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Original Research Article

# Identification and Prioritization of Key Factors in Blockchain-Based Resilient Supply Chain Risk Management in the Laboratory Equipment Industry

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## Abstract

The increasing complexity of supply chains and the importance of resilience in facing diverse risks underscore the need to examine factors affecting resilient supply chain risk management. While blockchain technology offers promising capabilities for enhancing supply chain transparency, traceability, and security, there is limited research on its integration with risk management practices in specialized industries. This research aims to identify and rank factors affecting blockchain-based resilient supply chain risk management in the laboratory equipment industry, where product traceability and quality assurance are crucial. The research methodology combines qualitative and quantitative approaches. Initially, using the meta-synthesis method, 342 articles from reputable databases were reviewed for the period 2015 to 2024. After screening and quality assessment, 38 articles were selected for final analysis, leading to the identification of 110 indicators within 24 components and 6 main dimensions. Subsequently, using the fuzzy Delphi method and the input of 12 industry experts, the initial model was evaluated and modified, resulting in a final model with 114 indicators. Finally, using the Best-Worst Method (BWM) of multi-criteria decision-making and the opinion of 8 experts, the factors were ranked. Findings revealed that "Digital Technology and Infrastructure," with a weight of 0.323, is the most important dimension, emphasizing the critical role of blockchain infrastructure in enabling secure and transparent supply chain operations. "Information Management and Transparency" (0.239) and "Operational Flexibility and Resilience" (0.177) ranked next, highlighting how blockchain enhances traceability and adaptability. The most crucial components identified were "Technical Infrastructure and Specialized Human Resources" (0.331), "Product Traceability and Tracking Capability" (0.451), and "Speed in Recovery from Disruptions" (0.362), demonstrating how blockchain technology can strengthen key operational capabilities. The primary contribution of this research is developing a comprehensive framework that integrates blockchain capabilities with risk management processes and resilience factors, specifically tailored to the laboratory equipment industry's unique requirements. This integration provides supply chain managers with a structured approach to leverage blockchain technology for enhancing transparency, reducing risks, and improving operational resilience, ultimately leading to more secure and efficient supply chain operations in this critical industry.

**Keywords:** Blockchain; Laboratory Equipment Industry; Multi-Criteria Decision Making (MCDM); Resilience; Supply Chain Risk Management (SCRM).

## 1. Introduction

In today's complex and interconnected world, supply chain management has become one of the most significant challenges facing organizations across various industries [1]. The laboratory equipment industry, as a vital infrastructure sector in medical, research, and industrial fields, faces numerous challenges in supply chain risk management. Due to the sensitive and precise nature of its products, this industry requires a reliable,

flexible, and resilient supply chain capable of withstanding potential disruptions, including global crises such as pandemics, economic sanctions, and sudden changes in demand and supply [2].

In recent years, the concept of resilience in supply chains has increasingly attracted the attention of researchers and professionals. Resilience refers to a system's ability to return to its normal state after facing disruptions and external shocks. In the context of supply chains, resilience means creating structures and processes

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capable of anticipating, resisting, and quickly recovering from disruptive events [3]. Given the critical importance of laboratory equipment in advancing scientific research, disease diagnosis, and product quality control, creating a resilient supply chain in this industry is paramount.

The emergence of new technologies, such as blockchain, has opened new horizons in supply chain management. Blockchain, as a decentralized and immutable technology, has significant potential for increasing transparency, traceability, and security in the supply chain [4]. This technology can enhance trust between supply chain members and improve risk management processes by creating a tamper-proof system for recording and maintaining information [5]. In the laboratory equipment industry, which requires high precision and complete product traceability, the use of blockchain can create a fundamental transformation in supply chain management.

Despite extensive studies in the field of supply chain risk management and blockchain applications in this area, there is a significant research gap regarding the identification and prioritization of key factors affecting risk management in blockchain-based resilient supply chains, especially in the laboratory equipment industry. Most previous studies have either focused on traditional risk management [6] or merely examined blockchain applications in supply chains [7] without investigating the relationship between these two concepts with supply chain resilience and the specific characteristics of the laboratory equipment industry.

The integration of risk management, resilience, and blockchain technology in the supply chain is an innovative and comprehensive approach to addressing complex and variable challenges in today's business environment. This integrated approach seeks to create synergy between three key elements to create a supply chain that is not only capable of identifying and managing risks but is also resilient to disruptions and benefits from advanced blockchain technology. In this integrated approach, risk management acts as the foundation. By identifying, assessing, and prioritizing various risks throughout the supply chain, organizations can develop appropriate strategies to mitigate or manage these risks [8].

Resilience, as the second layer, gives the supply chain the ability to quickly recover and return to normal performance in case of disruption. This includes creating additional capacities, diversifying supply sources, and designing flexible processes. Blockchain, as the third layer of this integrated approach, provides a powerful tool to strengthen both aspects of risk management and resilience. By using blockchain, organizations can create greater transparency in their supply chain, enabling faster identification of risks and adoption of preventive measures [9]. Additionally, blockchain's advanced traceability capability can contribute to increased resilience, as the source of a problem can be identified and addressed more quickly if it occurs [1].

One of the key advantages of this integrated approach is the creation of a dynamic and self-regulating system. By combining data from risk assessment, resilience indicators, and information recorded on the blockchain, organizations can identify patterns and trends that may not be detectable with traditional methods. This leads to better decision-making and faster reactions to environmental changes.

This research aims to fill this research gap by identifying and prioritizing key factors in blockchain-based resilient supply chain risk management in the laboratory equipment industry. The main innovation of this research lies in combining the three key concepts of risk management, resilience, and blockchain technology within a framework for the laboratory equipment supply chain. This integrated approach enables the identification of critical factors and complex relationships between them that have received less attention in previous studies.

The main question of this research is: "What are the key factors affecting risk management in blockchain-based resilient supply chains in the laboratory equipment industry, and how are these factors prioritized?" To answer this question, the present study uses a mixed qualitative-quantitative approach. In the first stage, key factors are identified using an in-depth study of existing literature through the meta-synthesis method and utilizing industry experts' opinions through the fuzzy Delphi method. Then, using the Best-Worst Method (BWM) of multi-criteria decision-making, these factors are prioritized, and the relationships between them are analyzed.

The importance and necessity of this research can be examined from several aspects. First, given the vital role of laboratory equipment in the advancement of science and technology, improving risk management in the supply chain of this industry can have a direct impact on the quality and accessibility of this equipment. Second, in today's turbulent economic and political conditions, creating resilient supply chains for strategic industries such as laboratory equipment is of strategic importance. Third, given the high potential of blockchain technology in transforming supply chains, a precise understanding of key factors in the successful implementation of this technology can pave the way for addressing many existing challenges.

The scientific contribution of this research can be considered in several dimensions. First, this research contributes to the development of theoretical literature in this field by presenting a comprehensive framework for risk management in blockchain-based resilient supply chains. Second, identifying and prioritizing key factors in the laboratory equipment industry provides a deeper understanding of the specific challenges and opportunities of this industry in supply chain management. Third, this study paves the way for future research on the convergence of these concepts by examining the relationship between resilience, risk management, and blockchain technology.

The results of this research can have multiple applications in various fields. At the industrial level, the findings of this research can help managers and decision-makers in the laboratory equipment industry develop more effective strategies for risk management and increasing supply chain resilience. Also, these results can serve as a practical guide for implementing blockchain technology in the supply chain of this industry. At the policy-making level, the findings of this research can contribute to the development of appropriate policies and regulations to support the development of resilient supply chains and the use of new technologies in strategic industries.

Furthermore, this research can pave the way for more studies in related fields. For example, the model presented in this research can be used, with modifications, for other sensitive industries such as pharmaceuticals, medical equipment, or defense industries. Additionally, this research can serve as a basis for more in-depth studies on the impact of emerging technologies on supply chain risk management and resilience.

The remainder of this article first reviews the existing literature on supply chain risk management, resilience, and blockchain applications in supply chains. Then, the research methodology, including data collection and analysis methods, is explained. In the findings section, the identified key factors and their prioritization results are presented. Finally, the discussion and conclusion revolve around the research findings, its limitations, and suggestions for future research.

This research, aiming to provide a comprehensive and practical perspective on the issue of risk management in blockchain-based resilient supply chains in the laboratory equipment industry, strives to take an effective step towards improving performance and increasing sustainability in this vital industry.

## 2. Literature Review

### 2.1 Supply Chain Management

Supply chain management, a crucial concept in operations management and logistics, involves the coordination and integration of material, information, and financial flows from primary suppliers to end consumers. This concept encompasses planning, executing, and controlling supply chain activities with the aim of creating value, building a competitive infrastructure, leveraging global logistics, synchronizing supply with demand, and measuring performance across the chain [10]. In today's complex and competitive world, effective supply chain management has become a key competitive advantage for organizations. This management not only focuses on reducing costs and improving efficiency but also seeks to increase customer satisfaction, enhance product and service quality, and create flexibility in response to market changes [11].

### 2.2 Risk Management in Supply Chain

Supply chain risk management is a process that identifies, assesses, and mitigates potential risks in the supply chain. This concept includes strategies and techniques for dealing with uncertainties and potential disruptions in the flow of materials, information, and financial resources. Supply chain risks can stem from various sources, such as sudden changes in demand, production disruptions, transportation problems, economic sanctions, natural disasters, and even cyber-attacks [8].

Effective management of these risks requires a comprehensive approach that includes risk identification, assessment of its probability and severity, development of risk mitigation strategies, and implementation of monitoring and control systems. In the laboratory equipment industry, given the sensitivity and importance of products, risk management is of particular importance and can have a direct impact on the quality, safety, and availability of vital equipment [2].

### 2.3 Resilience in Supply Chain

Supply chain resilience refers to a system's ability to return to normal or even improve performance after facing external disruptions and shocks. This concept goes beyond traditional risk management and emphasizes creating structures and processes that are not only capable of resisting disruptions but can also use these challenges as opportunities for improvement and innovation [3].

Supply chain resilience encompasses four main stages: preparedness, responsiveness, recovery, and learning. Preparedness involves identifying potential risks and creating contingency plans. Responsiveness refers to the ability to react quickly and effectively to disruptions. Recovery includes returning to normal performance or even surpassing previous levels. Finally, learning refers to the process of extracting lessons and continuous system improvement. In the laboratory equipment industry, supply chain resilience can ensure the continuity of vital equipment supply even under critical conditions [10].

### 2.4 Blockchain Technology and Its Applications in Supply Chain

Blockchain, as a revolutionary technology, has garnered significant attention in various fields, including supply chain management, in recent years. This technology, by providing a distributed, decentralized, and immutable record system, has substantial potential to address many existing challenges in the supply chain. At its core, blockchain is a distributed database that stores information in interconnected blocks, with each block linked to the previous one using cryptography. This structure ensures the security and integrity of data and minimizes the possibility of unauthorized manipulation or alteration of information [1].

In the supply chain context, blockchain offers multiple benefits. One of its most important applications is increasing transparency and traceability throughout the supply chain. Using blockchain, all supply chain stakeholders can access a single, up-to-date version of information, which leads to reduced disputes and increased trust between parties. Additionally, blockchain enables precise tracking of products from origin to destination [7], which is particularly valuable in industries like laboratory equipment that require rigorous quality control.

Blockchain can also help improve inventory management and logistics. Using blockchain-based smart contracts, ordering and delivery processes can be automated with minimal human intervention. This not only reduces human errors but also increases the speed of operations. Moreover, blockchain can contribute to better risk management in the supply chain. By recording all transactions and events in an immutable system, it enables more accurate risk analysis and the adoption of preventive measures [9].

Recent studies have provided valuable insights into blockchain implementation in supply chain risk management. Hong & Hales [12] demonstrated that manufacturing companies adopting blockchain technology have experienced significant improvements in managing supply chain-related risks, particularly in financial transaction reliability and information reliability. Their empirical study of 204 Indian manufacturing companies highlighted blockchain as a competitive advantage for supply chain management.

The integration of blockchain with other emerging technologies has also received attention. Gupta et al. [13] empirically investigated how blockchain technology, compared to artificial intelligence, shows stronger capabilities in facilitating supply chain financial resilience under environmental dynamism. Their mixed-method study, combining 202 survey responses with 25 semi-structured interviews, revealed that blockchain is particularly effective in seizing opportunities and reconfiguring supply chain operations.

In the context of specific industries, Kazancoglu et al. [14] examined blockchain implementation in food supply chains during the COVID-19 pandemic, identifying data security and management as critical risk factors. Their study emphasized the importance of blockchain in enhancing reverse logistics activities and increasing supply chain resilience.

Cooper [15] provided a comprehensive analysis of procurement risk management strategies, highlighting blockchain's role alongside other digital technologies in enhancing risk management capabilities and fostering transparency. The study emphasized the importance of an integrated approach that combines technological solutions with strategic planning for building resilient supply chains.

A systematic review by Hu & Ghadimi [16] affirmed blockchain's position as an enabling technology for

supply chain risk management across different industries. They noted that blockchain's integration with other advanced technologies could lead to more efficient and effective risk-reduction strategies. Similarly, Odimarha et al. (2024) explored how blockchain, combined with IoT and AI, is transforming traditional risk management approaches by providing real-time visibility and proactive mitigation strategies.

### 3. Research Background

In recent years, numerous studies have explored the role of blockchain technology in supply chain management and resilience. Nasiri Galeh & Sahraei [17] investigated the impact of blockchain implementation on the dairy products supply chain in Iran. Through questionnaires and data analysis, they demonstrated a significant positive impact of blockchain on data transparency and agility in the dairy products supply chain. This study highlights the importance of blockchain in the food industry, particularly in sectors dealing with perishable products.

Similarly, Hedayati et al. [18] identified and ranked barriers to using blockchain technology in the sustainable supply chain of food industries. Employing the TOE theory along with fuzzy Delphi and Interpretive Structural Modeling (ISM) methods, they identified 12 influential factors as barriers to blockchain adoption. Their results indicated that organizational, technological, and environmental factors are, respectively, the most significant barriers to blockchain adoption in the food industry supply chain.

Farhadi et al. [19] conducted a comparable study, identifying and prioritizing barriers to implementing blockchain technology in the sustainable supply chain of food packaging companies. Utilizing thematic analysis and the DEMATEL method, they identified a lack of management commitment as the most influential factor. This study underscores the importance of senior management support in successful blockchain implementation.

In another study, Farhadi [20] examined the significance of utilizing blockchain in enhancing supply chain management objectives. This research demonstrated that blockchain implementation can lead to improved performance, efficiency, and transparency across various supply chain processes, playing a crucial role in achieving key supply chain management objectives.

Taherkhani & Amouzad-khalili [21] examined factors affecting blockchain technology adoption in the supply chain. By combining the Innovation Diffusion Theory and the Technology-Organization-Environment framework, they identified 17 factors influencing blockchain technology adoption across various industries' supply chains. This study provides valuable insights for managers and policymakers in promoting blockchain adoption.

Rahimi et al. [22] identified key barriers to implementing blockchain technology in the food industry supply chain. Using Interpretive Structural Modeling, they highlighted barriers such as lack of understanding of cost-benefit exchange, misunderstanding of smart contract functionality, fraud risk, and shortage of expert personnel.

In the realm of supply chain risk management, Souri et al. [23] designed a qualitative risk management model for the supply chain and its impact on the financial and quality performance of Iran Khodro Company. Their results indicated that formal and social control, through supplier development and product recall, positively affect both quality and financial performance.

Fallahpour et al. [24] identified and determined the importance of effective risks in the dairy industry. Employing the fuzzy Delphi method and CRITIC method, they demonstrated that sanctions have the highest degree of importance among existing risks in the sustainable supply chain of dairy industries.

Esmaeili & Rajabzadeh-ghatarmi [25] examined the challenges facing blockchain adoption in the supply chain and categorized these challenges into four groups: organizational, inter-organizational, external/environmental, and technological. This study provides a comprehensive view of barriers to blockchain implementation in the supply chain.

At the international level, Nagariya et al. [5] analyzed blockchain-based supply chain flexibility strategies. They identified eight broad strategies and 32 sub-strategies, prioritizing them using BWM. The results revealed that building social capital, improving coordination capabilities, market sensitivity, process and production flexibility, reduction in process and lead time, and resource efficiency and redundancy are among the most critical strategies.

Manzoor et al. [26] examined factors facilitating or hindering the use of blockchain technology to increase supply chain resilience. They identified 11 enablers and 12 barriers, showing that shared databases, smart contracts, and real-time information are the main enablers, while lack of standardization, complexity, and government support are the primary barriers to blockchain-based flexible supply chains.

Petratos & Faccia [27] investigated the impact of fake news, misinformation, and disinformation on supply chain risks and disruptions. They demonstrated that blockchain can be effective in risk management and enhancing supply chain resilience, particularly in addressing risks arising from misinformation.

Chowdhury et al. [28] examined the adoption of blockchain technology for risk management in operations and supply chain management in Britain. They showed that understanding blockchain benefits, engaging in flexible organizational practices, and user-friendly

technology implementation have a positive and significant impact on the intention to adopt blockchain for risk management.

Singh et al. [29] conducted a systematic literature review on blockchain applications for secure and resilient supply chains. They identified six dominant themes related to blockchain and its adoption in the supply chain and provided suggestions for future research.

Rauniyar et al. [8] demonstrated that blockchain can aid supply chain risk management by preventing fraud, capturing counterfeit products, creating tamper-proof data records, and enhancing trust and cybersecurity. Wang et al. [30] also illustrated the application of blockchain in optimizing the information monitoring process in the rice supply chain.

Kouhizadeh et al. [31] examined barriers to blockchain adoption within the organization-technology-environment framework and showed that technological and supply chain barriers are the most significant among academic and industry experts. Reddy et al. [32] presented a framework for implementing blockchain in the automotive supply chain.

Abdel-Basset & Mohamed [33] examined sustainable supply chain risk management in a telecommunications equipment company and identified existing risks in order of importance. Gao et al. [34] analyzed the simulation of a supply chain risk management system based on the Internet of Things information platform and showed that IoT helps build and improve supply chain information.

Despite extensive studies on the application of blockchain in supply chain management and its resilience, there remains a significant gap in identifying and prioritizing key factors in blockchain-based resilient supply chain risk management, especially in the laboratory equipment industry. Most previous studies have either focused on specific industries, such as food and automotive or have generally examined the barriers and benefits of using blockchain in the supply chain. The laboratory equipment industry, given the sensitivity and importance of its products in medical, research, and industrial fields, requires special attention.

This research aims to fill this gap by identifying and prioritizing key factors in blockchain-based resilient supply chain risk management in the laboratory equipment industry. The results of this study can help managers and decision-makers in this industry to understand the influential factors better and adopt appropriate strategies for implementing blockchain and increasing the resilience of their supply chain.

To highlight the novelty and contributions of this research compared to previous studies, Table 1 presents a comparative analysis of key methodological characteristics and focus areas.

**Table 1.** Comparison of current research with previous related studies

Characteristics	Current Study	Nagariya et al. [5]	Rauniyar et al. [8]	Manzoor et al. [26]	Chowdhury et al. [28]
Industry Focus	Laboratory Equipment Industry	General Manufacturing	General Supply Chain	Multiple Industries	UK Manufacturing
Integration of Blockchain and Resilience	Yes	Partial	Partial	Yes	No
Risk Management Framework	Comprehensive	Limited	Moderate	Limited	Moderate
Mixed-Method Approach	Meta-synthesis + Fuzzy Delphi + BWM	Only BWM	Literature Review	Mixed Method	Survey Based
Expert Validation	Yes (Both Delphi and BWM)	Only BWM	No	Limited	Survey Only
Number of Identified Factors	114 indicators	32 strategies	Not Specified	23 factors	15 factors
Hierarchical Framework	6 dimensions, 24 components	Only strategies	No framework	Basic framework	Basic framework
Industry-Specific Solutions	Yes	No	No	No	Partial

As shown in Table 1, this research offers several unique contributions:

- First comprehensive study focusing specifically on the laboratory equipment industry
- Integration of three methodologies (meta-synthesis, fuzzy Delphi, and BWM) for robust results
- Development of a detailed hierarchical framework with 114 indicators
- Validation through both fuzzy Delphi and BWM expert panels
- Industry-specific solutions for blockchain implementation in supply chain risk management

## 4. Methodology

This research is applied in terms of purpose and employs a mixed (qualitative-quantitative) approach. The study is exploratory and utilizes meta-synthesis, fuzzy Delphi, and BWM techniques. Each method employed in this research offers specific strengths and limitations.

Meta-synthesis, as a qualitative method for integrating findings from multiple studies, provides comprehensive insights through a systematic review of existing literature. Its main strength lies in creating a holistic understanding of the research topic while identifying potential research gaps. However, it is limited by the quality and availability of primary studies and potential researcher bias in interpretation. The fuzzy Delphi method combines expert knowledge with fuzzy logic to handle uncertainty in expert opinions. Its strengths include the ability to achieve consensus through structured feedback and the capacity to handle vague or imprecise expert judgments. The main limitations are

potential expert bias and the challenge of selecting true experts in the field. BWM, as a multi-criteria decision-making method, offers advantages in terms of requiring fewer comparison data and providing more consistent results compared to traditional methods like AHP. Its structured approach helps in prioritizing factors with higher reliability. However, it may be limited by the subjective nature of expert judgments and the assumption of independence between criteria. The overall research process was conducted in three main stages, as described below.

In the first stage, the meta-synthesis method based on Sandelowski & Barroso's [35] approach was used to identify and extract general indicators affecting blockchain-based resilient supply chain risk management. This method comprises seven steps:

- **Step 1)** Formulating the research question: The primary research question at this stage was: "What are the factors affecting blockchain-based resilient supply chain risk management in the laboratory equipment industry?"
- **Step 2)** Systematic literature review: An extensive search was conducted in domestic (Civilica, Magiran, SID, Noormags) and international (Emerald, Springer, Science Direct, Wiley, Scholar) databases using relevant keywords presented in Table 2. The search time frame spanned from 2015 to 2024.

**Table 2.** Keywords used in article search

Row	Keywords
1	Supply Chain Risk Management
2	Supply Chain Resilience
3	Blockchain in Supply Chain
4	Laboratory Equipment Industry

Row	Keywords
5	Smart Supply Chain
6	Blockchain-based Track and Trace
7	Digital Risk Management
8	Supply Chain Security
9	Supply Chain Transparency
10	Smart Contracts in Supply Chain
11	Big Data Analytics in Risk Management

- **Step 3)** Searching and selecting appropriate texts: The initial search identified 342 articles. The Critical Appraisal Skills Programme (CASP) was employed to assess the quality of the articles. Articles were scored based on CASP criteria, and those scoring less than 30 were excluded. Ultimately, 38 articles were selected for further meta-synthesis analysis.
- **Step 4)** Extracting information from texts: Articles were categorized by subject, and factors related to the research topic were extracted and coded.
- **Step 5)** Analyzing and synthesizing qualitative findings: Coding was performed at three levels: first-order coding (indicators), second-order coding (components), and third-order coding (dimensions). This coding aimed to create a comprehensive classification of factors affecting blockchain-based resilient supply chain risk management in the laboratory equipment industry.
- **Step 6)** Quality control: To ensure the reliability of results, opinions of expert academic professors and researchers in the field were solicited. Additionally, the CASP tool was used to evaluate the studies.
- **Step 7)** Presenting findings: The results of the meta-synthesis were presented in the form of identified dimensions, components, and indicators.

In the second stage, the fuzzy Delphi method was employed to identify specific indicators affecting blockchain-based resilient supply chain risk management in the laboratory equipment industry. The statistical population in this section comprised 12 experts from the medical equipment industry who were selected through a rigorous set of criteria:

**1. Educational Qualifications:**

- Minimum of master's degree in relevant fields (Industrial Engineering, Medical Engineering, Information Technology Management, or Business Administration)
- 5 experts held PhD degrees in related fields
- All experts had formal training in blockchain technology and supply chain management.

**2. Professional Experience:**

- Minimum 5 years of experience in managerial positions
- Average industry experience of 10 years

- Direct involvement in at least one blockchain implementation project
- Demonstrated expertise in supply chain risk management

**3. Current Positions:**

- Senior management roles in laboratory equipment manufacturing or distribution companies
- Active involvement in strategic decision-making regarding supply chain operations
- Direct responsibility for technology implementation or risk management

These experts were selected through purposive sampling to ensure comprehensive coverage of different aspects of the industry. The characteristics of the expert group are shown in Table 3.

**Table 3.** Characteristics of the expert group in the fuzzy Delphi section

Education Degree	Work Experience (Years)	Area of Expertise	Job Title
PhD in Industrial Engineering	15	Supply Chain Management	Senior Supply Chain Manager
Master's in Executive Management	12	Risk Management	Organizational Risk Manager
PhD in Medical Engineering	18	Laboratory Equipment	R&D Manager
Master's in Industrial Engineering	8	Logistics and Supply	Logistics Manager
PhD in Information Technology Management	10	Blockchain Technology	Senior Technology Consultant
Master's in Medical Engineering	7	Equipment Quality Control	Quality Control Manager
PhD in Strategic Management	15	Supply Chain Strategy	CEO
Master's in Industrial Engineering	9	Production Planning	Production Planning Manager
PhD in Mechanical Engineering	14	Medical Equipment Design	Senior Engineering Manager

Education Degree	Work Experience (Years)	Area of Expertise	Job Title
Master's in Business Administration	11	Purchasing and Supply	Procurement Manager
PhD in Computer Science	13	Cybersecurity	Information Security Manager
Master's in Medical Engineering	6	Quality Assurance	Quality Assurance Manager

The fuzzy Delphi process was conducted in three stages:

- Defining linguistic variables and converting them to triangular fuzzy numbers;
- Collecting expert opinions and aggregating them using fuzzy mean;
- Defuzzifying results using the center of gravity (COG) method. This method was selected due to its mathematical robustness, sensitivity to the shape of fuzzy membership functions, and computational stability. For a triangular fuzzy number  $A = (l, m, u)$ , the defuzzified value was calculated using:

$$\text{Defuzzified Value} = [(u - l) + (m - l)] / 3 + l$$

where  $l$  is the lower bound,  $m$  is the middle value, and  $u$  is the upper bound of the triangular fuzzy number. A threshold of 0.7 was used to confirm and screen indicators. This threshold was chosen to ensure that only indicators with strong expert consensus were retained in the final model. Indicators with a defuzzified value equal to or greater than 0.7 in the final round were accepted. The COG method's comprehensive approach helped maintain the richness of expert opinions while providing clear, actionable results for indicator selection.

After finalizing the indicators, BWM was utilized to prioritize the factors. For this stage, 8 experts were carefully selected from the original pool of 12 Delphi participants. These experts were chosen based on additional criteria:

#### 1. Advanced Technical Knowledge:

- In-depth understanding of blockchain technology architecture and implementation
- Extensive experience in laboratory equipment supply chain operations
- Proven track record in risk management implementation

#### 2. Decision-Making Authority:

- Senior positions with strategic decision-making responsibilities
- Direct involvement in technology adoption decisions

- Authority in supply chain risk management policies

#### 3. Cross-functional Experience:

- Background in multiple areas, including operations, technology, and risk management
- Experience in both technical and managerial aspects of the supply chain
- Involvement in industry-wide standardization or regulatory compliance initiatives

The Best-Worst Method (BWM) was selected for prioritizing the identified factors due to its several advantages. As demonstrated by Shidpour et al. [36], BWM requires fewer comparison data compared to traditional methods like AHP, leading to more consistent results. Gupta [37] highlighted that BWM provides more reliable outputs due to its structured comparison system that reduces inconsistencies in expert judgments. The method has been successfully applied in various fields for criteria prioritization and decision-making problems. BWM's practical benefits include:

- More consistent comparisons due to structured reference comparisons
- Reliable results with fewer data points
- Straightforward implementation process
- Lower inconsistency ratio compared to similar methods
- Higher reliability in expert-based decision-making

These advantages make BWM particularly suitable for this study's context, where expert opinions need to be synthesized efficiently and reliably for factor prioritization in the laboratory equipment industry's supply chain. The BWM process included: 1) Designing the best and worst questionnaire; 2) Distributing the questionnaire among experts; 3) Collecting and analyzing data using BWM; 4) Ranking the influential dimensions, components, and indicators.

To ensure the validity and reliability of the research results, several measures were implemented:

- Utilizing the meta-synthesis method for comprehensive collection and analysis of existing literature
- Incorporating expert opinions at various stages of the research
- Employing the CASP tool to assess the quality of studies in the meta-synthesis stage
- Applying the fuzzy Delphi method to achieve consensus among expert opinions
- Utilizing BWM for quantification and prioritization of factors

This multi-stage, combined approach facilitated comprehensive identification and accurate prioritization of factors affecting blockchain-based resilient supply chain risk management.

## 5. Findings

### 5.1 Findings from Meta-synthesis

Following the implementation of the seven-stage meta-synthesis process based on Sandelowski & Barroso's [35] method, the analysis and synthesis of qualitative findings led to the identification of factors affecting blockchain-based

resilient supply chain risk management in the laboratory equipment industry. This process involved a thorough review of 38 selected articles from an initial pool of 342 articles. The final results of the meta-synthesis led to the extraction of 110 indicators, which were subsequently classified into 24 components and 6 main dimensions. Table 4 presents a summary of these findings.

**Table 4.** Meta-synthesis results - dimensions and components of blockchain-based resilient supply chain risk management in the laboratory equipment industry

Dimensions	Components	Row	Indicators	Ref.	
Information Management and Transparency	Information transparency in the supply chain	1	Real-time data sharing across the supply chain	[11, 36, 37]	
		2	Easy and secure access to information for all authorized stakeholders	[38, 39, 40]	
		3	Transparency regarding the origin, quality, and status of products	[17, 37, 41]	
		4	Transparency in processes and production methods of products	[17, 42]	
	Product traceability and tracking capability	5	Use of coding and tracking systems such as RFID or QR codes	[11, 43, 44]	
		6	Recording and storage of product route and movement information	[38, 39]	
		7	Ability to quickly retrieve information when tracing is needed	[36, 39, 42]	
		8	Traceability to ensure compliance with standards and legal requirements	[37, 42, 43]	
		9	Ability to quickly identify and isolate defective or unsafe products	[38, 41]	
	Coordination and information exchange among supply chain partners			Use of integrated supply chain management (SCM) systems	[11, 43]
		11	Establishing effective and timely communications among supply chain members	[38, 39, 42]	
		12	Exchange of data and information in standard formats understandable to all	[17, 37]	
		13	Use of shared platforms for data sharing and planning	[11, 40, 44]	
		14	Coordination in demand planning, supply, and logistical capacities	[17, 36, 39]	
Operational Flexibility and Resilience	Flexibility in response to demand and supply changes	15	Extra capacity in production, storage, and logistics	[10, 41, 45]	
		16	Ability to quickly adjust production and supply chain plans	[36, 37]	
		17	Use of flexible contracts with suppliers and logistics partners	[40, 42]	
		18	Possibility of replacing supply sources and distribution channels if needed	[10, 37, 45]	
		19	Ability to quickly change product mix and production lines	[42, 43]	
		20	Flexibility in pricing and marketing strategies	[10, 36]	
	Extra capacity in the supply chain to compensate for disruptions	21	Amount of extra production capacity compared to normal demand	[41, 44, 46]	
		22	Amount of extra storage space for safety stock	[37, 45]	
		23	Number of alternative sources for goods and logistics services	[41, 42, 46]	
		24	The volume of budget and financial resources allocated for emergency management	[10, 37, 43]	
	Multi-sourcing and diversity in supply sources	25	Number of suppliers for raw materials and key components	[11, 18, 44]	
		26	Geographical diversity of main and alternative supply sources	[11, 46]	

Dimensions	Components	Row	Indicators	Ref.	
	and distribution channels	27	Number of logistics and transportation partners for final products	[40, 46, 47]	
		28	Diversity of product distribution methods to different markets	[41, 46]	
	Speed in recovery from disruptions and damages	29	Time required to identify and respond to a disruptive event	[18, 42]	
		30	Speed of recovery and restarting production lines after a crisis	[17, 47]	
		31	Time to return to normal performance level after a shock	[11, 337, 47]	
		32	Time required to repair damages to the supply chain	[40, 41, 42]	
Risk and Crisis Management	The existence of crisis management plan and preparedness for emergencies	33	Planning and training for identifying and responding to crises	[48, 49]	
		34	Development of alternative plans and recovery processes after a crisis	[49, 50, 51]	
		35	Creation of a crisis management team and allocation of necessary resources	[3, 50, 52]	
		36	Emergency recovery plans for quick restoration of operations after a crisis	[3, 48, 49]	
		37	Training and simulation of crisis conditions for employee preparedness	[51, 52, 53]	
		38	Creation of safety reserves and backup resources for emergencies	[49, 51, 53]	
	Ability to learn and transfer experiences from crises	39	The existence of a system for documenting and recording experiences from previous disruptions	[3, 50]	
		40	Level of training and knowledge transfer from past experiences to employees	[3, 49, 52]	
		41	Root cause analysis of past incidents for future prevention	[52, 54]	
		42	Ability to implement changes in processes based on lessons learned	[48, 50, 51]	
	Cultural and psychological readiness to accept changes	43	Level of flexibility and psychological readiness of employees for change	[3, 48, 49]	
		44	Existence of a culture of learning, innovation, and adaptability in the organization	[3, 50, 52]	
		45	Understanding and acceptance of the importance of change among senior managers and leaders	[48, 50, 51]	
		46	Creating motivation and encouragement for employees to embrace necessary changes	[49, 54]	
	Relationships and Collaboration in the Supply Chain	Trust and strong relationships among supply chain members	47	Establishing transparent and honest communications between partners	[53, 54]
			48	Long-term commitment and mutual support in difficult conditions	[48, 51, 53]
			49	Adherence to ethical principles and privacy in business relationships	[52, 53]
			50	Transparency regarding performance information, quality, and prices	[3, 50]
51			Respect for intellectual property rights and trade secrets of partners	[52, 54]	
52			Close interaction and participation in important decision-making	[3, 54]	
Integration and coordination throughout the supply chain		53	Level of integration of planning and operation execution systems	[49, 53]	
		54	Degree of coordination and cooperation between units and supply chain partners	[49, 52]	
		55	Alignment of goals and plans throughout the supply chain	[52, 53]	

Dimensions	Components	Row	Indicators	Ref.
		56	Existence of a single point of coordination and decision-making in emergencies	[49, 53]
Digital Technology and Infrastructure	Level of acceptance and readiness for blockchain implementation	57	Level of awareness and knowledge of senior managers about blockchain technology	[1, 9, 55]
		58	Existence of training programs to familiarize employees with blockchain	[55, 56, 57]
		59	Level of willingness and motivation among stakeholders to use blockchain	[1, 58]
		60	Level of belief in blockchain benefits compared to traditional systems	[9, 56]
		61	Degree of organizational readiness for necessary changes in processes and structures	[1, 9, 55]
	Existence of technical infrastructure and specialized human resources	62	Access to network infrastructure with adequate bandwidth and security	[1, 56]
		63	Number of IT specialists familiar with blockchain in the organization	[56, 57]
		64	Level of experience and skill of human resources in blockchain design and implementation	[1, 9, 58]
		65	Access to educational and consulting resources for developing blockchain skills	[1, 7, 58]
		66	Ability to recruit blockchain specialists from the job market	[58, 59]
	Costs associated with blockchain implementation and maintenance	67	Initial investment costs for setting up the blockchain network	[9, 57, 60]
		68	Operational and maintenance costs of the blockchain system over time	[7, 57, 59]
		69	Costs related to providing specialized blockchain human resources	[13, 58, 60]
		70	Costs of consulting, training, and transfer of blockchain technical knowledge	[7, 61]
		71	Costs related to changing and adapting processes to blockchain	[57, 59]
	Security and privacy in the blockchain network	72	Level of network security against cyber attacks and security threats	[7, 9, 61]
		73	Ability to control access and confidentiality of information in the blockchain network	[1, 61]
		74	Compliance with data privacy standards and laws	[9, 57, 60]
		75	Possibility of encryption and confidentiality of sensitive information in transactions	[59, 60]
		76	Capability for security monitoring and tracking of transactions	[9, 57, 61]
	Blockchain efficiency and scalability capability	77	Speed of processing and confirming transactions in the blockchain network	[7]
78		Network capacity for processing high volumes of transactions without performance degradation	[57, 61]	
79		Ability to increase or decrease network resources (scalability) based on need	[1, 7, 60]	
80		Optimization of energy consumption and computational resources in the blockchain network	[9, 57]	
81		Compatibility and integration with other organizational IT systems	[7, 57, 60]	
Legal and Industry Requirements	Appropriate legal and regulatory framework for blockchain use	82	Existence of clear laws and regulations for blockchain use in the industry	[58, 59]
		83	Level of support and encouragement from government and regulatory bodies for blockchain	[7, 61]
		84	Legal frameworks to ensure the validity and legal acceptance of blockchain transactions	[1, 59]

Dimensions	Components	Row	Indicators	Ref.
		85	Laws and standards governing security and privacy in blockchain	[1, 59, 61]
		86	Regulations related to ownership, digital currency transfer, and smart contracts	[7, 58, 59]
	Regulatory, legal, and quality standard requirements in this industry	87	National and international quality standards such as ISO 13485, IEC 61010	[6, 48, 62]
		88	Laws and regulations related to regulatory approvals such as FDA, CE Mark	[62, 53, 64]
		89	Legal requirements for product traceability and reporting	[2, 6, 63]
		90	Compliance with environmental and safety laws and regulations	[6, 48, 63]
	Risks related to safety and health in equipment use	91	Risks from non-compliance with safety standards in design and production	[65, 66]
		92	Biological or chemical hazards in using certain laboratory equipment	[24, 62, 67]
		93	Risks related to ionizing or non-ionizing radiation from equipment	[6, 63, 68]
		94	Dangers from misuse or improper use of equipment	[6, 62, 63]
	Risks of privacy violation and data security	95	Risk of unauthorized access to sensitive patient or test data	[66, 67]
		96	Risk of disclosure of confidential information related to employees or research	[65, 67]
		97	Security risks in transmission and storage of electronic data	[62, 65, 68]
		98	Cyber threats to laboratory IT infrastructure	[62, 65, 68]
	Technical complexity of products and production processes	99	Diversity and complex design of various laboratory equipment	[2, 24]
		100	Need for advanced technologies in production and quality control processes	[24, 65, 66]
		101	Need for technical and specialized workforce in product manufacturing and inspection	[48, 67]
		102	Complexity in sourcing parts and raw materials with specific requirements	[62, 63]
	Logistical needs and cold chain for certain equipment	103	Need for precise temperature control in transportation and storage of certain equipment	[6, 62, 68]
		104	Special packaging and transportation requirements to prevent damage	[6, 66]
105		Need for cold chain logistics infrastructure and temperature control in warehouses	[24, 62, 68]	
106		Challenges in transporting sensitive equipment over long distances	[6, 24, 65]	
Time constraints for delivery in some critical applications	107	Need for timely delivery of equipment for emergency or medical applications	[2, 48, 65]	
	108	Importance of speed in delivery for active research or industrial laboratories	[48, 63, 65]	
	109	Time constraints to prevent loss of samples or laboratory materials	[63, 66, 67]	
	110	Need for precise and coordinated planning to meet delivery schedules	[24, 62, 64]	

## 5.2 Findings from Fuzzy Delphi

Following the meta-synthesis stage, the fuzzy Delphi method was employed to validate and refine the identified indicators, as well as to incorporate specific indicators relevant to the laboratory equipment industry. This process was conducted over three rounds with the participation of industry experts. The results of this stage

led to modifications in the initial model, which are presented in Table 5.

According to Table 5, 13 indicators deemed less important in the context of laboratory equipment by the experts were removed from the model. Conversely, 17 new and industry-specific indicators were added to the model. As a result of the fuzzy Delphi process, the final model encompassed 6 dimensions, 24 components, and 114 indicators.

This adjusted model provides a more accurate representation of the factors affecting blockchain-based resilient supply chain risk management in the laboratory

equipment industry. The refinement reflects the incorporation of expert opinions in this specialized field.

**Table 5.** Modified Indicators in the Fuzzy Delphi Section According to Expert Opinions

Proposed Indicators		
Dimensions	Components	Indicators
Information Management and Transparency	Information transparency in the supply chain	Level of use of Non-Fungible Tokens (NFTs) for equipment authenticity verification
	Product traceability and tracking capability	Level of implementation of blockchain-based tracking systems for laboratory equipment
		Level of use of blockchain technology in warranty and after-sales service management
Coordination and information exchange among supply chain partners	Level of use of artificial intelligence algorithms in blockchain data analysis	
Operational Flexibility and Resilience	Flexibility in response to demand and supply changes	Level of automation in supply chain processes using smart contracts
	Extra capacity in the supply chain to compensate for disruptions	Level of implementation of blockchain-based inventory management systems
Risk and Crisis Management	Existence of a crisis management plan and preparedness for emergencies	Level of implementation of blockchain-based risk management systems
Relationships and Collaboration in the Supply Chain	Trust and strong relationships among supply chain members	Level of use of smart contracts in supplier relationship management
	Integration and coordination throughout the supply chain	Level of integration of supply chain data in a shared blockchain platform
Digital Technology and Infrastructure	Costs associated with blockchain implementation and maintenance	Level of use of digital currencies in supply chain transactions
	Security and privacy in the blockchain network	Level of implementation of blockchain-based clinical data management systems
	Blockchain efficiency and scalability capability	Level of integration of Internet of Things (IoT) systems with blockchain platform
Legal and Industry Requirements	Appropriate legal and regulatory framework for blockchain use	Level of use of blockchain technology in managing intellectual property rights for laboratory equipment
	Regulatory, legal, and quality standard requirements in this industry	Level of implementation of blockchain-based quality control systems
		Level of use of blockchain technology in managing validation and verification processes for laboratory equipment
		Level of use of blockchain technology in managing licenses and certifications for laboratory equipment
Logistical needs and cold chain for certain equipment	Level of use of blockchain technology in cold chain management	
Removed Indicators		
Flexibility in pricing and marketing strategies		
The volume of budget and financial resources allocated for emergency management		
Diversity of product distribution methods to different markets		
Respect for intellectual property rights and trade secrets of partners		
The existence of a single point of coordination and decision-making in emergencies		
Degree of organizational readiness for necessary changes in processes and structures		
Ability to recruit blockchain specialists from the job market		
Costs related to changing and adapting processes to blockchain		
Optimization of energy consumption and computational resources in the blockchain network		
Regulations related to ownership, digital currency transfer, and smart contracts		
Compliance needs with environmental and safety laws and regulations.		
Dangers from misuse or improper use of equipment		
Cyber threats to laboratory IT infrastructure		

### 5.3 Findings from BWM

In this stage of the research, BWM of multi-criteria decision-making was employed to prioritize the factors affecting blockchain-based resilient supply chain risk management in the laboratory equipment industry. This method was selected due to its high accuracy and the requirement for fewer comparisons compared to other multi-criteria decision-making methods. The process involved the following steps:

- Design and distribution of the best and worst questionnaires among experts.
- Collection of completed questionnaires.
- Implementation of BWM using the questionnaire results.
- Ranking of influential dimensions and components.

The results of the BWM analysis are visually presented in Figures 1-7. Figure 1 presents a radar chart illustrating the relative weights of the six main dimensions identified in this research. As shown, "Digital Technology and Infrastructure" emerged as the most significant dimension with a weight of 0.323, followed by "Information Management and Transparency" (0.239) and "Operational Flexibility and Resilience" (0.177). The subsequent dimensions, in order of importance, are "Risk and Crisis Management" (0.131), "Relationships and Collaboration in the Supply Chain" (0.084), and "Legal and Industry Requirements" (0.046).

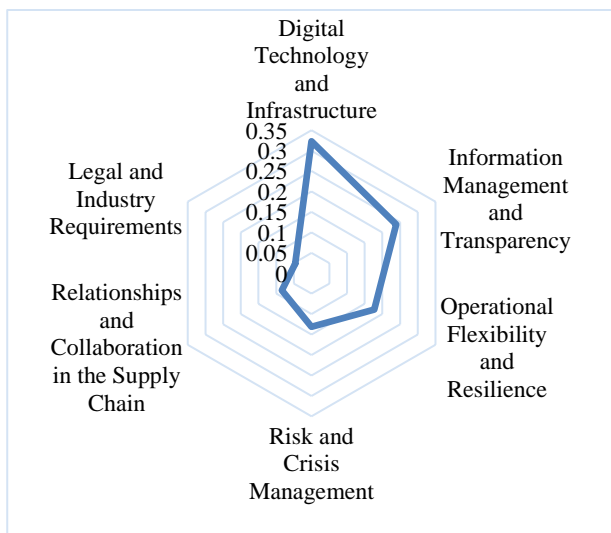


Figure 1. Radar chart of main dimensions' weights in blockchain-based resilient supply chain risk management

Figures 2-7 present detailed breakdowns of components within each dimension, highlighting their relative importance through clustered bar charts.

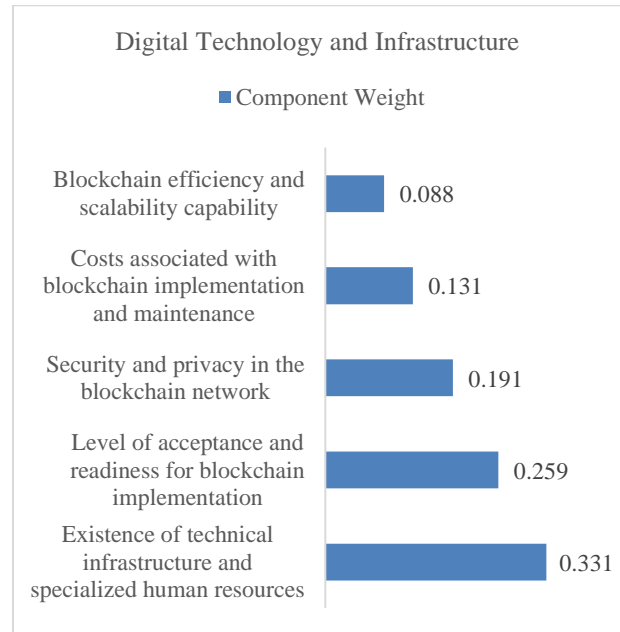


Figure 2. Component weights within Digital Technology and Infrastructure dimension

In the "Digital Technology and Infrastructure" dimension, "Existence of technical infrastructure and specialized human resources" carries the highest weight (0.331), demonstrating the critical importance of foundational technological capabilities. This is followed by "Level of acceptance and readiness for blockchain implementation" (0.259) and "Security and privacy in the blockchain network" (0.191).

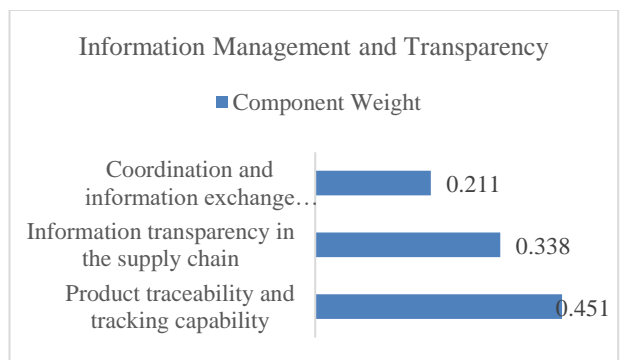
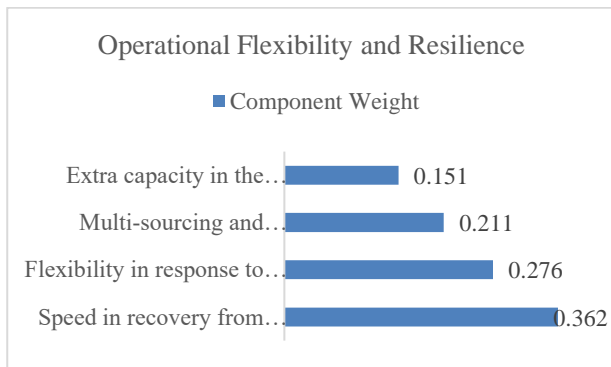


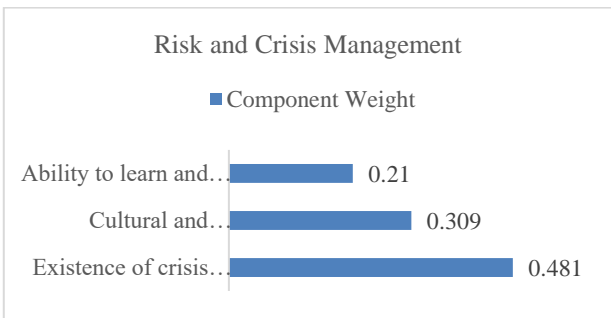
Figure 3. Component weights within the Information Management and Transparency dimension

Within "Information Management and Transparency", "Product traceability and tracking capability" emerges as the most crucial component (0.451), followed by "Information transparency in the supply chain" (0.338) and "Coordination and information exchange among supply chain partners" (0.211).



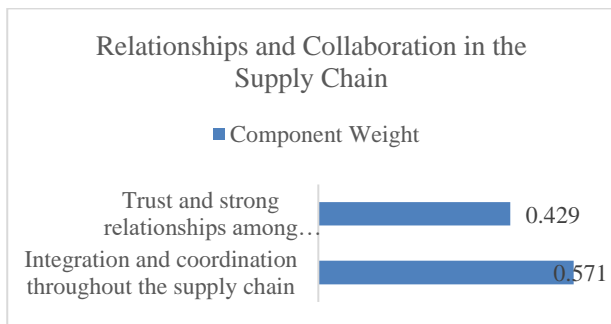
**Figure 4.** Component weights within the Operational Flexibility and Resilience dimension

The "Operational Flexibility and Resilience" dimension is led by "Speed in recovery from disruptions and damages" (0.362), highlighting the importance of rapid response capabilities. "Flexibility in response to demand and supply changes" (0.276) and "Multi-sourcing and diversity in supply sources and distribution channels" (0.211) follow in significance.



**Figure 5.** Component weights within the Risk and Crisis Management dimension

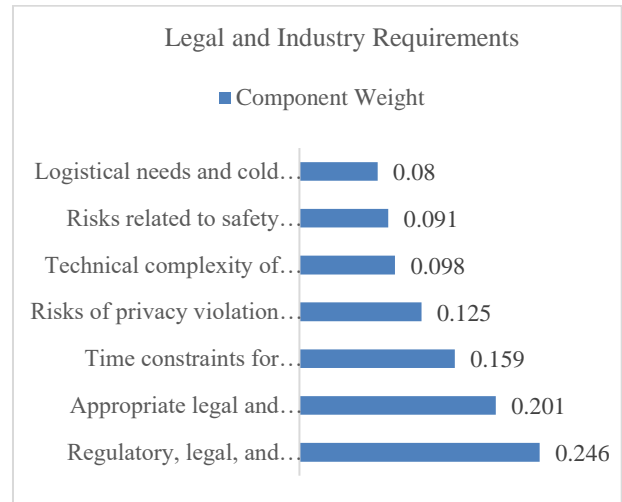
For "Risk and Crisis Management", "Existence of crisis management plan and preparedness for emergencies" ranks highest (0.481), followed by "Cultural and psychological readiness to accept changes" (0.309) and "Ability to learn and transfer experiences from crises" (0.210).



**Figure 6.** Component weights within the Relationships and Collaboration dimension

The "Relationships and Collaboration" dimension shows "Integration and coordination throughout the supply chain" as the leading component (0.571), with

"Trust and strong relationships among supply chain members" (0.429) as the second key component.



**Figure 7.** Component weights within the Legal and Industry Requirements dimension

Finally, within "Legal and Industry Requirements," "Regulatory, legal, and quality standard requirements" ranks highest (0.246), followed by "Appropriate legal and regulatory framework for blockchain use" (0.201) and "Time constraints for delivery in some critical applications" (0.159).

The identified dimensions and components have specific implications for addressing unique challenges in the laboratory equipment industry:

- Digital Technology and Infrastructure:** The prominence of this dimension directly addresses the industry's need for precise tracking and validation of sensitive equipment. Technical infrastructure and specialized human resources are particularly crucial as laboratory equipment often requires specialized handling and calibration procedures. For instance, blockchain infrastructure enables real-time monitoring of temperature-sensitive analyzers during transportation and storage, ensuring equipment integrity.
- Information Management and Transparency:** With a weight of 0.239, this dimension is critical for meeting strict regulatory requirements in the laboratory equipment industry. Product traceability and tracking capability help manufacturers comply with FDA and CE marking requirements by maintaining comprehensive equipment history from production to end-use. This is particularly vital for equipment used in clinical diagnostics where audit trails are mandatory.
- Operational Flexibility and Resilience:** This dimension addresses the industry's challenge of maintaining consistent equipment supply during disruptions. Speed in recovery from disruptions is especially crucial for laboratory equipment

such as PCR machines or blood analyzers, where supply interruptions can significantly impact healthcare services. The ability to quickly switch production lines or activate alternative suppliers becomes essential for maintaining critical equipment availability.

- **Risk and Crisis Management:** Weighted at 0.131, this dimension tackles the industry's specific risks related to equipment calibration and validation. Crisis management planning is particularly important for managing situations involving equipment malfunction or recall, which can have serious implications for laboratory operations and patient safety.
- **Relationships and Collaboration:** This dimension addresses the complex network of stakeholders in the laboratory equipment supply chain, including manufacturers, calibration services, and end-users. Integration and coordination are crucial for maintaining equipment quality and reliability through collaborative quality control and validation processes.
- **Legal and Industry Requirements:** Though weighted lowest, this dimension is fundamental for addressing regulatory compliance challenges. The high weight of regulatory and quality standard requirements reflects the industry's need to comply with standards like ISO 13485 and IEC 61010, which are mandatory for laboratory equipment manufacturers.

## 6. Discussion and Conclusion

In today's complex and interconnected world, supply chain risk management has become a fundamental challenge for organizations. The laboratory equipment industry, due to the sensitive nature of its products and its crucial role in medical, research, and industrial fields, faces unique challenges in this domain. Concurrently, the emergence of blockchain technology as an innovative solution offers significant potential for enhancing risk management and bolstering supply chain resilience. The primary objective of this research was to identify and prioritize factors influencing blockchain-based resilient supply chain risk management in the laboratory equipment industry.

To achieve this goal, a comprehensive approach comprising three main stages was employed. Initially, utilizing the meta-synthesis method, previous studies on supply chain risk management and resilience were reviewed. Subsequently, employing the fuzzy Delphi method and leveraging industry expert opinions, specific factors pertinent to the laboratory equipment industry were identified and validated. Finally, these factors were ranked using BWM of multi-criteria decision-making. The research findings led to the identification of 114 indicators within 24 components and 6 main dimensions. These dimensions, in order of priority, are: 1) Digital

Technology and Infrastructure, 2) Information Management and Transparency, 3) Operational Flexibility and Resilience, 4) Risk and Crisis Management, 5) Relationships and Collaboration in the Supply Chain, and 6) Legal and Industry Requirements.

The findings reveal important insights about supply chain resilience in the laboratory equipment industry. The top three components identified - Integration and coordination (0.571), Crisis management planning (0.481), and Product traceability (0.451) - form a comprehensive resilience framework. This triangulation of capabilities enables organizations to:

### 1. Enhance Visibility through Integration (0.571):

- Facilitates real-time information sharing across supply chain nodes
- Enables quick detection of potential disruptions
- Supports coordinated response to challenges
- Strengthens collaborative decision-making capabilities

### 2. Build Preparedness through Crisis Management (0.481):

- Establishes structured approach to disruption handling
- Creates clear protocols for emergency response
- Enables proactive risk mitigation
- Develops organizational resilience capabilities

### 3. Ensure Traceability for Quick Response (0.451):

- Provides detailed visibility of product movement
- Enables rapid identification of disruption points
- Supports swift implementation of corrective measures
- Enhances overall supply chain agility

This resilience-focused analysis demonstrates how blockchain technology can strengthen each component:

- ✓ Integration: Blockchain provides a shared, immutable platform for coordination
- ✓ Crisis Management: Smart contracts automate emergency responses
- ✓ Traceability: Distributed ledger ensures transparent product tracking

The high weightings of these components (>0.45) emphasize their critical role in building resilient supply chains in the laboratory equipment industry.

The "Digital Technology and Infrastructure" dimension, with a weight of 0.323, emerged as the most critical dimension. This finding aligns with previous studies such as Dutta et al. [57] and Liu et al. [9], which emphasized the significance of technological infrastructure in blockchain implementation. Within this dimension, the component "Existence of technical infrastructure and specialized human resources" was deemed most crucial. This indicates that for successful blockchain implementation, investment in technical

infrastructure and human resource skill development is paramount.

"Information Management and Transparency" ranked second with a weight of 0.239. This finding corroborates the results of Nasiri Galeh & Sahraei's [17] research, which demonstrated blockchain's positive impact on data transparency in the supply chain. In this dimension, "Product traceability and tracking capability" was identified as the most vital component, underscoring the importance of traceability in the laboratory equipment industry.

"Operational Flexibility and Resilience" ranked third with a weight of 0.177. This dimension aligns with studies by Kilubi [47] and Emrouznejad et al. [43], which highlighted the importance of flexibility in addressing disruptions. "Speed in recovery from disruptions and damages" was recognized as the most critical component in this dimension, emphasizing the significance of rapid recovery capability in the face of challenges.

"Risk and Crisis Management" was identified as the fourth most important dimension. This finding is consistent with previous research, such as El baz & Ruel [46], which stressed the importance of crisis preparedness. "Existence of crisis management plan and preparedness for emergencies" emerged as the most crucial component in this dimension, indicating that a comprehensive crisis management plan is essential.

"Relationships and Collaboration in the Supply Chain" was ranked as the fifth important dimension. This finding aligns with studies by Gurtu & Johny [42] and Li et al. [48], which emphasized the significance of collaboration and trust in the supply chain. "Integration and coordination throughout the supply chain" was identified as the most critical component in this dimension, suggesting that coordination among supply chain members is vital for successful blockchain implementation.

Finally, "Legal and Industry Requirements" was identified as the least important dimension, though this does not diminish its significance. This dimension aligns with studies by Charles et al. [58] and Alkhudary et al. [59], which emphasized the importance of legal and regulatory frameworks in blockchain implementation. "Regulatory, legal, and quality standard requirements in this industry" was the most crucial component in this dimension, indicating that compliance with standards and regulations in the laboratory equipment industry is of particular importance.

These findings suggest that the successful implementation of blockchain for resilient supply chain risk management in the laboratory equipment industry requires a comprehensive and multidimensional approach addressing technical, informational, operational, managerial, communicational, and legal aspects. Based on the results of this research, recommendations are provided for enhancing blockchain-based resilient supply chain risk management in the laboratory equipment industry.

In the realm of digital technology and infrastructure, organizations are advised to make substantial investments in developing technical infrastructure and training specialized human resources. This could encompass establishing a dedicated blockchain team, conducting ongoing training programs, and partnering with technology firms for the implementation and maintenance of blockchain systems. Furthermore, heightened attention to security and privacy within the blockchain network is crucial and achievable through the deployment of advanced security protocols and regular security assessments.

Concerning information management and transparency, the implementation of blockchain-based product tracking and tracing systems is recommended. These systems should be capable of recording and storing precise information about product origin, quality, and status throughout all supply chain stages. Moreover, creating a shared platform for data exchange among all supply chain partners can enhance coordination and transparency.

To bolster operational flexibility and resilience, organizations are encouraged to develop comprehensive plans for managing disruptions and facilitating rapid recovery. These plans should encompass various disruption scenarios, strategies for addressing each scenario, and detailed processes for returning to normal operations. Additionally, establishing surplus capacity in production, warehousing, and logistics can contribute to increased flexibility.

In the domain of risk and crisis management, it is proposed that organizations form a dedicated crisis management team and regularly develop, review, and practice crisis management plans. This team should be tasked with identifying potential risks, formulating coping strategies, and coordinating actions during crises. The utilization of blockchain-based intelligent systems for early risk prediction and identification can also prove highly effective.

To enhance relationships and collaboration within the supply chain, it is recommended to establish cooperation and trust-building mechanisms among partners. This may include organizing regular meetings, facilitating transparent information exchange, and implementing incentive systems for collaboration. The adoption of blockchain-based smart contracts can help reinforce trust and transparency in business relationships.

Lastly, regarding legal and industry requirements, organizations are advised to actively engage with legislative and regulatory bodies to develop appropriate legal frameworks for blockchain utilization in the laboratory equipment industry. Furthermore, the implementation of blockchain-based quality control systems can aid in ensuring compliance with standards and legal requirements.

The practical recommendations derived from our research findings can be implemented in different aspects of supply chain management. For instance, in the dimension of "Digital Technology and Infrastructure,"

which received the highest weight (0.323), organizations should focus on developing technical infrastructure and specialized human resources (weight: 0.331). This could be achieved through systematic investment in blockchain infrastructure development and comprehensive training programs.

Similarly, for "Information Management and Transparency" (weight: 0.239), organizations should prioritize implementing robust product traceability systems (weight: 0.451) that can effectively track and trace laboratory equipment throughout the supply chain. The high weight of "Speed in recovery from disruptions and damages" (0.362) in the Operational Flexibility dimension suggests that organizations should develop rapid response capabilities through well-defined protocols and procedures.

Despite the comprehensive efforts made, this research has been subject to certain limitations that warrant consideration when interpreting and applying the results. A primary limitation was the focus on the laboratory equipment industry in Iran, potentially constraining the generalizability of findings to other industries or countries. Given the nascent nature of blockchain technology, the number of organizations with practical experience in implementing this technology in supply chains was limited, which may have influenced the comprehensiveness of the perspectives presented. The expert selection process, while rigorous, may introduce inherent biases as experts' judgments could be influenced by their specific organizational contexts, technological preferences, and individual experiences with blockchain implementation. Moreover, the dynamic and rapidly evolving nature of blockchain technology poses a particular challenge, as new architectures, consensus mechanisms, and integration capabilities with other emerging technologies (such as AI and IoT) are continuously developing, which could impact some of the research findings in the near future. Additionally, the utilization of qualitative methods such as fuzzy Delphi, while offering opportunities for deep insights, may be susceptible to consensus bias, where experts might lean towards conformity rather than maintaining divergent viewpoints.

In light of these limitations, several promising directions for future research emerge. A primary recommendation is to conduct longitudinal mixed-method studies that combine qualitative insights with quantitative performance metrics to assess the actual impact of blockchain implementation on supply chain resilience. These studies could analyze key performance indicators before and after blockchain implementation while documenting the implementation process and challenges through detailed case studies. Additionally, researchers could employ more sophisticated methodological approaches, such as system dynamics modeling and structural equation modeling, to capture the complex interactions between blockchain technology and supply chain risk factors while validating the relationships between identified dimensions. Such

advanced modeling techniques would provide deeper insights into the dynamic nature of blockchain adoption in supply chain systems.

Furthermore, expanding the geographical and industrial scope of research would enhance our understanding of blockchain implementation across different contexts. Comparative studies across various countries and industries could help identify generalizable patterns while highlighting context-specific challenges and solutions. The integration of blockchain with other emerging technologies, such as artificial intelligence and the Internet of Things, presents another crucial area for investigation. Future research could examine how these technological convergences impact supply chain resilience and risk management effectiveness. These research directions would contribute to a more comprehensive understanding of blockchain's practical impact on supply chain risk management and provide valuable insights for both academics and practitioners in the field.

Key practical implications of this research for laboratory equipment industry stakeholders include:

- Development of Technical Infrastructure
- Investment priority should be given to blockchain infrastructure and specialized training
- Focus on security protocols and privacy measures is essential
- Integration with existing systems should be carefully planned
- Supply Chain Transparency Enhancement
- Implementation of end-to-end product tracking systems
- Development of shared data platforms among partners
- Regular monitoring and updating of information-sharing protocols
- Operational Resilience Building
- Development of comprehensive disruption management plans
- Creation of redundant capacity in critical areas
- Establishment of multiple supplier relationships
- Risk Management Implementation
- Formation of dedicated crisis management teams
- Regular testing and updating of contingency plans
- Investment in early warning systems

These findings provide a practical roadmap for organizations seeking to enhance their supply chain resilience through blockchain technology implementation. In conclusion, this research has taken a significant step towards enhancing our understanding of the factors influencing blockchain-based resilient supply chain risk management in the laboratory equipment industry. The findings of this study can serve as a valuable guide for managers and decision-makers in implementing and leveraging blockchain technology

within supply chains while also laying the groundwork for further research in this domain.

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