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Review

Carbon Capture, Utilization, and Storage Risks from Supply Chain Perspective: A Review of the Literature and Conceptual Framework Development

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Abstract: The technology called carbon capture, utilization, and storage (CCUS) is important for capturing CO_2 emissions before they enter the air. Because everyone wants to stop global warming by reducing CO_2 emissions, CCUS is an important and emerging technology that can help slow down climate change, lower emissions in many areas, and support the move toward a sustainable and carbon-neutral future. As CCUS technology and its adaptation increases, it is very important to pay attention to the CCUS risks from a supply chain (SC) point of view. The goal of this study was to identify CCUS supply chain risks and develop a conceptual framework (CF) that provides a structured approach to ensure safe and reliable CCUS supply chain operations. Therefore, this study analyzed the literature related to the SCs of different sectors and identified the SC risks, which was the foundation for CCUS SC risk identification. This study demonstrates that there is no research article that provides a comprehensive CCUS SC risk management framework that connects with risk management strategies. The conceptual framework that is proposed in this study connects CCUS SC functions, risks, and risk management strategies to construct a complete CCUS supply chain risk management system. Moreover, the CF provides guidelines for future research, which will enrich the CCUS supply chain risk management system as well as fight climate change.

Keywords: carbon capture, utilization, and storage (CCUS); supply chain (SC); supply chain risk; CCUS supply chain risk; risk identification; risk management (RM); conceptual framework (CF)

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1. Introduction

Carbon dioxide (CO_2) levels in the environment have sharply increased due to the rapid increase in the energy and industrial sectors, especially when they burn fossil fuels [1]. Therefore, there are a lot of worries about how to stop global warming and establish climate mitigation strategies by 2050 for a low-carbon and sustainable future [1]. For climate change to be less severe, greenhouse gas pollution, especially carbon dioxide, must be cut down. CCUS technology is one of the methods that scientists are working on to reduce CO_2 pollution from factories and power plants and safely store or use the captured carbon [2–4]. In addition, as the industrial output is expected to grow and decarbonization is a pressing social and political need, CCUS is expected to play a key role in supporting economic growth and decarbonization at the same time [4]. As the international community works harder to fight climate change and lower greenhouse gas emissions, CCUS has become a key tool for meeting the goals of the Paris Agreement. In a world where CO_2 levels are rising, the Chinese government is helping to adapt technology and use CCUS in the real world, and great progress is being made [5]. With the increase in CCUS, the SC activities related to CCUS have gained much attention [6]. Nevertheless, there are a few issues with establishing a robust and efficient CCUS SC system [7]. This study focused on CCUS SC risk identification in the SC RM literature review for different SC sectors. This will help the global effort to fight climate change.

CCUS is a technology that captures carbon dioxide emissions from industrial and power generation processes to reduce greenhouse gas emissions and environmental impacts [8,9]. CCUS is key to the fight against climate change because it includes technologies that absorb CO_2 emissions from high-emission sources, move the captured CO_2, and either use it again or store it forever [10]. With the main goal of reducing CO_2 emissions and battling environmental impacts, CCUS is a comprehensive process for capturing carbon dioxide emissions from industrial activities, followed by their transportation to a storage location, where they are either sequestered underground or used in a variety of applications like enhanced oil recovery, chemical production, and building materials [4]. The immediate implementation and current usage of CCUS in a few industries highlight its current viability, but to successfully achieve net zero by the middle of this century, significant investments and policy backing are indispensable, emphasizing the urgent need to accelerate CCUS technology deployment [10]. Cutting CO_2 emissions is the most important thing that can be undertaken to fight climate change, and renewable energy has a lot of promise. However, the current energy world is complicated, and the fact that countries and businesses are setting more and more ambitious net-zero emissions goals shows how hard it is to rely only on renewable energy. To reach the 1.5 °C goal, energy efficiency and the use of low-carbon alternative energy sources must be five times higher in 2050 than they were in 2015 [11]. CCUS helps to protect the environment by capturing and storing CO_2 emissions. It is important to remember that CCUS is not a replacement for renewable energy. Instead, it is a technology that works with renewables to help reduce emissions in places where renewables alone may not be enough [12].

The CCUS SC involves collecting CO_2 from factories and power plants, moving it, storing it underground, or using it for other purposes [13]. The CCUS SC is intricate and comprises numerous components, including carbon capture, compression, transport, storage, and utilization [3]. Each of these components necessitates specialized knowledge and apparatuses, and collaboration between various stakeholders is essential for the success of CCUS solutions. Capturing CO_2 from the source of emissions is the first step in the CCUS SC. There are different ways to capture CO_2: post-combustion capture, precombustion capture, and oxyfuel combustion [14]. After being captured, the CO_2 needs to be compressed under more pressure in order to be moved and stored [15]. The compressed CO_2 is then moved from where it was captured to where it will be used or stored. A pipeline, ship, or vehicle can all be used to achieve this. In the next step of the CCUS SC, storage, the compressed CO_2 is placed underground in rock formations, salt formations, or deep coal fissures [16,17].

To use CCUS well and reach carbon neutrality, the risks related to the CCUS SC need to be understood to find ways to lower them [4,18]. There needs to be a full risk study of CCUS projects to find out what the risks are. Finding, evaluating, and lowering the risks that might come with CCUS technologies are all parts of CCUS RM. This needs to be carried out regularly and with regular risk assessments [10]. Successful CCUS RM requires a full understanding of the complexity involved and the use of methods from different fields to measure the possible effects. The CCUS SC includes capturing carbon dioxide emissions from different sources, like power plants or industrial facilities, and then transporting them to a storage site for use or sequestration. These steps, which include capture, compression, transportation, and storage, are very important for reducing greenhouse gas emissions and promoting sustainable energy from renewable sources [19]. A CCUS SC risk is a possible threat or uncertainty that could affect the flow of the compressed CO_2, transportation system, health and safety, tools, and services that are needed for CCUS technologies. Therefore, CCUS technology cannot be used or put into place without effective SC RM. Environmental and safety risks are part of the CCUS SC risk throughout the entire carbon capture, use, and storage process, from CO_2 emission sources to capture, transportation, and storage/use technology modules [20]. In the CCUS SC process, if compressed CO_2 cannot reach the place where it will be stored or used because of a problem with transportation or technology, itis likely that CO_2 will be released into the environment until the problem is fixed. With this interruption in the CCUS SC, the process of capturing CO_2 would slow down because the plant would not have enough space to store it. If risks are not taken care of ahead of time, the effects of CCUS SC will be even worse when shipping is carried out only through a pipeline as continuous flow. Thus, the CCUS SC RM has to find, evaluate, and eliminate possible environmental, safety, and operating risks throughout the whole process.

The 2015 Paris agreement is an international agreement that drives the whole world in working together to fight climate change [21]. Its primary goal is to limit global warming to below 2 degrees Celsius above preindustrial levels, with aspirations of reaching a more ambitious goal of 1.5 degrees Celsius [22–24]. To achieve these lofty objectives, widespread adoption of CCUS technology is required [25]. This process stores or utilizes CO_2 emissions, preventing their discharge into the atmosphere and thereby reducing the overall concentrations of greenhouse gases [26]. The complex nature of the CCUS SC, which includes emission sources and storage, makes it difficult to identify and fully assess environmental and safety risks [20]. One of the storage facilities in CCUS SC is oil and gas reservoirs, which requires risk management efforts and prioritizing stability [27]. However, a significant knowledge deficit regarding the inherent risks of CCUS SC was identified through an exhaustive review of the literature. Recognizing the importance of bridging this gap, the purpose of this research was to systematically identify and validate the risks associated with the CCUS SC, thereby contributing to the development of sustainable and secure CCUS SC risk management. Therefore, the creation and implementation of a robust and efficient CCUS SC are essential for achieving the objectives of the Paris Agreement and mitigating the effects of climate change in the growing number of energy and industrial sectors. The analysis reveals that substantial work has been conducted in life cycle assessment (LCA) and climate action (CA), indicating a strong emphasis on understanding the environmental effects of CCUS SC and implementing climate mitigation strategies. However, there is not much study on SC RM (SCRM) in the context of CCUS, as shown in Appendix A. This finding highlights the importance of conducting further studies on the potential risks of CCUS SC and developing effective ways to manage those risks. This article provides a thorough examination of gaps in research in the area of CCUS SC risk identification. To determine the scope and focus of the study in this area, a thorough review of the literature on the CCUS SC was carried out. The study found that CCUS SC RM has not been given enough attention. Even though CCUS SC RM (SCRM) was the topic of four research papers, none gave a complete list of the risks involved with the CCUS SC. Therefore, by identifying risks associated with the CCUS SC, this study makes a direct contribution to the successful implementation of CCUS initiatives. This makes it easier to move to a low-carbon economy, which is one of the goals of the Paris Agreement [28,29]. This study provides answers to the following questions:

RQ1: What is the current status of CCUS risk from an SC perspective in scientific databases?

RQ2: Which CCUS SC risk is associated with which CCUS SC function?

More and more CCUS is being used, and new technologies are being developed to lower CO_2 emissions. This emphasizes the importance of addressing SC concerns in this field. To make sure that CCUS systems work reliably, it is important to know the risks that come with their SCs. This knowledge is vital for creating effective frameworks for managing the SC and putting in place good strategies for managing risks. Therefore, this study primarily focuses on two main goals: finding the CCUS SC risks and establishing a conceptual framework. The primary objective is to clarify how CCUS practices can be adapted to minimize risks and the occurrence of uncertain events that could pose dangers. By achieving these goals, CCUS operations can be made much more reliable and long-lasting while also encouraging people to act in an environmentally friendly way. In the end, this will help the world's efforts to fight climate change and lower CO_2 emissions.

This manuscript is divided into six sections. In Section 1, an introduction to CCUS is provided, including a discussion on the supply chain, risk management, motivation, and scope of the study. Section 2 represents the research methodology adopted in this research work. Section 3 covers the literature analysis with an understanding of research cluster. Section 4 covers the findings and discussion, and Section 5 explains the importance of a CCUS SC risk management framework and presents a conceptual framework. Section 6 provides the implications of this research work. Finally, a conclusion and future directions are provided in Sections 7 and 8.

2. Review Methodology

In order to answer the abovementioned research questions, the objective of this study is to analyze the evolution and extent of work carried out in the area of CCUS risk from the SC perspective. Furthermore, this research focuses on classifying and regrouping the CCUS SC risks at each CCUS SC function. Finally, a conceptual framework for CCUS risk management from the SC perspective is proposed. As a first step, the literature related to the CCUS was analyzed to identify the gaps. PRISMA analysis, a systematic method, was used to identify relevant research papers for gap analysis [30]. The research paper identification is depicted in Figure 1. This research was divided into four main steps, which are gap analysis, CCUS SC risks identification, conceptual framework development, and conclusion and future directions.

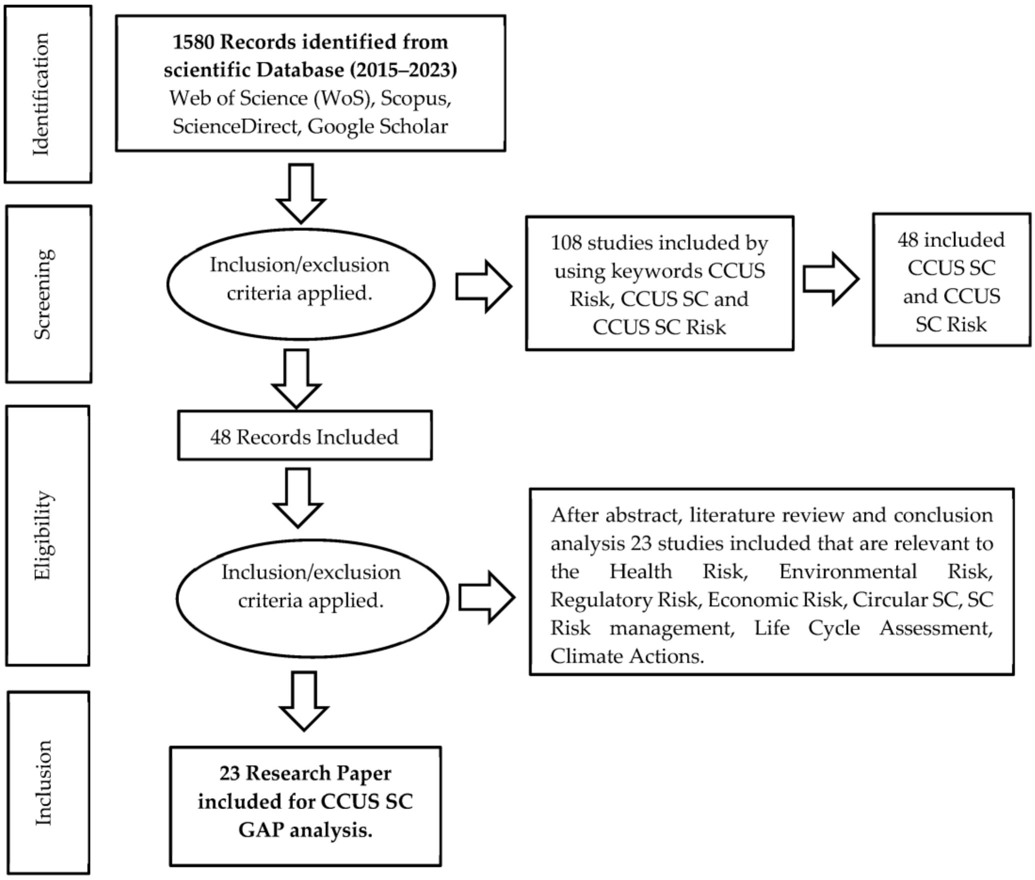

Figure 1. Research paper identification using PRISMA analysis.

2.1. Identifying Research Gap

Research gap analysis consisted of five more steps, including database selection, keyword selection, collecting articles, filtering, and then identifying the CCUS gap. Web of Science (WoS), Scopus, ScienceDirect, and Google Scholar, which are the largest databases containing most of the works of the CCUS field, were considered. As a second step, keywords such as carbon capture, utilization, and storage (CCUS), CCUS SC, CCUS risks, and CCUS SC risks were considered. In this stage, the articles related to CCUS SC and

CCUS SC risks were kept for the next step. Among 49 articles, 23 research works related to CCUS SC and CCUS SC risk management were filtered to determine the research gap (Appendix A).

2.1.1. Descriptive Statistics

In this section, different descriptive statistics are presented for research analysis. Figures 2 and 3 represent the distribution of research publications by year from 2015 to the present. The reason for considering 2015 as a starting point is due to the Paris Agreement and demonstrating the influence of this agreement. The descriptive statistics depict that the number of publications on CCUS has received much attention from 2015 till today due to the climate actions announced by the different countries. Figure 2 shows that the overall CCUS articles increased exponentially from 2015, whereas CCUS RM has received less attention. However, the CCUS SC topic has received very little attention compared to the growth of CCUS application and research, and CCUS SC RM remains a domain to explore (Figure 3).

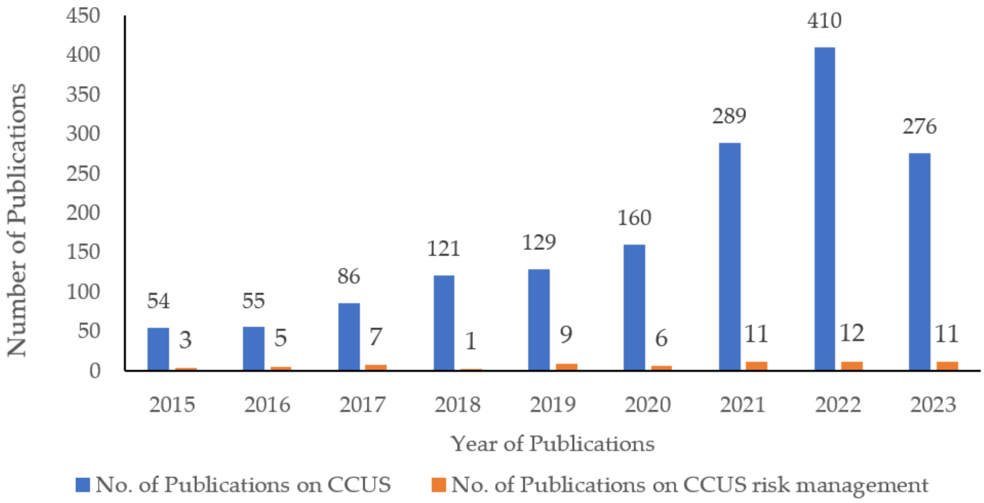

Figure 2. Number of publications on CCUS and CCUS RM since 2015.

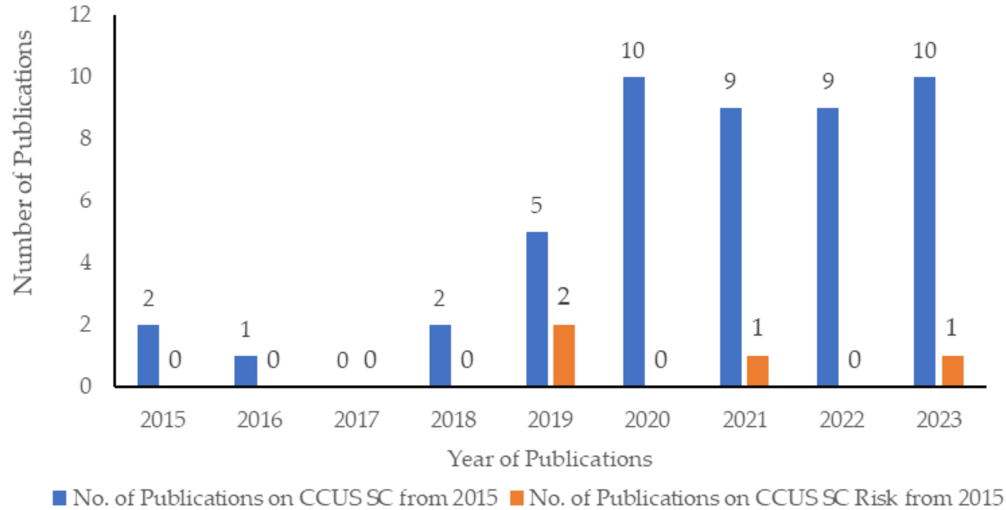

Figure 3. Number of publications on CCUS SC and CCUS SC risk management since 2015.

Statistics show that the CCUS has received much attention since 2015, and the contribution towards this topic is increasing with time. Along with CCUS, RM of CCUS has received much attention comparatively, but the number is far lower (54) compared to the overall articles published (1580) on CCUS. However, the number of publications on CCUS SC remains limited (48), whereas the CCUS SC RM remains a new exploration field for the researchers (Appendix A). From the descriptive statistics, it can be pointed out that there is an enormous opportunity to work on CCUS SC RM and contribute to the literature.

Due to the limited number of studies on CCUS SC RM, we aimed to identify CCUS SC risks from the existing SC RM research in different SC sectors.

2.1.2. Analysis of Risks Based on SC Sectors

Due to the lack of research papers focusing specifically on risk identification in the carbon capture, utilization, and storage (CCUS) SC, the research initiative shifted to conducting a literature review of SC management (SCM) in various industries. By examining the extant literature on SCM in diverse industries, such as manufacturing, production, retail, process industry, agribusiness, and healthcare SC, valuable insights regarding risks can be garnered. This broader perspective will allow for identifying potential risks applicable to the CCUS SC and facilitate the adaptation of relevant RM practices to the specific context of CCUS operations. The findings of this literature review will serve as the basis for developing a comprehensive risk analysis framework tailored specifically to the CCUS SC, filling the existing research void and enhancing the understanding of risk dynamics in this crucial domain.

The risks associated with the SC were summarized into five different sectors. These risks related to these five SC sectors are represented as manufacturing and production SC (MFSC/PSC) risks in one frame, retail SC (RSC) risks, process SC (PSC), agricultural SC (ASC) risks, and healthcare SC (HCSC) risks. The manufacturing SC comprises the people, places, and things that work together to make, deliver, and distribute goods to customers. It plays a crucial role in the global economy, with potential disruptions affecting businesses and consumers [31], whereas the retail SC consists of a complex web of entities and operations, such as sourcing, production, logistics, and distribution, to move goods and services from suppliers to end consumers while meeting market demands [32]. The energy SC (ESC) is a complex system that includes resource, energy conversion, and energy distribution to end users and has effects on the economy, the environment, and the health of society [33]. The oil and gas SC is a part of the energy SC, which is the process of making, moving, and selling different types of energy [34]. Process SC (PRSC) is an umbrella term for oil and gas, power, energy, and chemical SC. An agricultural SC (ASC) is making, distributing, and delivering agricultural products from farms to consumers. It involves farmers, suppliers, processors, distributors, retailers, and consumers to achieve an efficient and sustainable product flow [35]. A healthcare SC (HCSC) includes the people and organizations that buy, distribute, and manage medical goods and services quickly and efficiently [36].

The literature review looks at SC risks in a few areas, including manufacturing/production (MFSC), retail (RSC), energy/process (ESC/PRSC), agriculture (ASC), and healthcare (HCSC). Natural disasters, government rules, and globalization are all threats affecting these SC sectors. Table 1 lists the risks that each sector faces, such as political instability, terrorism, stockouts, financial problems, and different levels of output. Due to the interconnected and complex nature of modern SCs, the study highlights the need for RM strategies in SC operations, as a number of common risks impact multiple industries [37].

Table 1. SC risks in different sectors.

Risks	References	MFSC/PSC	RSC	ESC/PRSC	ASC	HCSC
Natural Disaster	[38–47]	☑	☑	☑	☑	☑
Changes in Government regulations and Policies	[38,39,43,48,49]	☑	☑	☑	☑	☑
Globalization	[42,50]		☑	☑		
Political Instability and Unrest	[39,47,48]	☑		☑		
Terrorism and War	[38,39]	☑		☑		
Trade Agreement	[42,47]			☑		
Stockout Risk/Shortage	[51–53]		☑			☑
Product Return	[54]				☑	
Financial Risk	[38,39,48,50,55]	☑	☑	☑		
Environmental Threat	[38,44,45,47,48]			☑		☑
Inflation and Currency Exchange Risk	[39]	☑				
High Insurance Cost	[38]			☑		
Safety and Human Risk	[38,47,56]			☑		☑
Production Variability	[38,47,56]		☑	☑	☑	
Transportation Delay	[38,43,46,50,57]		☑	☑	☑	☑
Product Quality	[43,44,48,50,54]	☑	☑	☑	☑	
Supply Delay	[39,44,54,58–60]	☑	☑	☑	☑	
Lack of Supplier Coordination	[39,59,61]	☑				
Production Capacity	[38,46,48,62]			☑	☑	
Continuous Production	[58]			☑		
Scheduling Problem	[47,56]			☑		☑
Cross-contamination	[57]				☑	
Perishability	[41,57]				☑	
Chemical Contaminants	[54]				☑	
Retail Price Variability	[60,63]		☑		☑	
Demand variability	[38,39,41,47,50,54, 60,62–67]	☑	☑	☑	☑	☑
Price Volatility	[41,47,60]			☑	☑	
Loss of Customer	[43,68]		☑			
Information Flow Management	[39,43,55,59,69]	☑	☑	☑	☑	
Short Product Life Cycle	[39,41,61]	☑			☑	
Infrastructure Risk	[38,46,48,50,55,67]		☑	☑		☑
Processing Unit Disruption	[58]			☑		
Technical Failure	[47]			☑		
Transportation Cost	[47]			☑		
Damage during process	[54]				☑	
SC Interconnection between nodes	[43,52]		☑		☑	☑

Table 1. *Cont.*

Risks	References	MFSC/PSC	RSC	ESC/PRSC	ASC	HCSC
Unused Retail Capacity	[70]		☑			
Internal Disruption	[39]	☑				
Transport Breakdown	[39,55]	☑		☑		
Labor Strike	[39]	☑				
Storage Technology	[41,58]			☑		
Technological advancement	[47,48]			☑		
Preservation Equipment and Technology	[43]				☑	
Machine Damage	[48,54]				☑	
Picking Technology	[41,43]				☑	
Rapid Changes in Technologies	[1,39,55]	☑		☑		
MFSC—manufacturing SC PSC—production SC RSC—retail SC				PRSC—process SC ESC—energy SC ASC—agricultural SC HCSC—healthcare SC		

2.1.3. Linking with CCUS SC Risk

The SC faces various risks, many of which are prevalent across industries. However, certain SC risks are unique to specific industries. Consequently, identifying SC risks is crucial in every industry, as it facilitates the comprehension of global risk factors and enables proactive measures and preparations. Notably, our study is limited by the availability of only four literature sources that focus on different aspects of carbon capture, utilization, and storage (CCUS) SC risks, and, sadly, no single literature source focuses on the entire spectrum of CCUS SC risks. Due to the paucity of relevant literature, SC risks are categorized by industry. Given that the CCUS SC involves CO_2, which is a component of the chemical, power, and energy SCs, CCUS SC risks are classified the same as the energy/process SC (ESC/PRSC) sector. This classification identifies 28 risks for the CCUS SC, as shown in Table 1.

3. Literature Analysis

In this section, the literature is analyzed and we present results of the modularity analysis and describe the literature for clear understanding.

3.1. Description of Literature Analysis

The SC risks identified by sectors were analyzed by Gephi Software. In this step, we followed a modularity check and visualized risks by cluster. As per our findings, five clusters were identified with many nodes. Due to its 3D real-time rendering, customizable layout algorithms, dynamic visualization capabilities, graphical modules for enhancing display, and extensible architecture, Gephi is highly flexible for visualizing network data. Modularity refers to using Gephi's Louvain method for community detection, which seeks to identify distinct groups of nodes in the network by maximizing the modularity score, allowing resolution adjustments and weighted analysis to reveal regional divisions and relationships within the network [71]. Figure 4 represents the clusters of SC risks by sector and visually represents the risks common in different sectors based on the literature review. Energy/process SC risks are considered as CCUS SC risks due to the nature of the material handled in this SC, which is a chemical.

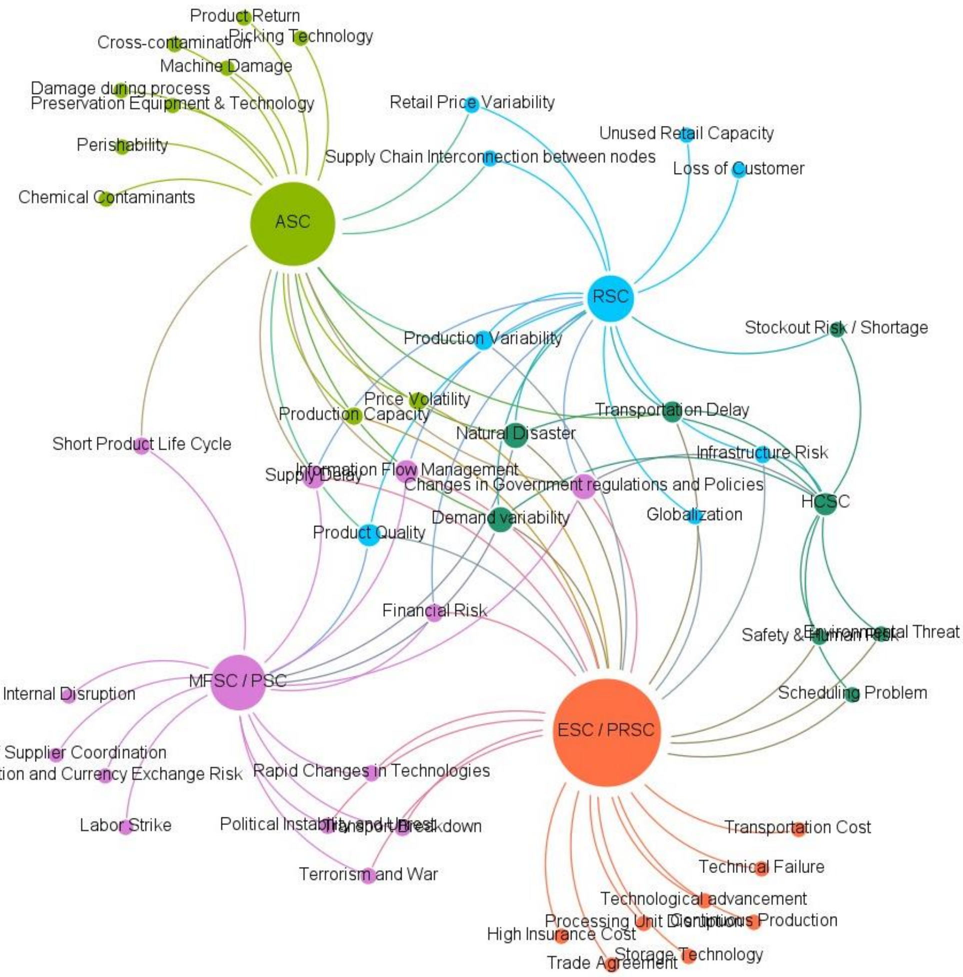

Figure 4. Cluster of SC risks by SC sectors.

3.2. Understanding Literature

To identify SC risks, at first, the literature that focuses on SC risks was identified. Then, these articles were categorized based on SC sectors. Table 2 represents the list of publications that were considered for this study. A few articles are applicable for multiple sectors, and they are mentioned in different sectors accordingly.

Table 2. Sector-wise literature reviewed for SC risk identification.

SC Sectors	References
Manufacturing/Production Supply Chain (MFSC/PSC) RM	[31,38,39,42,44,45,47,48,56]
Retail SC (RSC) Risk Management	[42,43,50,52,57,60,62,63,67]
Energy/Process SC (ESC/PRSC) RM	[38,42,44,45,47,48,54,55,58]
Agricultural SC (ASC) RM	[41,43,45,48,54,72]
Health Care SC (HCSC) RM	[36,51–53,67]

SCs across various industries are susceptible to various risks, including natural disasters, regulatory changes, globalization, political instability, terrorism, stockouts, transportation delays, and more. Researchers have extensively explored the effects of these risks on SC disruptions, recovery efforts, and resilience-building measures [38,39,43,44,47]. Government regulations and policies can significantly impact SC operations and decision-making processes, necessitating adaptation and alignment strategies with evolving regulations [48,49]. Ref. [73] analyzed the impact of legal and regulatory risks CCUS SC, highlighting obstacles such as regulatory clarity, financial viability, and compliance with international law, and proposed regulatory changes to mitigate these risks. Globalization has implications for SC management practices, emphasizing adaptability and collaboration [42,50]. At the same time, political instability and unrest can disrupt SCs, requiring RM strategies [39,47]. Similarly, terrorism and conflict can influence SC operations, urging the need for adaptive strategies and contingency planning [38,39].

Stockouts and shortages are challenges in retail and healthcare SCs, prompting strategies for inventory management and coordination [51–53]. Additional risk and product returns impact agricultural SCs, highlighting the importance of understanding factors contributing to returns and mitigation strategies [54]. Financial risks in SCs underscore the need for RM practices [38,48,55]. Environmental risks and their impact on SCs call for sustainable practices and proactive measures [38,44,45,47,48,74]. Additionally, inflation, currency exchange risks, and insurance premiums challenge SCs, requiring effective RM strategies [38,39,56]. Safety measures and RM practices are crucial in addressing safety and human hazards [39,47,56]. Safety is important in CCUS SCs due to the possibility of accidents, leaks, or failures at various stages, such as capture, transportation, and storage, which could result in negative environmental impacts, risks to human health, and economic liabilities [20]. Production variability affects retail, energy/process, and agricultural SCs, necessitating strategies for demand forecasting and inventory management [45,57,60,62]. Transportation delays impact various sectors, urging logistics optimization and efficient transportation planning [43,46,50,57]. Furthermore, product quality is pivotal, demanding quality control measures and process optimization [43,44,48,50,54]. Ref. [75] analyzed the risks associated with reducing CO_2 emissions, including investment challenges, policy uncertainty, technology and engineering uncertainties, and financial and operational risks, while emphasizing the significance of implementing effective RM strategies.

Supply delays challenge industries, emphasizing coordination and resource allocation [39,44,54,58–60,76]. Therefore, supplier coordination is pivotal to mitigate disruption [39,59,61]. Production capacity challenges require planning and optimization [38,46,48,62]. Continuous production strategies ensure efficiency [58]. Scheduling challenges are addressed mostly through optimization techniques [47,56]. Cross-contamination, perishability, and chemical contaminants are concerns in process SCs [57]. Retail price variability necessitates pricing strategies and coordination [60,63]. At the same time, demand variability management strategies include adaptive practices and collaborative forecasting [38,39,47,50,54,60,62–65,67,77]. Therefore, price volatility mitigation involves hedging and collaboration [41,47,60]. Loss of consumers prompts retention strategies [43,68]. Information flow, coordination, and collaboration enhance SC performance [39,43,59,69]. Risks like product life cycle challenges require agility and adaptation [39,41]. Transport failure demands dependable networks and contingency plans [39,61]. Modern storage technology improves operational efficiency [58]. Retail and healthcare SCs rely on node coordination to ensure SC effectiveness [43,52]. Underutilized retail capacity prompts optimization strategies [70].

Machine breakdown challenges call for maintenance and contingency planning [48,54]. In addition to that, picking technology, automation, and efficiency are crucial in agricultural SCs [41,43]. Manufacturing and process SCs face internal disruptions, whereas transport failure mitigation strategies ensure operational continuity, and labor disruptions highlight labor management and collaboration [39]. Energy/process SCs benefit from the adoption of storage technology and require continuous operation strategies [58]. Machine breakdown risks necessitate maintenance and contingency plans [48,54].

4. Review Findings and Discussion

This study focuses on analyzing risks based on SC sectors, particularly in the context of the carbon capture, utilization, and storage (CCUS) SC. The analysis was conducted through a literature review of SC RM in various industries, including manufacturing, production, retail, energy/process industry, agribusiness, and healthcare SC. The goal was to identify potential risks applicable to the CCUS SC.

As a first step, 46 risks were identified associated with different SC sectors, categorizing them into manufacturing/production SC (MFSC/PSC), retail SC (RSC), energy/process SC (ESC/PRSC), agricultural SC (ASC), and healthcare SC (HCSC). Each sector identifies and discusses various risks, including natural disasters, government regulations, globalization, political instability, terrorism, stockouts, financial issues, production variability, transportation delays, product quality, safety and human risks, and many others. One SC risk can be common in multiple SC sectors. Throughout this study, 16 risks associated with MFSC/PSC, 16 risks associated with RSC, 28 risks associated with ESC/PRSC, 21 risks associated with ASC, and 10 risks associated with HCSC were identified. As per the definition and research consideration, these 28 energy/process SC (ESC/PRSC) risks are considered the CCUS SC risks (Figure 5).

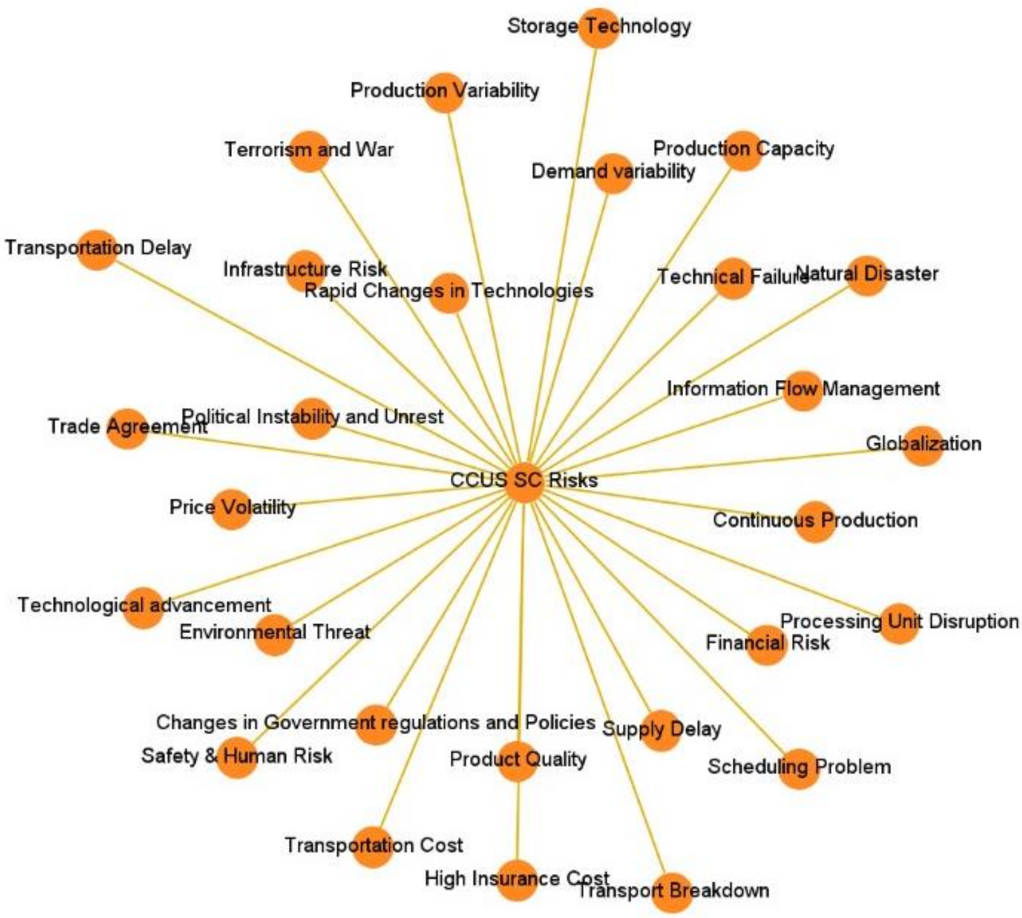

Figure 5. CCUS SC risks.

In the context of CCUS, this risk identification has enormous importance for safety measures and risk management practices to address potential accidents, leaks, or failures at different stages of CCUS operations, which could lead to adverse environmental impacts, human health risks, and economic liabilities. Moreover, a risk cluster was developed, showing risks in five different SC sectors and visualizing them with a network analysis in Gephi. In general, the findings of the review indicate that SCs in various industries encounter several common risks, and that adapting RM practices to the specific characteristics of the CCUS SC is essential for ensuring its safe and efficient operation.

Creating a conceptual framework for CCUS SC RM is one of the main goals of this study. CCUS technology has received much attention because of the ongoing fight against climate change and the urgent need to cut carbon emissions. Regarding CCUS operations, the SC is one of the most important parts. It involves a lot of different people, innovative technologies, and big investments. Thus, the success of CCUS projects depends on more than just new technology. It also depends on how well SC management works. It is very important to stress this because the study found 28 different risks in CCUS SC, and each one directly affects the project's success as a whole. If these risks are not managed well, they will affect the environment, people's health and safety, finances, and the surrounding community. As a result, it is very important to develop a conceptual framework that connects these CCUS SC risks to the functions of the CCUS SC and offers complete risk management strategies. This kind of framework is likely to effectively lower these risks, increasing the success rate of CCUS projects. In turn, this helps people make smart decisions, ensures rules are followed, and boosts trust in the project among stakeholders. Therefore, a CF is proposed in the next section.

The limitation of this study is that it identifies risks from the literature of different SC sectors, and risks of process/energy SC were considered as CCUS SC risks, which were not validated by the subject matter experts. This experts' knowledge could have given us useful information and a more thorough check to see if the risks identified in other areas do present themselves in the CCUS supply chain. As a result, this limitation shows that these risks could be improved and proven real by working with experts in the field, which would strengthen the conceptual framework.

5. Conceptual Framework (CF) of CCUS SC Risk Management

A conceptual framework is a set of ideas that shows the main ideas, variables, and how they relate to each other in a certain research area [78]. It helps organize and make sense of what is already known and points the way for future research. Therefore, researchers in many fields need a conceptual framework because it helps develop and test hypotheses, figure out what the results mean, and share the findings with others [79]. At the same time, it helps to communicate clearly, promotes systematic decision making, and provides a structured approach to complex problem-solving. This article focuses on CCUS SC risk identification. However, the question arises: What are the functions of CCUS SC, and what risks are involved in each function? CCUS SC functions are the activities and operational processes involved in carbon capture, utilization, and storage. The functions related to the CCUS SC can be divided into CO_2 source, capture and compression, transportation, and utilization/storage. This study develops a conceptual framework (Figure 6) for future studies.

Developing a conceptual framework for managing risks in the CCUS SC has many important benefits for placing CCUS initiatives into action and running them day-to-day. This well-organized framework acts as a bridge, linking possible risks to the strategies meant to address them in a planned way. Taking this proactive stance gives CCUS stakeholders the power to make plans and take precautions that will lessen the negative effects of these risks on CCUS SC activities to avoid CCUS SC disruption. Because CCUS projects often need big financial investments, this framework is essential for making sure that resources are used wisely. It helps people decide where to place their resources, so they can focus on the biggest risks and keep risk management efficient and low-cost. This CF is also a useful tool for helping everyone involved in CCUS make decisions. It gives a structured way to think about how to design CCUS SC, how to use technology, and how to handle risks. In this way, it improves the process of making decisions. The success of CCUS projects is also often closely watched by investors, policymakers, and the public, as everyone has a big stake in how they turn out. Instilling more confidence and support for CCUS initiatives and having a CF makes it clear that responsible and risk-aware management practices are important to prevent CCUS SC disruption.

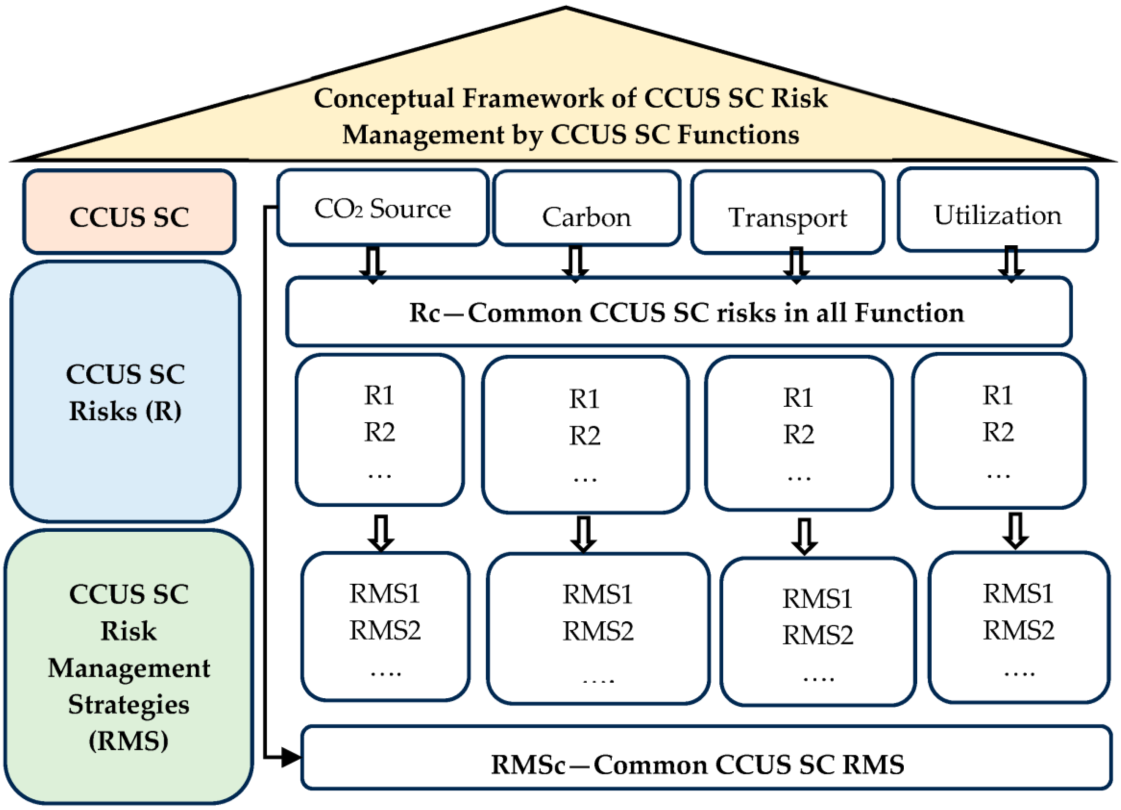

Figure 6. CCUS SC risk management conceptual framework.

The uniqueness of this CF is to connect the functions of CCUS SC with its risk. Moreover, it connects with the risk management strategies to develop a complete CCUS SC RM system. This CF consists of three interconnected layers to provide a complete CCUS SC RM system. Layer 1 represents the CCUS SC functions, layer 2 represents risks, and layer three is for RM strategies. To understand the CF, one can start with layer 1, then move on to layer 2, and finally to layer 3. Therefore, the CF helps in effective communication with researchers. The risks involved in layer 2 can be divided into three groups. Risk group 1 represents the common risks impacting all CCUS SC functions. Risk group 2 indicates the risks that belong to more than one CCUS SC function. Finally, risk group 3 indicates the risks that belong to only one CCUS SC function. Similarly, layer 3 has three risk management strategies linked to each risk group.

A conceptual framework is useful for more than just making research and decision making easier. It is an extremely useful tool for people working in the CCUS field, like practitioners and policymakers. Using this conceptual framework as guidance, decision-makers can establish and follow an outline for creating and implementing effective risk-management strategies. Because it is naturally comprehensive, it gives everyone involved the tools they need to find potential weak spots ahead of time. This makes CCUS supply chains more resilient overall. What really makes this framework stand out is how well it can connect the constantly changing fields of risk management, climate change, and supply chains. It is a flexible and forward-thinking approach that fits perfectly with how quickly it is necessary to deal with climate change risks in global SC.

This new way of looking at problems not only moves the CCUS sector forward but also fits in well with larger goals for sustainability and climate change mitigation. When it comes to talking about adaptability, this framework's strength is that it gives stakeholders the freedom to make risk management plans that suit the unique circumstances of the CCUS supply chain. It considers the unique problems and chances that might come up in a world where climate change is always developing and the supply chain is always becoming more complicated. Another thing that makes the framework unique is that it uses systems thinking. This method considers how climate change, SC, and risk management affect each other in complex ways. The framework helps a more complete study of climate change risks and how they affect global SC by looking at things from a big-picture point of view. By looking at things from different fields, the framework helps make CCUS operations more resilient and long-lasting, making them an even more valuable tool in the fight against climate change worldwide.

6. Research Implications

6.1. Environmental Implications

The analysis of SC risks across multiple industries, including the CCUS SC, reveals several environmental repercussions. The identified risks, such as natural disasters, environmental threats, and safety risks, have substantial environmental repercussions. In the context of CCUS, where carbon capture, utilization, and storage processes are involved, the possibility of accidents, SC disruption, or operational failures at various phases of SC operation can result in the release of captured CO_2. This could cause contamination of the climate and air pollution, as well as harm to ecosystems and human health. Also, the need for safe CO_2 transport and storage shows the importance of the right infrastructure and technology to keep the environment from becoming harmed.

In the context of CCUS and the global pursuit of carbon net-zero targets, as defined by the Paris Agreement, the environmental ramifications of CCUS SC risks become even more significant. Within the framework of CCUS, the identified risks, such as natural disasters, environmental threats, and safety risks, acquire greater significance. As the world moves toward decarbonization and reducing greenhouse gas emissions, CCUS plays a crucial role in capturing carbon dioxide (CO_2) emissions from various sources, such as industrial processes and electricity generation, and preventing their release into the atmosphere. Consequently, any disruptions or malfunctions within the CCUS SC that result in the unintended release of captured CO_2 could directly undermine efforts to achieve carbon neutrality [10] and the objectives of the Paris Agreement.

In addition, the broader environmental implications in the CCUS SC sector highlight the need for an all-encompassing and integrated approach to sustainable development [80]. The demand of the Paris Agreement to limit global warming to well below 2 degrees Celsius and strive for 1.5 degrees Celsius necessitates not only the reduction of greenhouse gas emissions, but also the protection of ecosystems, biodiversity, and human health. Consequently, effective risk identification and management in the CCUS SC is crucial not only for preventing imminent environmental damage, but also for preserving the long-term ecological balance that supports the global transition to a low-carbon future. Therefore, the CF generates ideas to manage these risks effectively. Thus, this CF has enormous potential to develop an overall RM system to protect the environment.

6.2. Managerial Implications

Effective management strategies reduce risks and ensure the efficiency of the CCUS SC. The analysis of risks across industries, including CCUS, reveals important managerial implications. Particularly affected are the complex carbon capture, utilization, and storage processes of the CCUS SC. CCUS can be affected by evolving environmental regulations and policies. The managers of the SC must anticipate changes and invest in regulatory intelligence. This includes engaging actively with regulatory bodies and industry associations and aligning the SC with current and future regulations. Changes in policy and international agreements such as the Paris Agreement can impact the CCUS SC. Therefore, managers are required to monitor policy changes, evaluate risks, and modify SC strategies. Rapid technological progress can affect the CCUS SC [81]. Managers should keep an eye on emerging technologies, assess their impact, and adopt or incorporate applicable innovations. Management involves regulating the variability of production. This involves production planning that accounts for fluctuations in the CCUS SC. Planning the route, mode, and schedule is necessary to avoid delays. Robust logistics, real-time tracking, and contingency plans reduce transportation risks, while technology integration improves visibility for proactive decision making. Interindustry risks emphasize the sharing of information and collaborative RM. Collaboration, networks, and partnerships enhance CCUS SC insights and practices.

Safety protocols, regulations, and standards are essential for environmental sustainability and safety in the CCUS SC. Risk assessments, emergency plans, and training reduce accidents and environmental damage [82]. Strategic investments are required for unique risks such as storage technology and infrastructure. Resilient storage, monitoring, and maintenance enhance the safety and effectiveness of carbon capture and storage. Regular evaluations, scenario planning, and adaptable frameworks identify risks and opportunities, enhancing the CCUS SC's resiliency. Therefore, the CF helps management make effective and efficient decisions based on organizational policy. Moreover, this CF gives an insight to organize the ideas and systematically connect them to develop a robust and resilient RM system for the organization.

6.3. Economic Implications

In the complex CCUS SC, financial challenges, inflation, currency exchange fluctuations, and economic disruptions can disrupt operations' cost-effectiveness and financial stability. These risks in CCUS are exacerbated by the large investments required for cutting-edge carbon capture technologies, infrastructure development, and compliance with changing regulations. These dangers can also disrupt the SC, resulting in production delays, increased expenses, and revenue losses.

Inflation and currency exchange risks increase costs and reduce profits, aggravating economic fragility. These risks impact the costs associated with technology adoption, equipment procurement, and global collaboration in the CCUS industry. It is essential to recognize that CCUS SC risks have broader economic implications. Significant investments are required for infrastructure development, technology deployment, and regulatory compliance; therefore, proactive RM is required to optimize resource allocation and attract funding. However, the increasing trend of CCUS applications and technological innovation help to reduce costs [1]. Thus, CCUS SC risk management is crucial in controlling costs and developing new businesses, which leads to economic growth. The CF facilitates a new understanding of the CCUS SC RM system and drives economic growth with the increasing CCUS application. This CF connects financial risk with its RM strategies, which lowers the economy for the government and organizations.

7. Conclusions

This article examines the risks associated with SC sectors, specifically emphasizing the carbon capture, utilization, and storage (CCUS) SC. This study aims to find and categorize possible risks that are related to the SC of carbon capture, utilization, and storage (CCUS) by thoroughly reviewing the relevant literature from a wide range of industries, such as manufacturing, production, retail, energy/process, agribusiness, and healthcare. A total of 46 different risks were found in a lot of different places. A lot of different things can be considered risks, like natural disasters, government rules, globalization, political unrest, terrorism, stock-outs, money problems, changes in production, shipping delays, product quality, safety concerns, and risks that involve people. It is important to know that the energy/process SC (ESC/PRSC) is connected to 28 different risks. These risks are generally considered the most important ones for the CCUS SC. It is very important to ensure that RM strategies work well with the CCUS SC by making them fit its specific needs. This study also suggests a CF that links CCUS SC functions, risks, and RM strategies to support a full CCUS SC RM system.

The study highlights the significant environmental consequences associated with the CCUS SC risks. The results underscore the importance of promptly implementing comprehensive RM strategies to prevent negative environmental consequences. Furthermore, the research sheds light on the managerial implications, emphasizing the need for proactive adjustments in response to changing environmental regulations, policy advancements, and technological progress. The research also examines the economic consequences associated with the CCUS SC risks, including financial stability, inflation, currency exchange rate fluctuations, and operational disruptions that pose challenges to achieving cost-effectiveness and revenue stability. To address this growing concern, the CF provides an idea of a complete CCUS SC RM system. This CF is the first of its kind in the CCUS SC field, which focuses on the functional level of CCUS SC. The CF also includes risk management strategies that need further study.

8. Future Directions

In this study, CCUS SC risks are identified through research that needs to be validated through experts' opinions; for example, the Delphi method can be used. Further investigation is required to explore the intricacies of developing and executing all-encompassing RM strategies tailored to address the distinctive obstacles encountered within the CCUS SC functions. This entails the creation of an RM framework aimed at addressing CCUS SC functions, risks, and RM strategies. Therefore, one of the future directions can be identifying an RM framework to develop a CCUS SC RM system that connects risks with risk management strategies. Additional investigation could delve into the socioeconomic ramifications of SC risks associated with CCUS. This could encompass examining their impact on nearby communities, employment opportunities, and public health. Comprehensive evaluation has the potential to provide valuable insights for the development of policies and the involvement of relevant stakeholders. The examination of international collaborations, regulatory frameworks, and policy harmonization is of utmost importance to effectively tackle the risks associated with the transboundary nature of CCUS SCs. The implementation of collaborative endeavors can contribute to establishing standardized RM protocols, thereby fostering global sustainability. Another future direction can be environmental impact analysis through life cycle assessment (LCA) for CCUS SC functions.

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Abbreviations

HR—health risk, ENR—environmental risk, RR—regulatory risk, ER—economic risk, CSC—circular SC, SCRM—SC risk management, LCA—life cycle Assessment, CA—climate actions.

Appendix A

Table A1. GAP Analysis of Carbon Capture, Utilization, and Storage (CCUS) SC.

Work	CO_2 Source	Transportation Mode	HR	ENR	RR	ER	TR	SCRM	Optimization	CSC	LCA	CA
[6]	Power plants Cement plants Steel and iron plants										☑	☑
[20]	Fossil fuel power Chemical industries Steel, cement plants	Pipeline Ship Tanker						☑				
[13]	Industrial processes	Pipeline, truck							☑			☑

Table A1. *Cont.*

Work	CO_2 Source	Transportation Mode	HR	ENR	RR	ER	TR	SCRM	Optimization	CSC	LCA	CA
[83]	Power plant Industrial sites Others	Pipeline, ship, truck, rail							☑		☑	☑
[84]	Not specified	Not specified							☑			☑
[10]	High-emission sources (power plants, industries) and air	Pipeline, ship, truck			☑	☑	☑					☑
[85]	Industrial and energy sites								☑			☑
[86]	Power plant										☑	☑
[87]	Power plants, biogas plants, gas processing plants, refineries, cement production plants and others	Road, rail, pipeline							☑			☑
[88]	Power plants and multiple other sources	Pipeline, sea carriers, rail, road										☑
[73]	Oil and gas							☑				
[89]	Various industrial and power plants	Pipeline							☑			☑
[90]	Not specified	Pipeline					☑					
[91]	Not specified	Pipeline							☑			
[19]	Not specified								☑			
[92]	European coal and gas power plant	Pipeline							☑			☑
[75]	Power plants, cement, iron and steel refineries	Pipeline (tank and ship as alternative)						☑	☑			
[93]	Not specified	Pipeline							☑			
[94]	Power plants		☑	☑			☑					
[74]	Power plants, steel plants, oil refinery plants, petrochemical plants							☑	☑			
[95]	Power plants. Iron and steel plants, cement industries	Pipeline, ship, rail, road							☑			☑
[96]	Not specified	Pipeline, ship, road, rail				☑			☑			☑
[97]	Energy and manufacturing sector	Pipeline							☑			☑

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