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Presenting a Sustainable Supply Chain Model of the Pharmaceutical Industry in Conditions of Uncertainty and Based on Blockchain

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ABSTRACT

The ever-increasing changes in the business world and the new requirements of production and trade in this era have provided the basis for the emergence of new attitudes. The supply chain in the current environment faces significant complexity and diversity. In response to the change in the market environment, the demand of the supply chain has also encountered considerable uncertainty. In the modern supply chain, the coordination and cooperation among different members of the supply chain, as well as the integration of the production and commercial processes, are essential elements. These factors are essential for the success of companies, leading to achieving a competitive advantage and reducing costs. Since medicine is deemed a strategic commodity and the smallest disruption in its supply chain may cause severe crises, one of the most important and vital factors in the pharmaceutical industry is its supply chain. Given the potential of emerging technologies, such as blockchain in drug supply, which can enhance security and optimize the drug supply chain, an intelligent supply chain utilizing this technology can achieve greater stability through a transparent environment. Therefore, this research proposes an innovative model for a sustainable supply chain in the pharmaceutical industry. This model can serve as a valuable guide for managers of supply chain systems in manufacturing and especially in high-consumption industries.

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1. Introduction

The global supply chain has become a vast and complex system that businesses use to manufacture and distribute their products globally. Its complexity has led to many technological innovations in the past few years, including the adoption of blockchain technology. In the modern supply chain, the coordination and cooperation among different members of the supply chain, as well as the integration of the production and commercial processes are considered the main pillars of the success of companies, leading to achieving a competitive advantage and reducing costs. As a result, the supply chain and its performance, as one of the paradigms of the 21st century for improving competitiveness, should be taken into account (Aliahmadi et al., 2023).

Considering the fluctuations in the world price of oil and the exhaustion of this underground resource, the pharmaceutical industry is considered one of the attractive sectors for investment and profitability. Providing medicine as a strategic commodity is of particular importance in countries. One of the most important measures of a society's progress is the state of medical services in that society, which is directly related to the timely and sufficient supply of vital drugs. Like other fast-consuming goods, medicine is considered a strategic commodity, and the smallest disturbance in its supply chain may cause severe crises (Ghahremani-Nahr et al., 2022). For this reason, one of the most important and vital elements in the pharmaceutical industry is its supply chain. The pharmaceutical supply chain (PSC) consists of multiple stakeholders, including raw material suppliers, manufacturers, distributors, regulatory authorities, pharmacies, hospitals, and patients (Vu et al., 2023).

Despite many advances in drug production, storage, and distribution methods, many pharmaceutical companies are still trying to effectively meet the market's needs. Drug safety is always one of the serious concerns as it directly affects the general health of society. Researchers and industrialists widely acknowledge that an essential strategy to ensure drug safety is to establish a reliable and traceable pharmaceutical system, encompassing drug production, procurement, and sales. For this reason, during the past few decades, pharmaceutical industries have sought to address supply chain security problems by adopting new policies. However, in today's digital world, policy alone cannot resolve the challenges of legacy platforms that are not optimized to operate in the shared data economy. Recently, emerging technologies, such as blockchain, have been proposed in drug supply, which can be used in the field of security and optimization of the drug supply chain (Nozari & Nahr, 2022).

Blockchain provides a distributed, secure, and transparent approach to information exchange in the supply chain. The features of decentralization, transparency, openness, immutability, data provenance, time-stamping, and auditability are useful to ensure that the problem of counterfeit and distributed drugs is contained. All transactions related to prescription drugs, from their production, distribution, and delivery to the final consumer, are registered, and all stakeholders are interconnected. In this way, any change or action in this area is detected by each party, making the production and distribution of counterfeit drugs impossible. Due to its remarkable features, blockchain technology can address several current challenges in the pharmaceutical industry's supply chain, including fraud, preservation, corruption, smuggling, theft, on-time delivery, and performance, by improving quality, speed, and reliability (Liu et al., 2023).

Looking at the current supply chain problems in the pharmaceutical industry and studying the existing theoretical foundations indicate positive effects of blockchain in many industries, leading to the improvement of efficiency and reduction of their problems, as well as the concepts of supply chain sustainability that can improve chain performance. Therefore, the main question addressed in this research is how to develop a sustainable supply chain model in the conditions of uncertainty and based on blockchain in the pharmaceutical industry.

The objective of this research is to develop a sustainable pharmaceutical supply chain model that effectively incorporates blockchain technology to address uncertainties and enhance operational efficiency. The study aims to investigate the role of blockchain in improving transparency, reducing costs, optimizing logistics, and ensuring the timely and secure distribution of medicines. By examining the integration of blockchain with sustainability principles, the research seeks to determine how this technology can contribute to reducing environmental impact, increasing social responsibility, and strengthening supply chain resilience.

To achieve this, the study addresses the following key research questions:

- How can blockchain technology contribute to enhancing the sustainability of the pharmaceutical supply chain under uncertain conditions?
- What are the specific impacts of blockchain adoption on cost efficiency, environmental responsibility, and social aspects, such as employment within the supply chain?
- How does blockchain influence demand certainty, inventory management, and the reduction of counterfeiting in pharmaceutical logistics?
- What challenges and opportunities arise from integrating blockchain into the pharmaceutical supply chain, and how can they be addressed?

The motivation behind formulating these research questions stems from the growing complexity and challenges within the pharmaceutical supply chain, particularly in the face of increasing global uncertainties. The pharmaceutical industry, due to its strategic importance, requires a highly efficient and transparent supply chain to ensure the timely delivery of medicines, prevent counterfeiting, and optimize costs. Traditional supply chain management approaches have struggled to address these issues effectively, especially in environments characterized by fluctuating demand, regulatory constraints, and logistical inefficiencies.

Blockchain technology has emerged as a promising solution to these challenges by offering enhanced traceability, security, and decentralized control. However, despite its potential, there remains a significant research gap regarding its practical implementation in the pharmaceutical supply chain, particularly in terms of sustainability. Existing studies have explored blockchain's benefits in general supply chain contexts; however, there is limited understanding of its specific impact on cost efficiency, environmental sustainability, and social responsibility within pharmaceutical logistics.

Given these considerations, this research aims to investigate how blockchain can contribute to a more sustainable and resilient pharmaceutical supply chain under conditions of uncertainty. The focus is on determining whether blockchain adoption can mitigate supply chain risks, improve operational efficiency, and enhance sustainability metrics, such as carbon footprint reduction and employment generation. By addressing these gaps, the study seeks to provide practical insights for industry practitioners and policymakers.

The structure of this article is as follows: In the second part, the literature review is discussed. In the third part, mathematical modeling is presented according to the category of sustainability and blockchain effects. In the fifth part, the analytical results are presented, and finally, the conclusion is presented in the last part.

2. Literature Review

The features of decentralization, transparency, openness, immutability, data provenance, time-stamping, and auditability are useful to ensure that the problems of counterfeit and distributed drugs are effectively contained. All transactions related to prescription drugs, from their production, distribution to delivery to the final consumer, are registered, and all stakeholders are interconnected. In this way, any change or action in this area is detected by each party, and with this approach, the production and distribution of counterfeit drugs becomes impossible. The tracking of low-quality drugs extends to the manufacturer, and even stolen drugs can be tracked if registered at the time of production. Due to the rapid advancement of technologies in recent years, numerous studies have been conducted on the use of these technologies in business processes.

Agrawal et al. (2022) investigated the blockchain network in drug manufacturing, which allows manufacturers to effectively control a drug in the supply chain while improving security and transparency in the entire process. This research also seeks to minimize the cost and time of the manufacturing company to transfer the medicine to the end user by providing mathematical models of direct and reverse supply chains. The direct supply chain model supports drug delivery from manufacturer to end user in less time with a reliable mode of delivery. The reverse supply chain model is explicitly focused on reducing the additional time and cost imposed on the manufacturer in pursuing defective drug readouts. In addition, a real implementation of a blockchain-enabled supply chain management system is performed to demonstrate process transparency. Queiroz & Wamba (2019), identified, analyzed, and organized the literature on blockchain in the field of supply chain management (SCM). This study aims to investigate the main issues in current blockchain applications in SCM, the major changes in trends and challenges in SCM due to the adoption of blockchain and the future of blockchains in SCM. Based on their research, blockchain-supply chain integration has evolved. Nilsson and Linn (2019), using resource-based perspectives, outlined the concepts of supply chain and blockchain.

In this study, the identification of the types of resources required for the successful implementation of blockchain, and ultimately, the potential achievement of a beneficial supply chain perspective has been targeted. This study is qualitative in nature and adopts deductive reasoning. To modify and complete the existing theories, a multiple case study with semi-structured interviews has been adopted to extract empirical data. Different units have been used for analysis, and the collected data are analyzed within each case, using content analysis. Banerjee (2018) investigated how ERP systems along with blockchain technology will powerfully improve supply chain operations. His research shows how these two technologies will complement each other in every aspect of supply chain function, bringing transparency, efficiency, and cost reduction. All aspects of the supply chain are addressed for an organization with ERP capabilities, including details related to master data, engineering design, sales processes, purchasing processes, demand and planning processes, manufacturing processes, and logistics management processes. It also emphasizes the use of blockchain in the distribution industry and explains how to resolve the associated problems. Finally, it examines how this will shape the future and the challenges that lie ahead.

Kshetri (2018) examines how blockchain affects supply chain management objectives, including cost, quality, speed, reliability, risk reduction, sustainability, and flexibility, and finally, provides preliminary evidence that the use of blockchain in activities connects the supply chain to increase transparency and accountability. Case studies of blockchain projects in different phases of development for a variety of purposes are discussed. This study represents several mechanisms; through which it can help in achieving supply chain goals. In this article, special emphasis has been placed on the role of the Internet of Things in blockchain-based solutions and the degree of blockchain deployment for the validation of people and the identity of assets.

Toyoda et al. (2017), reviewed the current state of blockchain technology and some of its applications. The potential benefit of such technology in the supply chain is explored and the future perspective of the supply chain and blockchain is proposed. Then, they provide an example to show how to employ such technology in a global supply chain network. Finally, the requirements and challenges of using this technology in future production systems were stated.

Omar et al. (2022), in their research, proposed an intelligent tracking platform based on a five-layer blockchain and the Internet of Things (BIoT3, for short) to provide a decentralized tracking solution in the drug supply chain. Following the five-layer blockchain platform architecture, a practical roadmap is provided for the pharmaceutical industry to achieve blockchain design, development, application, and evaluation. In addition, three main enabling components are presented: Internet of Things-based pharmaceutical identity management, on-chain and off-chain mechanisms, and smart contract-based pharmaceutical services. The feasibility and efficiency of the blockchain platform using the Hyper Ledger Fabric blockchain have been confirmed based on real data from partner companies. The case study indicate that it gains useful insight into configuring transaction sizes for optimal blockchain performance and provides a practical blockchain-based solution for drug traceability and visibility.

Recent studies have examined blockchain integration into supply chain management, highlighting its potential to enhance traceability, security, and efficiency (Najafi & Nozari, 2024). However, most of these investigations have primarily focused on general supply chains or industries, such as agriculture and food production, with limited attention given to the pharmaceutical sector (Nozari et al., 2024). While blockchain has been widely recognized as a tool to mitigate counterfeiting and improve transparency, the extent of its impact on broader sustainability challenges within pharmaceutical supply chains remains insufficiently explored (Rahmaty & Nozari, 2023). Specifically, there is a lack of comprehensive research analyzing how blockchain can simultaneously optimize economic, environmental, and social dimensions of sustainability in an industry where supply chain disruptions can have critical consequences (Abbas et al., 2020). Furthermore, previous research has not adequately addressed the role of blockchain in managing demand uncertainty and reducing inefficiencies in pharmaceutical logistics (Abdallah & Nizamuddin, 2023).

Another significant gap in the literature concerns the scalability and practical feasibility of blockchain adoption in pharmaceutical supply chains (Lokesh et al., 2021). While theoretical models and case studies have demonstrated its potential benefits, real-world implementation remains challenging due to high costs, regulatory constraints, and difficulties in integrating blockchain with existing supply chain infrastructures (Nozari et al., 2023). Additionally, the interplay between blockchain adoption and multi-objective optimization in pharmaceutical logistics has not been thoroughly examined (Panda et al., 2025). Most existing frameworks fail to incorporate dynamic variables, such as fluctuating demand, heterogeneous cost structures, and evolving environmental regulations (Pimple et al., 2025). Without a robust, data-driven approach that considers these complexities, the true impact of blockchain on pharmaceutical supply chain sustainability remains unclear (Mahirah et al., 2025). Addressing this gap requires an in-depth analysis of how blockchain can be strategically integrated into pharmaceutical supply chains to maximize its benefits while mitigating the associated risks (Majeed et al., 2025).

In Table 1, the most important research conducted in recent years and the research gaps are presented.

Table 1. Literature Review and Research Gaps

Authors	Year	Target	Methods	sustainability	uncertainty	Blockchain	Pharmaceutical supply chain	Direct and reverse logistics
Nayak, & Dhaigude,	2019	Presenting a conceptual model regarding sustainable supply chain management in small and medium-sized companies using blockchain	Multi-criteria decision-making techniques	✓		✓		
kamilaris et al	2019	Investigating the impact of blockchain technology in agriculture and food supply chain	Qualitative			✓		
Bathaee et al.	2023	Outlining the concepts of supply chain and blockchain	Qualitative			✓		
Chen & Bellavitis	2019	Investigating the use of blockchain technology in the food supply chain	Qualitative			✓		
Lang et al.	2018	Providing a public blockchain supply chain for agribusiness	Mathematical modeling and meta-heuristics	✓		✓		
Nozari et al.	2023	The impact of blockchain technology in agriculture and food distribution	Qualitative			✓		
Current Research		Blockchain-based sustainable supply chain model under uncertainty	Mathematical modeling	✓	✓	✓	✓	✓

3. Mathematical Modeling

In this section, a multi-objective mixed-integer mathematical programming model is presented, aiming to optimize the drug supply chain based on blockchain technology. In fact, the current research seeks to provide a sustainable supply chain model based on blockchain including manufacturers, distributors, and pharmacies. Distributors and pharmacies have the option to connect to the blockchain system; if they choose to do so, they will automatically record their drug needs. Connecting to the blockchain system ensures demand certainty, as the demand is recorded by the blockchain, while failing to connect leads to demand uncertainty. Finally, a three-objective model based on reducing costs, mitigating environmental issues, and enhancing employment or social responsibility is designed. The schematic of the model is presented in Figure 1.

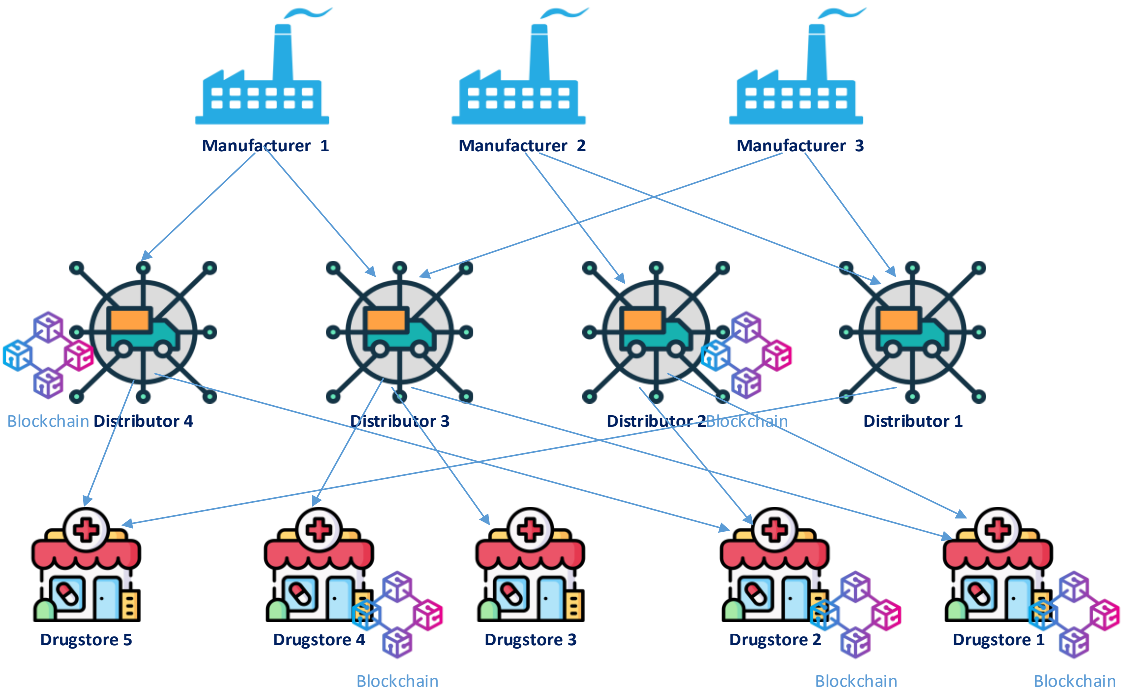

Fig. 1. Blockchain-Based Sustainable Supply Chain Model in the Pharmaceutical Industry

The assumptions of the model are as follows:

1. The model is uncertain
2. It is possible to either choose or forgo the blockchain system.
3. The supply chain has three levels.
4. It is a multi-product model.
5. It is a multi-period model.
6. The model is based on three objectives of sustainability.
7. The amount of employment is determined based on the inventory and the amount of production
8. The amount of energy consumption is determined based on the inventory and the amount of production.
9. The cost of maintenance is different for each pharmacy and distributor.
10. The cost of production is considered different for each producer.
11. Producers, distributors, and pharmacies have limited capacity.

Indices

i Producer
j Distributor
k pharmacy
p the product
t period
s scenario

Parameters

FJ_j	The cost of building a distributor j
FK_k	The cost of building a pharmacy k
DIJ_{ij}	Distance between producer i and distributor j
DJK_{jk}	Distance between distributor j and pharmacy k
TC	Unit transfer fee
BDK_{kt}	The amount of demand for product p in pharmacy k in period t recorded by the blockchain system
BDJ_{jt}	The amount of demand for product p at distribution center j in period t recorded by the blockchain system
DK_{kts}	The amount of demand for product p in pharmacy k in period t without blockchain system under scenario s
DJ_{jts}	Demand rate of product p at distribution center j in period t recorded without blockchain system under scenario s
$CAPI_i$	Producer capacity i
$CAPJ_j$	distributor capacity j
$CAPK_k$	Pharmacy capacity k
BCJ	The cost of connecting to the blockchain system for the pharmacy
BCK	The cost of connecting to the blockchain system for the distributor
MC_i	Unit cost of drug production by the manufacturer i
DC_jl	The unit cost of drug storage by the distributor j
KC_k	Drug storage unit cost by pharmacy k
ECI_{ip}	The amount of energy consumed per unit of product p by producer i
ECJ_{jp}	The amount of energy consumption per unit of product p by distributor j
ECK_{kp}	The amount of energy consumption per unit of product p by pharmacy k
$EMPI$	The number of labor required for the producers of each unit of product
$EMPJ$	The number of labor required for distributors per unit of product
$EMPK$	The number of labor required for the pharmacy per unit of inventory
MM	A big number

Decision variables

XJ_j	if distributor j is built, and zero otherwise
XK_k	1 if pharmacy k is built, and zero otherwise
XIJ_{ij}	Transfer flow of product p between producer i and distributor j
XJK_{jk}	Transfer flow of product p between distributor j and pharmacy k
YBK_{ktp}	Inventory of product p in pharmacy k in period t based on blockchain system
YBJ_{jtp}	Inventory of product p in distribution center j in period t based on a blockchain system
YK_{ktsp}	Inventory of product p in pharmacy k in period t without blockchain system under scenario s
YJ_{jtsp}	Inventory of product p at distribution center j in period t without blockchain system under scenario s
ZK_k	1 if pharmacy k connects to the blockchain system, and zero otherwise
ZJ_j	1 if distributor j connects to the blockchain system, and zero otherwise
U_i	The amount of drug production by the manufacturer i
$JOBI_{ip}$	The amount of production of employment by the producer i
$JOBJ_{jp}$	The amount of employment produced by the distributor j
$JOBK_{kp}$	The amount of employment generated by the pharmacy k
VI_{ipt}	The energy consumption of producer i in period t for product p
VJ_{jpt}	The energy consumption of distributor j in period t for product p
VK_{kpt}	Energy consumption of pharmacy k in period t for product p

Mathematical Modeling

$$\begin{aligned}\min z1 = &\sum_j FJ_j XJ_j + \sum_k FK_k XK_k + \sum_i\sum_j DIJ_{ij} TC\ XIJ_{ij} + \sum_j\sum_k DJK_{jk} TC\ XJK_{jk} + \sum_j BCJ\ Z_j + \sum_j BCK\ Z_k \\ &+ \sum_i MC_i U_i + \sum_j\sum_t\sum_p DC_j YBJ_{jtp} + \sum_k\sum_t\sum_p KC_k YBK_{ktp} + \sum_j\sum_t\sum_p\sum_s DC_j YJ_{jtsp} + \sum_k\sum_t\sum_p\sum_s KC_k YK_{ktsp}\end{aligned} \tag{1}$$

$$\min z2 = \sum_i\sum_p\sum_t VI_{ipt} + \sum_j\sum_p\sum_t VJ_{jpt} + \sum_k\sum_p\sum_t VK_{kpt} \tag{2}$$

$$\max z2 = \sum_i \sum_p JOBI_{ip} + \sum_j \sum_p JOBJ_{jp} + \sum_k \sum_p JOBK_{kp} \tag{3}$$

$$\sum_j XJ_j \geq 1 \tag{4}$$

$$\sum_k XK_k \geq 1 \tag{5}$$

$$\sum_i XIJ_{ij} \leq CAPJ_j \tag{6}$$

$$XIJ_{ij} \leq MMXJ_j \tag{7}$$

$$\sum_j XJK_{jk} \leq \sum_i XIJ_{ij} \tag{8}$$

$$\sum_j XJK_{jk} \leq CAPK_k \tag{9}$$

$$XJK_{jk} \leq MMXK_k \tag{10}$$

$$U_i \leq \sum_j XIJ_{ij} \tag{11}$$

$$U_i \leq CAPI_i \tag{12}$$

$$YBJ_{jtp} \leq MMZ_j \tag{13}$$

$$YBJ_{jtp} = YBJ_{jt-1\,p} + \sum_i XIJ_{ij} - BDJ_{jt} \tag{14}$$

$$YBK_{ktp} \leq MMZ_k \tag{15}$$

$$YBK_{ktp} = YBK_{kt-1\,p} + \sum_j XJK_{jk} - BDK_{kt} \tag{16}$$

$$YJ_{jtsp} = YJ_{jt-1\,p} + \sum_i XIJ_{ij} - DJ_{sjt} \tag{17}$$

$$YK_{ktsp} = YK_{kt-1\,sp} + \sum_j XJK_{jk} - DK_{kts} \tag{18}$$

$$VI_{ipt} = ECI_{ip} U_i \tag{19}$$

$$VJ_{ipt} = ECJ_{jp} YBJ_{jtp} + ECJ_{jp} YJ_{jtsp} \tag{20}$$

$$VK_{kpt} = ECK_{kp} YBK_{ktp} + ECK_{kp} YK_{ktsp} \tag{21}$$

$$JOBI_{ip} = EMPI / U_i \tag{22}$$

$$JOBJ_{jp} = \frac{EMPJ}{YBJ_{jtp} + YJ_{jtsp}} \tag{23}$$

$$JOBK_{kp} = \frac{EMPK}{YBK_{ktp} + YK_{ktsp}} \tag{24}$$

$$XJ_j \in \{0.1\} \tag{25}$$

$$XK_k \in \{0.1\} \tag{26}$$

$$ZK_k \in \{0.1\} \tag{27}$$

$$ZJ_j \in \{0.1\} \tag{28}$$

$$XIJ_{ij} \geq 0 \tag{29}$$

$$XJK_{jk} \geq 0 \tag{30}$$

$$YBK_{ktp} \geq 0 \tag{31}$$

$$YBJ_{jtp} \geq 0 \tag{32}$$

$$YK_{ktsp} \geq 0 \tag{33}$$

$$YJ_{jtsp} \geq 0 \tag{34}$$

$$U_i \geq 0 \tag{35}$$

$$JOBI_{ip} \geq 0 \tag{36}$$

$$JOBJ_{jp} \geq 0 \tag{37}$$

$$JOBK_{kp} \geq 0 \tag{38}$$

$$VI_{ipt} \geq 0 \tag{39}$$

$$VJ_{jpt} \geq 0 \tag{40}$$

$$VK_{kpt} \geq 0 \tag{41}$$

Equation 1 seeks to minimize the costs of the drug supply chain. Equation 2 seeks to minimize the environmental issues of the drug supply chain. Equation 3 seeks to maximize social responsibility in the drug supply chain. Equation 4 indicate that, at least, a distributor should be built. Equation 5 indicate that, at least, one pharmacy should be built. Equation 6 shows that the total transmission flow to distributors cannot exceed their capacity. Equation 7 states that if the distributor is not built, there will be no flow for it. Equation 8 represents that the total flow sent from distributors to pharmacies cannot naturally exceed the total flow sent from manufacturers to distributors. Equation 9 shows that the total flow sent from all distributors to pharmacies cannot exceed the capacity of pharmacies. Equation 10 states that if a pharmacy is built, there will be a flow for it. Equation 11 shows that the amount of production by a producer cannot be more than the flow sent to all distributors. Equation 12 indicates the limitation of the producer's capacity. Equation 13 shows that if the blockchain system is selected for a distributor, the inventory is recorded accordingly. Equation 14 seeks to calculate the amount of inventory based on the blockchain. Equation 15 states that if the blockchain system is selected for the pharmacy, the inventory will be calculated based on the blockchain. Equation 16 seeks to calculate the amount of inventory for the pharmacy based on the blockchain. Equation 17 calculates the amount of inventory without blockchain for distributors. Equation 18 calculates inventory without blockchain for pharmacies. Equation 19 calculates the amount of energy consumption for the producer. Equation 20 calculates the amount of energy consumption for the distributor. Equation 21 calculates the amount of energy consumption for the pharmacy. Equation 22 calculates the amount of employment generated by the manufacturer. Equation 23 calculates the amount of employment generated by the distributor. Equation 24 calculates the amount of employment generated by the pharmacy. Equations 25 to 28 determine the range of binary variables. Equations 29 to 41 include the range of integer variables.

4. Research Findings

The NSGA II meta-heuristic algorithm is one of the most widely used and powerful algorithms available for solving multi-objective optimization problems, and its effectiveness in solving various problems has been proven.

Along with all the functions of NSGA-II meta-heuristic algorithm, it can be regarded as a functional model for the formation of various multi-objective optimization algorithms. This algorithm, with its unique way of dealing with multi-objective optimization problems, has been employed numerous times by different people to create innovative multi-objective optimization algorithms. Undoubtedly, this algorithm is one of the most basic members of the collection of evolutionary multi-objective optimization algorithms, which can be called the second generation of such methods. The pseudocode of this algorithm is presented in Figure 2.

First, the model is validated, and then, the model is solved in large dimensions, followed by sensitivity analysis and uncertainty analysis. The algorithm used is the NSGA II algorithm, which is implemented in MATLAB software.

At this stage, various dimensions of the model are introduced, and the problem is addressed across these dimensions. The model's natural response to changes in dimensions will result in an increase in the values of the objective functions and decision variables.

```
Input: Population S
initialize population: the number of population;
Generate random population S
Evaluate objectives values
Assign Rank
Generate Child Population for size S
for i = 1 : Max do
    for each parent and child ∈ S do
        Assign Rank
        Generate sets of nodominated solutions
        Cross over and mutation
        Loop based on existing solution to next generation
    end for
    Select points on the lower front with high distance
    Generate next generation
end for
Output: Child
```

Fig. 2. Pseudo Code of NSGA II Algorithm

Table 2. Different Dimensions of the Model

problem	Manufacturers	Manufacturers	Drugstore	product	period	scenario
1	1	1	4	2	1	1
2	2	1	8	4	1	1
3	3	2	12	5	1	1
4	4	2	16	7	1	1
5	5	3	20	8	2	2
6	6	3	24	9	2	2
7	7	4	28	10	2	2
8	8	4	32	11	3	2
9	9	5	36	12	3	3
10	10	5	40	12	3	3
11	11	6	44	12	3	3
12	12	6	48	12	3	3
13	13	7	52	12	3	3
14	14	7	56	14	3	3
15	15	8	60	14	3	3
16	16	8	64	14	4	3
17	17	9	68	15	4	3
18	18	9	72	15	4	3
19	19	10	76	15	4	3
20	20	10	80	15	4	3

As it can be seen, 20 examples are introduced in this research. In each example, the dimensions of the problem have increased compared to the previous problem, and therefore, the model response to the increase in dimensions should be checked. As a result, the model is solved in different dimensions and the results obtained from the cost values of environmental issues and social responsibility, as well as calculation time are obtained.

After checking and solving the model, it can be determined that the model can be addressed in different dimensions. However, the exact method is responsive only up to the tenth example; beyond that, we encounter low memory errors, which are characteristic of NP-hard problems. As the dimensions of the problem increase, it can only be solved to a certain extent. Beyond that point, meta-heuristic methods should be employed, as they provide nearly optimal solutions that are not necessarily exact. The selected algorithm at this stage is the NSGA-II algorithm. In this section, we aim to compare its results with those of the exact method. This comparison is presented in Table 3.

Table 3. Comparison of Exact Method and NSGA II Algorithm

	The exact method				NSGA II				Gap			
problem	Cost	Environmental issues	Social responsibility	Calculation time	Cost	Environmental issues	Social responsibility	Calculation time	Cost	Environmental issues	Social responsibility	Calculation time
1	570845	42322	17096	5	570841	42320	17089	5	4	2	7	0
2	572065	43736	17260	15	572058	43732	17245	15	7	4	15	0
3	573405	44939	17429	20	573374	44930	17412	18	31	9	17	2
4	574844	46174	17603	28	574810	46154	17585	24	34	20	18	4
5	576709	48045	17721	33	576670	48020	17703	29	39	25	18	4
6	577916	49171	17896	41	577875	49138	17875	37	41	33	21	4
7	579826	50580	18072	46	579780	50546	18051	42	46	34	21	4
8	581712	51674	18208	51	581656	51635	18173	47	56	39	35	4
9	583109	53393	18335	61	583037	53348	18292	56	72	45	43	5
10	584214	54513	18474	71	584131	54468	18424	66	83	45	50	5
11	…….	…….	…….	low memory	599006	55832	19716	72				
12	…….	…….	…….	low memory	618747	56979	21410	77				
13	…….	…….	…….	low memory	637535	58661	23371	82				
14	…….	…….	…….	low memory	654954	60030	24816	92				
15	…….	…….	…….	low memory	673999	61372	25817	102				
16	…….	…….	…….	low memory	687268	63138	27162	108				
17	…….	…….	…….	low memory	706465	64324	28807	116				
18	…….	…….	…….	low memory	722972	65832	30002	126				
19	…….	…….	…….	low memory	737574	66908	31373	132				
20	…….	…….	…….	low memory	748592	68643	32646	142				

As it can be seen, with the increase in the dimensions of the problem, the gap between the two methods also increases, and the biggest gap is observed in the cost, indicating the superiority of this method over the exact method. On the other hand, as the dimensions increase, the disparity between the results of the two methods widens, and there is a significant gap in calculation time. Notably, the largest gap is observed in cost, followed by environmental issues, and finally, in social issues.

4-1. Sensitivity Analysis

Considering that the current research is focused on the use of the blockchain system, in this section, the effect of connecting to the blockchain system and the costs imposed on it will be investigated. Table 4 indicates that the connection to the blockchain system will cause changes in the objective functions of the current research, which is based on sustainability.

Table 4. Sensitivity Analysis of Connecting and not Connecting to the Blockchain System in the Drug Supply Chain

	Connecting to the blockchain system			No connection to the blockchain system			Contradiction			Percent discrepancy		
Problem	Cost	Environmental issues	Social responsibility	Cost	Environmental issues	Social responsibility	Cost	Environmental issues	Social responsibility	Cost	Environmental issues	Social responsibility
1	570841	42320	17089	583171	43255	16230	12330	935	859	0.021143	0.021616	0.052927
2	572058	43732	17245	589325	44661	16490	17267	929	755	0.0293	0.020801	0.045785
3	573374	44930	17412	583573	45613	16613	10199	683	799	0.017477	0.014974	0.048095
4	574810	46154	17585	585873	46901	16750	11063	747	835	0.018883	0.015927	0.049851
5	576670	48020	17703	588174	48550	16821	11504	530	882	0.019559	0.010917	0.052434
6	577875	49138	17875	593522	49669	17064	15647	531	811	0.026363	0.010691	0.047527
7	579780	50546	18051	591843	51370	17180	12063	824	871	0.020382	0.01604	0.050698
8	581656	51635	18173	594885	52508	17617	13229	873	556	0.022238	0.016626	0.03156
9	583037	53348	18292	602175	54111	17308	19138	763	984	0.031781	0.014101	0.056852
10	584131	54468	18424	595455	55396	17862	11324	928	562	0.019017	0.016752	0.031463
11	599006	55832	19716	616141	56614	19126	17135	782	590	0.02781	0.013813	0.030848
12	618747	56979	21410	638603	57925	20559	19856	946	851	0.031093	0.016331	0.041393
13	637535	58661	23371	649376	59584	22754	11841	923	617	0.018234	0.015491	0.027116
14	654954	60030	24816	673627	60915	24310	18673	885	506	0.02772	0.014528	0.020814
15	673999	61372	25817	690086	62335	24825	16087	963	992	0.023312	0.015449	0.03996
16	687268	63138	27162	702293	63760	26236	15025	622	926	0.021394	0.009755	0.035295
17	706465	64324	28807	724996	64951	28124	18531	627	683	0.02556	0.009653	0.024285
18	722972	65832	30002	733061	66402	29433	10089	570	569	0.013763	0.008584	0.019332
19	737574	66908	31373	749434	67548	30757	11860	640	616	0.015825	0.009475	0.020028
20	748592	68643	32646	766986	69304	31898	18394	661	748	0.023982	0.009538	0.02345

As you can see, there is a distinction between connecting to and not connecting to the blockchain system. Connecting to the blockchain system can reduce costs and environmental issues, while also improving social issues, such as employment. This indicates that, in general, connecting to the blockchain system benefits the drug supply chain. However, it is noteworthy that as the dimensions increase, the gap between the two modes gradually decreases. Specifically, the advantages of cost reduction, environmental improvements, and increased employment associated with connecting to the blockchain system diminish as dimensions grow larger. Thus, in higher dimensions, the benefits of connection generally decrease.

5. Conclusion

The use of blockchain technology in the supply chain allows companies to track all types of transactions with greater security and transparency. Using blockchain, companies can trace the history of a product right from its point of origin to where it currently is. With the help of this powerful technology, parties collaborating on a common platform can dramatically reduce the time delays, overhead, and human error, often associated with transactions. Reducing intermediaries is another benefit of using blockchain in the supply chain, mitigating the risks of fraud.

The aim of the current research was to provide a sustainable supply chain model under uncertainty conditions, based on blockchain. Conducting library-based research indicated a research gap in the field of using blockchain in the sustainable drug supply chain. Regarding the studies, a three-objective sustainable supply chain model was designed based on sustainability. The first objective is cost reduction, the second objective is the reduction of environmental issues, and the third objective is the increase in employment or social issues. The drug supply chain model was divided into three sectors: manufacturing, distribution, and pharmacies, which formed the layers of the supply chain. In this chain, the nodes had the authority to join the blockchain system; that is, any pharmacy or distribution center could connect to the blockchain. This connection offers both benefits and costs for the supply chain.

At first, the model was validated by solving it in different dimensions, and then, the NSGA II algorithm was used to solve the model in large dimensions. The results indicated the success of the algorithm in solving the model in large dimensions. Subsequently, a sensitivity analysis was conducted to assess the effects of connecting to the blockchain, as well as the costs associated with connecting and increasing the number of pharmacies and distribution centers that join the blockchain, on the objective functions of the problem. The analysis revealed a clear and significant impact of using the blockchain system. Regarding environmental issues, the current research focuses on energy consumption, and the goal is to minimize energy consumption in the supply chain. According to this, each node in every layer that exhibits lower energy consumption is selected. Just as centers with low costs are prioritized, pharmacies, distribution centers, or manufacturers with lower energy consumption will also be prioritized. Regarding social responsibility, this research emphasizes creating employment. In each component of the drug supply chain—whether it be the manufacturer, distributor, or pharmacy—those with higher employment levels are given priority. However, in multi-faceted issues, determining the weight for each goal or assigning equal weight to each may not effectively differentiate between social responsibility, environmental responsibility, and cost. Ultimately, by considering all three criteria, the best options are selected; for example, a center that has low costs. High employment or low energy consumption is prioritized, but it is rare that a pharmacy or distribution center excels in all three criteria.

A comparison between the findings of this study and previous research reveals important insights into the role of blockchain in pharmaceutical supply chains. While prior studies have primarily focused on the theoretical benefits of blockchain, such as enhanced traceability, security, and transparency, this research extends the discussion by demonstrating its impact on sustainability through a multi-objective optimization approach. Earlier studies have explored blockchain’s potential in mitigating counterfeiting and improving supply chain visibility, yet they often lack quantitative assessments of its influence on cost efficiency, environmental responsibility, and employment generation. In contrast, this study provides an empirical and mathematical framework that quantifies the trade-offs and benefits associated with blockchain adoption in an uncertain pharmaceutical supply chain environment.

Additionally, previous studies have largely examined blockchain in the context of general supply chains or industries, such as agriculture and food production, with limited focus on the pharmaceutical sector. This research bridges that gap by specifically addressing the unique complexities of pharmaceutical logistics, where factors such as fluctuating demand, regulatory requirements, and product safety standards play a crucial role. Unlike earlier models that primarily highlight blockchain's security advantages, the findings of this study suggest that its integration can lead to significant cost reductions, lower environmental impact, and improved social responsibility by optimizing employment distribution. Moreover, previous research has often overlooked the scalability challenges of blockchain adoption, while this study incorporates uncertainty analysis and sensitivity assessments to evaluate its feasibility in large-scale pharmaceutical operations.

The practical implications of this research extend to multiple stakeholders within the pharmaceutical supply chain, including manufacturers, distributors, regulators, and policymakers. By demonstrating how blockchain can enhance transparency and traceability, this study provides practical insights for pharmaceutical companies seeking to mitigate risks associated with counterfeit drugs and supply chain inefficiencies. The findings suggest that adopting blockchain technology can significantly improve inventory management by reducing demand uncertainty and enhancing coordination between different supply chain entities. This has direct implications for manufacturers and distributors, enabling them to optimize production schedules, reduce wastage, and improve the overall responsiveness of the supply chain.

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