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Quantum of Trust: Overview of Blockchain Technology for Product Authentication in Food and Pharmaceutical Supply Chains

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ABSTRACT

Background: Food and pharmaceutical supply chains face similar issues, such as product counterfeits allowing low-quality products to enter the market and supply chain inefficiencies. Applying blockchain technology could increase transparency and efficiency in the supply chains. However, the technology is still relatively young and, thus, has barely been implemented.

Scope and Approach: This work aims to provide an overview of blockchain applications in food and pharmaceutical supply chains. Following the PRISMA method, the systematic literature review analyzes 78 applications in 74 publications. Deriving from the results, a general framework for blockchain applications in food and pharmaceutical supply chains is proposed, which should support practitioners in implementing blockchains and researchers in identifying research challenges.

Key Findings and Conclusions: The literature review reveals that permissioned and private blockchain networks are most commonly applied, using Ethereum and Hyperledger Fabric as leading platforms. Many applications stored data off the blockchain and implemented different techniques to restrict access to confidential data. Smart contracts are crucial for improving supply chain management as they enable automatization. The general framework recommends a permissioned consortium network using the Hyperledger Fabric platform and Proof-of-Authority consensus protocol for supply chains. Challenges like regulations, standardization, and infrastructure must be solved to foster technology adoption in operations.

1. Introduction

Ensuring food safety and quality is one of the most essential challenges nowadays (Wang, He et al., 2022). Over time, food supply chains (FSCs) evolved and became more globally distributed, allowing for increased production, greater product variety, and more international trade (Katsikouli et al., 2021). However, issues such as persistent food loss and waste, distributed supply chain (SC) networks with non-transparent and inefficient information flows, and food fraud (Boller et al., 2023; Nasir et al., 2022) also increasingly arose. Thus, increasing food authentication and traceability is crucial.

Similarly to food, the authenticity of pharmaceuticals is significantly relevant to human health. Therefore, counterfeit pharmaceutical products are a serious problem (Ghadge et al., 2023). Pharmaceutical supply chains (PSCs) and FSCs have similar characteristics, such as following strict regulatory compliance, ensuring the products' quality and safety, and imperatively having to react very fast in the event of product recalls (Nam Vu & Bourlakis, 2023; Uddin et al., 2021). Blockchain technology offers several potential benefits to both SCs by enhancing traceability, product safety, SC efficiency, quality assurance, preventing counterfeits, and promoting sustainability and ethical sourcing (Kamilaris et al., 2019; Lin et al., 2019; Nam Vu & Bourlakis, 2023; Treiblmaier et al., 2021).

Blockchain is a distributed ledger technology (Nakamoto, 2008). The original idea was to enable transparent and secure information sharing without the control of a central trust authority. Developed for cryptocurrencies, blockchain has since entered various application areas like SCs. In combination with Internet-of-Things (IoT) and smart contracts, blockchain technology improves supply chain management (SCM) by eliminating manual paperwork, reducing administrative tasks, and automating transactions (Christopher, 2011; Kamilaris et al., 2019; Katsikouli et al., 2021). However, the application of blockchains in food and pharmaceutical SCs is still in its infancy.

This work primarily aims to overview blockchain applications in food and pharmaceutical SCs. Therefore, a systematic literature review first examines blockchain applications in both SCs. Deriving from the

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analysis of current blockchain configurations, we propose a general framework to foster research and support practitioners with a reference design suited for the food and pharmaceutical SCs. Afterward, we discuss the challenges and potentials of blockchains in these SCs derived from the literature analysis.

The remainder of this work is structured as follows: Next, Section 2 explains fundamentals related to blockchain technology and FSC and PSC. Then, Section 3 presents the methodological approach for the literature review. Subsequently, Section 4 evaluates the results of the literature review. Afterward, Section 5 presents the framework for integrating blockchain technology in FSC and PSC and discusses the challenges of implementing blockchains. Following, Section 6 summarizes related work. Finally, Section 7 concludes this paper.

2. Background

This section describes fundamental concepts for understanding the remainder of this paper. First, Section 2.1 provides a basic understanding of FSCs and PSCs. Afterward, Section 2.2 explains the basic concepts of the blockchain technology. Finally, Section 2.3 summarizes some real-world implementations of blockchain technology in food and pharmaceutical SCs.

2.1. Supply chains

In general, a supply chain (SC) is a network of actors structured around activities and processes that aim to satisfy given consumer demand by bringing products or services to market (Christopher, 2011). This network includes feedback and circular economy aspects, e.g., for sustainability reasons such as the recycling of materials (Teigiserova et al., 2019). The actors within the SC are linked through upstream or downstream processes and activities that produce value in the form of finished products or services (Christopher, 2011). In the same sense, a food supply chain (FSC) encompasses all activities involved in the creation and transformation of raw materials into food products as well as their retail and consumption (Kamilaris et al., 2019), and a pharmaceutical supply chain (PSC) refers to the network of activities and entities involved in the production, distribution, and delivery of pharmaceutical products, including prescription drugs, over-the-counter medications, vaccines, and other medical products (Musamih et al., 2021).

Although it is important to consider not only the primary flow but also the tangential and secondary flows that are contained within the SCs, as these are opportunities to reduce losses and wastes through reuse and recycling (Teigiserova et al., 2019), SCs are often presented as simplified, linear, and straight forwarded structures. This is sufficient for this work since the focus is on discussing a general framework for integrating blockchains in food and pharmaceutical SCs. Commonly, the FSC begins with production, which is usually an agricultural farm, continues with supply, processing, distribution, and retail, and ends with consumption (Henrichs et al., 2022). Several challenges exist in the FSC (Angarita-Zapata et al., 2021): the production estimation and optimization; the production planning regarding the post-harvest loss as well as demand prediction; the prediction of SC risks and disruptions, maintaining adequate storage conditions and shelf-life prediction during the distribution; and finally, the consumption. Traceability is an important concept in this regard, as tracking the origin, movement, and handling of food products is crucial to maintain food safety and quality (Kamilaris et al., 2019).

Similarly to the FSC, the main stages of the PSC include manufacturing, distribution, wholesale, and retail, including pharmacies or healthcare providers, and end at the patients (Musamih et al., 2021; Uddin et al., 2021). It is worth noting that the global pharmaceutical industry is heavily regulated to ensure drug safety, quality, and efficacy (Jangir et al., 2019; Uddin et al., 2021). Regulatory authorities, such as the U.S. Food and Drug Administration (FDA) or the European Medicines Agency (EMA), enforce compliance with regulations, perform inspections, and grant approvals for drug manufacturing, import and export, and distribution. Nevertheless, the PSC faces several challenges (Narayana et al., 2014; Sangari & Mashatan, 2022; Uddin et al., 2021): counterfeit or substandard drugs, the maintenance of proper storage conditions, the protection against tampering or contamination, drug shortages, demand fluctuations, or disruptions in the availability of medications. Therefore, the PSC requires robust systems for traceability and serialization, enabling the tracking of medications from production to dispensing to patients (Musamih et al., 2021).

2.2. Blockchain technology

Blockchain technology is a distributed ledger technology, meaning that a copy of the ledger is stored on several nodes in the related blockchain network (Agarwal et al., 2022; Nakamoto, 2008). Blockchain ensures tamper-proof entries in the ledger without a centralized trusted authority, enabling transparency and trust in data exchange as every stakeholder in the blockchain has access to the data. Usually, strong market players, such as producers in the pharmaceutical sector or producers and retailers in the food sector, dominate the SCs (Christopher, 2011). Those might act as centralized authorities, managing (and potentially blocking) access to data. However, the absence of a centralized authority helps to democratize the benefits of data access as all participants have equal access to data.

The blockchain technology stores data in so-called blocks (Agarwal et al., 2022). In SCs, two interacting parties might agree on the values of such a block, e.g., if it represents the data of a transaction. Such a block consists of the data item itself and a hash value calculated by a so-called hash function based on the data properties and the previous block's hash value. Integrating the hash value of the previous block creates "chains" of the blocks together (Zheng et al., 2018). As the cryptographic hash function calculates an individual fingerprint (Agarwal et al., 2022; Juma et al., 2019), changing a data item after hashing results in re-calculating the hash value of that block. This would cause the break of the chain and would thus be recognizable (Juma et al., 2019; Nakamoto, 2008; Xu et al., 2017), especially as succeeding blocks will integrate the hash value when calculating the corresponding hash values for those blocks. Hence, an update of those hash values would also be required.

Access to the blockchain network can require explicit permission (Agarwal et al., 2022; Xu et al., 2017). In such *permissioned* networks, participants have restricted access to data, and their actions are controlled. In contrast, in *permissionless* networks, everyone can participate and get access to all data, making it transparent.

Further, blockchains are distinguished into public, consortium, and private blockchains (Agarwal et al., 2022; Juma et al., 2019; Zheng et al., 2018). *Public* blockchains allow everyone to join, participate, and validate blocks. They are often permissionless but could also require permission. This would support the idea that each party can read the data but not add new data without any control. In contrast to them, access to *private* blockchains is controlled by a single entity. This single entity decides on participation, consensus, and responsibilities regarding the maintenance of the blockchain. *Consortium* blockchains are similar to private blockchains but controlled by a consortium of entities. Additionally, *hybrid* blockchains are a mix of private and public blockchains (Tsoukas et al., 2021). They usually consist of two blockchains that interact: a public chain to manage participants' identities and a private chain to store confidential data. Nevertheless, data could also be stored confidentially in public blockchains without providing access to all participants, e.g., by encrypting the data (Biswas et al., 2017), i.e., the data is transformed to a cipher which cannot be read without access to a key.

To agree on the validity of information and to keep reliable records in the distributed ledgers, nodes in the blockchain network must achieve consensus (Xu et al., 2017; Zheng et al., 2018). Therefore, a consensus protocol is applied, which depends on the network structure. The *Proof-of-Work* (PoW) chooses the validator based on a complex mathematical puzzle. The network participant who first solves this puzzle becomes the miner who adds the new block to the chain. The block can be linked to a reward, which could be used as an incentive. This consensus protocol is usually used in public blockchains of cryptocurrencies, e.g., Bitcoin. The *Proof-of-Stake* (PoS) selects the validator based on their stake in the blockchain, e.g., rated by their amount of cryptocurrency. This does not have to be the biggest share but could be selected randomly by the protocol, adaptively changed over time, or voted on. The *Proof-of-Authority* (PoA) selects the validator based on the identity and reputation of the node (Maftei et al., 2023; Manolache et al., 2022). Hence, this consensus protocol is not feasible for public blockchain networks since the identity of the nodes must be known. The *Proof-of-Elapsed-Time* (PoET) assigns random waiting times to nodes before they are allowed to generate a new block (Chen et al., 2017; Pal & Kant, 2021). The nodes must prove their waiting time, which is evaluated statistically (Chen et al., 2017). After the block generation, other nodes verify the block before adding it to the chain. The PoET requires trusted environments; hence, it is not feasible in public blockchains (Pal & Kant, 2021).

Byzantine Fault Tolerance (BFT) is the function of a distributed network to reach consensus (agreement on the same value) even if some of the nodes in the network do not respond or respond with incorrect information. The goal of a BFT mechanism is to protect against system failures by using collective decision-making (both correct and faulty nodes) to reduce the influence of the faulty nodes (Wang et al., 2023; Xu et al., 2017). *Practical Byzantine Fault Tolerance* (PBFT) is a consensus protocol for permissioned blockchain networks that strives to achieve BFT, even in systems with malicious nodes. *Crash Fault Tolerance* (CFT) protocols such as *Raft* or *Kafka* work similarly to PBFT: nodes reach consensus as long as at most half of the nodes are erroneous, e.g., through communication faults or malicious behavior (Huang et al., 2020; Li et al., 2021).

Blockchain platforms are the software frameworks that provide the necessary tools, functionality, and protocols to build, launch, and operate blockchain applications (Buterin, 2014; IBM Corp., 2019). There are many different providers for blockchain platforms, following different intentions and using different configurations. Two of the most famous platforms – *Bitcoin* and *Ethereum* – originate from electronically secured and trusted transactions (Buterin, 2014; Nakamoto, 2008), generally known as cryptocurrencies. *NEM* and *Quorum*, an advancement of Ethereum, are further examples of blockchain platforms for cryptocurrencies (BloodyRookie et al., 2018; Consensys, 2018). Similarly, *G-Coin* manages the digital ownership of one gram of responsible gold kilobars (Qenta, 2022). Although these platforms focus primarily on tracing financial transactions, new developments have enabled them (except Bitcoin) to be used in other application areas. However, the Hyperledger Foundation provides platforms, including *Hyperledger Fabric*, *Hyperledger Sawtooth*, and *Hyperledger Besu*, to improve business processes more comprehensively through a shared database (Blummer et al., 2018; Lusard et al., 2021).

A *smart contract* is a transparent and immutable program executed if predefined terms and conditions are met without any action from intermediaries (Buterin, 2014; Finck, 2019). Smart contracts are implemented to automate transactions and enable blockchain-based applications (Finck, 2019). Smart contracts are manifold: They execute and verify ownership transactions, manage automatized payments, or process data queries (Lin et al., 2019; Malik et al., 2022; Queiroz et al., 2019). One example of a smart contract might be implementing procurement processes. The smart contract might describe the conditions (item quality and quantity, price, etc.). The payment is triggered if the receiving party confirms the reception of the items as defined in the smart contract. For both products and payments, the necessary data could be stored in the blockchain, and the smart contract controls the adjustments, such as the stored ownership of the items or the payment in the case of digital currency.

2.3. Real-world use cases of blockchains in the FSC and PSC

Although blockchain is a new concept for distributed data storage, the first prototypes and implementations of Blockchains in food and pharmaceutical SCs exist. In the following, we present some use cases. These examples are intended to represent a selection of existing use cases in addition to and independent of the literature review performed and do not claim to be exhaustive. We focus on real-world applications by companies rather than examples from research.

Blockchain technology was not utilized in the food industry until Carrefour became a pioneer in Europe. In March 2018, Carrefour implemented blockchain for the first time in its Auvergne Filière Qualité Carrefour (FQC) chicken (Carrefour, 2022). By 2019, Carrefour began expanding the use of blockchain across several Carrefour Quality Lines, including Auvergne chicken, Cauralina tomatoes, farm-raised eggs from Loué, Rocamadour AOC cheese, Gillot fresh milk, Norwegian salmon, and Christmas chicken.

Albert Heijn, a Dutch supermarket, implemented a blockchain-based system for its own brand of orange juice, allowing consumers to trace the product's journey from farm to shelf via a QR code and smartphone app (Southey, 2019). The system provides detailed information about the oranges' origin from Rainforest Alliance-certified farms, harvest time, and sweetness while also addressing sustainability concerns and promoting transparency in the supply chain. This collaborative effort between Albert Heijn, Louis Dreyfus Company Juice, Refresco, and Supply Chain Information Management not only enhances consumer trust but also aligns manufacturer concerns with customer interests, covering aspects such as worker conditions, environmental impact, and product quality.

Princes Group addressed the challenge of siloed sourcing data by creating a transparent and accessible digital experience to showcase its sustainability initiatives (Provenance Ltd, 2024). Using blockchain-enabled software integrated with SAP ERP, the company provides dynamic, evidence-backed information about the journey and impact of its canned tuna from sea to shelf. This transparency is accessible to consumers via on-pack QR codes and retailers through an online Transparency Hub. The initiative has enhanced industry credibility, strengthened customer loyalty, and enabled scalable solutions for other product ranges, such as mackerel and salmon.

Sonoco ThermoSafe is creating PharmaPortal™, a vendor-neutral blockchain platform powered by IBM Blockchain Transparent Supply, to improve transparency and traceability in the pharmaceutical supply chain (IBM, 2024). This platform focuses on providing comprehensive tracking of temperature-controlled medications, including an audit trail for monitoring environmental conditions, to safeguard the effectiveness of essential drugs. By establishing a permissioned, industry-wide network, PharmaPortal™ will facilitate collaboration between pharmaceutical manufacturers and carriers, enhancing visibility and transparency across the distribution process and tackling challenges in drug sourcing and logistics.

In clinical trials, blockchain ensures data integrity by securely storing trial data in an immutable ledger (Quantzig, 2024). This transparency facilitates real-time access for researchers, regulators, and participants, reducing errors and accelerating the trial process. Further, blockchains enable patients to control access to their health records through private and public keys, reducing reliance on third parties and enhancing privacy. The technology's immutable nature ensures that health information cannot be deleted or tampered with, providing a secure method for managing electronic health records.

3. Methodology

The central part of this work included a comprehensive literature review, which followed an adjusted version of the PRISMA methodology (Page et al., 2021). Fig. 1 provides an overview of the basic steps of this work.

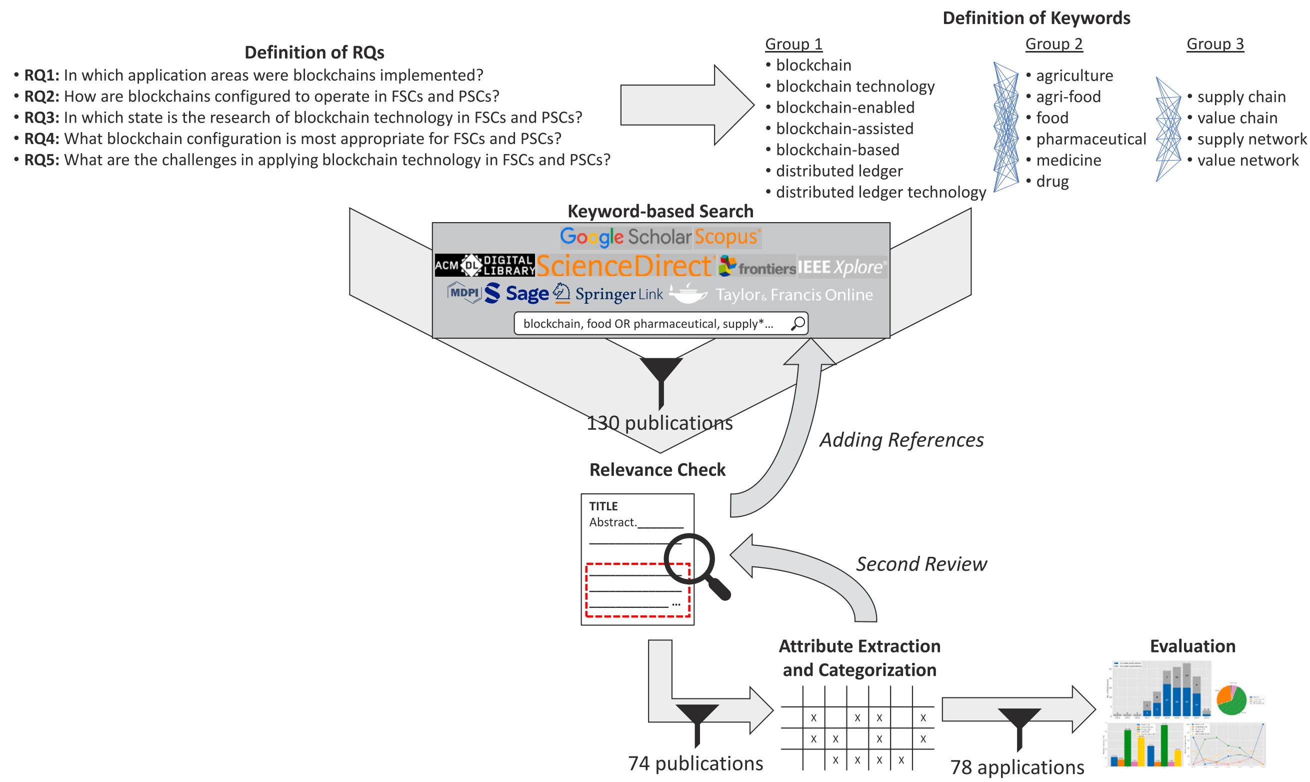


Fig. 1. Overview of the methodology for the classification in this survey. Publications found through a keyword-based search were first selected based on the title and abstract. Afterward, the publications were analyzed, and relevant publications were categorized in a previously defined taxonomy.

3.1. Definition of research questions

The underlying research questions are derived from the research goals. First, literature on profound blockchain applications in food and pharmaceutical SCs was analyzed regarding specific product categories and their reasons for use (RQ1). The detailed analysis of the implemented blockchain technology continued the research to investigate the current state of the art and ongoing trends (RQ2), focusing on network types, platforms, consensus protocols, data storage, and data access techniques. Further, assessing the blockchain applications' Technology Readiness Levels (TRLs) determined the deployment state (RQ3). Proposing a general blockchain framework analyzed the applicability and benefits of blockchain technology in FSCs and PSCs (RQ4). Then, we discuss opportunities and challenges to implement this framework (RQ5). These considerations led to the following research questions:

- **RQ1:** For which products and purposes were blockchains in FSCs and PSCs used?
- **RQ2:** How are blockchains configured to operate in FSCs and PSCs?
- **RQ3:** What is the state of blockchain deployment in FSCs and PSCs?
- **RQ4:** What blockchain configuration is most appropriate for FSCs and PSCs?
- **RQ5:** What are the challenges in applying blockchain technology in FSCs and PSCs?

3.2. Literature review

We followed the PRISMA approach as the methodology for the literature review. It is divided into three steps: identification, screening, and inclusion (Page et al., 2021). The keyword-based search to identify relevant literature covered a wide range of publications. The found literature was initially selected based on title and abstract, followed by a relevance analysis based on a full paper screening applying exclusion and inclusion criteria. Subsequently, we classified descriptions and properties of the blockchain applications. The following describes these steps in detail.

3.2.1. Identification

To find blockchain applications in food and pharmaceutical SCs (answering RQ1 to RQ3), we conducted a literature review and included publications available until the end of September 2023. Therefore, we searched the databases Google Scholar and Scopus and the online libraries from ACM, Elsevier, Frontiers, IEEE, MDPI, SAGE Publications, Springer, and Taylor and Francis.

The creation of three groups of keywords allowed an extensive literature search. The first group was concerned with blockchain technology, including the keywords `blockchain`, `blockchain technology`, `blockchain-enabled`, `blockchain-assisted`, `blockchain-based`, `distributed ledger`, and `distributed ledger technology`. While the second group addressed a specific SC, containing the keywords `agriculture`, `agri-food`, `food`, `pharmaceutical`, `medicine`, and `drug`, the third group related to the SC itself, i.e., consisting of the keywords `supply chain`, `value chain`, `supply network`, and `value network`. The search was performed by combining each of the keywords of all groups, resulting in 168 combined search strings.

Additionally, publications not found directly complemented the literature list if they were referred by other publications and possibly relevant to this research (backward search). The literature search process also identified reviews, which were only included if they provided their own blockchain application. Furthermore, conducting a free web search with Google and DuckDuckGo allowed us to find blockchain applications in the food and pharmaceutical industries. While this search provided many results, a few (BlockGrain, 2018; Farm2Kitchen, 2018; IBM Corp., 2019; Rakic et al., 2017) completed the list as the detail level was often not precise enough for classification.

3.2.2. Screening

The authors selected the publications based on the title and abstract. Additionally, the entire paper was searched to overcome the disadvantages of a keyword-based search. Therefore, the publication must fulfill the following criteria: First, the works must have been published after 2008, as this is the year the predominant work on blockchain technology was published (Nakamoto, 2008). Second, the works must describe the application of blockchain technology to regulate, control, improve, optimize, trace, or track the supply of products. Third, the works must show a relation to food or pharmaceutical products.

The initial set of 130 publications was investigated regarding the described use of blockchain technology based on an assessment of TRLs. If it was impossible to determine the TRL of the related application, the application was excluded.

3.2.3. Inclusion

We used the resulting set of 74 included publications and retrieved the relevant information for the analysis. Using the research questions as the foundation, we derived a taxonomy with properties of the blockchain applications. Each publication was reviewed and classified according to the taxonomy by one of the authors. In addition to the metadata analysis regarding publication type and publication date, the targeted SC and applied blockchain configuration were determined and added to the taxonomy to answer RQ1 and RQ2. Further, the TRLs determined the state of maturity of blockchain applications (RQ3).

Afterward, another of the authors reviewed each classification. If an application was classified differently, all authors discussed the classification. It is worth mentioning that the characteristics must have been available in the publication; for example, the authors did not assume a specific consensus protocol if only the platform used was mentioned.

4. Results

In total, 130 publications were analyzed, from which 74 (around 56.9%) were included after applying inclusion and exclusion criteria. The publication range spanned works from 2014 to 2023. However, publications included only range from 2017 to 2023. Further, as the considered time period ends in September 2023, the number of publications from 2023 is lower, with 2 included publications.

Of the selected publications, the majority (63.5%) were originally published in journals, followed by conference publications (29.7%, see Fig. 2(a)). Further, we included non-peer-reviewed publications (6.8%) from books (1 publication) and white papers (4 publications). Including non-scientific publication types is appropriate for several reasons: Blockchain technology is still a relatively young research topic (particularly in the food and pharma industries), and the research is driven by the industry since the implementation of blockchains for traceability applications is strongly practice-oriented. However, non-scientific publications often do not provide sufficient details for a classification; hence, this number of included works is limited.

In the following, this section answers the research questions regarding the use of blockchain technology in food and pharmaceutical SCs (RQ1), the configuration of the blockchain applications (RQ2), and the maturity of blockchain applications in FSCs and PSCs (RQ3).

4.1. Targeted supply chains and intended use

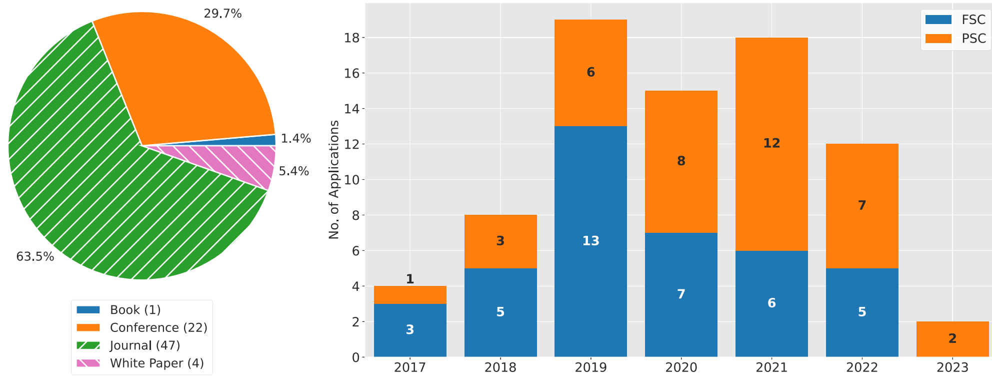
The 74 included publications provided a total of 78 blockchain applications, of which 39 applications (50.0%) were related to the FSC and 39 applications (50.0%) were related to the PSC (Fig. 2(b)). This section answers the first research question:

- **RQ1:** For which products and purposes were blockchains in FSCs and PSCs used?

Fig. 3(a) shows the share of specific FSC groups in which the blockchains were applied. Most applications (38.5%) did not specify a specific FSC. Hence, they were classified as not available. Apart from this group, the majority (23.1%) was applied in grain SCs. The second most frequent area (15.4%) was dairy product SCs. Further application SCs were related to alcoholic beverages (7.7%), meat and seafood (7.7%), fats and oils (2.6%), fruits and vegetables (2.6%), and general perishable foods (2.6%). It is worth mentioning that although dairy products, meat and seafood, and fruits and vegetables are also considered perishable foods, we noted them as separate categories to provide a more fine-grained overview of blockchain applications.

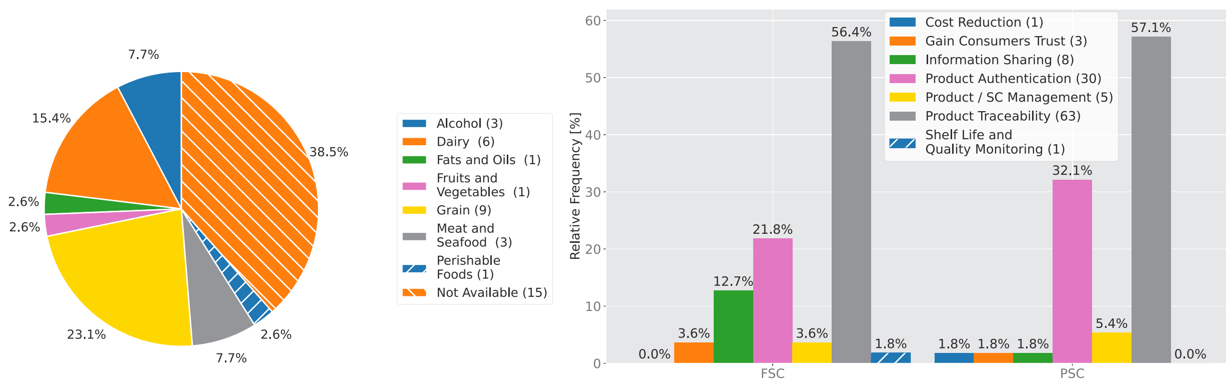
Compared to the FSC, it was impossible to classify the blockchain applications to specific PSCs since most publications considered a more general application of the blockchain technology. A reason could be that most PSCs are – to a certain extent – standardized and uniform due to the strict regulatory environment in which they operate. Worth mentioning are the 7 blockchain applications dealing specifically with COVID-19 vaccines (Antal et al., 2021; Chauhan et al., 2021; Das et al., 2021; Egala et al., 2022; Kamenivskyy et al., 2022; Verma et al., 2022). Furthermore, one application each was related to non-specified vaccines (Yong et al., 2020) and to returned drug supply (Debe et al., 2020). However, the major proportion did not specify a specific PSC.

In addition to the analysis of SCs, Fig. 3(b) provides an overview of the intended uses of the blockchain application. In total, 55 and 56 intended uses were identified for FSC and PSC, respectively. Most applications focused on product traceability, containing 56.4% of FSC applications and 57.1% of PSC applications. These applications focused mainly the assurance of food safety and good food quality, the prevention of pharmaceutical product counterfeiting, and the safety of medicines. Thereby, some applications specifically monitored the compliance of cold chains. Furthermore, one application tracked food items to allow farmers to verify their income and another to enable faster product recalls. Product authentication was the second most frequent intention, with 21.8% and 32.1%, respectively. The FSC-related applications were mainly applied to products with unique characteristics that defined the unique quality of these products. These included the product's origin of coffee, wine, or Carasau bread, but also the product's conditions of manufacture of Extra Virgin Olive Oil, liquors, dairy products, meat, or grains (wheat and organic oats). Regarding the PSC, the applications verified the medicines to combat counterfeit pharmaceutical products. Further reasons to apply blockchains that the FSC and PSC have in common were the sharing of product information (12.7% and 1.8%, respectively), the gaining of consumers' trust (3.6% and 1.8%, respectively), and the management of products or the SC (3.6% and 5.4%, respectively). Reasons to share product information with SC stakeholders were to cope with information fragmentation in order to improve demand predictions (Bapatla et al., 2023), ensure product quality (Behnke & Janssen, 2020; Casino et al., 2019, 2021), ensure food safety (Salah et al., 2019; Zhang et al., 2020), allow faster food recalls (Malik et al., 2018), and reduce food losses and administrative overheads (BlockGrain, 2018). Other applications were implemented to increase consumer trust due to increased transparency (Kamenivskyy et al., 2022; Shahid, Almogren et al., 2020; Shahid, Sarfraz et al., 2020). Further applications managed the distribution of vaccines (Verma et al., 2022), the recall of products (Agrawal, Minocha et al., 2022), and handling uncertainties in different SC parts by allowing them to adapt the manufacturing process (Zhang et al., 2021). Two applications combined blockchain with machine learning techniques to recommend appropriate drugs (Abbas et al., 2020) and to optimize profits (Chen et al., 2021). 1 application (1.8%) focused on shelf life and quality monitoring (Tsang et al., 2019), which is particularly important for food but also pharmaceutical products. Similarly, one application (1.8%) in the PSC aimed to reduce management and distribution costs (Kamenivskyy et al., 2022).



(a) (b)

Fig. 2. Overview of the literature review – (a) Share of the publication type of 74 included publications and (b) Distribution of 78 included blockchain applications in food and pharmaceutical supply chains (FSC and PSC, respectively) per year.



(a) (b)

Fig. 3. Overview of blockchain applications – (a) Targeted FSC of blockchain applications and (b) intended uses of blockchain applications. As several applications followed multiple intentions, the total number of counts is 111.

4.2. Blockchain configuration

This section analyzes the literature regarding the configuration of blockchain applications in order to answer the following research question:

- **RQ2:** How are blockchains configured to operate in FSCs and PSCs?

Therefore, this research question contains five dimensions, which are answered in subquestions, investigating which blockchain network types were applied (RQ2.1, cf. Section 4.2.1), which blockchain platforms were used (RQ2.2, cf. Section 4.2.2), which consensus protocols were applied (RQ2.3, cf. Section 4.2.3), which data storage systems were integrated (RQ2.4, cf. Section 4.2.4), and which techniques to manage the access to confidential data were applied (RQ2.5, cf. Section 4.2.5).

4.2.1. Applied network types

One of the most critical decisions is selecting blockchain network type, which also influences the choice of blockchain platforms and consensus protocols. Therefore, this section answers the following research question:

- **RQ2.1:** Which blockchain network types are applied in FSCs and PSCs?

In both SCs, the majority used permissioned networks, containing 59.0% of applications in FSCs and 74.4% in PSCs. Further, 2.6% and 10.3% of applications are permissionless networks in FSC and PSC, respectively. 1 application in FSC and 2 applications in PSC (5.1% and 2.6%) followed a hybrid approach, combining a permissionless and a permissioned network (Jaisimha & Kumar, 2022; Khan et al., 2022; Sun et al., 2019). Finally, 33.3% and 12.8% of applications could not be classified; hence, they were marked as unavailable.

Fig. 4(a) shows the relative frequency of applied network types separated for both SCs. Private blockchains are applied most frequently in FSCs and PSCs, with 41.0% and 48.7%, respectively. Further, 10.3% of FSC and 23.1% of PSC applications implemented public blockchain networks, and 7.7% and 5.1% consortium networks. 5.1% and 5.1% of the applications applied hybrid networks, combining a public and private blockchain (BlockGrain, 2018; Jaisimha & Kumar, 2022; Khan et al., 2022; Subramanian et al., 2021). Finally, 35.9% and 17.9% of applications were unavailable since the related publications did not explicitly specify the network types.

Fig. 4(b) presents the timeline of applied network types. Due to the low number of included works in 2017 and 2023, the focus will be on 2018 to 2022. Overall, the use of private blockchains is decreasing. While in 2018 and 2019, more than 60.0% of all applications were configured as private networks, they were still 46.7% and 44.4% in 2020 and 2021, respectively, but only 8.3% in 2022. In contrast, the application of public blockchains increased from 0.0% in 2018 over 5.3% and 20.0% in 2019 and 2020, respectively, to 22.2% in 2021. In 2022, 16.7% of the applications were public networks, indicating a slight decrease. Consortium blockchains and hybrid approaches also showed an increasing trend in the later years. While both shared 12.5%

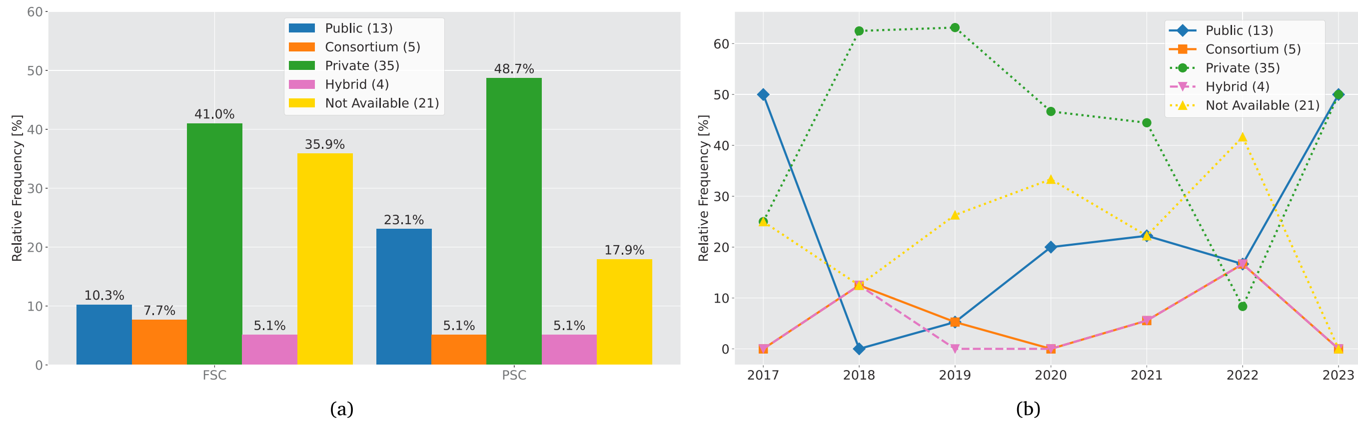


Fig. 4. Overview of applied blockchain network types – (a) Applied blockchain networks in FSC and PSC and (b) timeline of applied network types.

in 2018, their proportions first decreased from over 5.3% of consortium blockchains and 0.0% of hybrid approaches in 2019 to 0.0% in 2020. Afterward, the share of consortium and hybrid networks increased to 5.6% and 16.7% in 2021 and 2022, respectively.

Private blockchain network types were selected primarily due to high security and confidentiality requirements (Pandey & Litoriya, 2021; Shahid, Almogren et al., 2020; Uddin et al., 2021). The same holds for consortium blockchains, but they further reduce the dominant influence of a single decision maker (Baralla, Pinna et al., 2019; Malik et al., 2018), and they include all stakeholders (Kamenivskyy et al., 2022). Similarly, hybrid approaches were chosen to restrict access to confidential data (Subramanian et al., 2021), enable activities within SC such as finance or logistics (Subramanian et al., 2021), and manage the amount of data (BlockGrain, 2018) by using the private network, but also to verify transactions (Khan et al., 2022) and provide traceability (Jaisimha & Kumar, 2022) by using the public network. Public blockchains were used to incorporate public participation in the model (Antal et al., 2021), to allow all members to check and verify the data (Debe et al., 2020), and to increase trust in their SC, and, in particular, build trust in a vaccine's effectiveness by connecting the blockchain to a public reporting system of side effects (Antal et al., 2021).

4.2.2. *Used blockchain platforms*

Many different blockchain platforms are available, allowing different configurations. Thus, this section answers the following research question:

- **RQ2.2:** Which platforms are used in FSCs and PSCs?

Fig. 5(a) shows the relative frequency of used blockchain platforms separated for both SCs. The most used platform is Ethereum, with 50.0% and 38.5% of applications in FSCs and PSCs, respectively. The second largest share of applications deployed Hyperledger Fabric at 22.5% in FSCs and 25.6% in PSCs. Further, 5.0% and 5.1% applied Hyperledger Sawtooth in FSCs and PSCs, respectively, and 5.1% Hyperledger Besu in PSCs only. 1 application each used Multichain, Quorum (both in FSC), G-Coin, and NEM (both in PSC), making 5.0% and 5.1% of others. Finally, 12.5% and 5.1% developed their own blockchain implementations, and 5.0% and 15.4% did not specify the platforms used in FSCs and PSCs, respectively.

The blockchain platform timeline analysis did not identify any clear trends. Ethereum and Hyperledger Fabric were the most used platforms. While the use of Ethereum first increased from 33.3% in 2018 to 53.3% in 2020 and decreased afterward, Hyperledger Fabric was constantly at approx. 30.0% used after 2019. It is worth mentioning that the development of own blockchain implementations decreased, sharing 22.2% in 2018 and dropping steadily to 0.0% in 2022.

Ethereum was selected since smart contract deployment is integrated (Salah et al., 2019; Shahid, Almogren et al., 2020). This is also why Hyperledger Fabric was chosen (Yang et al., 2021). In addition, Hyperledger Fabric provides high modularity (Blummer et al., 2018), enabling the development of individual distributed ledger-based SCs and the flexibility of implementing the models into practice (Arena et al., 2019; Kumar et al., 2019). For similar reasons, Hyperledger Sawtooth was deployed, which was additionally supplemented by its novel consensus protocol that was particularly suitable for tiny devices (Caro et al., 2018) and the written permissions and rules to access the SC (Baralla, Pinna et al., 2019). Proprietary platforms were developed within the development of completely new conceptual frameworks or to test theoretical models to various degrees (Chen et al., 2021, 2020; Khan et al., 2022; Mondal et al., 2019; Tsang et al., 2019). However, due to the decrease in proprietary platforms, one can assume that the blockchain platforms provide enough possibilities, and it is no longer necessary to customize a blockchain.

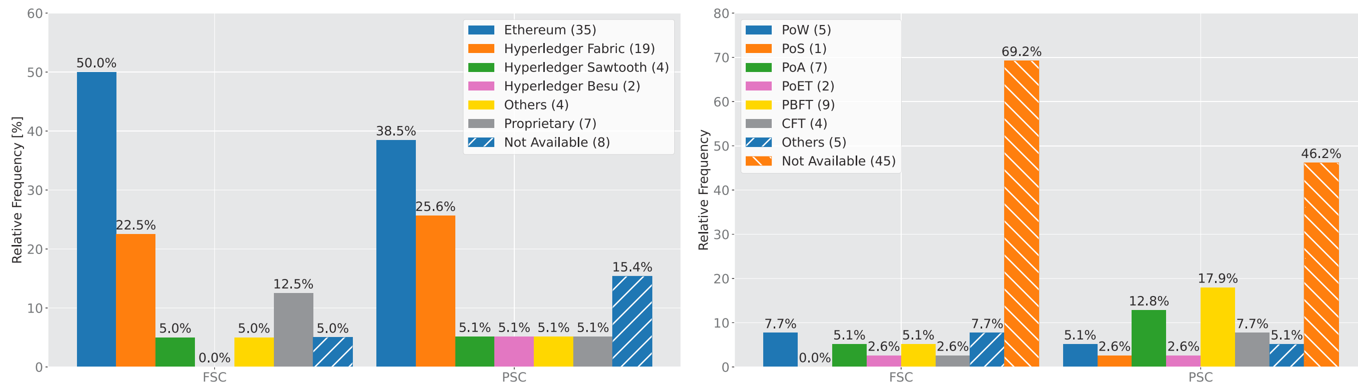
4.2.3. *Applied consensus protocols*

The choice of consensus protocols is strongly related to the selected network structure and used blockchain platform since they follow different principles depending on the participating nodes. This section answers the following research question:

- **RQ2.3:** Which consensus protocols are applied in FSCs and PSCs?

Fig. 5(b) shows the relative frequency of applied consensus protocols separated for both SCs. Most of the publications did not mention the consensus protocol applied or considered. Hence, 69.2% and 46.2% of applications in FSCs and PSCs, respectively, were marked as not available. Most applications specifying the consensus mechanism followed PBFT algorithms, containing 5.1% in FSCs and 17.9% in PSCs. PoA was applied by 5.1% and 12.8% and PoW by 7.7% and 5.1% of applications in FSCs and PSCs, respectively. 2.6% and 7.7% of FSC and PSC applications applied CFT. Further, one application each used PoET in FSCs (2.6%) and in PSCs (2.6%), as well as PoS (2.6%) in PSC. Finally, 7.7% in FSCs and 5.1% in PSCs were summarized under "Other", including a Proof-of-Object (PoO), a Proof-of-Supply-Chain-Share (PoSCS), and a proprietary algorithm (1 application each) in FSCs, and a Proof-of-Consequentiality (PoC), and Solo – a single ordering node based algorithm used in Hyperledger Fabric test networks (Hyperledger Foundation, 2023) – with 1 application each in PSCs.

PoO works similar to PoW as other nodes verify that a node cryptographically proved the physical possession of an object (Mondal et al., 2019). PoSCS is similar to PoS as the validators, which are SC stakeholders, are selected based on a normalized SC share – a metric that



(a) (b)

Fig. 5. Overview of used platforms and applied consensus protocols – (a) Blockchain platforms in FSCs and PSCs. As one FSC application (BlockGrain, 2018) combines two platforms, the total number of counts is 79. (b) Consensus protocols in FSC and PSC blockchain applications.

considers further parameters as the stakeholders' interest in and their effort to achieve traceability (Tsang et al., 2019). Rakic et al. (2017) suggested a proprietary approach in which the stakeholders approve each other using ZKPs to verify confidential information, and supervising organizations can validate data. The approach of Subramanian et al. (2021) did not only consider blockchains to provide product traceability but also to buy medicines with cryptocurrency. This allows the selection of validators based on "how long a [user] kept an astronomically immense balance in [their] wallet", which they call PoC.

Regarding the development of applied consensus protocols over time, no clear trend regarding a particular consensus protocol is apparent. PoA slightly increased from 0.0% in 2018 to 16.7% in 2022, but it is not dominating other consensus mechanisms. Worth mentioning is that the proprietary algorithms were mainly developed in the earlier years (the approach by Rakic et al. (2017) in 2017, the PoO and PoSCS both in 2019, and the PoC as an exception in 2021). However, as Ethereum enabled only the use of PoW until 2022 but also established PoS in 2022 (Ethereum Foundation, 2022), the share of PoW is assumed to be higher and the share of unavailable protocols to be lower.

The deployment of the consensus protocol is strongly related to the network type, e.g., PoA is used in permissioned networks, as trust among participants is required (Mattke et al., 2019; Sunny et al., 2020). However, there are several reasons to consider other consensus protocols, such as security, scalability, throughput, and energy consumption (Singh et al., 2020). For instance, due to its enhanced security, PoW was the preferred consensus protocol in public networks (Antal et al., 2021). However, the nodes require lots of energy to become miners because of the tough calculation competition (Yan, 2022). As the total number of currency, e.g., Bitcoins, is limited to an upper number, the required calculation increases complexity, resulting in increased energy needs. However, this is not associated with the required energy of the blockchain to maintain the blocks; it is only associated with the process of creating new information defined by the cryptocurrency. Nevertheless, PoS is often preferred to overcome this drawback (Ethereum Foundation, 2022). Furthermore, PoS does not differentiate among participants, which works to eliminate bias and empower individuals (Ferdousi et al., 2020). Regarding scalability and throughput, PoA is an alternative to PoW as it is less computationally expensive, faster at processing complex functions, allows more data to be stored, and facilitates improved data security (Ferdousi et al., 2020; Kamenivskyy et al., 2022). Similarly, PBFT mechanisms require fewer resources to provide fast processing times and security against attacks (Arena et al., 2019; Egala et al., 2022; Saxena et al., 2020; Zhu et al., 2020).

4.2.4. *Integrated data storage systems*

Blockchains record information such as transactions but can also store data such as sensor data. However, the integration of several data storage systems was recognized during the literature review. Hence, this section answers the research question:

- **RQ2.4:** Which systems are used to store data in FSCs and PSCs?

Fig. 6 shows the systems that are applied to store data. Most stored data directly on the blockchain, accounting for 35.9% of FSC and 56.4% of PSC applications. Further, data was entirely stored off the blockchain in 38.5% and 20.5% of applications in FSCs and PSCs. Thereby, 6 FSC applications and 4 PSC used an InterPlanetary File System (IPFS) – a distributed peer-to-peer (P2P) storage network. Data was stored in local databases in 4 FSC and 2 PSC applications, respectively. Additionally, 3 and 2 of FSC and PSC applications applied cloud storage. 1 FSC application stored the data in another decentralized P2P network (Rakic et al., 2017), and another application did not specify the off-chain storage system (Xu et al., 2019).

12.8% of FSC and 12.8% of PSC applications applied hybrid concepts, meaning they combined storing data on the blockchain and another storage system. From that, 2 FSC and 1 PSC applications integrated a local database. Furthermore, 1 FSC and 1 PSC applications combined the blockchain with cloud storage. 1 application of each SC integrated an IPFS, and 1 FSC and 2 PSC applications did not further specify the storage system to combine the blockchain with. Finally, 12.8% of FSC and 10.3% of PSC applications could not be classified; hence, they were marked as unavailable.

Data stored directly on the blockchain mainly contained information regarding authentication and traceability, such as locations, timestamps, certificates, expiry dates, and batch sizes and quantities. Most applications tracked the change of ownership and the origin of raw materials. A few applications also stored tracking information concerning sensor data on the chain (Arena et al., 2019; Hulea et al., 2018). However, coping with the massive amount of data is usually a reason to store data only partially on the blockchain (Khan et al., 2022; Malik et al., 2019, 2018; Musamih et al., 2021; Salah et al., 2019). The more data is uploaded to the blockchain network, the slower transaction processes and more ineffective query processes become (Casino et al., 2019; Rakic et al., 2017; Yang et al., 2021). Some decided to store data in local databases for data privacy and ownership reasons (Agarwal et al., 2022; Ferdousi et al., 2020). Others selected an IPFS to avoid a possible single point of failure and ensure data availability (Shahid, Almogren et al., 2020; Shahid, Sarfraz et al.,

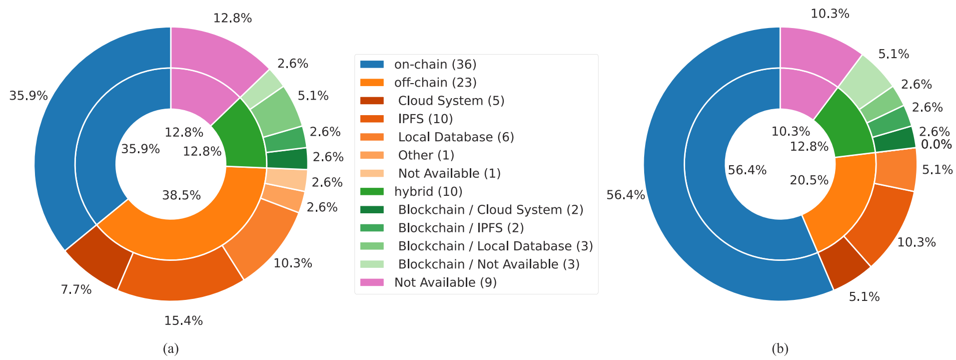


Fig. 6. Applied systems to store data in (a) FSCs and (b) PSCs. The inner pies depict the nature of primary storage, while the outer pies specify the storage systems used.

2020). Further, the integration of cloud storage was argued with the standard system to store data of IoT devices. Another reason to keep data off the chain was to control access to the data (Shahid, Almogren et al., 2020).

4.2.5. Used techniques for confidential data management

Increasing transparency is a key idea of the blockchain technology. However, depending on the intended use (see Section 4.1) and the data shared via blockchain, some information in SCs is confidential and should consequently not be shared to the full extent with all participants. In addition to the network types (see Section 4.2.1) and data storage systems (see Section 4.2.4), this section answers the following research question:

- **RQ2.5:** Which techniques are implemented to manage the access to confidential data in FSCs and PSCs?

Several options exist to manage confidential data regarding privacy and security measures. Depending on the level of privacy, permissioned blockchains might be an easy option since they are only accessible to specific groups of participants (Wang, Yao et al., 2022). Hence, permissioned blockchains ensure that sensitive data is only shared among trusted entities. However, access to confidential data can also be controlled in other network types, e.g., by assigning access rights to specific roles using Access Control Lists (Buterin, 2014; Lusard et al., 2021). Another option is layered architectures such as hybrid blockchains to separate sensitive data from the publicly accessible blockchain layer (Hyun, 2021). The public layer contains non-sensitive data and hashes or references to the confidential data stored in a separate private layer. Alternatively, the data could be stored off-chain while keeping a hash or reference of the data on the blockchain (Wang, Yao et al., 2022). Further, the confidential data could be encrypted before being stored on the blockchain (Habib et al., 2022). Authorized parties with the related decryption keys could access the encrypted data. However, Malik et al. (2022) stated that data encryption is not feasible in blockchains due to the verification process. Therefore, zero-knowledge proofs (ZKPs) are suggested. ZKPs are cryptographic techniques that allow one party to prove knowledge of a specific piece of information without revealing the actual information itself (Wang, Yao et al., 2022). ZKPs can be used in blockchains to verify the validity of confidential data without exposing the data itself.

In both SCs, most applications controlled the access to data stored in the blockchain, containing 48.9% and 46.7% in FSCs and PSCs, respectively. Further, 15.6% and 13.3% of applications in FSCs and PSCs, respectively, encrypted confidential data. Consequently, this encrypted data can only be read by trusted parties which have the corresponding key. Layered architectures were used by 8.9% and 4.4% of applications in FSCs and PSCs, respectively. Other techniques were smart contracts (4.4% in FSCs and 2.2% in PSCs) and ZKPs (2.2% in PSCs only), while 4.4% of applications in FSCs and 11.1% in PSCs did not restrict the data access. Finally, 17.8% and 20.0% of FSC and PSC applications were marked as unavailable due to missing information in the publications. Although smart contracts rely on controlling access to information, they are listed as separate categories to expose their application, and they might include an option to share the requested information. Additionally, ZKPs somehow encrypt data, but the approach by Mattke et al. (2019) is particularly notable since the data cannot be decoded with a matching key.

Applications that did not restrict access to data in the blockchain focused mainly on product traceability and authentication, disclosing the product's origin to ensure the product's safety and quality (Pradana et al., 2020; Yong et al., 2020). Other applications tracked the compliance of vaccines' cold chains (Antal et al., 2021; Chauhan et al., 2021). Further, Das et al. (2021) considered transnational SCs, which shared information across a public blockchain. Another application targeted the disclosure of fair payments for farmers (Sudha et al., 2021). All applications had in common that they (i) did not share private information or (ii) the information was of public interest. Thereby, the applications of Antal et al. (2021) and Pradana et al. (2020) used quick-response (QR) codes to retrieve the related information. However, QR codes also provoked the execution of smart contracts, in which the information provided is controlled (Tsang et al., 2019). In general, 84.6% of FSC and 89.7% of PSC applications used smart contracts. Only 10.3% and 2.6% of FSC and PSC applications did not consider smart contracts, and 5.1% and 7.7% could not be classified.

The implementation of data encryption was argued to ensure data privacy for confidential data, such as production costs or recipes (Sun et al., 2019; Zhang et al., 2020). For the same reason, Mattke et al. (2019) applied ZKPs to allow data sharing while keeping data privacy. Furthermore, encryption should provide confidentiality (Singh et al., 2020). It is worth mentioning that the focus was not on consumers but on the system infrastructure, so the block generation would not have been stopped depending on the block's content.

Many applications controlled access to information, basically using permissioned blockchain networks. Similarly, layered architectures were applied to control access to private information stored in private layers (BlockGrain, 2018; Jaisimha & Kumar, 2022; Khan et al., 2022). Furthermore, private layers allow the storage of large data volumes, e.g., sensor data, while coping with transaction times and costs (BlockGrain, 2018; Malik et al., 2019, 2018). However, a public network was still integrated to verify the data and ensure immutability (BlockGrain, 2018; Jaisimha & Kumar, 2022; Khan et al., 2022).

Finally, several applications implemented multiple techniques for the same reasons previously mentioned but to improve the security level further. For instance, Casino et al. (2019) and Zhu et al. (2020) controlled the access to and the editing of information using smart contracts, while (Egala et al., 2022) allowed only verified users to access data. Arena et al. (2019) and Subramanian et al. (2021) further

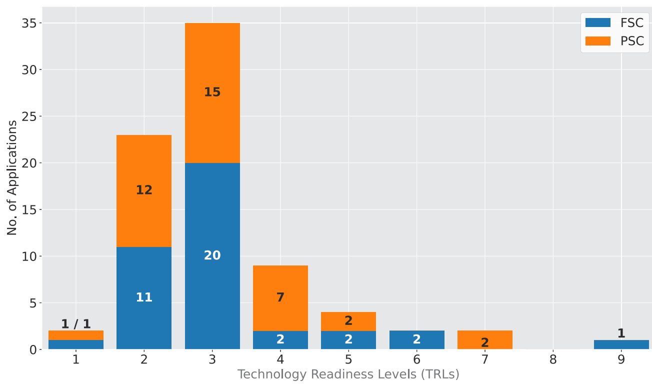


Fig. 7. Overview of 78 investigated applications per Technology Readiness Level (TRL) depicted by SC.

applied data encryption in combination with access control to avoid unrestricted data access. Others argue that the use of layered architectures is mainly for handling large data volumes rather than for data confidentiality reasons (Malik et al., 2019, 2022, 2018); still, those approaches implement data encryption to keep competitive advantages.

4.3. Technology readiness levels of blockchain applications

In order to determine the maturity and deployment of blockchain technology in food and pharmaceutical SCs, the TRLs of the blockchain applications were analyzed, answering the research question:

- **RQ3:** What is the state of blockchain deployment in FSCs and PSCs?

The TRLs provide nine levels – from basic research via technology and system development to system launch (European Commission (EC), 2017). Concept TRLs contain TRL 1, at which basic principles are observed, and TRL 2, which describes the technological concept. Prototype TLs include the actual physical development, beginning at TRL 3. In the following TRL 4, the technology is validated in a laboratory environment, while the technology is validated in a relevant or simulated environment for TRL 5. The development and demonstration of a prototype in a relevant environment is achieved at TRL 6. Lastly, deployment TRLs include TRL 7, demonstrating a prototype in an operational or real-world environment. Further, TRL 8 is usually considered the end of development since the systems are complete and deployed. Finally, the system is fully deployed in operational environments at TRL 9, i.e., the system is in use.

Fig. 7 provides an overview of the number of applications per TRL. In general, most applications were found in prototype levels (TRL 3-TRL 6; 64.1%), followed by concept levels (TRL 1-TRL 2; 32.1%), and only a few applications in deployment levels (TRL 7-TRL 9; 3.8%), i.e., ready for application in companies. In more detail, the majority (44.9%) was assigned to TRL 3, comprising 51.3% of FSCs and 38.5% of PSCs. TRL 2 was the second most frequent level (29.5%), including 28.2% and 30.8% of FSC and PSC applications, respectively. It is worth mentioning that a few PSC applications (11.5%) are at TRL 4, making it the third most frequent level, and the applications in deployment levels (TRL 7–9) were present in 2017 and 2019. Consequently, most applications were in the research and development stages, investigating and attempting various configurations. Therefore, the demands and needs for applying blockchain must be defined. However, the technological capabilities and required knowledge might not have been sufficient to develop deployable applications.

5. Discussion

The literature review identified various configurations for blockchains in food and pharmaceutical SCs. Therefore, Section 5.1 first proposes a general framework for integrating blockchain technology in these SCs. Afterward, Section 5.2 discusses the challenges of implementing blockchain in these SCs and how to overcome them. Section 5.3 closes this discussion with an explanation of threats to validity.

5.1. Proposing a general blockchain framework for food and pharmaceutical supply chains

Although food and pharmaceutical SCs differ in detail, they still have several aspects in common: In both, raw materials are produced and supplied to a manufacturer who processes the final products. Afterward, the products are distributed – often via wholesalers – to retailers or pharmacies, respectively, where they get to the consumer. In this process, the products are usually not sold directly by the manufacturers and pass through long and complex SCs, in which intermediate products can be traded, by-products can be produced, or various product streams converge. Within this process, food and pharmaceutical SCs are strongly regulated by law. Furthermore, the product's origin often determines its quality, and thus, is from interest regarding product price and safety. Hence, traceability of raw materials and all products is crucial. Furthermore, efficient SCM is essential to ensure product quality and safety. Section 4.3 shows that only a few blockchain applications are deployed in the industry. Therefore, based on the results of the literature review, we derived a general framework for applying blockchain technology in food and pharmaceutical SCs. Further, this section discusses the framework to answer the research question:

- **RQ4:** What blockchain configuration is most appropriate for FSCs and PSCs?

Considering the Gartner Hype Cycle for Blockchain and Web3 (Rimol, 2022), blockchain technology is in different development stages: While consensus protocols and platforms were in the trough of disillusionment, most topics, including smart contracts, blockchain interoperability, or blockchain and IoT, were behind the peak of expectations in the descent into the trough. The Gartner Hype Cycle is a graphical tool to determine the deployment and acceptance of technologies in five phases. An enthusiastic peak of interest follows the technology's introduction before the expectations decrease into a trough of disillusionment. Afterward, the expectations increase slightly again, and they finally become productive.

The analysis of TRLs (Section 4.3) revealed only a few applications at deployment TRLs, which could be explained by the small number of white papers included. However, a broader scope of experimentally verified concepts (prototype levels) was suggested in the literature over time, indicating a slightly positive trend. Nevertheless, a cursory examination of patent registrations in the PATENTSCOPE Database of the World Intellectual Property Organization (WIPO)[1] using the search string "`blockchain AND (food OR pharma)`" yielded a growing number of applications per year starting from 2015 to the present (2023). Therefore, developing a general framework for integrating blockchain technology in FSCs and PSCs is appropriate to foster research and implementation.

Many decisions on the configuration influence each other. For instance, a particular platform depends on the network type but also determines the choice of the consensus protocol. Further, responsibilities such as who provides and maintains the (server) infrastructure must be clarified since these define restrictions, e.g., who validates data blocks and adds them to the chain. Additionally, as the literature review

[1] https://patentscope.wipo.int/search/en/search.jsf (Last Accessed 18/12/23)

revealed a variety of product categories and intended uses, and each SC is unique, the blockchain framework must still be customizable.

Most applications used permissioned and private blockchain networks mainly to control access to the network and information stored. However, applying a consortium blockchain would overcome the dependency on a single decision-maker (Baralla, Ibba et al., 2019; Malik et al., 2018). Although the network access is permissioned, the network must allow new stakeholders, e.g., another retailer, to be added.

Deciding on a specific platform is more complicated. Ethereum and Hyperledger Fabric were most applied, often justified by enabling smart contracts. Implementing smart contracts is a key point since they allow information retrieving and enable more complex SCM actions. Some advantageous actions would be an automated quality assessment, the control of compliance with the cold chain, demand predictions, or automated product distribution. Regarding the consensus protocol, applying PoA or similar is reasonable since it does not only select the validator based on the identity (or SC share) but also on the node's reputation. This could be used to promote the stakeholders' interest and effort to achieve traceability and trustworthiness. Furthermore, PoA achieves a high throughput and fast processing times while consuming little energy compared to PoW. However, the authors of this work suggest using Hyperledger Fabric as a platform since its identity management is better than Ethereum's (Uddin et al., 2021), and it also provides high modularity. Moreover, Hyperledger Fabric allows the creation of so-called channels where organizations can share information with channel members rather than the complete network. Additionally, PBFT and CFT algorithms have characteristics similar to PoA.

Concerning data storage, many publications suggest storing the data off the chain, particularly if they include sensor data or data from IoT devices. Only the related data hashes should be stored on the chain to verify the data while keeping scalability and reducing processing costs, which seems reasonable. Nevertheless, data availability must be ensured, e.g., by integrating an distributed file storage system. The permissoned network also controls access to confidential data. For instance, a smart contract could be executed via a QR code to provide a consumer with information. The smart contract would check which information the consumer can see, e.g., the product's origin or production date, but not the price that the manufacturer paid for raw materials. Additionally, further techniques such as encryption might be applied to enhance security.

As applying blockchain involves many decisions and some compromises, the proposed framework is not definitive. Another option could be a hybrid blockchain, consisting of a private layer to store confidential data and a public layer. While the private layer would be structured similarly to the previously discussed approach, the public layer might increase the SCs' trustworthiness by incentivizing the public stakeholders with a high level of involvement with a product to act as validators. However, the more complex the implementation becomes, the more computing resources and knowledge are required (Zhao et al., 2019). Therefore, the suggested permissioned consortium blockchain is currently preferable.

5.2. Challenges in implementing blockchains in food and pharmaceutical supply chains

In addition to the previously described potentials of blockchain, their implementation in food and pharmaceutical SCs faces several challenges. The applications considered various food products, from alcoholic beverages to perishable products like dairy products, fruits and vegetables, or meat and seafood, and pharmaceutical products, including drugs, medicines, or vaccines. However, as every SC is unique, some challenges remain in applying blockchain in food and pharmaceutical SCs. Hence, this section discusses these challenges and ways to solve them, answering the research question:

- **RQ5:** What are the challenges in applying blockchain technology in FSCs and PSCs?

Motivation: Stakeholders must see an advantage in implementing blockchains in their SCs (Nam Vu & Bourlakis, 2023). Consumer interest in more product traceability is one of the main drivers of blockchain implementation (Damoska Sekuloska & Erceg, 2022). Additionally, consumers see the need for technological innovation in order to reduce food waste (Henrichs et al., 2025). Integrating IoT devices to monitor food quality in real-time might contribute to this. Nevertheless, checking the suitability of applying blockchains for a specific SC or product is necessary since low-value products or small, local SCs do not benefit from blockchain technology (Musamih et al., 2021; Nam Vu & Bourlakis, 2023). Additionally, each SC contains a leading organization that is, from the consumers' point of view, responsible for a product (Kramer et al., 2021). Usually, retailers are mainly responsible for compliance with regulations (van Hilten et al., 2020) as they must ensure that the food is safe when placed on the market (The European Parliament and the Council of the European Union, 2002). Thus, the leading organization, as well as other stakeholders, can enforce the remaining stakeholders to use blockchain technology (Ghadge et al., 2023). Therefore, public awareness and knowledge about the benefits of the technology are required (Kumar et al., 2022; Treiblmaier et al., 2021). Furthermore, the blockchain-enabled system might provide incentives, e.g., financial, to motivate the stakeholders (Lo et al., 2019). Nevertheless, organizations might have concerns that must be discussed. Trust between the SC stakeholders is a crucial requirement (Damoska Sekuloska & Erceg, 2022; Kumar et al., 2022; Okorie et al., 2022). However, stakeholders already rely on each other, and thus, a minimum of trust is given, which could not be further enhanced technically (Okorie et al., 2022). Implementing blockchains could increase reliability by lowering the risk of information loss due to reduced paperwork (Katsikouli et al., 2021). The integration of IoT could further improve the continuous tracing of relevant parameters. Furthermore, additional techniques like machine learning could improve the SC's resilience by optimizing demand forecasting (Krupitzer & Stein, 2021). The COVID-19 pandemic recently disclosed SC issues (Blossey et al., 2021). Nevertheless, the associated concerns of potential deskilling, a common aspect in introducing emerging technologies, are without foundation since every new technology requires new skills (Kamilaris et al., 2019). Concerns regarding information disclosure (Treiblmaier et al., 2021) could be solved by the blockchain configuration, e.g., the application of access control. While leading organizations might have enough resources to implement blockchain, it is challenging for smaller SC actors (Damoska Sekuloska & Erceg, 2022; Nam Vu & Bourlakis, 2023). Thus, a fair distribution of profits between the SC actors and the support of smaller stakeholders (by the leading organizations) are necessary.

Laws and Regulations: Governmental laws and regulations are additional drivers that provide the legal framework for blockchain implementation. On the one hand, laws and regulations must allow the use of blockchain and associated technologies (Okorie et al., 2022). On the other hand, they could force SC stakeholders to implement blockchain, e.g., the Drug Supply Chain Security Act by the FDA requires "to collaborate and generate an electronic and interoperable system to trace prescribed drugs through their physical movement" (Ghadge et al., 2023). Blockchain could also facilitate the enforcement of regulations (Kamilaris et al., 2019) such as the Canadian Cannabis Act to regulate the legal cannabis supply (Canadian Minister of Justice, 2018) or the German Supply Chain Act to ensure compliance with human rights in global SCs (Federal Ministry of Labour and Social Affairs (BMAS), 2023). Besides these national regulations, SCs are often more globally distributed. Thus, new global laws and regulations are required (Damoska Sekuloska & Erceg, 2022; Zhao et al., 2019), particularly regarding standards on traceability (Behnke & Janssen, 2020). The lack of data ownership is another hurdle regarding the responsibility of data maintenance and availability (Kumar et al., 2022). The involvement of governmental institutions in the blockchain network could possibly solve this issue.

Standardization: As SCs are global, they often lack standards (Kumar et al., 2022). Accompanying the required laws, the food and pharmaceutical industries must agree on standards (Behnke & Janssen, 2020; Ghadge et al., 2023), i.e., what information should be stored (Nam Vu & Bourlakis, 2023). Within this regard, country-specific legal regulations must be considered, as well as differences in technological capabilities in developed and developing countries (Kamilaris et al., 2019). However, technological capabilities also differ between stakeholders (Okorie et al., 2022). Therefore, interoperability, i.e., compatibility of different technologies, must be ensured to interact with blockchain (Katsikouli et al., 2021; Zakari et al., 2022). Further, IoT and similar technologies enable the generation of a massive amount of data, resulting in a complex data structure that must be handled (Zakari et al., 2022). Additionally, avoiding redundancy is crucial to reduce processing times. Finally, various cultures might follow different approaches to production planning, demand forecasting, or quality management (Treiblmaier et al., 2021). Thus, standardization is required to meet the demands of subsequent stakeholders. However, the efforts for standardization can also have further benefits as they can reduce the workload and, especially, the costs for interactions.

Costs: The organizations have to manage investment, operational costs, and maintenance costs (Ghadge et al., 2023; Treiblmaier et al., 2021). Particularly, the investment costs at the beginning are deterrent for many SCs. Nevertheless, (financial) rewards are expected after a while, especially for pioneers and larger enterprises (Nam Vu & Bourlakis, 2023). Further, the complexity of the blockchain application must be considered since a higher complexity requires more computing resources (Zhao et al., 2019). However, automatizing processes by implementing smart contracts reduces administration and personnel costs (Kumar et al., 2022). In addition, establishing long-term relationships between stakeholders could reduce costs through more precise forecasts, more efficient resource utilization, and reduced storage costs (Ghode et al., 2020). Another aspect is the acceptance of higher product prices if the consumers are more risk- than price-sensitive (Liu et al., 2022). In summary, the cost estimation is currently uncertain (Treiblmaier et al., 2021) and dependent on various factors. Hence, concerns regarding costs are founded, but long-term development must also be considered as the permanent implementation takes time (Kumar et al., 2022). For instance, IBM and Maersk recently stopped the TradeLens project due to a lack of viability (Kjærgaard-Winther, 2022), again showing the necessity of SC stakeholders' acceptance.

Infrastructure: Establishing the infrastructure for the blockchain application is strongly related to the costs. The infrastructure includes primarily servers and access points to the blockchain network. Although the primary purposes were to improve the traceability and authentication of the products, blockchain could further improve the SCM, integrating IoT and artificial intelligence techniques, e.g., to control the compliance of cold chains (Ghadge et al., 2023). Therefore, sensors and transmission technologies like radio frequency identification (RFID) or near-field communication (NFC) must be implemented to gather real-time information (Treiblmaier et al., 2021). Enhancing these technologies and expanding the network infrastructure to provide sufficient bandwidth (Kumar et al., 2022) is crucial. Nevertheless, deployable frameworks are lacking (Okorie et al., 2022). Particularly, these frameworks must provide enough storage capacity, a high throughput, and a low latency while enabling scalability (Zhao et al., 2019). The frameworks must provide customization since SCs change, e.g., by adding new suppliers or retailers. Further, flexibility is required as recipes or production processes might change. Finally, blockchains need to adapt to established workflows and processes.

Data authenticity: Blockchain technology ensures the integrity and traceability of data across supply chains but relies on accurate initial input (Musamih et al., 2021). Food and pharmaceutical quality assurance can track every step from production to distribution, recording details such as origin, processing dates, and transport conditions. Integrating blockchain with IoT devices enhances this system by automatically uploading real-time data, like temperature or humidity, during storage and transit (Agarwal et al., 2022). For example, a cold chain for vaccines can document temperature compliance, flagging deviations that compromise quality (Ghadge et al., 2023; Hulea et al., 2018). While blockchain secures the recorded data against tampering, the authenticity of the initial input depends on robust verification methods, such as certification or calibration of sensors. Intelligent algorithms, e.g., using artificial intelligence, might help to analyze the patterns of data before adding it to the blockchain to guarantee the authenticity of data (Krupitzer & Stein, 2024). Ensuring the authenticity of the data, combined with the transparency and data exchange enabled by the blockchain design, helps promote product authentication using blockchain technology.

Data verification: In addition to the integration of IoT devices and the application of intelligent algorithms, the missing digital-physical link between the data and products requires physical monitoring and surveillance (Agetu, 2020; Katsikouli et al., 2021; Nam Vu & Bourlakis, 2023). Besides audits from governmental institutions, integrating IoT and, among others, RFID enables continuous monitoring of the products. Additionally, barcodes, serial numbers, or QR codes could enable the link between the physical objects and their digital data (Lo et al., 2019). However, the unique identification of the physical entities is essential. Furthermore, implementing smart contracts and risk management practices allows subsequent SC actors to verify the data input of preceding actors (Katsikouli et al., 2021; Lo et al., 2019). Therefore, data triangulation is a fundamental concept in food and pharmaceutical SCs. For products requiring strict handling and tracking, e.g., most medicines and drugs, blockchain combined with monitoring technologies facilitates the documentation during shipping and insurance. In addition, regulatory authorities could control and certificate products faster and easier through complete SC visibility and data access.

Data privacy and security: Many organizations are concerned about information security and privacy (Zakari et al., 2022). Although the application of a private and permissioned blockchain network already considers this, it cannot guarantee complete privacy (Zhao et al., 2019). Consequently, data should be encrypted to impede unauthorized information access. However, the proposed configurations differ from the primary idea of blockchains securing data through transparency (Nasir et al., 2022). Further, the participation of fewer entities increases the risk of manipulation through collaboration by malicious participants, i.e., it is easier for the participants to manipulate data after the initial block creation and related hash values to keep the blockchain validated, as fewer data records need to be manipulated. Once again, the involvement of governmental institutions could solve this issue.

Lack of knowledge: Applying blockchain requires specific knowledge (Nam Vu & Bourlakis, 2023; Zhao et al., 2019), usually unavailable in food and pharmaceutical enterprises. Since digital technologies influence SC operations (Treiblmaier et al., 2021), multidisciplinary knowledge is required, including knowledge about the SC, the product, laws, blockchain technology, and related information technologies. Further, the required knowledge and set of skills are not limited, as new challenges might arise when applying new technologies (Kamilaris et al., 2019). Due to the global interaction in FSC and PSC, another question arises regarding the availability of digital technology and the required knowledge for handling the technologies in underdeveloped regions. Specific training must be taken into account. Another aspect is that consumers usually have less domain-specific knowledge and have to trust the information on packaging, e.g., regarding the production method or the product's origin (Agetu, 2020). Consequently, the information provided by such a system must be contextualized to avoid misunderstandings or misinterpretations (Katsikouli et al., 2021). Specifically-designed dashboards, such as web pages or apps, can support the visualization of the relevant information. Nevertheless, it is unlikely that SC stakeholders themselves set up blockchain systems. Hence, external service providers must develop and provide blockchain applications and advice.

5.3. Threats to validity

Although this work followed a well-structured approach for the literature review to provide a structured analysis, some threats to validity still exist. To reduce human bias, each identified paper was read and classified by at least two authors of this work. All authors discussed unclear classifications and deviations between authors to reduce human bias.

The choice of keywords might be restricted. Although this survey revealed many blockchain applications in food and pharmaceutical SCs, the search was not extended to more specific keywords. However, it is common practice to narrow the scope to handle a topic's complexity, and Section 3.2.1 clearly describes the used keywords.

Further, the free web search using a search engine (rather than only a scientific database) provided many results, including scientific publications, press releases, white papers, and more. Despite the authors' great efforts, they could not analyze all search results to the fullest extent. However, the analysis also showed that non-scientific publications from industry often missed the required depth of detail to analyze and classify those publications thoroughly; hence, the additional contribution is limited.

6. Related work

This section presents an overview of related publications on blockchains in general SCs (Section 6.1) with a focus on FSCs (Section 6.2) and PSCs (Section 6.3). Further, Section 6.4 delineates this work from related work.

6.1. Blockchains for supply chain management

Many works reviewed publications and summarized the potentials and challenges of blockchains in SCM: (Nam Vu & Bourlakis, 2023) derived drivers and barriers of adopting blockchain. The results showed improved traceability as well as food safety and quality as the most important objectives, while scalability, regulations, privacy, and incentivization still need to be researched. Ghode et al. (2020) investigated the influence of various factors on the adoption of blockchain in SCs in general. The results showed that inter-organizational trust, interoperability, and relational governance were the most significant factors influencing the decision to implement blockchain technology.

(Kramer et al., 2021) investigated the influence of blockchain in the SCM, analyzing literature and use cases. Therefore, they described the differences between traditional and blockchain-assisted SCs. Although the authors proposed applying private or consortium blockchains, they also emphasized that blockchains could not currently decentralize the SCM. Further, they concluded that vertical coordination is needed to implement blockchain in SCs successfully.

(Kamilaris et al., 2019) examined the potentials and challenges of blockchains, emphasizing the important roles of government in fostering digitalization and research. Treiblmaier et al. (2021) evaluated the barriers to adopting blockchains of established and start-up enterprises. Their results revealed low knowledge about blockchains is the biggest hurdle.

Analyzing the financial aspects of applying blockchain, Liu et al. (2022) revealed that manufacturers and retailers mainly profit from the implementation, particularly if consumers are less concerned about safety. Further, SC stakeholders applied blockchain to reduce demand uncertainties.

6.2. Blockchains for food supply chains

Related to FSCs, Nasir et al. (2022) presented the challenges of blockchains in agribusiness. The authors conclude that a permissioned, private blockchain would be necessary to restrict access to private information and allow close real-time transaction processing. Katsikouli et al. (2021) discussed the benefits and challenges for FSC, particularly for small and medium enterprises. The study showed that enterprises could benefit by promoting fair trade, documenting product authentication, exposing good practices, and reducing management costs, but they also require legal regulations and technology knowledge. Further, Aamer et al. (2021) executed a systematic literature review concerning the challenges of adopting IoT in FSCs. Their results revealed similar challenges for IoT for blockchain technology to improve SCM, such as data security and trust, scalability, and technical competence. Kumar et al. (2022) determined that the biggest hurdles to integrate IoT into blockchains are the lack of legal regulations and knowledge. Additionally, Zhao et al. (2019) performed a systematic literature review to investigate the state of blockchain applications in the agri-food chain. They concluded that blockchain combined with information and communications technologies and IoT could improve FSCs regarding traceability, information security, manufacturing, and sustainable water management.

Some works focused on more specific FSCs. Okorie et al. (2022) determined barriers to blockchain implementation in circular FSC, revealing organizational challenges as primary barriers, followed by functional, business environment, funding, security and law, and technical challenges. Investigating drivers and challenges of blockchains to trace organic and fair-trade food products, van Hilten et al. (2020) studied use cases. The authors concluded that complex FSCs would benefit from its feature to track products. Damoska Sekuloska and Erceg (2022) proposed a three-layered model for local FSCs: a business, a platform, and an application layer. Additionally, Agetu (2020) described briefly the application of blockchain technology to verify food safety using a case study without providing any details.

6.3. Blockchains for pharmaceutical supply chains

Focusing on PSCs, Blossey et al. (2021) investigated quantitative models regarding uncertainty determination in the context of drug shortages based on a systematic literature review. They concluded that blockchains can improve the resilience of PSCs through real-time information. Zakari et al. (2022) conducted a systematic literature review, focusing on white and vision papers, and revealed combating counterfeit products as mainly intended use of blockchain, followed by the distribution, tracking and tracing, and safety and security of the products. Ghadge et al. (2023) showed that blockchain implementation is at an early stage, but they expected blockchains to be established in PSCs.

6.4. Delineation from related work

As shown, several reviews already provide an overview of specific aspects of using blockchains in general SCs, FSCs, and PSCs. However, none of the mentioned publications proposed blockchain frameworks for food or pharmaceutical SCs but focused on specific aspects such as legal and organizational conditions, applications that benefit from blockchains, or specific implementation details. Further, to the best of the authors' knowledge, no comprehensive publication currently exists that discusses and reviews the application of blockchain technology in food and pharmaceutical SCs.

7. Conclusion

Modern food and pharmaceutical SCs face many challenges, including product authentication, safety, and quality. This work analyzed 78 existing applications in 74 publications based on a systematic literature review showing various configurations. The results revealed that permissioned and private blockchain networks are the most applied network types, with Ethereum and Hyperledger Fabric as leading platforms and PBFT, PoA, and PoW as the most used consensus protocols. Data access was restricted in most applications by applying different technologies.

We propose a general framework for blockchain implementation, recommending a permissioned, consortium blockchain network using Hyperledger Fabric, PoA or similar consensus protocols, integrating combining off-chain data storage, using smart contracts to increase efficiency, tracing data and products, and providing real-time information. This work does not address implementing a blockchain system but might support researchers and practitioners in better understanding requirements when implementing new blockchain systems. Future work might include a study of integrating artificial intelligence techniques and modern communication technologies, such as edge computing or 5G networking. Further, integrating IoT devices to enable real-time food quality monitoring for reducing food waste might be another aspect (Henrichs et al., 2025). Moreover, this shows huge potential in assisting reduce food waste.

Nevertheless, some challenges remain, including the roles and responsibilities of SC actors, the scalability and interoperability of blockchain solutions, the adaptation of current laws and regulations, and the behavioral implications of employees and managers working with blockchain. Therefore, adaptive monitoring with sensors can reduce the amount of data captured (Henrichs & Krupitzer, 2022). Finally, this transforms FSCs and PSCs with blockchains that offer greater transparency, improved traceability, reduced disruption risk, optimized processing, and improved consumer trust in a systematic approach (Krupitzer & Stein, 2024).

CRediT authorship contribution statement

Elia Henrichs: Conceptualization, Writing – review & editing, Data curation, Methodology, Formal analysis, Visualization. **Meta Leonie Boller:** Writing – review & editing, Formal analysis. **Johnathan Stolz:** Writing – original draft, Methodology, Formal analysis, Visualization. **Christian Krupitzer:** Conceptualization, Supervision, Writing – review & editing.

Declaration of Generative AI and AI-assisted technologies in the writing process

During the preparation of this work the authors used *Grammarly* in order to check spelling and grammar. After using this tool/service, the authors reviewed and edited the content as needed and take full responsibility for the content of the publication.

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.

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Data availability

The data is available on Zenodo at https://doi.org/10.5281/zenodo.12819971.

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