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RESEARCH ARTICLE

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# Internet of Things (IoT)–blockchain-enabled pharmaceutical supply chain resilience in the post-pandemic era



**Abstract** During the COVID-19 pandemic, the current operating environment of pharmaceutical supply chain (PSC) has rapidly changed and faced increasing risks of disruption. The Internet of Things (IoT) and blockchain not only help enhance the efficiency of PSC operations in the information technology domain but also address complex related issues and improve the visibility, flexibility, and transparency of these operations. Although IoT and blockchain have been widely examined in the areas of supply chain and logistics management, further work on PSC is expected by the public to enhance its resilience. To respond to this call, this paper combines a literature review with semi-structured interviews to investigate the characteristics of PSC, the key aspects affecting PSC, and the challenges faced by PSC in the post-pandemic era. An IoT–blockchain-integrated hospital-side oriented PSC management model is also developed. This paper highlights how IoT and blockchain technology can enhance supply chain resilience and provides a reference on how PSC members can cope with the associated risks.

**Keywords** pharmaceutical supply chain, Internet of Things, blockchain, resilience, post-pandemic era

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## 1 Introduction

The COVID-19 pandemic has seriously affected the lives and economic activities of people and businesses all over the world, with supply chains in various industries suffering to varying degrees (Choi, 2021; Ivanov, 2021; Ivanov and Dolgui, 2021; Pujawan and Bah, 2022; Wang et al., 2022). In China, both the state and the government have taken active measures to prevent the further spread of the virus and have taken the lead in the "post-pandemic era" (Wang, 2022). The COVID-19 pandemic has made supply chain resilience (SCR) a hot topic among researchers, especially during the post-pandemic era when mitigating the increasing risks of disruptions has become a key issue in global supply chain management (SCM) (Belhadi et al., 2021; Burgos and Ivanov, 2021; Spieske et al., 2022).

The pharmaceutical supply chain (PSC) has suffered an unprecedented impact from the COVID-19 pandemic (Sharma et al., 2020; Yu et al., 2020). Unlike supply chains in other industries, the PSC involves numerous stakeholders, including raw material suppliers, pharmaceutical manufacturers, distributors, hospitals and retail pharmacies, third-party logistics providers, consumers, medical insurance bureaus, and regulators, along with complex distribution networks, long supply chains, and large number of nodes. Under the current pharmaceutical system of China, hospitals and doctors are the sole representatives of the needs of consumers and greatly dominate the entire PSC. Furthermore, the pharmaceutical industry is closely related to the life and health of people and is treated as a special industry related to the national economy and the livelihood of the people. Therefore, any disruption in the PSC not only results in wasted resources and economic losses but also poses a great threat to the lives and health of patients by blocking their access to timely treatment (Schneider et al., 2010; Senna et al., 2021). Although medical supply shortages resulting from inventory and worker shortages have been addressed in the post-pandemic era, the changing environment and increasing probability of disruptions have forced PSC members to rethink how to cope with risks and uncertainties in the future. As a result, the application of information technology (IT) in enhancing SCR has attracted widespread attention. Paul and Rahman (2018) observed a rapid development in the significance of IT in predicting and recovering from future disruptions in SCM. In particular, the support provided by the Internet of things (IoT) and blockchain technology extremely enhances the efficient use of data and helps enterprises cope with disruptions (Ivanov et al., 2021).

Previous studies on the COVID-19 pandemic and SCM have explored the various applications of IoT and blockchain technology in the pharmaceutical industry, such as drug traceability, safety regulation, and technology upgrades (Remko, 2020; Sarkis, 2020; Chowdhury et al., 2021). However, only few studies have examined the potential disruptions to the PSC in the post-epidemic era and how to make the PSC more resilient to these risks by integrating IT (Ehrenberg and King, 2020). Given the special attributes of the PSC and the tremendous uncertainties faced by the supply chain in the post-pandemic era, this paper examines the challenges and risks being faced by the PSC in the post-epidemic era and how IoT and blockchain technology can be integrated to address these risks and improve the resilience of the supply chain.

As its first contribution, this paper provides a comprehensive understanding of the characteristics and alterations presented by the PSC in the post-pandemic era by reviewing the literature and conducting semi-structured interviews with pharmaceutical industry stakeholders, including hospitals, pharmaceutical manufacturing and distribution companies, and patients. The most critical risk in the PSC originates from the hospital-side dominated pharmaceutical distribution chain. Specifically, the uncertainty of sudden outbreaks and changes in consumer behavior in the post-pandemic era can introduce challenges in medicine access and trigger fluctuations in demand. The competition for interest among various entities in the PSC and the issue related to the privacy of patients have created obstacles to the sharing of hospital data, thereby preventing downstream consumers in the PSC from accurately transmitting their medicine needs without delay, upstream pharmaceutical companies from adjusting their medicine production and supply strategies in a timely manner, and patients from accessing relevant treatment.

As its second contribution, this study focuses on IT that affects SCR, namely, the IoT and blockchain technology. The IoT can provide real-time data and enhance supply chain connectivity and control (Rejeb et al., 2019; Al-Talib et al., 2020; Koot et al., 2021). However, IoT devices are generally unable to withstand the malicious impacts on the network and have huge security flaws; in addition, the personal and sensitive user data accumulated by IoT are exposed to security risks (Reyna et al., 2018; Hussain et al., 2021). This drawback can be precisely remedied by combining IoT with blockchain technology, which has distributed storage and tamper-evident features that can improve the pain points of multiple subjects and complex information in the PSC (Cui et al., 2019; Min, 2019; Pavithran et al., 2020). Banerjee (2019) found that combining IoT with blockchain technology can effectively address supply chain risks. Such integration will manifest its great advantages in improving the visibility, flexibility, and transparency of supply chains (Awan et al., 2021; Zamiela et al., 2022). Therefore, this study proposes an IoT–blockchain-integrated hospital-side led PSC management model that includes i) an IoT-based physical data layer, ii) a blockchain-based data control layer, and iii) a data storage and management layer. This model contributes to enhanced visibility, flexibility, and rapid response in the PSC and supports the matching of medicine supply and demand.

The rest of this paper is organized as follows. Section 2 summarizes the relevant literature and describes the research gaps. Section 3 describes the PSC and its characteristics, key aspects, and possible disruptions in the post-epidemic era. Section 4 presents the proposed IoT–blockchain integration for hospital-side led PSC management model. Section 5 concludes the paper.

## 2 Literature review

### 2.1 Pharmaceutical supply chain resilience and COVID-19

This section reviews the literature on pharmaceutical SCR (PSCR) and the COVID-19 pandemic and discusses the general topic of optimizing SCR during the pandemic. In SCM, the term “resilience” refers to the ability of a system to return to its original state or move to a new, more desirable state after a disruption (Christopher and Peck, 2004; Ponomarov and Holcomb, 2009). Mandal (2017) extended the concept of resilience to the healthcare supply chain and defined this term as the ability of entities in the healthcare supply chain to maintain a coordinated effort to prepare for the risk of feasible disruptions and to deliver care to patients. Yaroson et al. (2021) conducted semi-structured interviews with stakeholders in the UK PSC and used complex adaptive system theory to systematically describe PSCR from the perspectives of PSC characteristics, environment, and vulnerability.

Other scholars have examined the effects of the COVID-19 pandemic on the risk of supply chain disruptions and how supply chain risk management can mitigate the disruptions caused by global outbreaks (Queiroz and Ivanov et al., 2020; Pujawan and Bah, 2022). For instance, Ivanov (2020a) conducted a simulation study on how COVID-19 pandemic affects global supply chains, assessed SCR by looking at the length of long-term disruptions (e.g., COVID-19) that cause chain reactions throughout the network, and illustrated the characteristics of an outbreak as supply chain disruption. In response to a pandemic, supply chains exhibit unprecedented vulnerability in terms of delivery cycles and order volumes, network structure disruptions, and frequent demand fluctuations (Ivanov and Dolgui, 2021). Accordingly, several studies have investigated the risk of supply chain disruptions due to the COVID-19 pandemic (Ozdemir et al., 2022). For instance, in their empirical survey of 470 French companies, El Baz and Ruel (2021) revealed the mediating and prominent roles of supply chain risk management practices in promoting supply chain robustness and resilience. Ivanov (2020b) integrated supply chain agility, resilience, and sustainability to propose a viability supply chain model that can facilitate the design of adaptive structures for supply and demand distribution and enable supply chains to survive in a changing environment.

Other studies have explored industry-specific resilience dimensions, such as Belhadi et al. (2021), who assessed the resilience levels of manufacturing and service supply chains in response to the COVID-19 pandemic for the automotive and aviation industries and proposed coping strategies to mitigate the short- and long-term risks. Burgos and Ivanov (2021) developed a model for simulating the impact of the COVID-19 pandemic on food supply chains resilience, revealed that demand surges and transportation disruptions can lead to severe disruptions to supply chain operations, and proposed an implementation plan for improving food SCR using digital twin technology.

In the SCM of the pharmaceutical industry, Lücker and Seifert (2017) developed a mathematical model for examining the impact of risk mitigation measures on the supply chain of a large pharmaceutical company under the risks of supply chain disruption and proposed an optimal risk mitigation strategy. Zahiri et al. (2017) used a mixed integer linear programming model to design and propose a new PSC network with improved sustainability and resilience. Liza et al. (2022) applied two decision tools, namely, Interpretive Structural Modeling (ISM) and Multiplicative Matrix of Categorical Cross-Impacts (MICMAC), to analyze the possible obstacles to PSC sustainability in the post-pandemic era and then identified the lack of flexibility in the PSC — in addition to the poor information structure at all levels of the supply chain — as the most critical barrier to enhancing PSCR. Goodarzian et al. (2021) developed a mathematical model to address the uncertainty of medicine demand during a pandemic. Using a simulation–optimization method, they found that the volume of medicine required by patients during a pandemic follows a normal distribution. Their simulation model also identified an optimal site selection and inventory strategy for establishing a pharmaceutical distribution center during a pandemic. With the massive spread of the COVID-19 pandemic, the PSCR has been tested by new complexities, especially in developing markets where supply chains are less transparent and visible (Scala and Lindsay, 2021; Nayeri et al., 2022; Spieske et al., 2022). Compared with supply chains in other industries, the PSC not only has very complex networks but also suffers from a lack of scale and intensification of drug distribution (Uthayakumar and Priyan, 2013). According to Ivanov and Dolgui (2021), the challenge in enhancing PSCR lies in the inability to predict how each disruption will affect the market demand and medicine transportation and how to respond to such challenge in a timely manner. Therefore, the digitization of the PSC needs to be improved to enhance its resilience and adaption to a dynamic environment.

Although studies on the changes in the PSC during the post-epidemic era have reported some progress, only few scholars have studied how PSCR can be enhanced from the perspective of its characteristics and key aspects. This paper attempts to systematically address the risks faced by the PSC by analyzing its characteristics and the key aspects of pharmaceutical distribution dominated by the hospital side.

### 2.2 Application of IoT and blockchain technology

Studies on the application of IoT and blockchain technology in supply chains have mainly highlighted the importance for supply chain subjects to use such technologies to enhance their SCR (Gu et al., 2020; Nasiri et al., 2020). A blockchain is a peer-to-peer IT network whose greatest advantage lies in its capability to build trust and collaboration in a supply chain (Min, 2019; Dubey et al., 2020). Lohmer et al. (2020) modeled a complex agent-based supply chain network affected by disruptions to precisely define the impact of blockchains on SCR and found that the smart contracts used during disruptions can improve SCR. Choi et al. (2019) found that blockchains can improve supply chain visibility, simplify contract designs through smart contracts, and accelerate forecasting and scheduling. Ivanov et al. (2019) emphasized that the application of blockchain can enhance the efficiency of recording data for planning responses to disruptions and argued that the implementation of such technology can effectively suppress ripple effects.

With the current level of science and technology, IoT has emerged as a key technology for enhancing SCR (Tu, 2018; Lam and Ip, 2019). IoT components can be used to track every movement of containers, products and packaging, and goods in real time and obtain big data on the status of supply chain operations (Huang and Chang, 2016; Tian, 2016). From their analysis of Chinese manufacturing companies, Zhang and Zhao (2019) found a direct relationship between big data and SCR and argued that big data enhance resilience by improving supply chain visibility. Rejeb et al. (2021) reviewed the application, potential, and challenges in the use of IoT in the halal food supply chain and found that IoT helps manage risks in the supply chain. Yadav et al. (2021) constructed a multi-layer model for the agricultural products supply chain system that integrates IoT into digital technologies, such as blockchain, big data analytics, and cloud computing, to achieve supply chain sustainability. Dolgui and Ivanov (2022) found that the big data obtained from IoT can be connected end-to-end at a high granularity level through 5G technology, which is helpful in digitizing supply chain processes, such as manufacturing, warehousing, and logistics. The implementation of IoT provides fast and accurate data for supply chain risk management, increases risk transparency, and supports faster supply chain response to risks (Birkel and Hartmann, 2020).

The combination of IoT and blockchain technology has received some scholarly attention (Al-Rakhami and Al-Mashari, 2021; Awan et al., 2021; Hussain et al., 2021). Banerjee (2019) discussed the integration of blockchain and IoT to enable a new supply chain paradigm and highlighted the opportunities that the combination of these two disruptive technologies can bring to SCM. Pal and Yasar (2020) focused on the textile and apparel industry supply chain and proposed a blockchain-based IoT application architecture that uses blockchain for distributed data management to support supply chain transaction services.

Researchers have also started examining the role of digital transformation in PSC management (Moro Visconti and Morea, 2020). Joyia et al. (2017) discussed the application of IoT in healthcare services through a literature review and defined the application of IoT in healthcare as the Internet of Medical Things. IoT has demonstrated an increasingly significant role in PSC management (Rodrigues et al., 2018). Kumar and Pundir (2020) proposed a blockchain–IoT-enabled PSC network and argued that the visibility, transparency, and reliability in a supply chain can be enhanced by integrating blockchain and IoT. Farouk et al. (2020) built a blockchain–IoT platform for the healthcare industry to facilitate information sharing and to provide decision support for various members of the supply chain.

The above review reveals a wealth of research on the application of IoT and blockchain in multiple industries, such as food and agricultural products. Although various combinations of IoT–blockchain and PSC have emerged, how IoT and blockchain can address the resilience dimension of PSC has not been extensively studied. Specifically, researchers have ignored how these technologies can enhance resilience from the supply chain information sharing dimension, which is vital in the post-pandemic era. This paper attempts to bridge this gap by highlighting how IoT and blockchain can be integrated to build a hospital-side information sharing management model to enhance PSCR.

## 3 PSC in the post-pandemic era

The COVID-19 pandemic has had a prominent impact on the global economy (Chowdhury et al., 2022). Among the many affected industries, the pharmaceutical industry is vital to the lives and health of the people. To understand the impact of the COVID-19 pandemic on the PSC, a series of research and semi-structured interviews were conducted based on an extensive review of the literature. The participants for this study included the National Healthcare Security Administration, several provincial and sub-provincial healthcare security administrations, hospitals (e.g., Xiangya Hospital), national pharmaceutical distribution and sales companies (e.g., Jointown Pharmaceutical Group, LBX Pharmacy, and Yifeng Pharmacy), and many nationwide pharmaceutical company giants (e.g., Yunnan Baiyao Group). This section describes the characteristics and key aspects of the PSC and the issues faced by the supply chain in the post-pandemic era based on the literature review and interview data.

### 3.1 Characteristics and key links of PSC

PSC is a pharmaceutical network chain structure formed by upstream and downstream pharmaceutical companies, hospitals, and pharmacies in the process of pharmaceutical production and distribution, which involves providing medicine or medical services to the final patients or users. With the intensive introduction of pharmaceutical industry policies, the "two-invoice system", the "4 + 7 centralized procurement", and other comprehensive and deepening healthcare reforms to further deepen the promotion, the PSC circulation model abruptly altered likewise the channel continues to sink. The PSC has shifted from a single linear structure to a dynamic mesh topology with a clear trend of flattening and decentralization such that any weak link in the PSC may affect the normal operation of the entire supply chain. The PSC has multiple members involved in a series of processes from production to final use by consumers. The PSC stakeholders discussed in this paper include raw material providers, pharmaceutical manufacturers, pharmaceutical distribution companies, hospitals, retail pharmacies, and end consumers (patients). The PSC is a complex dynamic network with several suppliers and multiple downstream customers located in the middle. Several characteristics distinguishing the PSC from other industries will be discussed in the following subsection.

#### 3.1.1 Characteristics of PSC

First, the unique features of pharmaceuticals that distinguish them from other general consumer products are related to their high life-relatedness, strict high quality, and timely access (Uthayakumar and Priyan, 2013).

Medicine directly affects human life and health, and its use value is reflected in its ability to prevent and treat diseases and save lives. Therefore, pharmaceuticals not only have extremely stringent quality requirements but also are treated as a commodity without distinction between superior and inferior products, and only those pharmaceuticals that meet the qualified standards can enter circulation. Furthermore, medicine is absolutely crucial to patients, especially those suffering from heart diseases or hypertension and those who need to take medicine steadily for an extended period. Therefore, a shortage of medicine can be life threatening to these patients, hence underscoring the need to ensure the timeliness and accessibility of medicine.

Second, the circulation of medicine in the PSC is more restricted than that of general commodities. This restriction is mainly manifested in the strict regulation of the distribution channels in the PSC. To ensure the quality of medicine and prevent counterfeit or substandard medicine from entering the market, the law stipulates that "medicine manufacturers and medicine wholesalers cannot sell medicine to individuals", thereby resulting in restricted sales channels as upstream pharmaceutical manufacturers and midstream pharmaceutical distribution enterprises cannot sell their medicine directly to patients. In the event of a disaster or pandemic, the demand for certain medicine surges, thereby making it extremely easy for a mismatch between supply and demand and a failure of emergency management to occur.

Third, given that the demand for medicine in the PSC is obviously influenced by the downstream, the hospital side occupies a dominant role in the supply chain. This feature distinguishes the PSC from other industry supply chains in three aspects. 1) In the channel structure of pharmaceutical circulation (Fig. 1), patients only have a single channel from where they can obtain medicine, such as qualified hospitals or pharmacies. Nevertheless, given that public hospitals and medical institutions account for nearly 80% of China's pharmaceutical sales market, the hospital side has a great say in the whole PSC. Accordingly, the medicine being sold in the market becomes highly specialized due to the expertise of physicians, and diagnosis plays a dominant role in determining the medication behavior of patients. 2) A gap can be observed between doctors and patients in terms of how they understand medical information, and the principal–agent relationship formed between them leads to an information asymmetry in the consumption process. Unlike when purchasing general commodities, patients need to follow the guidance of hospitalists or pharmacists when purchasing medicine, especially prescription ones, hence exacerbating the monopolistic nature of sellers in the PSC. 3) The demand–price in the pharmaceutical market does not exactly follow the market mechanism (Yu et al., 2010) due to the life-related nature of medicine, that is, the rigid demand for medicine by patients also makes the price of medicine rigid. This characteristic is exacerbated by the implementation of health insurance policies, which reduces the commodity price elasticity of demand for medicine and increases the insensitivity of patient demand to changes in medicine prices.

### 3.1.2 Key links of the PSC

Among the nodes of the PSC, hospitals, as the key node directly facing consumers, play a leading role in the pharmaceutical demand chain. Therefore, the hospital-side led pharmaceutical distribution link is a key link that affects the normal operation of the entire PSC. First, hospitals are the most pivotal trading places for terminal sales in China's pharmaceutical distribution. According to a survey, the market share of public hospitals and primary care institutions in China's pharmaceutical sales terminal market reached 73.1% in 2021 (China Business

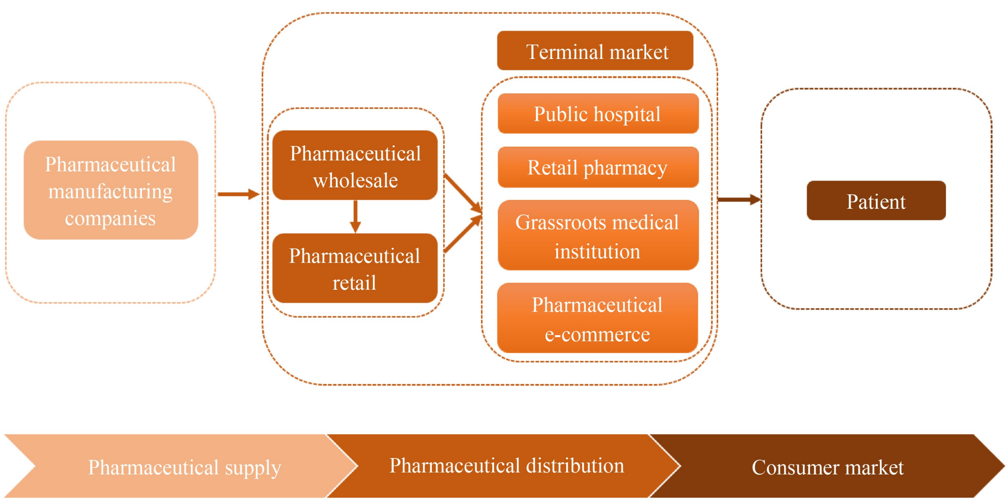


**Fig. 1** Channel circulation structure and parties involved in PSC circulation in China.

Intelligence Network, 2022), of which more than 85% of the pharmaceutical terminal market share of prescription drugs are sold by the hospital end (Zhou, 2022). Second, due to the information asymmetry between doctors and patients, hospitals are the sole representatives of patients in terms of medicine demand and medicine information. The end-consumer demand gathered by hospitals is crucial to upstream pharmaceutical distribution enterprises and pharmaceutical manufacturers, which serves as the reverse drivers to make the whole PSC run efficiently. Third, the hospital is both a special and vital node and core enterprise in the PSC. As hospitalists decide the diagnostic scheme and medicine selection, the hospital assumes the role of both the supplier of medicine and the decision maker of demand, hence occupying the leading role of the node unit.

### 3.2 Challenges to the PSC in the post-pandemic era

During the early stages of the COVID-19 pandemic, a number of industries were severely impacted as the lack of inventory supply resulted in plant closures and logistics stagnation prevented products from being shipped, thereby disrupting the global supply chain network (Ivanov and Dolgui, 2021). Although the COVID-19 pandemic has now been effectively contained in China, the possibility of small outbreaks of viral infections at any time in the post-pandemic era has made its impact longer than expected, and the risk of uncertainty and disruption to the PSC remains (Liza et al., 2022). In the entire PSC, the hospital-side dominated pharmaceutical distribution link, as the most significant and critical link, faces key problems that can lead to PSC disruptions in two aspects.

#### 3.2.1 Uncertainty of medicine demand

The unpredictability of outbreaks in the post-pandemic era causes uncertainty in the demand for medicine (Cundell et al., 2020). First, the source of infection for outbreaks is invisible and variable, and the current absolute dominant global strain, the Omicron variant, is characterized by rapid transmission and high symptom concealment, thereby making the transmission route and range arduous to determine. For this reason, a high degree of uncertainty lingers in the post-pandemic era (del Rio et al., 2022). The influx of infected patients and close contacts into hospitals during the pandemic has led to severe overcrowding of medical resources and a surge in demand for medicine, hence preventing other patients from seeking timely medical care (Emanuel et al., 2020). In addition, the medical resources of local hospitals during sudden outbreaks would rapidly tend to epidemic prevention and control, so that the diagnosis and treatment of non-epidemic diseases might be suspended, which, to a certain extent, reduces the demand for related medicine.

Moreover, medicine demand is constantly affected by alterations in consumer behavior in the post-pandemic era. To avoid the risk of infection and cope with the restriction policies during the pandemic, hospitals have opened online medical channels, such as online hospitals. As some non-emergency cases choose to purchase their medicine online as a complementary medical channel, the demand for online hospitals has increased significantly during the pandemic. For example, in managing chronic diseases such as hypertension and diabetes, the demand for chronic medicine varies widely and cannot be interrupted, while online hospitals have alleviated this dilemma to some extent. However, the overall shortage of medical resources and unbalanced regional resource allocation, coupled with the inconvenience caused by quarantine policies, have limited the flow and accessibility of medicine, thereby making it difficult for patients to obtain medicine in a timely manner. As a consequence, the demand for medicine exhibits high volatility.

In sum, while the COVID-19 pandemic has greatly affected the demand for medicine in the short term, the rigid medical demand will only demonstrate a time lag instead of disappearing completely. Meanwhile, upstream and midstream pharmaceutical manufacturers and pharmaceutical distribution companies may face some trouble in perceiving the fluctuations in demand or adjusting their production and decision making in a timely manner, thereby explaining why PSC is highly susceptible to supply shortages due to disruptions (Yaroson et al., 2019).

#### 3.2.2 Hospital-side data opacity leads to barriers to information sharing in the PSC

Another problem that affects the normal operation of the PSC is the poor flow of pharmaceutical information brought about by the data barriers at the hospital end. In the first place, as mentioned above, hospitals play a dominant role in the PSC, and most of the information related to the medicine demand of end patients is held by public hospitals. However, hospitals are not that open in terms of sharing medical information mainly because prescription and medication information are fundamental to their core competitiveness. There are competing interests among hospitals and between hospitals and pharmaceutical companies in terms of sharing subjects. Moreover, the high cost of sharing medical data and the lack of obvious short-term returns have discouraged hospitals from sharing such information.

Moreover, patient-related information, such as type of disease, medicine variety, and dosage, is considered private. Medical data has a much higher commercial, academic, and social value than the data in other industries and is therefore exposed to a very high risk of data leakage. For example, in August 2021, the Memorial Health System in Ohio, USA was attacked, which exposed the health information of about 210000 patients to a risk of leakage or malicious use by unscrupulous individuals to practice extortion, thereby negatively affecting both the society and individuals (Coble, 2022).

Given that hospital data are overwhelmingly sensitive, hospitals are not willing to share such information, and the private nature of patient data introduces additional challenges in sharing medical data. These restrictions have led to the passive state of upstream pharmaceutical companies, and the demand information transmission barrier has seriously affected the normal supply of the PSC.

Under the dual impact of the pandemic and information sharing barriers, upstream pharmaceutical companies cannot easily obtain timely information about changing demands, whereas end patients are unable to receive medical treatment and medicine in a timely manner. To address the increasing risks being faced by the PSC, visibility, flexibility, and rapid response should be established immediately at the hospital end of the pharmaceutical distribution chain, and the information sharing and collaboration among all parties in the hospital-led PSC should be promoted.

## 4 IoT–blockchain integration for the hospital-side led PSC management model

With the increasing penetration of Industry 4.0 (Ivanov et al., 2019), studies on the digitization of pharmaceutical and smart healthcare have received extensive attention. In the hospital-side-dominated PSC distribution, the efficient and collaborative development of the entire PSC is hindered by the uncertainty of medicine demand and the opacity of hospital-side data, which leads to barriers to information sharing in the PSC, especially for upstream pharmaceutical companies. This paper integrates IoT and blockchain technology to eliminate the PSC disruptions caused by these barriers. This section briefly reviews and introduces the IoT and blockchain technology, establishes a hospital-side led PSC management model integrated with IoT–blockchain, and illustrates the benefits of such integration to both PSC and PSCR.

### 4.1 Principles and applications of IoT and blockchain technology

#### 4.1.1 IoT technology

The concept of IoT was introduced by the MIT Auto-ID Center in 1999, while the Chinese Academy of Sciences has initiated the research and development of sensor networks during the same year. As research on these sensor networks continued, they gradually expanded and evolved into IoT (Feng and Ye, 2010). The IoT connects physical objects, such as consumer goods and pallets, to the network through information sensing devices in accordance with agreed protocols. These objects exchange and communicate information through information dissemination media to achieve intelligent identification, positioning, tracking, and supervision. The IoT supports billions of devices or smart objects to connect and interact with other systems through the Internet (Li et al., 2015). Five key IoT technologies are broadly applied in supply chain and logistics, namely, radio frequency identification (RFID) technology, wireless sensor networks (WSN), middleware, cloud computing, and IoT applications (Lee and Lee, 2015). Machine-to-machine and human-to-machine interaction is accelerated by these key technologies, which allow the transmission and analysis of data in a timely and accurate manner across the Internet. Data from the IoT help companies sense and respond to operational conditions in real time and support automated manufacturing and predictive analytics (Tzounis et al., 2017).

#### 4.1.2 Blockchain technology

Blockchain is another disruptive advancement in the era of Industry 4.0 proposed by Satoshi Nakamoto in his seminal paper published in 2008 (Nakamoto, 2008). Blockchains are tamper-evident distributed databases that record and encrypt the data of each transaction in a specific data structure through a decentralized network (Pavithran et al., 2020). Each transaction is bound to a block with a timestamp, and the transaction information on each block is encrypted by a hashing algorithm so that each block is identified by the hash of this block and the hash of the previous block. These blocks are connected to each other to form a linear sequence (i.e., a blockchain) as shown in Fig. 2. The blockchain is supported and maintained by a network of nodes, where each transaction is replicated and recorded at the nodes and each node on the chain can read the transaction (Min, 2019).

Blockchain has unique characteristics, including decentralization, openness and consensus, traceability and immutability, as well as transaction transparency and anonymity (Cui et al., 2019). This technology has expanded from cryptocurrency and finance to smart cities, the pharmaceutical industry, and information extraction (Sharma et al., 2021; Tyan et al., 2021). Blockchain technology can provide a cryptographically trusted database for the PSC that can be used to monitor and track each transaction while handling the corresponding information and physical resources. The efficiency of participants and traceability of pharmaceutical products can also be improved by using blockchain as all participants in the PSC can access the information stored on the chain but

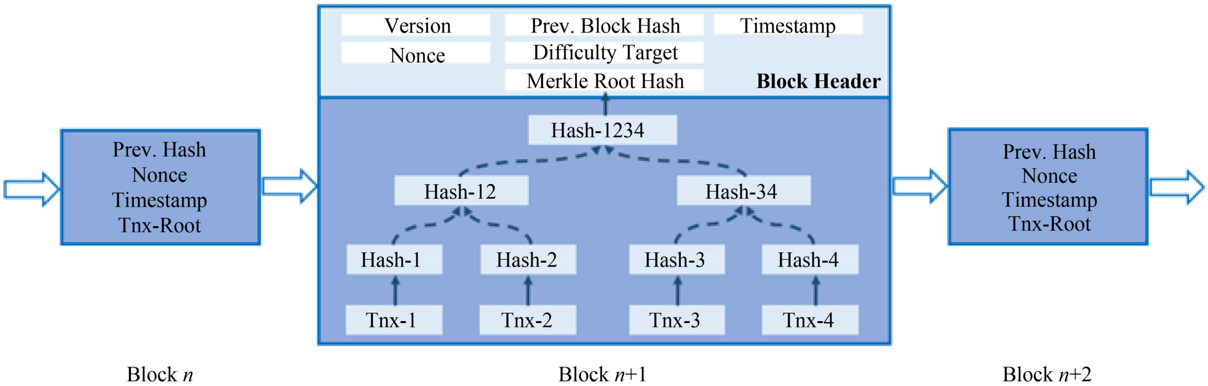


**Fig. 2** Blockchain structure schematic.

cannot tamper with these data arbitrarily (Clauson et al., 2018).

Smart contracts, as key technologies of the blockchain, are computer protocols that informally disseminate, self-verify or self-enforce contracts, embed contractual terms (e.g., guarantees, title definitions, and collaterals) in a computer system to allow transactions to take place without a third party, and guarantee the trustworthiness of transactions (Szabo, 1997). In a smart contract, the asset or currency is transferred to the program, and the contract can also be represented in computer code. The program starts to run when a transaction is made and automatically validates and enforces the conditions at a point in time. The code is stored in the computer system and is replicated and supervised by the computer network running the blockchain (Christidis and Devetsikiotis, 2016). Figure 3 illustrates the smart contract model, wherein a piece of code is deployed on a replicable shared ledger that maintains the state and controls its own assets while responding to information or assets from the outside world.

### 4.2 IoT–blockchain integration for hospital-side led PSC management model

The COVID-19 pandemic has forced pharmaceutical companies to focus on and improve the resilience of their own supply chains. However, an ocean of pharmaceutical companies are overwhelmed when it comes to advancing SCR toward excellence. An IoT–blockchain-integrated hospital-side led PSC provides an innovative solution to this goal (Cavalcante et al., 2019; Ivanov et al., 2019; Spieske and Birkel, 2021). Figure 4 illustrates the architecture of a hospital-side led PSC management model for IoT–blockchain integration. This model consists of three layers, namely, the IoT-based physical data layer, the blockchain-based data control layer, and the data storage and management layer. The following subsections discuss the role of stakeholders in the PSC in the overall system as well as the recorded information and functions of each layer.

#### 4.2.1 Stakeholders

**Raw material provider.** Raw material providers provide pharmaceutical companies with raw materials and excipients needed to produce medicine. They also record the quantity, quality, status, and other attributes of these materials.

**Pharmaceutical company.** Pharmaceutical companies produce a wide range of products that are required by downstream customers and are of the right quality. They also send detailed production information, such as variety, date, quantity in stock, and production process, to the Internet via digital tags, which can be accessed by all participants in the PSC.

**Distributor.** Distributors act as hubs between pharmaceutical companies and sales terminals by handling the supply, distribution, and dispensing of medicine. They

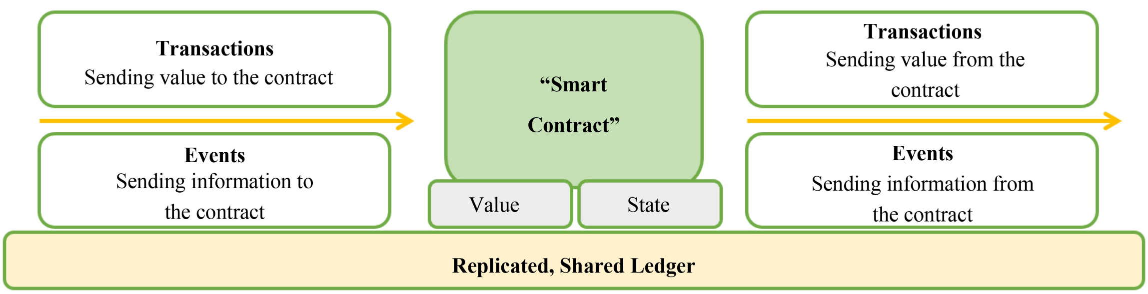


**Fig. 3** Smart contract model.

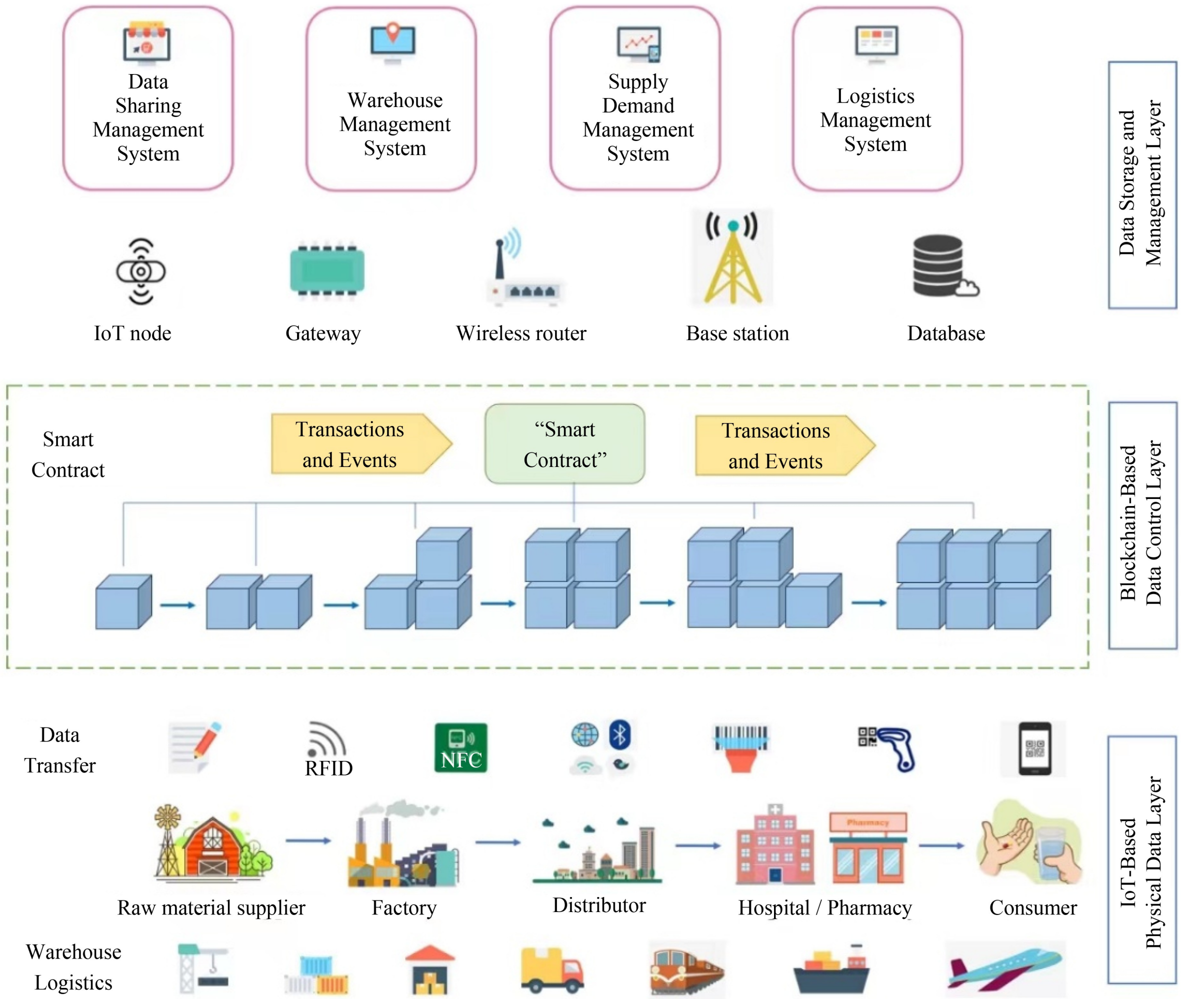


**Fig. 4** IoT–blockchain integration for hospital-side led PSC management model.

use sensors and other equipment to monitor and record information, such as product batches, storage conditions, and quantities in and out of the warehouse.

**Hospital.** As the core node in the PSC that dominates patient demand, hospitals are responsible for understanding and aggregating the alterations in the pharmaceutical market and the demands of patients at different endpoints and recording medicine storage conditions, sales volume, and inventory.

**Retail pharmacy.** Retail pharmacies are responsible for selling medications to patients and recording inventory.

**Logistics provider.** Logistics providers are mainly responsible for the commission of pharmaceutical companies and distributors to provide qualified drug acceptance, storage, logistics, and distribution services. They deliver drugs to patients and provide feedback through a transaction management system and a supply and demand management system.

**Consumer.** Patients are the end users of the medicine. They choose the nearest doctor based on intelligent recommendations from the supply and demand management system.

All of the above participants are required to record source, flow, and medicine transaction information. Such information needs to be authorized through authentication (online authentication and digital signature) supported by digital technologies, such as RFID and sensors. The Internet/Web is used as the infrastructure to establish connection, whereas application programming interface is used to transfer all information to the network (Casey and Wong, 2017).

#### 4.2.2 IoT-based physical data layer

The five pivotal technologies of IoT (i.e., RFID, WSN, middleware, cloud computing, and IoT applications) assist in capturing and integrating data in supply chain processes and support the exchange and interconnection of these data. In the IoT-based physical data layer, all physical objects, such as medicines, pallets, and cartons, are given digital identifiers (e.g., RFID tags), whereas the

IoT nodes collect the real-time location, status, and other information of physical resources through this digital identifier (Awan et al., 2021). When the medicine production is completed at the storage stage, each pallet has an IoT tag or device to help warehouse managers clearly understand their storage location, provide a real-time response to the storage situation, and reduce errors. While the medicine is in transit, RFID and smart sensors will feed the measured temperature and humidity and other status information to the base station and then provide real-time feedback on the location with the help of the satellite positioning system, traffic data, and map information to understand the real-time status and location of medicine and predict its delivery time.

#### 4.2.3 Blockchain-based data control layer

Given the sensitivity of data associated with the PSC, a data breach can result in significant losses. This challenge can be easily solved by blockchain-based data control. The distributed database supported by blockchain records the transactions that occur in each period on blocks, which are cryptographically represented as cryptographic hashes for linking by a hashing algorithm (Dutta et al., 2020). When a supply chain activity or information sharing is triggered, the parties determine the terms of the transaction or sharing based on negotiation, and when these parties agree on the exchange of terms, a smart contract is created, encoded, and archived on the blockchain. As a result, the smart contract automatically verifies whether the contract is established and chooses whether to execute it. Due to the distributed storage technology of blockchain, the transactions and data sharing information are copied and tamper-proofed at all participants who can quickly access and confirm the credit records and status of customers (e.g., inventory, orders, and data access records), thereby increasing the transparency of the PSC and ensuring the security of hospital and patient data.

#### 4.2.4 Data storage and management layer

The IoT nodes in the PSC track the production, storage, and transportation of medicine while recording the real-time location and status of each variety. The collected data are then transmitted to the base station through IoT gateways and wireless routers and eventually sent to the database. At the same time, the information related to medicine transactions is recorded in the distributed database of the blockchain, and the information about the physical flow and transaction dynamics is integrated to support the construction of a decision management system. Real data from supply chain processes can be used to establish new information sharing, warehouse, supply and demand, and logistics management systems with the help of other technologies, such as cloud computing and 5G (Dolgui and Ivanov, 2022).

### 4.3 IoT–blockchain integration for PSCR management

In response to the current challenges being faced by the PSC, this study proposes the use of IoT and blockchain technology in preventing the associated risks as summarized in Table 1.

Originally, the blockchain provides a credible environment for hospitals to share open data, and the application of IoT technology facilitates the control of medicine inventory and real-time location. These two technologies can be combined together to establish a credible, transparent, and traceable data sharing and business collaboration system for the PSC.

The various management systems supported by the IoT–blockchain integration will come into play when there is an unexpected peak in demand or shortage of medicine in hospitals during a pandemic. The warehouse management system provides hospitals and pharmaceutical companies with real-time medicine inventory information, including the type, batch, quantity, and storage location of medicines. The logistics management system tracks the location and environmental temperature of medicines

**Table 1** Risks and benefits of IoT–blockchain integration to the PSC

| Challenges | Risks | IoT–blockchain technology | Benefits |
|---|---|---|---|
| Demand fluctuations and medication difficulties caused by sudden pandemics and changes in consumer behavior | Lack of visibility, flexibility, and rapid response in the PSC | 1. Through identification tags and sensors and other intelligent devices, IoT captures the medicine in and out of storage information, tracks the location of medicines, measures the environmental temperature in real time using the Internet, and provides real-time feedback to the cloud. | Provide connectivity, transparency, and end-to-end visibility in the PSC, monitor medicine inventory in real time, and respond quickly to diverse patient needs |
| Barriers to hospital data sharing caused by competing interests among sharing subjects and patient privacy | The information flow of the hospital-led PSC is not smooth, and a synergy among pharmaceutical companies, hospitals, and other subjects is lacking | 2. The blockchain records the medicines corresponding to the new blocks by generating these blocks in the network. Smart contracts facilitate the creation of transactions and information sharing contracts between patients and hospitals and between hospitals and pharmaceutical companies.<br>3. The blockchain represents a complete record of medicine and transaction information and cannot be tampered with, and the participating entities can access the data with the key.<br>4. The data acquired and recorded by the IoT and blockchain stakes the realization of one-to-one optimal supply and demand matching decisions. | Effectively protect patient privacy and data sharing by ensuring the authenticity, timeliness, and integrity of medical data |

in transportation in real time to ensure that they are delivered intact. The supply and demand management system integrates the medical resources and medicine information of hospitals and pharmacies in a certain region with the help of artificial intelligence, cloud computing, and other technologies in order to plan the optimal medical strategy for non-infected individuals and to provide the optimal delivery strategy for patients who purchase medicines online. In the information sharing management system, each hospital and upstream pharmaceutical company reach a smart contract for using medical data to reasonably allocate the interests of all parties. With the endorsement of blockchain technology, these encrypted data can only be used by the relevant participants and cannot be taken away from the blockchain.

## 5 Conclusions

In the post-pandemic era, the PSC demonstrates enormous uncertainty and volatility brought about by its complex environment, while the emergence of digital technologies has increased the diversity of sales channels yet exacerbated the sophistication of the PSC. Therefore, the PSCR needs to be enhanced to withstand potential disruptions.

This paper determines the current operation status of PSC by performing a literature review and semi-structured interviews. The PSC has three special attributes that distinguish it from other industry supply chains, namely, life-relatedness, high quality, and timely access. The restricted distribution channels in the PSC have also led to a significant downstream impact on medicine demand, with the hospital end of the supply chain playing a dominant role. Therefore, the hospital side of the pharmaceutical distribution chain is considered the key link that affects the normal operation of the entire PSC. In the post-pandemic era, the dual role of the special attributes of the PSC and the uncertainty of unexpected epidemics expose the supply chain to an increasing amount of risk, such as fluctuations in the demand for medicine caused by unexpected medical event and alterations in consumer behavior and the barriers to sharing hospital data due to disputes over interests between the sharing entities and the personal privacy of patients. These issues prevent the upstream enterprises in the PSC from obtaining downstream demand information and downstream consumers from accessing medicine in a timely manner in the case of unexpected disease outbreaks. Consequently, the PSC lacks visibility, flexibility, and efficient information sharing mechanisms.

To address these problems, this study puts forward the use of IoT and blockchain technology in SCR and develops an IoT–blockchain-integrated hospital-side led PSC management model that comprises three layers, namely, the IoT-based physical data layer, blockchain-based data control layer, and data storage and management layer. This study also explains the role of stakeholders in the PSC and describes the functions of the three layers in detail. The management model supported by IoT–blockchain can help hospitals and pharmaceutical companies create a secure and efficient information sharing mechanism, thereby alleviating the worries of hospitals when sharing medical data, such as medicine demand and inventory information. As a consequence, upstream pharmaceutical manufacturers can obtain timely information to adjust their production, ensure their medicine delivery capacity, and improve their collaboration ability and PSCR to withstand disruptions caused by unexpected medical crises. The shared information about the supply and demand of medical institutions and patients in a specific region can also contribute to one-to-one supply and demand matching, rationalize the allocation of medical resources, realize medicine delivery in the vicinity, and improve the flexibility and responsiveness of the PSC.

However, the proposed approach is not the only way to improve SCR. Building digital twin supply chains is another solution that has received much attention from scholars (Ivanov et al., 2021; Burgos and Ivanov, 2021; Wang et al., 2022), and establishing appropriate supply chain "redundancy" presents another excellent option to promote SCR (Gao et al., 2021). Future research should also attempt to enhance SCR in both theory and practice.

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