concepts have been in use since the 1980s. In the year 1983, David Chaum proposed the concept of blind signatures [3], a new form of cryptography that allowed the automation of payments and constrained third parties from identifying the payee, amount, and time of payment. Later, in the year 1991, the concept of timestamped documents was introduced by a group of researchers who were trying to secure digital documents by stamping the documents with the date [4]. In 2004, Harold Thomas Finney II (Hal Finney) introduced the Reusable Proof of Work (RPoW) [5]. It was in 2008 when blockchain made its public debut with a paper titled "Bitcoin: A Peer-to-Peer Electronic Cash System" outlining the development of a secure and transparent currency without the involvement of a bank or central party [1]. The first bitcoin transaction took place in the year 2009 when a transaction of 10 BTC (BitCoin) was done to his friend Hal Finney [6]. This marked the beginning of the first generation of blockchain technology. In the year 2010, the world's first bitcoin exchange was set up by the name "Bitcoin market" [7]. In 2013, Vitalik Buterin proposed the concept of smart contracts in his white paper "Ethereum: The Ultimate Smart Contract and Decentralized Application Platform" [8]. In 2015 Ethereum launched its blockchain [9]. The Linux Foundation launched Hyperledger the same year which provides a set of tools for

Fig. 1. Key events in blockchain technology [6–14].

the creation of blockchain [10]. In 2016 the DAO project was built on top of Ethereum which raised US$ 150 million [11]. Later, in the same year, it was attacked causing a loss of around US$ 50 million [12]. Fig. 1 presents the major events in the development and widespread popularity of blockchain technology [6–14].

Ever since its inception in the year 2008, blockchain technology has gained attention from across the globe. Today, many nations are adopting this technology to bring reforms across various sectors including finance, healthcare, education, governance, supply-chain, agriculture, and energy. This paper presents the state-of-the-art of blockchain technology and gives a comprehensive overview of its historical background and evolution journey. The paper also presents in detail the various aspects of blockchain technology, its application areas, and the challenges faced.

The manuscript is organized into eight sections. To begin with, the paper sets the stage for the reader to understand the historical background and the timeline of events resulting in the popularity of blockchain technology. Section 2, provides the details of the past research and studies conducted in the field of blockchain technology. Section 3, presents a general introduction to blockchain technology including the structure of blocks and the basic working mechanism of a blockchain. Section 4, highlights the underlying concepts of the technology focusing on the key attributes of blockchain. The section also presents an analysis of the various consensus algorithms. The taxonomy and generations of blockchain are discussed in Section 5. The section further provides a comparison between the traditional databases and blockchain-based on multiple characteristics. Section 6 presents the use-cases of blockchain technology. It also provides a discussion on passwordless authentication using blockchain technology. The section also discusses the appropriate scenario for the implementation of blockchain technology over traditional systems. The various challenges and issues related to the adoption of blockchain technology are discussed in Section 7. The section also discusses the security threats and their root causes. Lastly, Section 8 presents the conclusion and future scope.

1.2. Major contributions

The presented work provides a comprehensive analysis and survey of blockchain technology covering all aspects from the background, history, needs, roles, issues, applications, and challenges. The major contributions of the paper are as follows

- **Highlighting the key challenges and issues in the large-scale adoption of blockchain technology**
  An exhaustive discussion on the issues and challenges associated with the mass adoption of blockchain is presented covering the various technical, social, environmental, and economic aspects.
- **Discusses the consensus algorithms used in blockchain technology in various application areas.**
  The major consensus mechanisms are identified and their respective pros and cons are highlighted.
- **An extensive discussion about the key application areas of blockchain technology is presented focusing on the current state-of-the-art.**
  A detailed discussion on the state-of-the-art blockchain implementations across multiple domains including decision analytics, healthcare, data management etc.
- **Highlights the application of blockchain technology in passwordless authentication**
- **Discussion about appropriate use-cases and situations where blockchains should be avoided.**
  Even though blockchain technology is finding its applications in varied domains, there are several situations and applications where blockchain technology is not preferred. In this paper, we have identified these use-cases where the use of blockchain technology must be avoided. To the best of our knowledge, these kinds of use-cases are not discussed in any of the related articles.

1.3. Methodology

A systematic literature review was conducted to retrieve the most relevant state-of-the-art in blockchain technology as per PRISMA 2020. Initially, the search query was run on ScienceDirect and IEEE Xplore databases. There were 5938 and 872 articles returned by the search query which were then further refined using the inclusion and exclusion criteria given below. After that, a period between 2015 to 2023 has been selected to further narrow down the number of relevant works of literature. Finally, a total of 93 articles were shortlisted which fulfilled all the desired criteria for conducting the review. These articles were primarily focusing on the issues and challenges of blockchain technology and the application areas of blockchain technology.

Search Key phrases: Applications, Challenges, and Issues of blockchain technology

Databases: ScienceDirect and IEEE Xplore.

Initial Query Results: ScienceDirect: resulted in 5938 items, and IEEE Xplore resulted in 872 items.

Inclusion Criteria: The following criteria were used to include the articles for conducting the review

- Time line: between 2015 to 2023
- Types of Articles: review, research, book chapters, edited books
- Article Venue: journals, International Conferences, Magazine, Edited Books, Book Chapters
- Access Type: Open Access and subscription-based
- Keywords: blockchain consensus mechanisms, blockchain application in healthcare, education, pharmacy, transportation, logistics, food and agriculture, banking, finance, IPR (Intellectual Property Rights), copyrights, entertainment and IoT etc.

Exclusion Criteria: The following criteria were used to exclude the articles

- Articles beyond the year range
- Articles in the pre-publication stage
- Editorials, notes, and other short type of publications.
- Articles where the title did not match the desired keywords/subject.
- Articles where the abstracts did not focus on the subject.

2. Related works

In the last few years, blockchain technology has been extensively explored across multiple domains. The introduction of bitcoin in the year 2008 attracted the attention of industry experts and academia and paved the way for blockchain-based solutions. Today, the rise of blockchain applications spans multiple domains beyond cryptocurrencies like healthcare [15,16], agriculture [17], education [18], supply chain [19], fashion and textile industry [20], energy [21], Internet of Things (IoT) [22], Transportation [23] etc. In a report published in the Harvard Business Review [24], it was discussed how blockchain technology can have a strong impact on various processes like the internet. In another report, it is estimated that with companies like IBM, Microsoft & Accenture driving the blockchain development, the blockchain market is headed to touch the $60 billion mark by 2024 and is headed to revolutionize international trade and transactions [25,26]. The evolution of blockchain technology over the years is presented in [27].

The parallels between blockchain technology and the TCP/IP (Transmission Control Protocol/Internet Protocol) are discussed in [28,29] highlighting how blockchain can lower the cost of transactions as TCP/IP has lowered the cost of connections. Once in the mainstream of business blockchain will bring about a radical shift in the economy. The work in [30] presents a blockchain-based data management system that allows users to have control and ownership of their personal data. The proposed system is made of three entities namely users, services, and nodes. The model uses transactions to store, share, and query data. Two types of transactions are used in the system Taccess and Tdata for access control management and data storage and retrieval respectively. The benefits of blockchain technology are also explored in domains like routing. The work presented in [31] discussed the use of blockchain for identity authentication in a decentralized system for routing registration. There are many notable kinds of research and studies about the various aspects of technology like research challenges [32], potential in industry 4.0 [33,34], and contribution towards a circular economy [35].

In [36] a comprehensive survey of blockchain technology focuses on the taxonomy, consensus algorithms, applications, and challenges. The paper further discusses the advances for tackling the challenges and gives an insight into the future directions for blockchain technology. A detailed overview of blockchain technology is presented. The different generations of blockchain are discussed comprehensively. The work also focuses on the advanced concepts and terminologies associated with blockchain and the limitations of the technology. The work presented in [37] discusses blockchain as an attractive technology to solve existing financial and non-financial problems. In [38] the architecture and key characteristics of blockchain technology are discussed. They have also discussed and compared some of the widely used consensus algorithms.

In, [39] the potential of blockchain in the finance sector is discussed and compare the blockchain boom to the internet of 1989's and claimed that blockchain will have the same effect on banking and finance as the internet had on media. Despite its rising popularity blockchain technology has received mixed reviews from the research community. The mainstream adoption of the technology is still a distant dream. Many factors including the organizational, technical, business, and market interact and influence each other and have a joint impact on the adoption of blockchain [40]. The Covid-19 crisis created a unique opportunity to develop blockchain-based applications and solutions for minimizing supply chain failures, record keeping, fighting counterfeit drugs, contact tracing, and patient identity [41].

Although blockchain technology provides significant advantages over traditional approaches in multiple application areas, it comes with its own set of challenges like scalability, electricity consumption, etc., and hence requires careful planning and understanding of the use cases before the implementation. The key ideas of blockchain technology like decentralization, transparency, immutability etc. can be utilized to ensure the privacy and security of the data generated by smart city infrastructure and services. The work presented in [42] discusses how blockchain technology provides security in smart cities. In education, blockchain technology can facilitate the open sharing of records [43], a decentralized online education model, and an equitable education model for all [44]. Blockchain technology also finds application in promoting gender equality and the inclusion process in corporate governance models [45]. Blockchain technology has the potential to play a significant role in applications like cab sharing [46], sustainable tourism [47], culture and heritage preservation [48], blood donation [49], waste management [50], accounting and auditing [51,52], marketing [53] etc.

Although blockchain technology provides significant advantages over traditional approaches in multiple application areas, it comes with its own set of challenges like scalability, sustainability, electricity consumption etc., and hence requires careful planning and understanding of the use cases before the implementation [51].

3. Blockchain technology

Blockchain is a digital distributed ledger that stores data in the form of blocks that are linked together using a cryptographic function. Although similar data structures have existed for a long time, blockchain technology was truly conceived and defined only in the year 2008 [1,54]. Blocks are the containers of data that define a piece of digital information consisting of transactions along with the timestamp and cryptographic functions. A block consists of a header and a list of transactions. The block header contains metadata that includes the hash of the previous block, timestamp, nonce, and Merkle tree root. Fig. 2 shows the basic structure of a block.

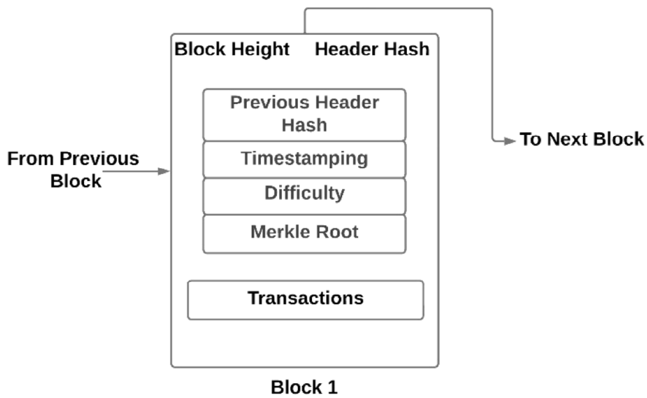

Fig. 2. Block structure in a blockchain.

A block is identified using either the block hash or the block height. Block hash is the hashID of the block that is generated while the block height defines the positioning of the block in the block chain. Merkle tree gives the digital fingerprint of the entire set of transactions. These blocks are linked together to form the blockchain structure. The block header contains a field to store the hashID of the previous block in the chain [54]. Fig. 3 shows the arrangement of blocks in a blockchain.

Whenever a user requests a new transaction from their wallet application, it is broadcast. The newly requested transaction is added to a pool of unconfirmed transactions from where it is picked up by the miners. The miners on the network select the transactions and mine them to create a new block to be added to the blockchain. A block consists of the selected transactions along with some metadata associated with the block. The miner finds a hash output for the block and broadcasts the block with its signatures. The other nodes in the network verify the signature of the block to establish its validity. Once the validity is confirmed a consensus is reached to add the block to the existing blockchain. Every other block that is added on top of this block is considered as the confirmation for the block [26,27,54]. Fig. 4 presents the process of the addition of blocks in the blockchain.

4. Blockchain concepts

4.1. Consensus

Consensus mechanisms form the backbone of any blockchain-based application. The decentralized nature of the blockchain requires a set of rules to identify a way for the users to agree on a particular state. This set of rules is provided by the consensus mechanisms. The first consensus algorithm Proof of Work (PoW) was introduced for the Bitcoin blockchain [53]. Since then, several consensus algorithms have been introduced to address the demands of blockchain applications. The common consensus approaches are described in the following subsection.

4.1.1. Proof of Work (PoW):

PoW works on the principle of a solution that is very difficult to identify but easy to verify. Most of the blockchain implementations use this PoW as their consensus mechanism. Here the new nodes are created by solving a complex problem. This process is highly compute-intensive and requires lots of computational capabilities [55–58].

4.1.2. Proof of Stake (PoS):

The proof of Stake consensus mechanism requires the validators to stake their ETH. Validators play the same role as miners in the PoW consensus mechanism. For the ethereal blockchain, the minimum stake value to become a validator is 32ETH. In PoS consensus the validators are selected at random to create the blocks and validate the blocks created by others. In both cases, the validators are rewarded [55–58].

4.1.3. Delegated PoS:

The DPoS consensus algorithm was developed by Daniel Larimer. It provides a modification on the conventional PoS consensus by maintaining an election system to choose the nodes called witnesses for verifying the blocks [55–58].

4.1.4. Practical Byzantine Fault Tolerance (pBFT):

The (pBFT) algorithm was introduced by "Miguel Castro" and "Barbara Liskov". The pBFT consensus algorithm is used in Hyperledger Fabric and Zilliqa. pBFT works by replicating a practical Byzantine state machine that tolerates malicious nodes (Byzantine faults). The nodes in a pBFT system communicate to bring all honest nodes to an agreement of the system state [55–58].

4.1.5. Proof of Activity (PoACT):

PoA combines the PoW and PoS consensus algorithms. The initial mining process is the same as the PoW mining. However, once the block is mined the PoS consensus is used to select a random group of validators who then validate the newly mined block [55–58].

4.1.6. Proof of Burn (PoB):

PoB provides an energy-efficient alternative to the PoW consensus algorithms. In PoW consensus, the mining power of a miner is determined by the number of coin burns. The higher the coin burns more is the mining power of a miner [55–58].

4.1.7. Proof of Capacity (PoC):

The PoC consensus decides the mining rights by using the dedicated hard drive space of the mining devices. The possible solutions are stored in the hard drive of the mining devices in advance. The algorithm employs a two-step process of plotting and mining [55–58].

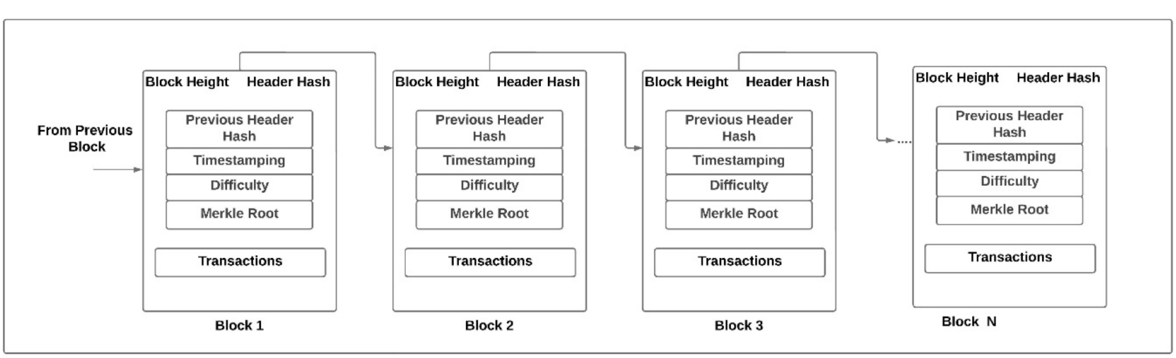

Fig. 3. Arrangement of blocks in a blockchain.

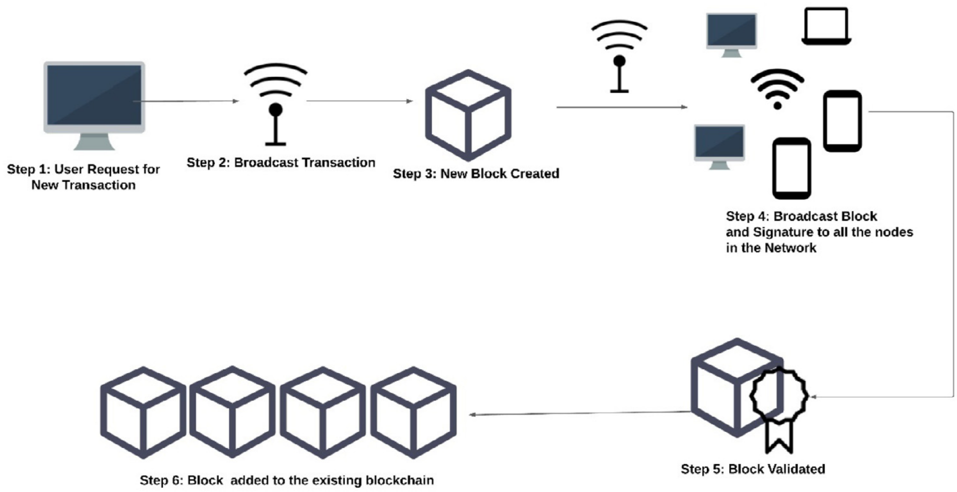

Fig. 4. Addition of blocks in the blockchain [26,27].

Table 1
Categories of consensus algorithms [55–59].

S.No	Categories	Examples of consensus algorithms
1	Proof of Work	• Proof of Work • Proof of Meaningful Work • Hybrid Proof of Work • Delayed Proof of Work • Proof of Work Time
2	Proof of Stake	• Proof of Stake (PoS) • Secure Proof of Stake (SPoS) • Delegated Proof of Stake (DPoS) • Proof of Stake Time (PoST) • High-Interest Proof of Stake (HiPoS)
3	pBFT AND BFT	• Albatross • Asynchronous BFT • BFTree • Federated Byzantine Agreement • LibraBFT
4	DAG	• Blockflow • Hashgraph
5	Trusted Computing	• Proof of Elapsed Time
6	Hybrid	• Proof of Authority • Proof of Activity
7	Proof of Capacity/ Space	• Proof of Existence • Proof of History • Proof of Location

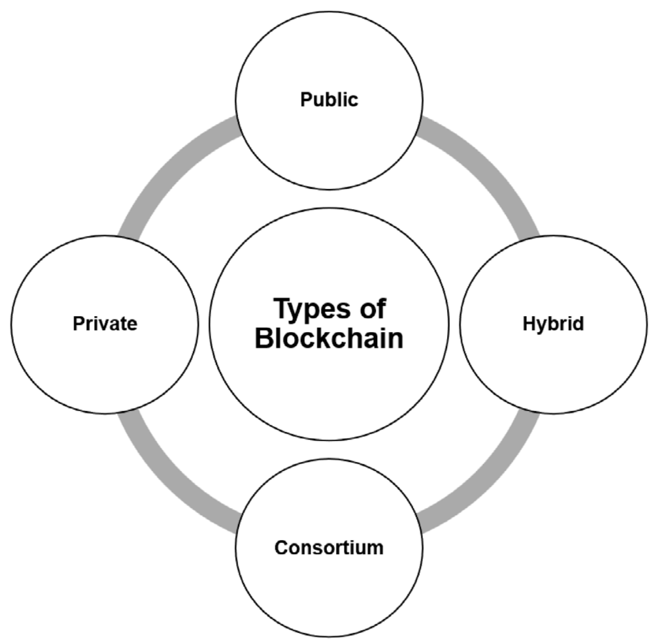

Fig. 5. Types of blockchain.

4.1.8. Proof of Elapsed Time (PoET):

The PoET consensus is based on a fair lottery system concept. It uses a randomly generated waiting time for deciding on the mining rights. Each participating node in a PoET system waits for a random amount of time. The node to complete the wait time first gets to commit the new block to the blockchain [55–59].

Table 1 gives an overview of the different categories of consensus algorithms based on some common features and implementation procedures.

Consensus is at the core of the much-hyped blockchain disruption that helps to bring the participants to an agreement on the contents of the blockchain in a decentralized distributed manner and trust-less environment. Table 2 discusses the advantages and disadvantages of various consensus algorithms used in different blockchain platforms and applications.

4.2. Decentralized distributed nature

Blockchain architecture depends upon two major aspects. Firstly, the ownership of the data infrastructure citing whether the blockchain is public or private, and secondly, the permissions associated with the joining, read, write, and commit operations. Based on these aspects the blockchain architecture and solutions are developed for the users. Open and closed blockchains are based on the write permissions while the public and private blockchains are based on the read permissions. Fig. 5 shows the architectural options for the blockchain solutions based on the above-mentioned aspects [60–62].

The public and private blockchains are generally defined in terms of who can write data. Considering the read and write permissions these blockchains can further be categorized as open public, closed public, open private, and closed private as shown in Table 3 [59–62].

4.3. Immutability

Immutability is one of the key attributes of blockchain technology that makes it highly secure and tamper-proof. Every transaction that is verified and added to a block is timestamped and cryptographically secured using a hash function. The hashing process is irreversible i.e. the

Table 2
Advantages and disadvantages of popular consensus algorithms [55–59].

S.no.	Consensus algorithm	Advantage	Disadvantage	Example
1	Proof of Work	Secure, reduces the chances for Denial-of-service attack	Computationally intensive, Slow, requires lots of energy, potential for 51% attack by obtaining computational power	Bitcoin, Ethereum
2	Proof of Stake	Computationally less intensive, Energy efficient, difficult to attack,	Nothing at stake problem, stakeholders can join power to form centralized authority, potential for 51% attack by obtaining enough stake	Peercoin
3	Delegated Proof of Stake	Energy efficient, fast	Moves towards centralization	Bitshare, EOS
4	Delayed Proof of Work	Energy efficient, improved security, adds value to other chains	PoW and PoS based solutions can be used as support chain	Komodo
5	Proof of Authority	Fast, Energy efficient	Permissioned	VeChain
6	Proof of Weight	Highly scalable and customizable	Hard to Incentivize	Algorand
7	Proof of Reputation	Efficient results for Private and permissioned blockchains	Only used in private and permissioned blockchains	GoChain
8	Proof of Space	Energy efficient, prevents Denial of Service attack	Incentive issue	Spacemint, Burstcoin
9	Proof of Elapsed time	Low cost of participation	Not apt for public blockchains	Hyperledger Sawtooth
10	Proof of Importance	Better stake evaluation, resistant to arbitrary manipulation.	No significant qualitative advantage with PoI gaming over actors with the same balance who do nothing.	NEM
11	Proof of Stake Velocity	Encourage ownership and velocity	Used as a part of Reddcoin ecosystem and not stand alone	Reddcoin
12	Proof of History	Provides an agreement on time, Supports horizontal scaling	Computational complexity	Solana
13	Proof of Believability	Decentralized, Fast Finality achieved	Security issue may arise due to one node. Verification	IOST
14	Proof of Burn	Expensive computer equipments no needed	Resources are wasted needlessly as mining power is given to those who burn money.	Slimcoin, TGCoin
15	Proof of Activity	Prospective solution to hyperinflation	Energy inefficient, no provisions to remove double signing	Decred
16	Proof of Time	Produces in the passage of time removing the dependency of future values on third party	Energy inefficient	Chronologic
17	Proof of Existence	Inexpensive way to verify the existence of a document at a particular time	Energy inefficient	POEX.io, HeroNode, DragonChain,
18	Byzantine Fault Tolerance	Scalable, Fast	Used in Private and Permissioned blockchains	Stellar, Ripple, Hyperledger Fabric
19	Proof of Retrievability	Lower communication complexity	Clients need to invest in storage along with the computational resources	PermaCoin, Microsoft
20	Ouroboros	Highly secure, Neutralizes selfish mining as honest behavior approximates Nash equilibrium	Energy inefficient	Cardano
21	Delegated Byzantine Fault Tolerance	Fast, Scalable	Multiple root chains can occur	Neo
22	Stellar Consensus Protocol	Low Latency, Flexible trust, Asymptotic Security, Decentralized Control	Energy inefficient	Stellar
23	RAFT	Multi-Language Implementation	Used in Private and Permissioned blockchains	IPFS Private Cluster, Quoram
24	Directed Acyclic Graphs	Scalable, energy efficient, Finality Achieved fast	Smart contract implementation through oracle only	IOTA, Hashgraph, Nano

output string generated cannot be reverse-engineered to determine the input data and any slight change in the input will change the hash value. Hashing of a new block also requires metadata from the previous block for generating the block hash which results in the formation of a back-linked chain of blocks. Once validated and added to the blockchain a block cannot be modified as it will result in an avalanche effect that will try to change all the blocks on the blockchain in a cascading manner eventually invalidating all the blocks. This makes the blockchain tamperproof and ensures that once a block is added to the blockchain its data cannot be modified, forged, replaced, or falsified. The immutability property of blockchain technology helps in achieving complete data integrity, easy and simplified auditing, increased efficiency, trust, and data provenance.

5. Taxonomy and generations of blockchain

Blockchain can roughly be categorized into three types namely, public, federated or consortium, and private as discussed in Table 4. This classification is done based on the different features and services provided by the blockchain [60–69]

Table 3
Blockchain based on read (R) and write (W) permissions [59–62].

	Open	Closed
PUBLIC	• Anyone can join • anyone can read • Anyone can write and commit • Hosted on Public servers • Anonymous • Low scalability	• Anyone can join • anyone can read • Authorized participants can write and commit • Medium Scalability
PRIVATE	• Only Legitimate users can access for R, W. • Hosted on private server • High Scalability	• Only Legitimate users can access for R, W • Only network operators can write and commit • Very High Scalability

Table 4
Comparisons of various types of blockchains [60–65,67–69].

Properties	Public blockchain	Federated blockchain	Private blockchain
Type	Distributed	Decentralized	Partially Centralized
Participation in Consensus	All miners can participate in consensus	Only the pre-selected nodes participate in consensus	One centralized authority takes decisions on who will participate in consensus
Read Permissions	Public	Restricted for Outsiders but public within themselves	Consent of administrator is required
Efficiency	Low	High	High
Energy consumption	Very High	Moderate	Low
Immutability	Impossible to tamper	Could be tampered	Could be tampered
Nature	Permissionless	Permissioned	Permissioned
Network Actors	Do not know each other	Preselected Group of nodes	Know Each other
Speed	Slow	Moderate	Fast
Security	More Secure	Moderately Secure	Less Secure
Privileges	No privileges are set, anyone can participate	All participants are equally privileged	Single Administrator defines the rules
Examples	Bitcoin, Ethereum, LiteCoin	Hyperledger, Corda, B3i	MONAX, Multichain

Table 5
Generations of blockchain [63–65,67–69].

	Generations of blockchain			
	I	II	III	IV
Examples	Bitcoin, Litecoin	Ethereum	Cardano, IOTA, Nano	Still in the development stage e.g. Insolar, Aergo, DeepBrain China, SingularityNet
Consensus Mechanism	PoW	PoW	PoS	Provisions for Variable Consensus mechanism
Energy Requirements	Requires more energy	Requires less energy as compared to I generation	Very Low	Low
Cost	High Cost	Medium Cost	Low Cost	Cost Effective
Smart Contracts	No control over the transactions, unavailability of smart contracts	Provisions for smart contracts, dApps	Supports smart contract with Intrinsic verification mechanism	Supports Smart Contracts
Scalability Challenges	Uses Lightening	Can use Sharding for improving scalability	Highly scalable with concepts like Sharding and with zero knowledge proofs	Highly Scalable with AI based blockchain mechanism for providing digital intelligence
Speed	Time Consuming	Time Consuming	High speed	Very High

The advancement in blockchain technology is inevitable and as a result, we already have three generations and the fourth one is knocking at our doors. The first generation of blockchain started with the introduction of Bitcoin and is more aligned towards the financial domain specifically cryptocurrencies. The second and third generations have a broader domain focusing on the industrial applications of blockchain technology. The fourth generation of blockchain technology may combine emerging technologies like artificial intelligence to create a blockchain as a service (uBaaS) platform [70]. Table 5 provides an overview of all the generations of blockchain technology and its key features.

5.1. Blockchain vs traditional databases

This section presents a comparison between traditional databases and blockchain-based storage mechanisms as present in Table 6 [63–75].

6. Use-cases of blockchain technology

This section discusses the various application domains of the blockchain technology. Due to the unique features of blockchain technology, it has been adopted widely in multiple domains including

Table 6
Blockchain Vs traditional databases.

S.No	Characteristics	Traditional databases	Blockchain
1	Architecture	Client Server	Peer to peer
2	Authority	Centralized	Distributed/Decentralized
3	Control	Administrator	Consensus (e.g. PoW, PoS)
4	Permissions	Permissioned	Public, Permissioned, Hybrid
5	Disintermediation	Data is centrally administered by a DBA	Trustless and decentralized; No need of intermediaries to validate and authorize the stored data
6	Robustness	Single point of failure	No single point of failure or control
7	Audit trail of all data instances	History of records and ownership of digital record not available. Data can be updated and modified.	History of records and ownership of digital record. Data is traceable to its source. A new block added for any new addition or modification
8	Data Handling	CRUD	RW
9	Data Storage	Tables	Blocks
10	Public Verifiability	Data integrity is low	Data Integrity and Transparency is maintained
11	Transparency	Database administer decides what is visible to the public	Public Blockchains Supports data transparency
12	Integrity	Data can be subjected to malicious attacks	Supports data Integrity
13	Data Persistence	Non-Persistent	Immutable

healthcare, supply chains, agriculture, food and beverages, transportation, education, etc. The blockchain technology has many significant use cases across all domains. Today many startups and businesses are coming up with innovative solutions based on blockchain to cater the key issues in areas like supply chain management, healthcare, education, agriculture, finance etc. Table 7 provides the recent developments in the blockchain technology [68–154]. The table presents the idea of using blockchain in various domains along with the significance and associated challenges [68–154]. Blockarray developed the project trust to provide solutions for the handouts material carriers and eliminated the requirement of manual document keeping. Maersk is enhancing the supply chain visibility for companies like Highland Food, which deals in meat products. Using the Tradelens Application Programming Interface (API) integration the stakeholders can track the shipments in real-time. Tradelens was jointly developed by Maersk and IBM. Another startup Shipchain based on the ethernet blockchain model is enhancing the global supply chain by allowing the stakeholders to track the shipments all over the world. Big companies like FedEx have collaborated with Hyperledger to use blockchain for dispute resolution. DLA is using blockchain to improve US army logistics.

Initially introduced as a technology to secure and handle the financial sector blockchain today has its applications across multiple domains. Even though not a fully matured technology, blockchain has already created a revolution in business, industry, finance, and other major domains as mentioned in [62–152].

The integration of blockchain in the many domain areas is still in its embryonic stage but has gained rapid popularity as it is conceived from already existing and well-understood techniques like cryptography, record keeping, decentralization, and timestamped documentation [62–152].

6.1. Blockchain application areas

This section presents the applicability of blockchain technology in various domains. Further, the various use cases where the integration of blockchain-based solutions can be avoided are also discussed.

6.1.1. Banking and finance

Since its inception in 2008, Blockchain technology has disrupted the financial sector and is still leading its way to realize its full potential in the banking and finance sector [101–106]. A recent white paper published on the "World Economic Forum's" website claimed that by the end of 2025, almost 10% of the global GDP will be stored on blockchain [106]. Some of the major use cases of blockchain in the banking and finance industry include cross-border payments, share trading and stock exchanges, identity verification, efficient and transparent syndicated lending, and standardization in the accounting, bookkeeping, and auditing process. Further, blockchain-based decentralized crypto hedge funds can help in inviting more investors and participants.

6.1.2. Governance

History shows that the governance model changes with societal and technological reforms. Earlier in the 19th century, the capitalist model of governance saw a transition to the more democratized bureaucratic model of governance that still has its imprint on the current governance model. However, with the changing needs and requirements, governments today are opting for new technologies to bring revolutionary changes in the way they function. With the rapid digitization of records, there is a need to protect sensitive data and streamline various processes including financial transactions to reduce fraud and corruption. A blockchain-based digital governance model can help to overcome the issues associated with the centralized and hierarchical legacy governance models by ensuring a decentralized platform that gives everyone equal access to the government and reestablishes trust [137–140]. Many governments across the globe are exploring this new technology to transform their work by reducing accountability and increasing trust. The National Research Council of Canada is using an Ethereal-based blockchain platform to ensure transparency in the government funding in the Industrial Research Assistance Program [153]. Cook County, Illinois (USA), is using blockchain to keep land records more securely [154]. In Mexico, the public administration leveraged the potential of blockchain to ensure transparency in public contracts through project HACKMX [155]. In the USA, DARPA is using blockchain to strengthen the existing cybersecurity [156]. In the current scenario, blockchain has a broad spectrum of applications in governance ranging from education to healthcare, voting to tax collection, and smart cities to finance.

6.1.3. Healthcare

The healthcare industry has seen many technological interventions in the last few years. However, despite the constant efforts by the Community Health Information Management Enterprise (CHIME) and the Healthcare Information and Management Systems Society (HIMSS), there is still no reliable identification mechanism for patients which increases the chances of patient record mismatch in electronic health records. Another major challenge that the healthcare industry faces is

Table 7
Recent advances in blockchain technology.

S.No	Ref	Application area	Core idea	Significance	Examples	Challenges
1	[77–82]	Logistics and Supply chain	Tracking and tracing of raw materials, intermediaries and finished products from inception till it reaches the end users.	• Shipment tracking • Transparent Processes • Dispute management • Inventory monitoring and management • Payments	Yojii, BLOCK ARRAY, MAERSK, SHIPCHAIN	High implementation and operational costs, not feasible for smaller organizations
2	[83–92]	Healthcare and Pharmaceuticals	Securing Electronic Health Records, Storing and share of records in a secured and privacy preserved manner. Ensure tamper proof, traceable and non-repudiation-based mechanism for health record and patient data. Identifying counterfeit medicines, Tracing and tracking of medicines supply chain	• Health supply chain • Counterfeit Drug detection • Finance and Insurance management • Patient data management • Medical data and device history tracking	MedChain, BURSTIQ, PATIENTORY, NEBULA GENOMICS, MEDI-CALCHAIN	Lack of standard data capturing and sharing procedures and mechanisms, data ownership and privacy issues
4	[93–97]	Food and Agriculture	Reducing food wastage, improving food supply chain, Tracking and tracing of food from farms to households.	• Traceability of Food supply chain • Quality control • Payments Logistics	HARA, Bananacoin	Absence of Standard rules and regulations, lack of technical knowhow, digital divide
	[98–100]	Energy	Tracking energy consumptions and distribution	• Transparent Energy metering • Tracking and Tracing of energy consumption • Promoting clean energy • P2P energy trading	Electrify, grid +	Authentication and verification involve high compute energy and costs, cyberattacks on grids
6	[101–106]	Banking and Finance	Loan approvals and tracking, crypto-based banking transactions, fraud detection and mitigation mechanisms, Tracking Money Laundering etc.	• Cryptocurrencies, • Asset management, • Trade processing & settlements, • Insurance, • Payments • Fraud Detection Know your customer	Xenchain, ChromaWay	Absence of Standard operating procedures and regulations
7	[107–110]	Transportation and logistics	Tracking and tracing, Fuel monitoring, Expediting payments, proving equitable opportunities for big and small transportation players	• Autonomous vehicle monitoring and management • Road Safety • Payments • Liability management	DACSEE	High implementation and operational costs, not feasible for smaller organizations
8	[111–113]	Real Estate	Land Titling, ensuring trust in citizen for real estate transactions, Ensuring Transparency in real estate	• Decentralized title registry • Land Registry	PROPY	Legality of process including in land titling, registry process etc.
9	[114–118]	IPR and Copyrights	Smart Contract based approaches to identify IPR and copyright infringements in software, music, education, fashion and manufacturing industries etc.	• Archiving of records	Ascribe	Legal issues including data storage and ownerships
10	[119–122]	Education	Approaches for identifying the authenticity of Marksheets and other Degree Certificates. Decentralized, Privacy preserved and customized lesson plans, results and other educational facilities.	• Student Record and identity management • Certificate, Badges and awards authentication • Payments • Plagiarism detection	Shikapa, Cubomania, NTok-X, Vivagogy, Edgecoin	High implementation costs, lack of trained manpower

(*continued on next page*)

information blocking. The large volumes and sensitive nature of medical data require efficient data handling that includes effective data standards, security and privacy protocols, transparency, and immutability. Today, most smart healthcare systems are organization-specific with hospital-centric interoperability where hospitals manage and monitor all patients' records and medical data. The key aspects of blockchain technology like data provenance, tamper-proof nature, transparency in processes, and security can play a major role in the transition from

Table 7 (*continued*).

S.No	Ref	Application area	Core idea	Significance	Examples	Challenges
12	[123–126]	e-Voting	Privacy preserved and secure voting mechanisms for individuals and organizations	• Secure, immutable and trusted voting mechanism	Luxoft, uport, Follow my Vote, Blockchain Voting machine, CommitCoin, VOATZ	High cost of authentication and verification as PoW requires higher compute capabilities
13	[127–131]	Entertainment and Multimedia	Protecting and managing the digital audio/video content	• Reducing Piracy Copyrights and Royalties Management	Artbit, MEDIACHAIN, MADHIVE, OPEN MUSIC INITIATIVE	OTT content filtering and viewer's certifications
14	[132–136]	Identity Management	Better authentication and verification	• Increased processing speed • Reduced loss, theft and frauds Portable and reliable identities	LifeID, Sovrin, Tykn, CIVIC	High implementation costs
15	[137–140]	Governance	Improved governance	• Record Management • Subsidies monitoring and tracking Reducing corruption	Illinois Blockchain Initiative	Lack of expertise and technical knowhow
16	[141–144]	Internet of Things	Securing IoT devices	• Transparent IoT ecosystems Reduced cybersecurity threats in IoT systems	FILAMENT, HYPR, XAGE SECURITY	Absence of standard operating procedures.
17	[145–147]	Decision and Data Analytics	Distributed Secured and Privacy Preserved data storage	• Big Data based Perspective Analytics for permissioned Blockchain supply chain • Quality and Control Analysis using Blockchain	AI and Blockchain are used in combination to provide improved decision making	Complexities in Consensus algorithms
	[148–152]	Smart Cities	Security and Privacy, Issues and Challenges	• Privacy preserved and Secured Smart city ecosystem	Light weight cryptography for IoT devices, Multi Factor Authentication (MFA), passwordless authentication	Interoperability, Data Security, Message Exchange etc.

organization-driven data management to patient-centric management of data. Although the integration of blockchain into the existing smart healthcare systems raises concerns related to the confidentiality of sensitive medical data especially on public blockchains, speed, and scalability aspects, still many notable innovations can be achieved by blockchain [15,16,83–92,157]. Many blockchain experts hold a viewpoint that the confidentiality issue related to medical data can be resolved by saving the hash on the blockchain while the actual data is maintained off-chain. The increasing incidents of data theft and security breaches have resulted in some strict regulatory compliances about medical data. In such a scenario blockchain technology can provide an effective solution to meet the evolving demands and guidelines of the smart healthcare systems. Many healthcare organizations, governments, and startups are working to integrate the concepts of blockchain in the existing systems to achieve high security and privacy of medical data. MedChain is using the concepts of blockchain technology to store healthcare data securely [158].

6.1.4. Insurance

The increasing popularity of insuring things apart from medical bills, homes, and cars has resulted in the insurance industry being susceptible to fraud and trust issues. With the increasing demands of people, the insurance industry today has expanded to insure body parts, pets, voices, etc. Considering the gaps in the visibility created due to the dependencies on multiple individuals and departments the insurance industry is highly vulnerable. The major issues faced by the insurance sector include the constant threat of fraud, inefficient information exchanges, middlemen, multiple data sources, manual claims review and processing of information, and data thefts. In January 2015, Anthem Insurance companies, one of the largest health benefits companies became a victim of data theft that resulted in the exposure of data records of 78.8 million customers that cost the company around $375 million [159]. Embracing blockchain technology can provide promising solutions to overcome these issues in the insurance sector by the use of smart contracts, cryptography, and automation. The insurance policies can be transformed into smart contracts that can assure trust, transparency, and automation [101–106,159–163]. openIDL network by the American Association of Insurance Services built on the "IBM Blockchain" platform improves the accuracy and efficiency of the process by streamlining the requirements and automating the processes [163].

6.1.5. Logistics and supply chain management

The logistics and supply chain industry are one of the most talked-about use cases of blockchain technology. The support for audit trail and tamper-proof history of records makes it a better choice for supply chain and logistics [107–110]. The traditional businesses were based on trust between individual parties but with the advent of technology and modernization of businesses, there was a significant disruption in the traditional processes. The integration of blockchain into existing supply chain processes will significantly decrease the incidence of fraud and cargo thefts by providing a single platform to ensure the authenticity, transparency, history, and origin of records. This will benefit all stakeholders including manufacturers, suppliers, auditors, customers, and logistic partners, and will address their largely varying interests and third parties [107–110]. Many organizations are using the key concepts of blockchain technology to make the existing supply chains more efficient and reliable. In one of its several blockchain-based applications, IBM is working to tackle the problem of counterfeit drugs in Africa by using blockchain technology to make end-users more confident in making their choices [164].

6.1.6. Internet of things

The applications of IoT have seen exponential growth since its inception and have come a long way spreading itself across multiple sectors [141–144]. Gartner in its report has predicted that the number of installed IoT devices will reach a 27.4 billion mark by 2025. Today, IoT has enabled us to fill the gap between the real world and the digital world and has brought reforms in multiple sectors. With such a large number of connected devices that are generating, and exchanging data, there is a need to focus on the security and integrity of the shared data. With such complex interconnections between devices, there is an increased chance of internal and external data threats resulting in data loss and tampering. The Mirai Botnet DDoS attack was one of the most threatening attacks on IoT devices that affected the Internet services across the East Coast of America [165]. In another case in September 2017, FDA recalled over 500K IoT-based pacemakers after a severe loophole was detected that may cause the tampering of the medical device implanted in human bodies resulting in life-threatening consequences [166]. The security breaches in the Internet of Things devices in the past were possible because of the architectural gaps. In traditional IoT systems, a centralized architecture is used where all the information is stored in a central cloud. Today, with the increasing number of connected devices, there is a need for decentralized secured mechanisms like blockchain technology to store the information in IoT systems.

6.1.7. Voting

The introduction of Blockchain in the voting process will clear the air around the common misconceptions that the online voting process cannot be implemented securely and efficiently. Blockchain technology offers security, accuracy, trust, transparency, and immutability to the entire electoral process [123–126]. The recent Iowa Democratic caucuses of 2020 have raised some serious questions on the reliability and credibility of the technology enabling voting processes. The entire process suffered criticism due to the failure of an app and lack of transparency. This incident has highlighted the need for a technological intervention that can support transparency, anonymity, efficiency, and immutability in the electoral process. Although with any new technology, there comes a pool of unforeseeable hurdles considering all that the distributed ledger technology has to offer, blockchain can prove to be a potential game-changer. Currently, many startups and even governments are exploring this new technology for implementing a secure and tamperproof voting system. Luxoft is applying blockchain concepts to develop a decentralized voting application ensuring a reliable voting mechanism [167].

6.1.8. Energy

According to a report published by Global Market Insights Inc, blockchain technology will reach a mark of USD 18 billion in the energy market by 2025 [168]. Out of the many application areas of blockchain technology, the energy sector is one of the least explored and talked about. The energy sector is continually threatened regarding grid security and network connections due to the increasing digitization and interconnections. A report by the world economic forum, PwC, and Stanford woods institute for the environment has highlighted more than 60 use cases of the decentralized distributed ledger technology in saving the planet and promoting energy efficiency and sustainability [98–100]. Today, many blockchain-based real-world projects are implemented in the energy sector. Grid+ is a blockchain-based project that helps to achieve reduced home energy costs by developing hardware and software that are energy efficient [169]. Another venture called ONDOFLO works in the oil and natural gas sector.

6.1.9. Education

With the advent of technology, the education sector has witnessed a significant shift from a centralized learning environment to a peer-to-peer system of interaction that occurs online. Today, the education community is harnessing modern-day technologies to bring transformations in the teaching and learning processes [119–122,170]. With the increasing popularity of online learning platforms like Google's GAFE, Amazon's textbook rental platform, and Massive Open Online Courses (MOOCs) available on platforms like Edx and Coursera, MIT etc, there is a need for enhanced security and privacy to ensure anonymity, immutability, transparency, and integrity. Distributed ledger technology can be leveraged to minimize the challenges faced by the education industry. Blockchain technology sets the stage for collaborations between educational institutions and businesses and also eliminates the chances of fraud that occurs in manual processes by providing a digital record of students' credentials that are immutable. It also ensures the safety of important documents in cases of wars, climatic catastrophes, and economic collapses. In a recent case of the Covid-19 pandemic, the education sector saw a paradigm shift from personalized face-to-face teaching and learning to a completely online mode. In such unprecedented situations, blockchain-based solutions can ensure the safety of important teaching and learning resources and academic degrees, certificates, and other credentials [119–122].

6.1.10. Travel and hospitality

Blockchain technology has shown tremendous potential in revolutionizing the travel and hospitality business. The technology offers numerous applications for storing, validating, authorizing, and processing digital transactions. The key characteristics of the blockchain help to maintain a distributed database of records, enhance security, eliminate the need for third parties, and enhance the ease of accessing information from anywhere. Many companies in the travel and hospitality business are adopting blockchain to enhance their existing processes. TUI, one of the prominent names in the tourism industry has adopted blockchain in their project BedSwap [171], which maintains a record of hotel bed inventories in real-time. Blockchain makes this inventory available without any intermediaries. LockChain [172] is another blockchain-based platform that works on a subscription model that allows companies to rent out properties without any middleman and a zero percent commission policy. Today, many hospitality companies are using blockchain to manage their loyalty programs and reward tokens. In another application, blockchain is used to implement home-sharing platforms. Beenest provides such a platform that connects hosts and guests to facilitate stays without intermediaries and commissions [173]. Blockchain also provides solutions for booking and baggage tracking. Many well-known airlines like Lufthansa are adopting blockchain to assist their processes in booking and baggage tracking.

6.1.11. Food and agriculture

A report by pwc China claimed that the fraud in the food and agricultural industry causes a loss of around 30–40 billion globally [174]. The major challenge faced by the agricultural sector is to track the agri-products which are majorly managed and coordinated by third

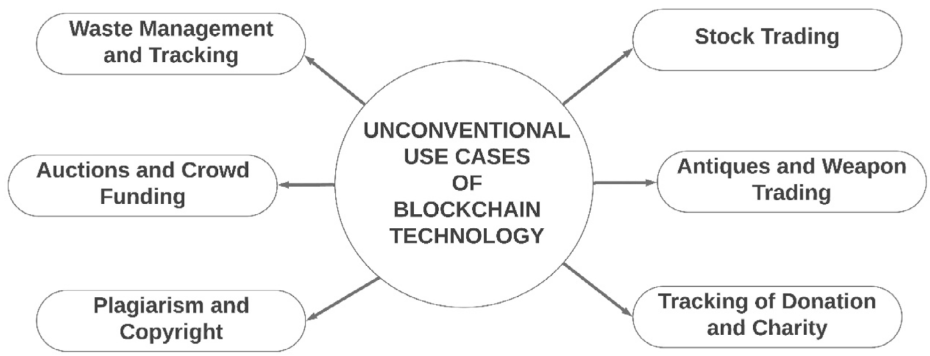

Fig. 6. Unconventional use-cases of blockchain [176–193].

parties. The integration of blockchain technology into the existing process can result in significant transformations and automation in key functional areas [175]. The introduction of blockchain will help to remodel the existing supply chains, payments, and tracking processes. The distributed ledger provides an immutable record of events right from the procurement of seeds and raw materials to the time the crops are harvested and food products are supplied for sale and reach consumers. With the increased suspicions about the quality of food and authenticity of products, consumers are more aware of the origin and quality measures of the food and underlying processes. The authenticity of raw materials and agricultural inputs is of primary concern to consumers around the globe. Blockchain has the potential to address all these issues by ensuring a list of immutable records. It also helps to eliminate the need for intermediaries resulting in decreased delaying increased profits [93–97]. It also helps to manage the government subsidies in the agriculture sector ensuring that the farmers are getting their share. With producers and consumers brought to a single platform, the logistics and supply chain process, and the marketing and sales processes are also enhanced.

6.1.12. Identity management

Identity and access management is one of the most promising use cases of Blockchain technology [132–136]. The current state of identity management involves paper-based identity cards and certificates and in some cases digital id proofs like thumb impressions, RFID tags, etc. stored in a centralized server or cloud storage in the respective organizations. These centralized servers and cloud storage are vulnerable to data theft and hacking. Identity management and access systems need secure and reliable tools for authentication and authorization. The digital identity records in these systems should be secure, private, portable, and verifiable from anywhere irrespective of the location. The key attributes of blockchain technology like decentralized distributed nature, immutability, and cryptographic hash functions provide a potential solution to address these major concerns and provide an authentication and authorization mechanism based on zero-knowledge proof allowing a user to prove identity without revealing the personal and private details. This provides a level of anonymity and transparency in the entire verification process. Blockchain has enormous potential to transform the existing identity management process by adding significant value to the current state of identity owners, identity issuers, and identity verifiers. LifeID uses blockchain principles to provide a universal account associated with an individual's identity [194].

6.1.13. Intellectual Property (IP)

Blockchain technology can provide an efficient platform to determine the creator-ship, origin, and ownership of Intellectual Property [114–118,176,177]. IP rights management and transfer of technology can be simplified securely and credibly by using digital distributed ledger technology. Further, Blockchain can be used as a digital registry for IP owners to seamlessly manage royalties for their inventions using smart contracts. The complexity of the approval process and the long list of laws governing IP make it a tedious task to maintain and verify the trail of audits and ownerships. Blockchain can help to manage copyrights by providing tamperproof evidence of the complete chain of ownership and ensuring fair remuneration and efficiency in the execution of royalties and copyrights [176,177]. IP-dependent businesses like entertainment, media, advertising, and software can create great value using the blockchain platform that will provide a secure way to manage sales, copyrights, licensing, and contracts.

6.1.14. Real estate

The real estate industry was traditionally concerned with the middleman/broker connecting the sellers with the potential buyers for any transactions. This entire transaction process included a commission/ brokerage. Most of these transactions were offline involving face-to-face communication between the stakeholders. With all things manual, there were high chances of fraud along with a broker fee. Today, with technologies like blockchain the entire real estate transaction process can be digitized with enhanced security and benefits. Smart contracts can be executed between the seller and buyer of the assets for all transactions thus eliminating the need for the middleman [111–113]. Further, real estate assets can be tokenized and traded on a digital platform. This will help the buyers to directly contact the sellers. Tokenization of assets will further facilitate the fractional purchasing of properties. Once tokenized the assets can be easily liquidated.

6.1.15. Transportation

Blockchain technology has the potential to address the existing issues in transportation like dispute resolution, administrative efficiency, shipment tracking, etc. by allowing close coordination between the stakeholders [107–110]. The technology helps to easily coordinate the documents on the digital distributed ledger. This helps in ensuring the easy availability of authentic and immutable data across multiple checkpoints in transportation systems. Further, shipment tracking helps increase the efficiency of logistics operations.

6.1.16. Entertainment

The key characteristics of blockchain technology like immutability, trust, transparency, etc. can benefit the entertainment and media industry by bringing significant changes in the way the various media contents are created, shared, consumed, and monetized. The adoption of blockchain can further help in fighting the piracy in entertainment and media industry and regularize the copyright and distribution of royalties [127–131].

Apart from the above classical use-case of blockchain technology, there are several unconventional use cases where blockchain technology can provide vital benefits. Fig. 6 presents some of those use cases [176–193].

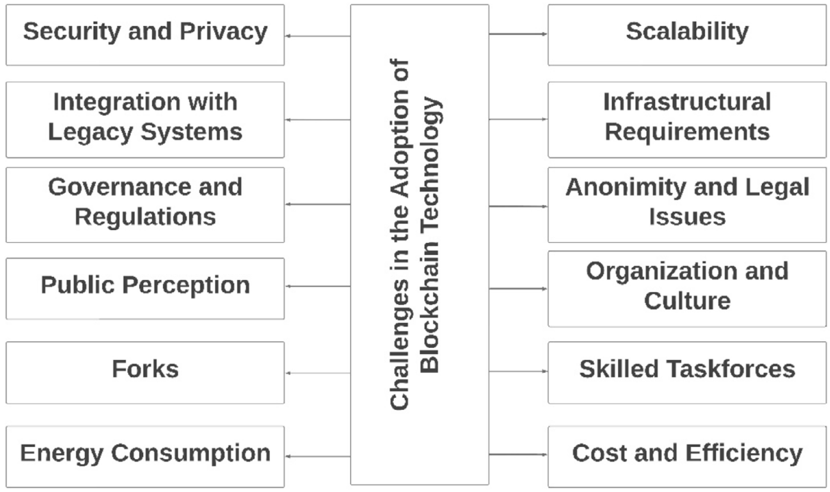

Fig. 7. Challenges in blockchain adoption.

6.1.17. *Waste management and tracking*

Blockchain technology can be used to track and trace the waste from the source to the disposal site creating an immutable, transparent, and tamper-proof mechanism of waste management life cycle [176,177].

6.1.18. *Stock trading*

Stock trading can be revolutionized with the help of blockchain technology. An optimal mechanism can be created using blockchain technology for automated and decentralized sales and purchases of stocks in real-time. Integrating blockchain technology in the trading software provides faster transaction speed and lowers the costs involved [178,179].

6.1.19. *Auctions and crowdfunding*

Blockchain technology ensures transparency, accountability, and security in crowdfunding. It further improves transaction time and the costs involved. As auctions involve bidding, the use of blockchain technology provides a tamper-proof and immutable mechanism wherein the bidding prices cannot be tampered with and thus helps in providing a fair auction process [180,181].

6.1.20. *Plagiarism and copyright*

Academic integrity can be maintained through the help of blockchain technology in the education domain which can be used to detect and deter plagiarism. Further, the ownership can be proved to determine the original writer of the content and thus prevent any copyright or plagiarism attempts [182–184].

6.1.21. *Antiques and weapon trading*

Blockchain technology enables the verification of original antiques and can be used to protect ancient artifacts and objects from being cloned by ensuring their provenance [185–188].

6.1.22. *Tracking of donation and charity*

The unaccounted donations and charity amounts can be easily traced and tracked through the help of blockchain-enabled systems. This can ensure a curb on black money and money laundering instances [189–193].

6.1.23. *Blockchain-based passwordless authentication*

The concept of blockchain-based Decentralized Digital Identities (DID) can be used to provide passwordless authentication mechanisms for enhancing user experiences. The biometric-based authentication approaches mitigate the weaknesses and limitations of the rudimentary password-based authentication approaches. A blockchain-based secured and privacy-preserved application can be created that can be used to capture biometrics (fingerprints, face recognitions etc.) of the users to provide seamless authentication [195,196].

6.2. *Use cases where blockchain can be avoided*

Although there are several unprecedented use-cases and application areas of blockchain technology, however, we should be careful about adopting this technology in all domains. It seems that blockchain technology can be applied to any field of application, however, this is not always true. Therefore, we should be well aware of when and why to use blockchain technology. Following are a few situations where the use of blockchain can be avoided [197–201].

- Legacy blockchain solutions suffer from scalability bottleneck, therefore whenever we are aware that the system is going to be scaled significantly and quite often, it is not advisable to use blockchain technology.
- Whenever there are frequent updations in transaction's terms and conditions, it becomes highly difficult, costly, and time-consuming to create a different smart contract for individual transactions.
- For real-time applications, blockchain technology is still considered a slow alternative. Therefore, it is advisable to avoid blockchain in real-time application domains.
- In blockchain-based transactions, it is difficult to reverse a transaction if the need arises. However, there are situations where a transaction needs to be reversed, so in such cases, blockchain must be avoided.
- Blockchain is still not a common practice and therefore the chances of its deniability are very high.

7. Issues and challenges with blockchain

Blockchain technology today faces many challenges and potential limitations that are both internal and external [202–212]. The major challenges faced by blockchain can be seen from the perspective of the developers, users, and policymakers. The implementation of blockchain-based solutions faces issues related to low scalability, limited interoperability, lack of standardization, and shortage of skilled developers. Further, at the organizational level, there is still a lack of awareness, understanding, lack of governance, and regulatory protocols about the technology. Considering the various issues, challenges, and associated costs the blockchain implementation is facing a productivity paradox. Today, blockchain is coping with the technical issues related to the underlying technology, thefts and security, general perception, regulations, and mainstream adoption. Fig. 7 highlights some of the major challenges faced by blockchain technology [202–212].

7.1. Scalability

Scalability is one of the prime concerns that restrict the mass adoption of blockchain technology. Bitcoin can currently handle 3–7 transactions per second (tps) while Ethereum can handle 15 tps. This is significantly less as compared to the other competitors like Visa which handles approximately 1736 transactions per second (is capable of handling more than 24,000 transactions per second Based on testing conducted in August 2010 with IBM). The current blockchains need to scale to avoid delays for consumers and businesses else the industry infrastructure will be unable to cope. Bitcoin cash (BCH) quadrupled the size of the blockchain to 32 Mb in May 2018 to keep pace with the increasing market demands. However, this upgrade has mixed reviews from the blockchain community. On one hand, the increased block size makes it superior to the bitcoin blockchain, on the other hand, the change also makes operating the full node expensive. There exist some other techniques like lightning, sharding, and off-chain to resolve the scalability issue of the blockchain. However, blockchain scalability is an issue that still needs an efficient solution.

The scalability issue comes bundled with other blockchain attributes like throughput, latency, propagation time, block size, and block time. Throughput defines the number of transactions a blockchain can support. It can mathematically be presented as the product of the number of blocks per second and the number of transactions per block.

$$Throughput = Number\ of\ \frac{Blocks}{second} * Number\ of\ \frac{Transactions}{Block}$$

Now for an efficient system, the throughput should be maximum. In this case, the throughput can be maximized by either increasing the block size or by increasing the block rate. In both cases, there will be a direct effect on the inner node latency and the propagation time where Latency can be defined as the amount of time to wait till a transaction is complete and Propagation time defines the time taken by a new block to reach the other nodes in the network. As the size of the blockchain grows the storage, bandwidth, and computer power requirements also grow. The increase in block size leads to an increase in the amount of data that needs to be verified by other nodes thus increasing the propagation time. [210] described this scenario using the scalability trilemma that involves decentralization, security, and scalability aspects of a blockchain. A blockchain platform that balances all three factors is challenging. The bigger block size creates a centralized system as it requires high computing power and longer to transmit across a network and verify. Scalability remains an issue. In the recent past, some new solutions were proposed to overcome or at least mitigate the issue of scalability with the blockchains. These solutions are categorized as first-layer and second-layer solutions. First-layer solutions like sharding, increasing block size etc. are based on modifying the blockchain structure while second-layer solutions like sidechains focus on methods that can be implemented outside of the blockchain. The various first- and second-layer solutions to scalability issues in blockchain are discussed in [209–212]. Recently, the ISO has made some efforts in the area of blockchain and Distributed Ledger Technology (DLT) standards ISO/TC 307 [213].

7.2. Energy consumption

The mining process especially in public blockchains requires a lot of energy in the form of electricity consumption translating into carbon footprints [214,215]. Since its inception in the year 2009, blockchain technology has brought revolutionary changes in the way things work. However, all these advantages come with a much higher cost in the form of high carbon footprints. Proof of Work is a scheme based on an SHA-256 hashing algorithm, which produces a cryptographic hash with a value less than a target nonce. The highly competitive process of mining and adding new blocks to the blockchain is computation-intensive consuming large amounts of energy.

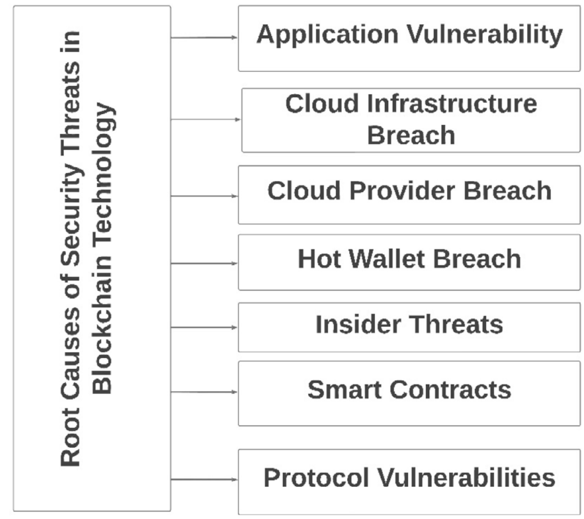

Fig. 8. Root causes of security threats in a blockchain.

In a study performed for over six months from January 2018 to June 2018 [214,215], the average energy consumption of mining cryptocurrencies was greater than that of mining the actual metals. The mining process resulted in 3–15 million tons of CO2 emissions. A study published in the "Nature Climate Change" by the University of Hawaii [214,215] states that the CO2 emissions due to bitcoin mining can push global warming to 2 degrees in the coming three decades.

The entire process of mining a valid block is based on large computations to calculate the right value of the nonce. This continuous block mining cycle incentivizes the miners which further motivates them to mine new blocks. This whole process results in large energy consumption. Today, the entire bitcoin network consumes more energy than some of the countries in the world [213–215].

7.3. Security and privacy

Over the years many cryptocurrencies and blockchain-based companies have suffered security breaches resulting in heavy financial losses and even shutdowns. Many kinds of research and studies have been reported on the security aspects of blockchain technology [215–222]. With the popularity of the technology and billions of investments, it has been in the eyes of hackers who are continuously looking out for vulnerabilities in the system. In the last few years, several incidents were reported where attackers were successful in executing attacks causing a loss of over billions. The root causes of these security threats are summarized in Fig. 8.

Blockchains which gained popularity as a non-hackable technology have seen several security breaches over the past few years where billions were lost in the hands of hacks and cybercrimes. A Hong Kong-based Cryptocurrency exchange Bitfinex lost over 120 000 bitcoins worth over $72 million in 2016 [223,224]. In November 2017, Tether announced that $31 million was removed from its treasury wallet [225]. A "South Korean cryptocurrency exchange Youbit" filed for bankruptcy in December 2017 after a hack caused it to lose around 17% of its assets [226]. Earlier the same year in April Youbit lost over $73 million to a cyber-attack [227]. In the same year, Slovenian-based NiceHash was hacked causing $62 million in losses [228,229]. In one of the most talked-about hacks in the blockchain world, Mt. Gox lost almost 840000 bitcoins out of which only 200 000 were recovered [229]. Coincheck a leading Japanese cryptocurrency exchange suspended the NEM coin services due to a hack that absconded over 500 million NEM tokens causing losses of over $530 million in January 2018 [230]. In the same month, $400 thousand worth of Steller Lumen (XLM) coins were withdrawn from the Blackwallets in a theft reported as a DNS hijack [231]. Later in the year in February 2018, a global cryptocurrency exchange Bitgrail was exposed to a cyber-attack resulting in a loss of over $150 million of NANO due to a discrepancy in its wallet maintenance code [232,233]. The incident was followed by a series of accusations and conspiracy claims by involved parties that further raised concerns about the security of the blockchains. In April 2018, an Indian cryptocurrency exchange Coinsecure lost bitcoins affecting over 11 000 customers [234]. The hack occurred due to the exposed private keys while extracting bitcoins. The lost funds were reported to be stored in the cold wallet. A cryptocurrency trading app Taylor was hacked and all their funds, ETH, and TAY tokens were stolen in May 2018 [235]. In June 2018, a South Korean cryptocurrency exchange Coinrail reported a cyber intrusion affecting NPXS tokens that caused them losses of over $40 million [236]. The ICO project launched on top of the Ethereum block, KICKICO suffered a smart contract breach resulting in a loss of over 70 million KICK with over $7.7 million in July 2018 [237]. A similar theft was reported earlier the same month by BANCOR where a compromised wallet was used to breach a smart contract causing damages worth over $13.5 million [238]. In September 2018 Japanese cryptocurrency exchange Zaif reported a loss of 60 billion Yen (approx. $60 million) in the hands of a hot wallet breach [239]. Later in October 2018, the Swiss blockchain company "trade.io" was hacked and a cold storage breach resulted in losses of over 50 million TIO (its own cryptocurrency) worth over $7.5 million [240]. A new kind of malicious activity called "Dusting Attack" was observed that attacks the privacy of the users by sending small amounts called dust to a large number of addresses to link these dusted addresses and wallets to individuals and organizations [241]. Once linked, the information can be misused to reveal the identities of the owners. In October 2018, bitcoin's samurai wallet reported a dusting attack on its users. A cybersecurity firm ESET reported an incident in November 2018 where hackers breached the web analytics platform StatCounter targeting the cryptocurrency exchange gate.io to steal bitcoins. Later, gate.io discontinued the services of StatCounter [242]. A New Zealand-based cryptocurrency exchange Cryptopia suffered a security breach in January 2019 resulting in a loss of over $4.5 million. Later in February 2021, currency worth more than $60 000 was stolen in a cold wallet breach [243]. In another incident, a popular wallet and exchange service Coinbase suspended trading in ETC after a reported deep chain reorganization including double spending was detected involving approximately $460 thousand [244]. In the same year, Binance discovered a hot wallet breach where hackers were successful in obtaining the user API keys and other potential information that caused them a loss of over $40 million [245].

7.4. Adoption issues and integration with the legacy systems

Despite the increasing popularity of blockchain technology, its mass adoption is still far from reality. The major reasons for this can be categorized into three classes: General, organizational, and implementational. General reasons that adversely affect the adoption of blockchain into the mainstream include its widespread association with cryptocurrencies which makes it susceptible to fraud in the minds of many. Apart from these the environmental aspects associated with this technology like energy consumption also add to this. Besides these when comes to implementation, it is still an immature technology that faces issues related to speed, scalability, integration into the legacy systems, lack of skilled task force, standard rules, interoperability, and infrastructure. Organizational issues like technological awareness amongst incumbents, employee attitudes and understanding, lack of governance and regulations etc., further pose challenges in the mainstream adoption of this technology. Also, legacy systems are not apt for handling the high energy consumption requirements of blockchain-based implementations.

7.5. Absence of universally accepted rule and regulations

Blockchain technology is still not considered valid in several countries [246]. There is no universally accepted set of rules and regulations for the implementation of blockchain technology [247].

7.6. Costs and efficiency

The initial setup cost of blockchain is high and thus it becomes difficult for small and medium-scale industries to integrate blockchain solutions in their existing setups. Furthermore, the transaction efficiency of public blockchain is not good which has a direct impact on the overall business.

8. Conclusion and future scope

The introduction of blockchain technology has significantly changed the way transactions are handled. The key characteristics of blockchain technology like decentralization, immutability, transparency etc. provide immense scope for enhancing the security, reliability, and privacy of the transactions and thus increasing trust amongst the users.

In this work, we presented a comprehensive overview of blockchain technology, its applications, and the major challenges in its widespread adoption. Although blockchain technology is considered a relatively new technology, historical evidence shows that it is built on well-understood and widely accepted cryptographic principles. Blockchain technology has significant potential to benefit different stakeholders like businesses, governments, private sector entities, and consumers. Despite being in its early stages of development, today blockchain has seen unprecedented growth and popularity across multiple domains. However, this popularity comes with its own set of pros and cons. On one hand, the technology provides transparency and immutability in transactions through various cryptographic principles while on the other hand, issues like lack of regulations governing the use of technology, scalability challenges, infrastructural requirements etc. result in hesitancy towards the use of blockchain-based solutions. A detailed study of the various challenges associated with this technology shows that the mass adoption of blockchain is still far from reality [248].

The paper also presents a detailed study of the major security breaches in blockchain in the past years and identifies the root causes of security thefts. The study shows that the majority of security breaches occur due to hot wallet breaches and application vulnerabilities. In the last few years, several cryptocurrencies and blockchain-based companies have faced heavy financial losses due to security breaches in the system. Researchers have also highlighted the impact of covid-19 pandemic on the world of cryptocurrencies [249].

Although the researchers hold different viewpoints related to the blockchain hype, its popularity is ever-increasing. In the future, the technology will grow with innovations in the area of improving scalability and minimizing energy consumption. Moreover, in the future generations of blockchain technology, it can be combined with other emerging technologies like Deep Learning and AI to create intelligence through smart contracts, consensus etc. Furthermore, there exists a few DAG-based systems that are fee-less and tackle the scalability issues to a certain extent, however, do not completely eliminate it [250].

Although blockchain technology is highly beneficial for several application domains, still one should be careful about when to use it to exploit the actual benefits of the revolutionary technology.

Table 8 given below provides some of the distinctions between when to use blockchain and when it is not a good option to use blockchain [216–218,251].

Therefore, it can be concluded that although blockchain promises extraordinary benefits for many application domains, it should be carefully chosen considering the requirements of the applications and the implementation costs involved. Blockchain technology has great potential to provide security to transactions. In the future, blockchain

Table 8
Blockchain adoption scenarios.

S.No	Scenarios	Use blockchain	Do not use blockchain
1	When the application requires frequent updations of records		✓
2	When High Scalability is required		✓
3	When decentralization storage is required	✓	
4	Implementation Cost Issue		✓
5	Transaction Speed is of prime concern		✓
6	Multiple Parties are involved	✓	
7	Organization requiring transparency, tracking and tracing	✓	
8	Archival Datasets	✓	
9	Redundancy is an issue		✓
10	Performance Matters		✓

technology can be explored to provide multi-factor authentication for providing an extra layer of security over the traditional approaches. Further, Zero-knowledge proof-based MFA approaches can be explored for providing privacy-preserving and efficient security mechanisms. Another area that can be of interest to the researchers is behavioral biometrics with which explicit behavioral patterns can be extracted and used for authenticating the users of the system.

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.

Data availability

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

References

[1] S. Nakamoto, Bitcoin: A peer-to-peer electronic cash system, 2008, https://bitcoin.org/bitcoin.pdf. (Accessed 14 March 2021).
[2] Bitcoin Pizza day: Celebrating the $20 million Pizza order, 2021, https://www.investopedia.com/news/bitcoin-pizza-day-celebrating-20-million-pizza-order/. (Accessed 24 July 2021).
[3] D. Chaum, Blind signatures for untraceable payments, in: Advances in Cryptology, Springer, Boston, MA., 1983, pp. 199–203.
[4] S. Haber, W.S. Stornetta, How to time-stamp a digital document, in: Conference on the Theory and Application of Cryptography, Springer, Berlin, Heidelberg, 1990, pp. 437–455.
[5] RPOW - Reusable Proofs of Work, 2004, https://nakamotoinstitute.org/finney/rpow/. (Accessed 23 August 2021).
[6] Hal finney received the first Bitcoin transaction. Here's how he describes it, 2021, https://www.washingtonpost.com/news/the-switch/wp/2014/01/03/hal-finney-received-the-first-bitcoin-transaction-heres-how-he-describes-it/. (Accessed 12 July 2021).
[7] History of Bitcoin exchanges and trading, 2021, https://academy.bit2me.com/en/history-exchanges-bitcoin-trading/. (Accessed 19 May 2021).
[8] V. Buterin, Ethereum: the ultimate smart contract and decentralized application platform, 2013, Libro blanco de Ethereum. Consultado en http://webarchive.org/web/20131228111141/http://vbuterin.com/ethereum.htmlel. 8 (Accessed 21 July 2022).
[9] Nathan Reiff, Bitcoin vs. Ethereum: What's the difference?, 2022, https://www.investopedia.com/articles/investing/031416/bitcoin-vs-ethereum-driven-different-purposes.asp. (Accessed 15 July 2022).
[10] The Linux foundation builds the global foundation for open source enterprise blockchain technologies, 2022, https://www.linuxfoundation.org/projects/case-studies/hyperledger/. (Accessed 18 August 2022).
[11] Chiefless company rakes in more than $100 million, 2021, https://www.wsj.com/articles/chiefless-company-rakes-in-more-than-100-million-1463399393. (Accessed 11 January 2021).
[12] A hacking of more than $50 million dashes hopes in the world of virtual currency, 2022, https://www.nytimes.com/2016/06/18/business/dealbook/hacker-may-have-removed-more-than-50-million-from-experimental-cybercurrency-project.html. (Accessed 13 February 2022).
[13] The blockchain timeline- from inception to maturity, 2022, https://www.grantthornton.global/globalassets/1.-member-firms/global/insights/blockchain-hub/blockchain-timeline_final.pdf. (Accessed 14 February 2022).
[14] Hobbes' blockchain timeline 0.1, 2022, https://www.zakon.org/robert/blockchain/timeline/. (Accessed 13 February 2022).
[15] G. Tripathi, M.A. Ahad, S. Paiva, S2HS-A blockchain based approach for smart healthcare system, in: Healthcare, 8 (1) (2020) 100391.
[16] G. Tripathi, M. Abdul Ahad, S. Paiva, SMS: A secure healthcare model for smart cities, Electronics 9 (7) (2020) 1135.
[17] A. Kamilaris, A. Fonts, F.X. Prenafeta-Boldú, The rise of blockchain technology in agriculture and food supply chains, Trends Food Sci. Technol. 91 (2019) 640–652.
[18] A. Grech, A.F. Camilleri, Blockchain in Education, Publications Office of the European Union, Luxembourg, 2017.
[19] S. Saberi, M. Kouhizadeh, J. Sarkis, L. Shen, Blockchain technology and its relationships to sustainable supply chain management, Int. J. Prod. Res. 57 (7) (2019) 2117–2135.
[20] G. Tripathi, V.T. Nautiyal, M.A. Ahad, N. Feroz, Blockchain technology and fashion industry-opportunities and challenges, in: Blockchain Technology: Applications and Challenges, Vol. 201.
[21] Q. Wang, M. Su, Integrating blockchain technology into the energy sector—from theory of blockchain to research and application of energy blockchain, Comp. Sci. Rev. 37 (2020) 100275.
[22] A. Dorri, S.S. Kanhere, R. Jurdak, Blockchain in Internet of Things: Challenges and solutions, 2016, arXiv preprint arXiv:1608.05187.
[23] G. Tripathi, M.A. Ahad, M. Sathiyanarayanan, The role of blockchain in Internet of Vehicles (IoV): Issues, challenges and opportunities, in: 2019 International Conference on contemporary Computing and Informatics, IC3I, IEEE, 2019, pp. 26–31.
[24] Joichi Ito, Neha Narula, Robleh Ali, The blockchain will do to the financial system what the internet did to media, 2021, https://hbr.org/2017/03/the-blockchain-will-do-to-banks-and-law-firms-what-the-internet-did-to-media. (Accessed 21 March 2021).
[25] Worldwide blockchain report: Market shares, strategies, and forecasts, 2018–2024: Market is anticipated to reach $60.7 billion with IBM, microsft & accenture driving blockchain, 2021, https://www.prnewswire.com/news-releases/worldwide-blockchain-report-market-shares-strategies-and-forecasts-2018-2024-market-is-anticipated-to-reach-607-billion-with-ibm-microsft--accenture-driving-blockchain-300581333.html. (Accessed 25 March 2021).
[26] Emmanuelle Ganne, Can blockchain revolutionize international trade? World trade organization, 2021, https://www.ibm.com/downloads/cas/KJDPQKBE. (Accessed on 13 April 2021).
[27] L. Ismail, H. Materwala, A review of blockchain architecture and consensus protocols: Use cases, challenges, and solutions, Symmetry 11 (10) (2019) 1198.
[28] F. Casino, T.K. Dasaklis, C. Patsakis, A systematic literature review of blockchain-based applications: Current status, classification and open issues, Telematics Inf. (2018).
[29] M. Iansiti, K.R. Lakhani, The truth about blockchain, Harv. Bus. Rev. 95 (1) (2017) 118–127.
[30] G. Zyskind, O. Nathan, Decentralizing privacy: Using blockchain to protect personal data, in: 2015 IEEE Security and Privacy Workshops, IEEE, 2015, pp. 180–184.
[31] Z. Zheng, S. Xie, H.N. Dai, X. Chen, H. Wang, Blockchain challenges and opportunities: A survey, Int. J. Web Grid Serv. 14 (4) (2018) 352–375.
[32] H. Lu, Y. Tang, Y. Sun, DRRS-BC: Decentralized routing registration system based on blockchain, IEEE/CAA J. Autom. Sin. 8 (12) (2021) 1868–1876.
[33] S. Namasudra, G.C. Deka, P. Johri, M. Hosseinpour, A.H. Gandomi, The revolution of blockchain: State-of-the-art and research challenges, Arch. Comput. Methods Eng. 28 (3) (2021) 1497–1515.
[34] M. Javaid, A. Haleem, R.P. Singh, S. Khan, R. Suman, Blockchain technology applications for Industry 4.0: A literature-based review, Blockchain: Res. Appl. (2021) 100027.
[35] A. Upadhyay, S. Mukhuty, V. Kumar, Y. Kazancoglu, Blockchain technology and the circular economy: Implications for sustainability and social responsibility, J. Clean. Prod. (2021) 126130.
[36] Y. Chen, H. Chen, Y. Zhang, M. Han, M. Siddula, Z. Cai, A survey on blockchain systems: Attacks, defenses, and privacy preservation, High-Confidence Comput. (2021) 100048.
[37] M. Swan, Blockchain: Blueprint for a New Economy, O'Reilly Media, Inc, 2015.

[38] M. Crosby, P. Pattanayak, S. Verma, V. Kalyanaraman, Blockchain technology: Beyond Bitcoin, Appl. Innov. 2 (6–10) (2016) 71.
[39] Z. Zheng, S. Xie, H. Dai, X. Chen, H. Wang, An overview of blockchain technology: Architecture, consensus, and future trends, in: 2017 IEEE International Congress on Big Data, BigData Congress, IEEE, 2017, pp. 557–564.
[40] J. Ito, N. Narula, R. Ali, The blockchain will do to the financial system what the internet did to media, Harv. Bus. Rev. 9 (March) (2017).
[41] A. Khurshid, Applying blockchain technology to address the crisis of trust during the COVID-19 pandemic, JMIR Med. Inf. 8 (9) (2020) e20477.
[42] T.M. Ghazal, M.K. Hasan, H.M. Alzoubi, M.Al. Hmmadi, N.A. Al-Dmour, S. Islam, et al., Securing smart cities using blockchain technology, in: 2022 1st International Conference on AI in Cybersecurity, ICAIC, IEEE, 2022, pp. 1–4.
[43] A. Alam, Platform utilising blockchain technology for elearning and online education for open sharing of academic proficiency and progress records, in: Smart Data Intelligence: Proceedings of ICSMDI 2022, Singapore Springer Nature, Singapore, 2022, pp. 307–320.
[44] A. Di Vaio, R. Hassan, R. Palladino, Blockchain technology and gender equality: A systematic literature review, Int. J. Inf. Manage. 68 (2023) 102517.
[45] T. Savelyeva, J. Park, Blockchain technology for sustainable education, Br. J. Educ. Technol. 53 (6) (2022) 1591–1604.
[46] S. Namasudra, P. Sharma, Achieving a decentralized and secure cab sharing system using blockchain technology, IEEE Trans. Intell. Transp. Syst. (2022).
[47] M.A. Kashem, M. Shamsuddoha, T. Nasir, A.A. Chowdhury, The role of artificial intelligence and blockchain technologies in sustainable tourism in the Middle East, 2022, Worldwide Hospitality and Tourism Themes, (ahead-of-print).
[48] D. Trček, Cultural heritage preservation by using blockchain technologies, Herit. Sci. 10 (1) (2022) 6.
[49] H.T. Le, T.T.L. Nguyen, T.A. Nguyen, X.S. Ha, N. Duong-Trung, BloodChain: A blood donation network managed by blockchain technologies, Network 2 (1) (2022) 21–35.
[50] G. Baralla, A. Pinna, R. Tonelli, M. Marchesi, Waste management: A comprehensive state of the art about the rise of blockchain technology, Comput. Ind. 145 (2023) 103812.
[51] H. Alshahrani, N. Islam, D. Syed, A. Sulaiman, M.S. Al Reshan, K. Rajab, et al., Sustainability in blockchain: A systematic literature review on scalability and power consumption issues, Energies 16 (3) (2023) 1510.
[52] H. Han, R.K. Shiwakoti, R. Jarvis, C. Mordi, D. Botchie, Accounting and auditing with blockchain technology and artificial intelligence: A literature review, Int. J. Account. Inf. Syst. 48 (2023) 100598.
[53] M. Wasiq, A. Bashar, S. Akmal, M.R. Rabbani, M.A. Saifi, N. Nawaz, Y.T. Nasef, Adoption and applications of blockchain technology in marketing: A retrospective overview and bibliometric analysis, Sustainability 15 (4) (2023) 3279.
[54] X. Yi, X. Yang, A. Kelarev, K.Y. Lam, Z. Tari, Blockchain Foundations and Applications, Springer Nature, 2022.
[55] D. Mingxiao, M. Xiaofeng, Z. Zhe, W. Xiangwei, C. Qijun, A review on consensus algorithm of blockchain, in: 2017 IEEE International Conference on Systems, Man, and Cybernetics, SMC, IEEE, 2017, pp. 2567–2572.
[56] M.S. Ferdous, M.J.M. Chowdhury, M.A. Hoque, A survey of consensus algorithms in public blockchain systems for crypto-currencies, J. Netw. Comput. Appl. (2021) 103035.
[57] S.M.H. Bamakan, A. Motavali, A.B. Bondarti, A survey of blockchain consensus algorithms performance evaluation criteria, Expert Syst. Appl. 154 (2020) 113385.
[58] L.M. Bach, B. Mihaljevic, M. Zagar, Comparative analysis of blockchain consensus algorithms, in: 2018 41st International Convention on Information and Communication Technology, Electronics and Microelectronics, MIPRO, IEEE, 2018, pp. 1545–1550.
[59] S.F. Aghili, H. Mala, C. Schindelhauer, M. Shojafar, R. Tafazolli, Closed-loop and open-loop authentication protocols for blockchain-based IoT systems, Inf. Process. Manage. 58 (4) (2021) 102568.
[60] Bhagirath Kumar Lader, Blockchain applications, 2023, https://www.foley.com/en/insights/publications/2021/08/types-of-blockchain-public--private-between. (Accessed 23 January 2023).
[61] Public vs private blockchains: Why public blockchains are the future, 2022, https://www.bitcoinsuisse.com/outlook/why-public-blockchains-are-the-future. (Accessed 12 February 2022).
[62] Wayne Vaughan, Open vs closed blockchains — Let's end this madness, 2022, https://medium.com/@WayneVaughan/open-vs-closed-blockchains-let-s-end-this-madness-8313e4095ead. (Accessed 24 February 2022).
[63] M. Xu, X. Chen, G. Kou, A systematic review of blockchain, Financ. Innov. 5 (1) (2019) 1–14.
[64] O. Labazova, T. Dehling, A. Sunyaev, From hype to reality: A taxonomy of blockchain applications, in: Proceedings of the 52nd Hawaii International Conference on System Sciences, HICSS 2019, 2019.
[65] O.F. Cangir, O. Cankur, A. Ozsoy, A taxonomy for blockchain based distributed storage technologies, Inf. Process. Manage. 58 (5) (2021) 102627.
[66] S. Bouraga, A taxonomy of blockchain consensus protocols: A survey and classification framework, Expert Syst. Appl. 168 (2021) 114384.
[67] J. Nijsse, A. Litchfield, A taxonomy of blockchain consensus methods, Cryptography 4 (4) (2020) 32.
[68] L. Madaan, A. Kumar, B. Bhushan, Working principle, application areas and challenges for blockchain technology, in: 2020 IEEE 9th International Conference on Communication Systems and Network Technologies, CSNT, IEEE, 2020, pp. 254–259.
[69] S. Ølnes, A. Jansen, Blockchain technology as s support infrastructure in e-government, in: International Conference on Electronic Government, Springer, Cham, 2017, pp. 215–227.
[70] Q. Lu, X. Xu, Y. Liu, I. Weber, L. Zhu, W. Zhang, Ubaas: A unified blockchain as a service platform, Future Gener. Comput. Syst. 101 (2019) 564–575.
[71] T. Alladi, V. Chamola, R.M. Parizi, K.K.R. Choo, Blockchain applications for Industry 4.0 and industrial IoT: A review, IEEE Access 7 (2019) 176935-176951.
[72] T. Alladi, V. Chamola, J.J. Rodrigues, S.A. Kozlov, Blockchain in smart grids: A review on different use cases, Sensors 19 (22) (2019) 4862.
[73] Building block(chain)s for a better planet, 2018, http://www3.weforum.org/docs/WEF_Building-Blockchains.pdf. (Accessed 5 May 2022).
[74] S. Anwar, S. Anayat, S. Butt, S. Butt, M. Saad, Generation analysis of blockchain technology: Bitcoin and ethereum, Int. J. Inf. Eng. Electron. Bus. 12 (4) (2020).
[75] A. Srivastava, P. Bhattacharya, A. Singh, A. Mathur, U. Pradesh, U. Pradesh, A systematic review on evolution of blockchain generations, Int. J. Inf. Technol. Electr. Eng. 7 (6) (2018) 1–8.
[76] Brand Connect, JD coin bringing resolution in blockchain with version 4.0 soon, 2020, https://www.forbesindia.com/article/brand-connect/jd-coin-bringing-resolution-in-blockchain-with-version-40-soon/61851/1. (Accessed on 25 December 2021).
[77] M.H. Ali, L. Chung, A. Kumar, S. Zailani, K.H. Tan, A sustainable blockchain framework for the halal food supply chain: Lessons from Malaysia, Technol. Forecast. Soc. Change 170 (2021) 120870.
[78] W. Powell, M. Foth, S. Cao, V. Natanelov, Garbage in garbage out: The precarious link between IoT and blockchain in food supply chains, J. Ind. Inf. Integr. (2021) 100261.
[79] P. Centobelli, R. Cerchione, P.Del. Vecchio, E. Oropallo, G. Secundo, Blockchain technology for bridging trust, traceability and transparency in circular supply chain, Inf. Manag. (2021) 103508.
[80] A. Budak, V. Çoban, Evaluation of the impact of blockchain technology on supply chain using cognitive maps, Expert Syst. Appl. 184 (2021) 115455.
[81] F. Longo, L. Nicoletti, A. Padovano, G. d'Atri, M. Forte, Blockchain-enabled supply chain: An experimental study, Comput. Ind. Eng. 136 (2019) 57–69.
[82] M.A. Agi, A.K. Jha, Blockchain technology for supply chain management: An integrated theoretical perspective of organizational adoption, Int. J. Prod. Econ. (2022) 108458.
[83] T. McGhin, K.K.R. Choo, C.Z. Liu, D. He, Blockchain in healthcare applications: Research challenges and opportunities, J. Netw. Comput. Appl. 135 (2019) 62–75.
[84] A. Ekblaw, A. Azaria, J.D. Halamka, A. Lippman, A case study for blockchain in healthcare:MedRec prototype for electronic health records and medical research data, in: Proceedings of IEEE Open & Big Data Conference, Vol. 13, no. 13, 2016.
[85] A. Hasselgren, K. Kralevska, D. Gligoroski, S.A. Pedersen, A. Faxvaag, Blockchain in healthcare and health sciences—A scoping review, Int. J. Med. Inf. 134 (2020) 104040.
[86] C. Pirtle, J. Ehrenfeld, Blockchain for healthcare: The next generation of medical records? 2018.
[87] L. Ismail, H. Materwala, S. Zeadally, Lightweight blockchain for healthcare, IEEE Access 7 (2019) 149935-149951.
[88] C.C. Agbo, Q.H. Mahmoud, J.M. Eklund, Blockchain technology in healthcare: A systematic review, in: Healthcare, Vol. 7, no. 2, Multidisciplinary Digital Publishing Institute, 2019, p. 56.
[89] V. Pashkov, O. Soloviov, Legal implementation of blockchain technology in pharmacy, in: SHS Web of Conferences, Vol. 68, no. 01027, EDP Sciences, 2019.
[90] G. Subramanian, A.S. Thampy, N.V. Ugwuoke, B. Ramnani, Crypto pharmacy–digital medicine: A mobile application integrated with hybrid blockchain to tackle the issues in pharma supply chain, IEEE Open J. Comput. Soc. 2 (2021) 26–37.
[91] B. Ying, W. Sun, N.R. Mohsen, A. Nayak, A secure blockchain-based prescription drug supply in health-care systems, in: 2019 International Conference on Smart Applications, Communications and Networking, SmartNets, IEEE, 2019, pp. 1–6.
[92] E. Fernando, Essential blockchain technology adoption factors in pharmaceutical industry, in: 2019 4th International Conference on Information Technology, Information Systems and Electrical Engineering, ICITISEE, IEEE, 2019, pp. 523–526.
[93] O. Bermeo-Almeida, M. Cardenas-Rodriguez, T. Samaniego-Cobo, E. Ferruzola-Gómez, R. Cabezas-Cabezas, W. Bazán-Vera, Blockchain in agriculture: A systematic literature review, in: International Conference on Technologies and Innovation, Springer, Cham, 2018, pp. 44–56.
[94] K. Demestichas, N. Peppes, T. Alexakis, E. Adamopoulou, Blockchain in agriculture traceability systems: A review, Appl. Sci. 10 (12) (2020) 4113.
[95] T. Kassanuk, K. Phasinam, Design of blockchain based smart agriculture framework to ensure safety and security, Mater. Today: Proc. (2021).

[96] Y.P. Lin, J.R. Petway, J. Anthony, H. Mukhtar, S.W. Liao, C.F. Chou, Y.F. Ho, Blockchain: The evolutionary next step for ICT e-agriculture, Environments 4 (3) (2017) 50.
[97] A. Kamilaris, I.R. Cole, F.X. Prenafeta-Boldú, Blockchain in agriculture, in: Food Technology Disruptions, Academic Press, 2021, pp. 247–284.
[98] A. Khatoon, P. Verma, J. Southernwood, B. Massey, P. Corcoran, Blockchain in energy efficiency: Potential applications and benefits, Energies 12 (17) (2019) 3317.
[99] U. Cali, M. Kuzlu, D.J. Sebastian-Cardenas, O. Elma, M. Pipattanasomporn, R. Reddi, Cybersecure and scalable, token-based renewable energy certificate framework using blockchain-enabled trading platform, Electr. Eng. (2022) 1–12.
[100] O. Juszczyk, K. Shahzad, Blockchain technology for renewable energy: Principles, applications and prospects, Energies 15 (13) (2022) 4603.
[101] Y. Zuo, Tokenizing renewable energy certificates (RECs)—A blockchain approach for REC issuance and trading, IEEE Access 10 (2022) 134477-134490.
[102] L. Pooja, J. Madhuri, Privacy preserved effective bill collection system using blockchain, in: Information and Communication Technology for Competitive Strategies (ICTCS 2022) Intelligent Strategies for ICT, Singapore Springer Nature, Singapore, 2023, pp. 23–32.
[103] M. Osmani, R. El-Haddadeh, N. Hindi, M. Janssen, V. Weerakkody, Blockchain for next generation services in banking and finance: Cost, benefit, risk and opportunity analysis, J. Enterprise Inf. Manag. (2020).
[104] Y. Guo, C. Liang, Blockchain application and outlook in the banking industry, Financ. Innov. 2 (1) (2016) 1–12.
[105] A. Tapscott, D. Tapscott, How blockchain is changing finance, Harv. Bus. Rev. 1 (9) (2017) 2–5.
[106] P. Garg, B. Gupta, A.K. Chauhan, U. Sivarajah, S. Gupta, S. Modgil, Measuring the perceived benefits of implementing blockchain technology in the banking sector, Technol. Forecast. Soc. Change 163 (2021) 120407.
[107] V. Astarita, V.P. Giofrè, G. Mirabelli, V. Solina, A review of blockchain-based systems in transportation, Information 11 (1) (2020) 21.
[108] Y. Yuan, F.Y. Wang, Towards blockchain-based intelligent transportation systems, in: 2016 IEEE 19th International Conference on Intelligent Transportation Systems, ITSC, IEEE, 2016, pp. 2663–2668.
[109] L.A. Hîrşan, C. Dobre, H. González-Vélez, Blockchain-based reputation for intelligent transportation systems, Sensors 20 (3) (2020) 791.
[110] R. Chaudhary, A. Jindal, G.S. Aujla, S. Aggarwal, N. Kumar, K.K.R. Choo, BEST: Blockchain-based secure energy trading in SDN-enabled intelligent transportation system, Comput. Secur. 85 (2019) 288–299.
[111] A. Spielman, Blockchain: Digitally Rebuilding the Real Estate Industry (Doctoral Dissertation), Massachusetts Institute of Technology, 2016.
[112] I. Karamitsos, M. Papadaki, N.B. Al Barghuthi, Design of the blockchain smart contract: A use case for real estate, J. Inf. Secur. 9 (03) (2018) 177.
[113] Veuger J., Trust in a viable real estate economy with disruption and blockchain, 2018, Facilities.
[114] B. Bodó, D. Gervais, J.P. Quintais, Blockchain and smart contracts: The missing link in copyright licensing? Int. J. Law Inf. Technol. 26 (4) (2018) 311–336.
[115] N. Jing, Q. Liu, V. Sugumaran, A blockchain-based code copyright management system, Inf. Process. Manage. 58 (3) (2021) 102518.
[116] Z. Meng, T. Morizumi, S. Miyata, H. Kinoshita, Design scheme of copyright management system based on digital watermarking and blockchain, in: 2018 IEEE 42nd Annual Computer Software and Applications Conference, Vol. 2, COMPSAC, IEEE, 2018, pp. 359–364.
[117] J.S. Hwang, H.G. Kim, Blockchain-based copyright management system capable of registering creative ideas, J. Internet Comput. Serv. 20 (5) (2019) 57–65.
[118] S. Zhao, D. O'Mahony, Bmcprotector: A blockchain and smart contract based application for music copyright protection, in: Proceedings of the 2018 International Conference on Blockchain Technology and Application, 2018, pp. 1–5.
[119] P. Bhaskar, C.K. Tiwari, A. Joshi, Blockchain in education management: Present and future applications, Interact. Technol. Smart Educ. (2020).
[120] M. Han, Z. Li, J. He, D. Wu, Y. Xie, A. Baba, A novel blockchain-based education records verification solution, in: Proceedings of the 19th Annual SIG Conference on Information Technology Education, 2018, pp. 178–183.
[121] G. Chen, B. Xu, M. Lu, N.S. Chen, Exploring blockchain technology and its potential applications for education, Smart Learn. Environ. 5 (1) (2018) 1–10.
[122] W. Gräther, S. Kolvenbach, R. Ruland, J. Schütte, C. Torres, F. Wendland, Blockchain for education: lifelong learning passport, in: Proceedings of 1st ERCIM Blockchain workshop 2018. European Society for Socially Embedded Technologies, EUSSET, 2018.
[123] A. Alshehri, M. Baza, G. Srivastava, W. Rajeh, M. Alrowaily, M. Almusali, Privacy-preserving E-voting system supporting score voting using blockchain, Appl. Sci. 13 (2) (2023) 1096.
[124] S. Gupta, A. Gupta, I.Y. Pandya, A. Bhatt, K. Mehta, End to end secure e-voting using blockchain & quantum key distribution, Mater. Today: Proc. 80 (2023) 3363–3370.
[125] M.V. Vladucu, Z. Dong, J. Medina, R. Rojas-Cessa, E-voting meets blockchain: A survey, IEEE Access 11 (2023) 23293–23308.
[126] S. Tanwar, N. Gupta, P. Kumar, Y.C. Hu, Implementation of blockchain-based e-voting system, Multimedia Tools Appl. (2023) 1–32.
[127] Q. Liu, S. Yang, J. Liu, L. Zhao, P. Xiong, J. Shen, An efficient video watermark method using blockchain, Knowl.-Based Syst. 259 (2023) 110066.
[128] B. Jiang, Q. He, P. Liu, S. Maharjan, Y. Zhang, Blockchain empowered secure video sharing with access control for vehicular edge computing, IEEE Trans. Intell. Transp. Syst. (2023).
[129] X. Zhang, G. Min, T. Li, Z. Ma, X. Cao, S. Wang, AI and blockchain empowered metaverse for web 3.0: Vision, architecture, and future directions, IEEE Commun. Mag. (2023).
[130] J. Santos, I. Amorim, A. Ulisses, J.C. Lopes, V. Filipe, Secure, dynamic and uncomplicated licensing of movies on a blockchain infrastructure, in: 2023 International Conference on Information Networking, ICOIN, IEEE, 2023, pp. 152–157.
[131] J.A. Costales, S. Shiromani, M. Devaraj, The impact of blockchain technology to protect image and video integrity from identity theft using deepfake analyzer, in: 2023 International Conference on Innovative Data Communication Technologies and Application, ICIDCA, IEEE, 2023, pp. 730–733.
[132] A. AlBadi, F. Hajamohideen, D. AlSaqri, A review on blockchain techniques used for identity management system: Privacy and access control, in: International Conference on Systems Engineering, Cham Springer Nature, Switzerland, 2023, pp. 361–375.
[133] D.A. Luong, J.H. Park, Privacy-preserving identity management system on blockchain using Zk-SNARK, IEEE Access 11 (2023) 1840–1853.
[134] M. Popa, S.M. Stoklossa, S. Mazumdar, ChainDiscipline-towards a blockchain-IoT-based self-sovereign identity management framework, IEEE Trans. Serv. Comput. (2023).
[135] K.M. Sadique, R. Rahmani, P. Johannesson, DIdM-EIoTD: Distributed identity management for edge Internet of Things (IoT) devices, Sensors 23 (8) (2023) 4046.
[136] P. Dunphy, F.A. Petitcolas, A first look at identity management schemes on the blockchain, IEEE Secur. Priv. 16 (4) (2018) 20–29.
[137] Y. Liu, Q. Lu, L. Zhu, H.Y. Paik, M. Staples, A systematic literature review on blockchain governance, J. Syst. Softw. 197 (2023) 111576.
[138] F. Cengiz, Blockchain governance and governance via blockchain: Decentralized utopia or centralized dystopia? Policy Des. Pract. (2023) 1–19.
[139] G. Laatikainen, M. Li, P. Abrahamsson, A system-based view of blockchain governance, Inf. Softw. Technol. 157 (2023) 107149.
[140] D. Basile, C. Di Ciccio, V. Goretti, S. Kirrane, Blockchain based resource governance for decentralized web environments, Front. Blockchain 6 (2023) 1141909.
[141] S.E. Abed, R. Jaffal, B.J. Mohd, A review on blockchain and IoT integration from energy, security and hardware perspectives, Wirel. Pers. Commun. 129 (3) (2023) 2079–2122.
[142] M. Oudani, A. Sebbar, K. Zkik, I. El Harraki, A. Belhadi, Green blockchain based IoT for secured supply chain of hazardous materials, Comput. Ind. Eng. 175 (2023) 108814.
[143] R. Huang, X. Yang, P. Ajay, Consensus mechanism for software-defined blockchain in Internet of Things, Internet Things Cyber-Phys. Syst. 3 (2023) 52–60.
[144] S. Tanwar, D. Ribadiya, P. Bhattacharya, A.R. Nair, N. Kumar, M. Jo, Fusion of blockchain and IoT in scientific publishing: Taxonomy, tools, and future directions, Future Gener. Comput. Syst. (2023).
[145] A. Karamchandani, S.K. Srivastava, A. Srivastava, A lower approximation based integrated decision analysis framework for a blockchain-based supply chain, Comput. Ind. Eng. 177 (2023) 109092.
[146] D. Su, L. Zhang, H. Peng, P. Saeidi, E.B. Tirkolaee, Technical challenges of blockchain technology for sustainable manufacturing paradigm in Industry 4.0 era using a fuzzy decision support system, Technol. Forecast. Soc. Change 188 (2023) 122275.
[147] S.C.H. Ng, G.T.S. Ho, C.H. Wu, Blockchain-IIoT-big data aided process control and quality analytics, Int. J. Prod. Econ. 261 (2023) 108871.
[148] H. Mora, J.C. Mendoza-Tello, E.G. Varela-Guzmán, J. Szymanski, Blockchain technologies to address smart city and society challenges, Comput. Hum. Behav. 122 (2021) 106854.
[149] J. Cha, S.K. Singh, T.W. Kim, J.H. Park, Blockchain-empowered cloud architecture based on secret sharing for smart city, J. Inf. Secur. Appl. 57 (2021) 102686.
[150] L. Tan, H. Xiao, K. Yu, M. Aloqaily, Y. Jararweh, A blockchain-empowered crowdsourcing system for 5G-enabled smart cities, Comput. Stand. Interfaces 76 (2021) 103517.
[151] S. Ibba, A. Pinna, M. Seu, F.E. Pani, CitySense: Blockchain-oriented smart cities, in: Proceedings of the XP2017 Scientific Workshops, 2017, pp. 1–5.
[152] J. Xie, H. Tang, T. Huang, F.R. Yu, R. Xie, J. Liu, Y. Liu, A survey of blockchain technology applied to smart cities: Research issues and challenges, IEEE Commun. Surv. Tutor. 21 (3) (2019) 2794–2830.
[153] Ottawa, Ontario exploring blockchain for better business, 2018, https://nrc.canada.ca/en/stories/exploring-blockchain-better-business. (Accessed on 15 2021).
[154] Adrianne Jeffries, Governments explore using blockchains to improve service, 2018, https://www.nytimes.com/2018/06/27/business/dealbook/governments-blockchains-services.html. (Accessed on 17 July 2021).

[155] Akash Takyar, Initiatives taken around blockchain development in Mexico, 2021, https://www.leewayhertz.com/blockchain-development-in-mexico/. (Accessed on 17 July 2021).
[156] DARPA and advancing cybersecurity infrastructure with blockchain, 2021, https://www.nasdaq.com/articles/darpa-and-advancing-cybersecurity-infrastructure-blockchain-2017-05-03. (Accessed on 18 July 2021).
[157] H.J. Yoon, Blockchain technology and healthcare, Healthc. Inf. Res. 25 (2) (2019) 59–60.
[158] B. Shen, J. Guo, Y. Yang, MedChain: Efficient healthcare data sharing via blockchain, Appl. Sci. 9 (6) (2019) 1207.
[159] Closing the gap cyber security and the asset management sector, 2018, https://assets.kpmg.com/content/dam/kpmg/uk/pdf/2018/01/closing-the-gap-cyber-security-asset-management.pdf. (Accessed on 18 July 2021).
[160] A.K. Kar, L. Navin, Diffusion of blockchain in insurance industry: An analysis through the review of academic and trade literature, Telemat. Inform. 58 (2021) 101532.
[161] T.Dominguez. Anguiano, L. Parte, The state of art, opportunities and challenges of blockchain in the insurance industry: A systematic literature review, Manag. Rev. Q. (2023) 1–22.
[162] N. Rahimi, S.S.V. Gudapati, Emergence of blockchain technology in the healthcare and insurance industries, in: Blockchain Technology Solutions for the Security of IoT-Based Healthcare Systems, Academic Press, 2023, pp. 167–182.
[163] IBM transforming insurance management with IBM blockchain, 2022, https://www.ibm.com/downloads/cas/OMJRXZAL. (Accessed on 12 August 2021).
[164] Toshendra Kumar Sharma, IBM working on a blockchain system to combat fake medicines in Africa, 2021, https://www.blockchain-council.org/blockchain/ibm-working-on-a-blockchain-system-to-combat-fake-medicines-in-africa/. (Accessed on 18 July 2021).
[165] M. Antonakakis, T. April, M. Bailey, M. Bernhard, E. Bursztein, J. Cochran, et al., Understanding the mirai botnet, in: 26th {USENIX} security symposium, {USENIX} Security 17, 2017, pp. 1093–1110.
[166] Alex Hern, Hacking risk leads to recall of 500, 000 pacemakers due to patient death fears, 2021, https://www.theguardian.com/technology/2017/aug/31/hacking-risk-recall-pacemakers-patient-death-fears-fda-firmware-update. (Accessed on 18 July 2021).
[167] Luxoft's E-voting platform enables first consultative vote based on blockchain in Switzerland, 2021, https://www.businesswire.com/news/home/20180625005668/en/Luxoft%E2%80%99s-E-Voting-Platform-Enables-First-Consultative-Vote-Based-on-Blockchain-in-Switzerland. (Accessed on 24 August 2021).
[168] Blockchain in energy market, 2021, https://www.gminsights.com/industry-analysis/blockchain-in-energy-market?utm_source=prnewswire.com&utm_medium=referral&utm_campaign=Paid_prnewswire. (Accessed on 14 April 2021).
[169] Grid+, 2021, https://gridplus.io/. (Accessed on 19 April 2022).
[170] G. Tripathi, Z.A. Haq, Big data analytics for industry oriented education system: An evolution of sustainable education model, in: Proceedings of ICETIT 2019, Springer, Cham, 2020, pp. 647–653.
[171] Bernard Marr, The awesome ways TUI uses blockchain to revolutionize the travel industry, 2022, https://www.forbes.com/sites/bernardmarr/2018/12/07/the-amazing-ways-tui-uses-blockchain-to-revolutionize-the-travel-industry/?sh=1b40329e1e7f. (Accessed on 18 December 2022).
[172] Obi, Blockchain revolution in hospitality industry led by lockchain, 2023, https://medium.com/@chima825/blockchain-revolution-in-hospitality-industry-led-by-lockchain-54e79cf24c08. (Accessed on 16 May 2023).
[173] What is beenest? How the bee token is revolutionizing the home sharing market, 2023, https://medium.com/@thebeetoken/what-is-beenest-how-the-bee-token-is-revolutionizing-the-home-sharing-market-8da32d79bbbb. (Accessed on 16 May 2023).
[174] Food fraud vulnerability assessment and mitigation. Are you doing enough to prevent food fraud?, 2023, Food-Fraud-Vulnerability-Assessment-and-Mitigation.pdf (pwc.co.nz). (Accessed on 16 May 2023).
[175] M.A. Alam, A. Ahad, S. Zafar, G. Tripathi, A neoteric smart and sustainable farming environment incorporating blockchain-based artificial intelligence approach, in: Cryptocurrencies and Blockchain Technology Applications, 2020, p. 197.
[176] K. Ito, M. O'Dair, A critical examination of the application of blockchain technology to intellectual property management, in: Business transformation through blockchain, Palgrave Macmillan, Cham, 2019, pp. 317–335.
[177] J. Wang, S. Wang, J. Guo, Y. Du, S. Cheng, X. Li, A summary of research on blockchain in the field of intellectual property, Procedia Comput. Sci. 147 (2019) 191–197.
[178] A.S.L. França, J.A. Neto, R.F. Gonçalves, C.M.V.B. Almeida, Proposing the use of blockchain to improve the solid waste management in small municipalities, J. Clean. Prod. 244 (2020) 118529.
[179] N. Gupta, P. Bedi, E-waste management using blockchain based smart contracts, in: 2018 International Conference on Advances in Computing, Communications and Informatics, ICACCI, IEEE, 2018, pp. 915–921.
[180] R. Nair, A. Bhagat, An application of blockchain in stock market, in: Transforming Businesses with Bitcoin Mining and Blockchain Applications, IGI Global, 2020, pp. 103–118.
[181] A. Oksanen, E. Mantere, I. Vuorinen, I. Savolainen, Gambling and online trading: Emerging risks of real-time stock and cryptocurrency trading platforms, Public Health 205 (2022) 72–78.
[182] I. Vakilinia, S. Badsha, S. Sengupta, Crowdfunding the insurance of a cyber-product using blockchain, in: 2018 9th IEEE Annual Ubiquitous Computing, Electronics & Mobile Communication Conference, UEMCON, IEEE, 2018, pp. 964–970.
[183] G. Fridgen, F. Regner, A. Schweizer, N. Urbach, Don't slip on the initial coin offering (ICO): A taxonomy for a blockchain-enabled form of crowdfunding, in: 26th European Conference on Information Systems, ECIS, 2018.
[184] N. Jing, Q. Liu, V. Sugumaran, A blockchain-based code copyright management system, Inf. Process. Manage. 58 (3) (2021) 102518.
[185] H.R. Saeidnia, B.D. Lund, Non-Fungible Tokens (NFT): A safe and effective way to prevent plagiarism in scientific publishing, Library Hi Tech News 40 (2) (2023) 18–19.
[186] R. García, A. Cediel, M. Teixidó, R. Gil, Semantics and non-fungible tokens for copyright management on the metaverse and beyond, ACM Trans. Multimed. Comput. Commun. Appl. (2022).
[187] M. Al Osimi, A. Aldweesh, Towards designing and development of an artifact storage and trading framework utilizing the ethereum blockchain, in: 2022 IEEE 13th International Conference on Software Engineering and Service Science, ICSESS, IEEE, 2022, pp. 101–104.
[188] N. Shaik, E.S. Reddy, Trusty URI learning-based secure blockchain management for making verifiable and reliable digital artifacts, Soft Comput. (2023) 1–11.
[189] H. Min, S.J. Joo, Blockchain technology for international arms trade, Int. J. Logist. Syst. Manag. 42 (2) (2022) 223–239.
[190] M. Sanli, Design of a tokenized blockchain architecture for tracking trade in the global defense market, in: The International Conference on Deep Learning, Big Data and Blockchain, Cham Springer Nature, Switzerland, 2023, pp. 30–40.
[191] A. Almaghrabi, A. Alhogail, Blockchain-based donations traceability framework, J. King Saud Univ.-Comput. Inf. Sci. 34 (10) (2022) 9442–9454.
[192] D. Saraswat, F. Patel, P. Bhattacharya, A. Verma, S. Tanwar, R. Sharma, UpHaaR: Blockchain-based charity donation scheme to handle financial irregularities, J. Inf. Secur. Appl. 68 (2022) 103245.
[193] A. Saxena, D. Kumar, B.P. Singh, B.L. Jatt, J.S. Kumar, Investigating the charity funding system using blockchain technology, in: 2022 IEEE World Conference on Applied Intelligence and Computing, AIC, IEEE, 2022, pp. 877–882.
[194] Lifeid, 2021, https://lifeid.io. (Accessed on 25 September 2021).
[195] V. Parmar, H.A. Sanghvi, R.H. Patel, A.S. Pandya, A comprehensive study on passwordless authentication, in: 2022 International Conference on Sustainable Computing and Data Communication Systems, ICSCDS, IEEE, 2022, pp. 1266–1275.
[196] S. Liu, T. Mu, S. Xu, G. He, Research on cross-chain method based on distributed digital identity, in: The 2022 4th International Conference on Blockchain Technology, 2022, pp. 59–73.
[197] S.K. Lo, X. Xu, Y.K. Chiam, Q. Lu, Evaluating suitability of applying blockchain, in: 2017 22nd International Conference on Engineering of Complex Computer Systems, ICECCS, IEEE, 2017, pp. 158–161.
[198] V. Gatteschi, F. Lamberti, C. Demartini, C. Pranteda, V. Santamaria, To blockchain or not to blockchain: That is the question, IT Prof. 20 (2) (2018) 62–74.
[199] A.B. Pedersen, M. Risius, R. Beck, A ten-step decision path to determine when to use blockchain technologies, MIS Q. Execut. 18 (2) (2019) 99–115.
[200] M.E. Peck, Blockchain world-do you need a blockchain? This chart will tell you if the technology can solve your problem, IEEE Spectr. 54 (10) (2017) 38–60.
[201] A.A. Austin, L.T. Williams, Evaluating company adoptions of blockchain technology: How do management and auditor communications affect nonprofessional investor judgments? J. Account. Public Policy (2021) 106882.
[202] S. Alam, M. Shuaib, W.Z. Khan, S. Garg, G. Kaddoum, M.S. Hossain, Y.B. Zikria, Blockchain-based initiatives: Current state and challenges, Comput. Netw. 198 (2021) 108395.
[203] M.A. Uddin, A. Stranieri, I. Gondal, V. Balasubramanian, A survey on the adoption of blockchain in IoT: Challenges and solutions, Blockchain: Res. Appl. (2021) 100006.
[204] I.C. Lin, T.C. Liao, A survey of blockchain security issues and challenges, IJ Netw. Secur. 19 (5) (2017) 653–659.
[205] S. Singh, A.S.M.S. Hosen, B. Yoon, Blockchain security attacks, challenges, and solutions for the future distributed IoT network, IEEE Access 9 (2021) 13938–13959, http://dx.doi.org/10.1109/ACCESS.2021.3051602.
[206] K. Gai, J. Guo, L. Zhu, S. Yu, Blockchain meets cloud computing: A survey, IEEE Commun. Surv. Tutor. 22 (3) (2020) 2009–2030, http://dx.doi.org/10.1109/COMST.2020.2989392.
[207] J. Zhang, C. Lu, G. Cheng, T. Guo, J. Kang, X. Zhang, X. Yuan, X. Yan, A blockchain-based trusted edge platform in edge computing environment, Sensors 21 (2021) 2126, http://dx.doi.org/10.3390/s21062126.
[208] R. Asif, K. Ghanem, J. Irvine, Proof-of-PUF enabled blockchain: Concurrent data and device security for internet-of-energy, Sensors 21 (2021) 28, http://dx.doi.org/10.3390/s21010028.
[209] D. Khan, L.T. Jung, M.A. Hashmani, Systematic literature review of challenges in blockchain scalability, Appl. Sci. 11 (20) (2021) 9372.

[210] A. Altarawneh, T. Herschberg, S. Medury, F. Kandah, A. Skjellum, Buterin's scalability trilemma viewed through a state-change-based classification for common consensus algorithms, in: 2020 10th Annual Computing and Communication Workshop and Conference, CCWC, IEEE, 2020, pp. 0727–0736.

[211] Steve Huckle, Martin White, Socialism and the blockchain, Future Internet (ISSN: 1999-5903) 8 (4) (2016) 49.

[212] A. Hafid, A.S. Hafid, M. Samih, Scaling blockchains: A comprehensive survey, IEEE Access 8 (2020) 125244-125262.

[213] Blockchain and distributed ledger technologies, 2022, https://www.iso.org/committee/6266604.html. (Accessed 21 March 2022).

[214] M.J. Krause, T. Tolaymat, Quantification of energy and carbon costs for mining cryptocurrencies, Nat. Sustain. 1 (11) (2018) 711.

[215] C. Mora, R.L. Rollins, K. Taladay, M.B. Kantar, M.K. Chock, M. Shimada, E.C. Franklin, Bitcoin emissions alone could push global warming above 2° C, Nature Clim. Change 8 (11) (2018) 931.

[216] Q. Bao, B. Li, T. Hu, X. Sun, A survey of blockchain consensus safety and security: State-of-the-art, challenges, and future work, J. Syst. Softw. 196 (2023) 111555.

[217] C. Connors, D. Sarkar, Survey of prominent blockchain development platforms, J. Netw. Comput. Appl. (2023) 103650.

[218] H. Guo, X. Yu, A survey on blockchain technology and its security, Blockchain: Res. Appl. 3 (2) (2022) 100067.

[219] A.S. Rajasekaran, M. Azees, F. Al-Turjman, A comprehensive survey on blockchain technology, Sustain. Energy Technol. Assess. 52 (2022) 102039.

[220] Bitcoin electronic waste monitor, 2021, https://digiconomist.net/bitcoin-electronic-waste-monitor/. (Accessed on 23 November 2021).

[221] Cambridge Bitcoin electricity consumption index, 2021, https://www.cbeci.org/methodology/. (Accessed on 23 November 2021).

[222] X. Li, P. Jiang, T. Chen, X. Luo, Q. Wen, A survey on the security of blockchain systems, Future Gener. Comput. Syst. 107 (2020) 841–853.

[223] Bitfinex security breach, 2021, https://spectrum.ieee.org/tech-talk/telecom/internet/bitfinex-hong-kong-bitcoin-exchange-loses-nearly-120000-bitcoin-in-hack. (Accessed on 20 December 2021).

[224] Bitfinex security breach, 2021, https://www.bbc.com/news/technology-42409815. (Accessed on 23 December 2022).

[225] Tether, 2021, https://tether.to/tether-critical-announcement/. (Accessed on 12 November 2021).

[226] Youbit, 2021, https://www.bbc.com/news/technology-42409815. (Accessed on 2 July 2021).

[227] NiceHash, 2021, https://www.reuters.com/article/us-cyber-nicehash-idUSKBN1E10AQ. (Accessed on 2 July 2021).

[228] NiceHash, 2021, https://www.coindesk.com/62-million-gone-cryptocurrency-mining-market-nicehash-hacked. (Accessed on 2 July 2021).

[229] Mt Gox Hack, 2021, https://blockonomi.com/mt-gox-hack/. (Accessed on 12 July 2021).

[230] Coincheck, 2021, https://blockonomi.com/coincheck-hack/. (Accessed on 12 July 2021).

[231] Stellar lumen, 2021, https://cointelegraph.com/news/blackwallet-hack-400k-in-stellar-stolen-hosting-provider-possibly-at-fault. (Accessed on 12 July 2021).

[232] Bitgrail, 2021, https://www.forbes.com/sites/francescoppola/2018/02/11/yet-another-theft-from-a-cryptocurrency-exchange-but-who-is-really-to-blame/?sh=4ed7fc6ef6dd. (Accessed on 12 July 2021).

[233] Bitgrail, 2021, https://www.reuters.com/article/italy-cyber-cryptocurrency-idUSL8N2J127X. (Accessed on 12 July 2021).

[234] Coinsecure, 2021, https://economictimes.indiatimes.com/industry/banking/finance/banking/coinsecure-announces-rs-20-lakh-reward-to-recover-lost-bitcoins-promises-refund-in-15-days/articleshow/63753530.cms. (Accessed on 12 July 2021).

[235] Taylor, 2021, https://medium.com/smarttaylor/this-is-a-dark-day-for-taylor-ded587463da7. (Accessed on 12 July 2021).

[236] Coinrail, 2021, https://www.coindesk.com/coinrail-exchange-hacked-loses-possibly-40-million-in-cryptos. (Accessed on 12 July 2021).

[237] Ethereum KICKICO, 2021, https://ethereumworldnews.com/kickico-hacked-7-7-million-stolen-after-smart-contract-breach/. (Accessed on 12 July, 2021).

[238] BANCOR, 2021, https://www.cnbc.com/2018/07/10/bancor-security-breach-13point5-million-worth-of-cryptocurrency-stolen.html. (Accessed on 12 July 2021).

[239] Zaif, 2021, https://www.coindesk.com/crypto-exchange-zaif-hacked-in-60-million-6000-bitcoin-theft. (Accessed on 12 July 2021).

[240] Trade.io, 2021, https://blockonomi.com/trade-io-hacked/. (Accessed on 12 July 2021).

[241] Dusting attack, 2021, https://www.binance.vision/security/what-is-a-dusting-attack. (Accessed on 12 July 2021).

[242] StatCounter, 2021, https://www.welivesecurity.com/2018/11/06/supply-chain-attack-cryptocurrency-exchange-gate-io/. (Accessed on 12 July 2021).

[243] Cryptopia, 2021, https://www.stuff.co.nz/national/crime/124249161/assets-worth-62000-allegedly-stolen-from-liquidated-company-cryptopia. (Accessed on 12 July 2021).

[244] Paddy Baker, Ethereum classic hack causes coinbase to suspend ETC trading, 2021, https://cryptobriefing.com/ethereum-classic-reorg-coinbase-etc/. (Accessed on 23 September 2021).

[245] Binance security breach update, 2022, https://binance.zendesk.com/hc/en-us/articles/360028031711-Binance-Security-Breach-Update. (Accessed on 26 November 2022).

[246] Five countries that have banned cryptocurrencies, 2022, https://www.news18.com/news/tech/five-countries-that-have-banned-cryptocurrencies-4233206.html. (Accessed on 27 November 2022).

[247] Countries where Bitcoin is banned or legal in 2023, 2021, https://cryptonews.com/guides/countries-in-which-bitcoin-is-banned-or-legal.htm. (Accessed on 26 November 2022).

[248] S. Johar, N. Ahmad, W. Asher, H. Cruickshank, A. Durrani, Research and applied perspective to blockchain technology: A comprehensive survey, Appl. Sci. 11 (14) (2021) 6252.

[249] M. Wątorek, S. Drozdz, J. Kwapień, L. Minati, P. Oświęcimka, M. Stanuszek, Multiscale characteristics of the emerging global cryptocurrency market, Phys. Rep. 901 (2021) 1–82.

[250] Q. Wang, J. Yu, S. Chen, Y. Xiang, SoK: Diving into DAG-based blockchain systems, 2020, arXiv preprint arXiv:2012.06128.

[251] D. Puthal, S.P. Mohanty, E. Kougianos, G. Das, When do we need the blockchain? IEEE Consum. Electron. Mag. 10 (2) (2021) 53–56, http://dx.doi.org/10.1109/MCE.2020.3015606.