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Research Article

Strengthening U.S. Supply Chains Through Sustainable Sourcing of Critical Raw Materials

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ABSTRACT
This systematic review evaluates the current state of sustainable sourcing practices for critical raw materials (CRMs) within U.S. supply chains. A comprehensive analysis of 26 peer-reviewed studies published between 2015 and 2025 is presented, focusing on key challenges, technological innovations, and strategies for enhancing CRM sourcing sustainability. The review identifies geopolitical, economic, and environmental risks that threaten the stability of CRM supply chains, highlighting the U.S.'s dependency on foreign sources for critical materials such as lithium, cobalt, and rare earth elements. Technological solutions, including Artificial Intelligence (AI), blockchain, and Industry 4.0 technologies, are explored as promising tools to improve supply chain resilience and transparency. Additionally, the review emphasizes the importance of adopting sustainable practices such as ethical sourcing, recycling, and greener mining technologies to mitigate environmental impacts and enhance the sustainability of CRM supply chains. The findings suggest that while significant challenges remain, a combination of technological advancements, sustainable practices, and policy reforms is crucial for securing a resilient and ethically sourced supply of CRMs. The review concludes with recommendations for future research and policy interventions to strengthen CRM supply chains in line with global sustainability goals.

Keywords: Critical Raw Materials, Sustainable Sourcing, Supply Chain Risks, Geopolitical Risks, Technological Innovations, Ethical Sourcing

1. Introduction

The global economy is in an in-depth shift towards more sustainable technology due to the necessity to decrease the carbon emissions and achieve climate targets (Söderholm, 2020; Chen et al., 2022). Key to this transition are critical raw materials (CRMs), (lithium, cobalt, rare earth elements (REEs) among others). To produce some of the most important technologies, such as the electric vehicles (EVs), solar panels, wind turbines, batteries, and even military systems, these materials are vital (Bahalkani et al., 2024). With the increasing demand of CRMs related to the high pace of implementation towards clean energy technologies, sourcing of these materials in a safe and sustainable manner has been an essential concern of national security as well as economic stability and environmental sustainability.

The United States is one of the most advanced economies in clean energy and defence technology; therefore it is overwhelming to secure the resilience of the CRM supply chains (Korkmaz, 2024). Many US longstanding materials are sources abroad, especially rare earth elements and lithium, where China is a major supplier (Gielen & Lyons, 2022). The presence of geopolitical tensions, trade wars, and the constant rivalry in obtaining world resources have uncovered a weakness amid the CRM supply chains, and the U.S. is thus vulnerable to supply disturbances (Timilehin, 2024). The existence of such geopolitical risks, in tandem with the environmental issues surrounding the actions of mining activity and the emergence of the growing number of users of these materials have brought concerns related to the lasting viability of sourcing strategies behind CRM (Theodosopoulos, 2020; Dyatkin, 2020).

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Besides geopolitical risks, the volatility of the economy based on CRM prices, paired by the negative effects of such traditional mining on the environment has highlighted the importance of industries and governments to find sustainable sources of similar resources (Girardi et al., 2023; Villalobos et al., 2022). Common in the extraction of CRMs are deforestation and pollution of water, among other environmental degradations and this attracts ethical issues regarding the social and environmental consequences of the sourcing practices (Nwankwo et al., 2024). Thus, it is high time that the policies and strategies should exist that can create a balance between economic and environmental protection and ethical norms regarding the sourcing of CRMs.

The systematic review here will help understand the existing literature on sustainable sourcing of critical raw materials in U.S. supply chains that seeks to address the risks, challenges, and technological advancements that can positively impact the sustainability of U.S. supply chains and make these supply chains more resilient. This review has conducted a synthesis of the findings within 26 peer-reviewed articles published between 2015 and 2025 and discovers the most important risks experienced by supply chains in the context of CRM, geopolitical and economical, environment challenges, and how technologically significant innovations mitigate the risk factors. Additionally, the review evaluates the solutions and best possible practices that were proposed by some researchers to increase the sustainability including such solutions as incorporating principles of the circular economy, adopting Industry 4.0 technologies, Net Positive, and ethical sourcing practices.

2. Methods and Materials

To be transparent and rigorous in the review process, the requirements of the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) were followed to complete this systematic review. The review summarises the results of 26 peer-purged papers reported through 2015 - 2025 that deal with sustainable data acquisition practices, hazards, and technologies, encompassing critical raw materials (CRMs) in U.S. supply chains. This review will aim at determining the main supply chain risks, technological advancements in supporting supply chain resilience, and evaluating the supply chain resilience as far as CRM sourcing is concerned in relation to sustainability.

2.1. Search Strategy

In order to ensure that the process of systematic review is systematic, the study commenced with a thorough search of various scholarly databases to find the appropriate peer-reviewed articles. Articles were retrieved by the use of the following databases:

Table 1: Databases and Keywords searched

Databases Searched	Keywords/Phrases Used
ScienceDirect	Critical Raw Materials (CRMs)
Scopus	Sustainable Sourcing of CRMs
Web of Science	CRM Supply Chains
Google Scholar	Geopolitical Risks in CRM Sourcing
JSTOR	Technological Innovations in CRM Supply Chains
	Circular Economy in Raw Material Sourcing
	Ethical Sourcing and Sustainability

Such search words were used in conjunction with Boolean operators (AND, OR) which were used to restrict the overall results into the most pertinent articles. It was restricted to the articles published in 2015-2025 to make sure that the overview presents the latest news on CRM sourcing.

2.2. Inclusion and Exclusion Criteria

The studies have been selected by using the following inclusion and exclusion criteria:

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Table 2: Inclusion and exclusion criteria

Criteria	Inclusion	Exclusion
Peer-Reviewed Articles	Only peer-reviewed articles published in journals. Ensures credibility of sources.	Non-peer-reviewed sources (e.g., articles from blogs, conference proceedings).
Time Frame	Articles published between January 2015 and May 2025. Focuses on the latest research.	Articles published before 2015 or those outdated for the review. Articles published before 2015 are considered outdated as they may not capture the recent advancements, policy reforms, and technological innovations shaping current CRM supply chain sustainability
Focus on CRMs and Supply Chains	Studies must focus on sourcing, supply chain risks, and sustainability of CRMs, particularly in the U.S. context.	Articles not addressing CRM sourcing, supply chain risks, or sustainability in the U.S. context.
Technological and Policy Innovation	Articles discussing technological innovations, sustainable practices, and policy interventions for CRM supply chains.	Studies not addressing technological innovations, sustainability practices, or policy interventions in CRM sourcing.
Non-Peer-Reviewed Sources	N/A	Articles not published in peer-reviewed journals or conferences.
Outdated Studies	N/A	Articles published before 2015 or those not relevant to the focus of CRM sourcing and sustainability.
Irrelevant Studies	N/A	Studies not addressing supply chain risks, CRM sourcing, or sustainability practices.

2.3. Article Selection Process (PRISMA)

Articles were selected according to the PRISMA process that includes four principal stages: identification, screening, eligibility, and inclusion. The selection process is represented in the form of a PRISMA flow diagram (Figure 1).

Identification: An overall search of the databases resulted in an initial sample of 126 articles that were published between January 2015 and May 2025 using the predetermined keywords. These articles were retrieved and stored in reference management software for further screening.

Screening: Titles and abstracts of the identified articles were screened to eliminate unrelated studies and duplicate records. 26 articles not relevant to CRM supply chain risks, sustainability, or technological innovations were excluded at this point, leaving 100 articles for further evaluation.

Eligibility: The remaining articles were assessed in full text to ensure compliance with the inclusion criteria. Studies that did not align with the review scope were excluded, resulting in the removal of 21 articles and leaving 79 studies for detailed analysis.

Inclusion: Finally, the 91 shortlisted studies were evaluated for quality and relevance. Out of these, 53 were excluded due to relevance and methodological issues and 26 peer-reviewed articles published between 2015 and 2025 were selected as the final set for the systematic review, based on their strong focus on CRM sourcing, sustainability practices, and technological advancements in U.S. supply chains

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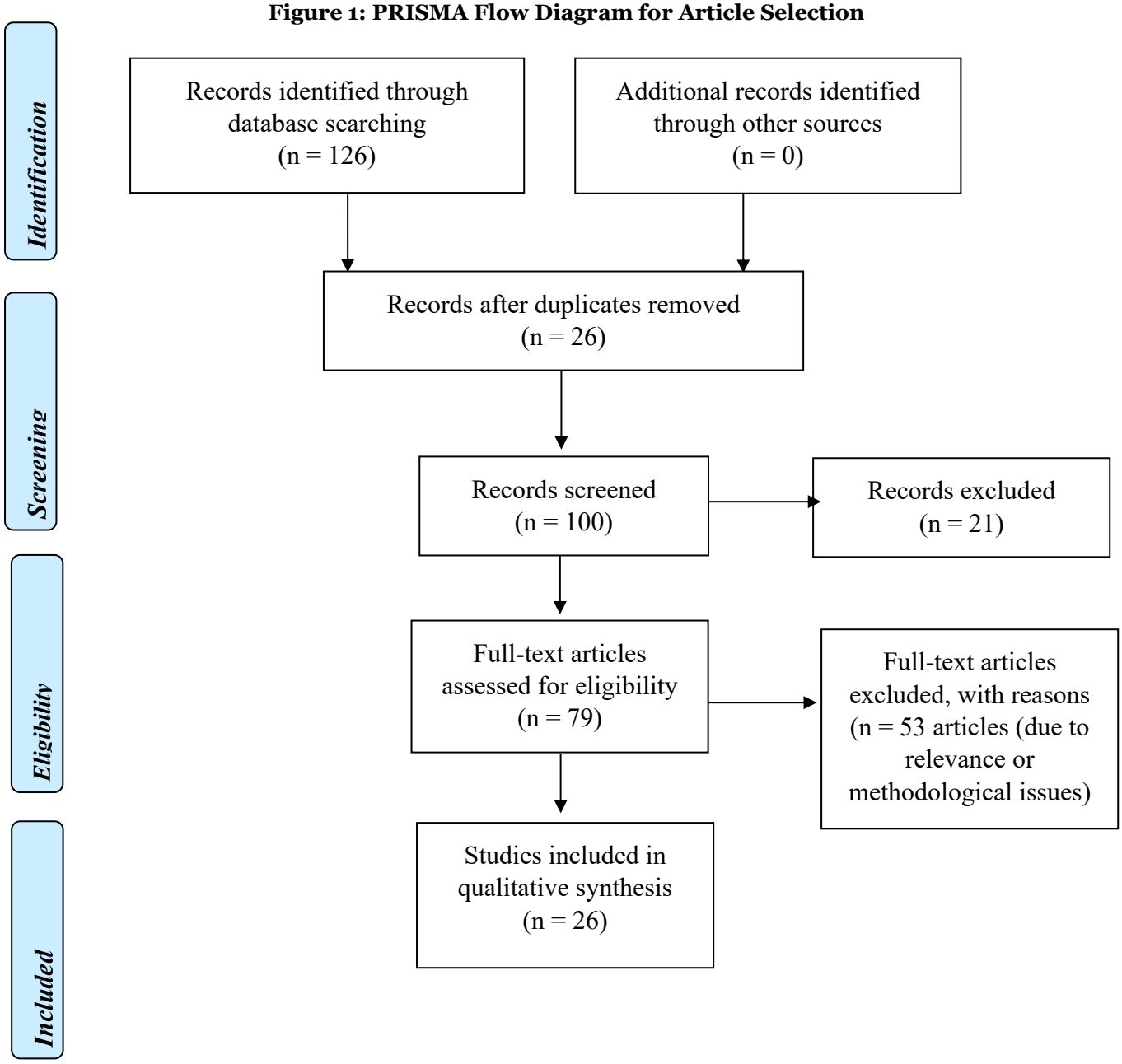
Figure 1: PRISMA Flow Diagram for Article Selection



2.4. Quality Assessment

To guarantee the validity and reliability of the evidence found, the quality of each of the selected studies was evaluated with the help of the Critical Appraisal Skills Programme (CASP) checklist (Appendix 1). The checklist assesses the rigor and quality of the research on the basis of, among others criteria, are:

- The clarity of the research question.
- The appropriateness of the study design.
- The methods of data collection and analysis.
- The reliability and validity of the findings.

Each study was rated on a scale from 1 (poor quality) to 5 (high quality), and those that scored below 3 were excluded from the review.

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2.5. Synthesis of Results

After the extraction of data and the evaluation of the qualities of the studies, narrative synthesis was made to capture the results. These were summarised as three broad themes according to the aim of the review as a result:

- **Supply Chain Risks and Challenges**: This theme includes the geopolitical, economic, and environmental risks identified in the literature.
- **Technological Innovations for Supply Chain Resilience**: The role of AI, blockchain, and Industry 4.0 technologies in enhancing CRM supply chain resilience.
- **Sustainability Practices in CRM Sourcing**: Sustainability practices and strategies to mitigate the environmental and ethical challenges in CRM sourcing.

Narrative synthesis method was employed to determine trends in the studies such as the points of convergence and discordance. As an illustration, most of the studies emphasised the power of ethical sourcing and technological amazement but did not provide consistent outcomes regarding the success of particular sustainability activities, which included recycling or modern circular economy designs.

3. Results

3.1. Descriptive Analysis

3.1.1. Type of Articles

The 26 articles that were identified to be used in this systematic review consist of a combination of various types of articles with research articles, review articles, and case studies as the most common type of articles. All these articles are really varied in terms of the methods used in research such as empirical studies, theoretical studies and studies on literature reviews.

Table 3: Type of Articles

Article Type	Number of Articles
Empirical Studies	12
Review Articles	5
Case Studies	9

Examples of empirical studies involve those that gather and analyse first hand data (e.g. surveys, interviews, experiments). Review papers are overviews and critique of other research, and case studies can delve into a particular CRM supply chain or industry as a whole.

3.1.2. Number of Articles Published by Year

Articles considered were written within the span of five years between 2015 and 2025. The number of publications has been reported to have been steadily rising over the past few years, which is evidence of the increasing focus on such practices as sustainable sourcing and CRM supply chains.

Table 4: Number of Articles Published by Year

Year	Number of Studies
2015	1
2016	2
2017	1
2018	1
2019	1
2020	1
2021	2
2022	2
2023	4
2024	7

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Year	Number of Studies
2025	4

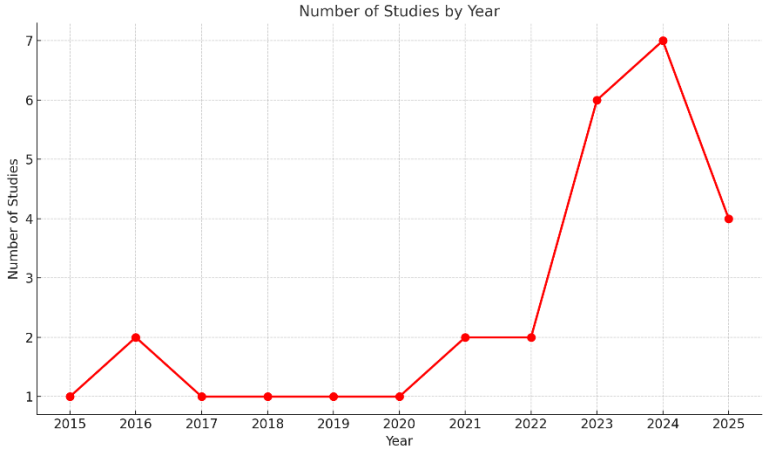

Figure 1: Number of Articles Published by Year

The above figure and table show that the growth in the number of publications began showing much gain after 2021, which shows the growing need to move towards clean energy and the significance of sustainable sources of CRM in regard to geopolitical tensions and future ecological challenges.

3.1.3. Distribution of Papers by Topic

The perspective articles were divided into a number of major issues, which cover some peculiarities of sustainable CRM sourcing and dilemmas it is connected with. The topic-based distribution displays the main areas of focus of the literature in the field.

Table 5: Distribution of Papers by Topic

Topic	Number of Articles
Supply Chain Risks and Challenges	9
Technological Innovations in CRM Sourcing	7
Sustainability Practices and Ethical Sourcing	7
Geopolitical and Economic Factors	3

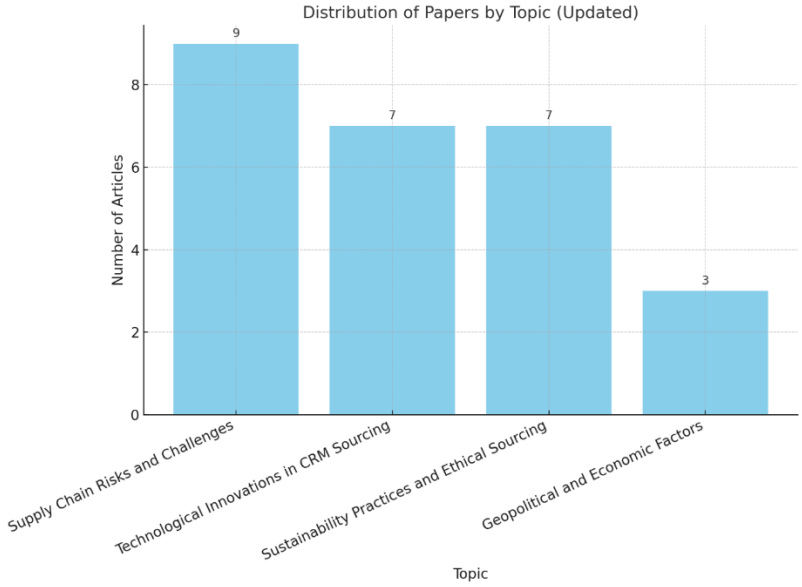

Figure 2: Distribution of Papers by Topic:

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The above figure and table show that almost all of the articles are related to finding and discussing the supply chain risks and difficulties in CRM, whereas comparatively minor yet important part of literature and study is about the technological developments and sustainable initiatives. Geopolitical and economic reasons are also addressed however they are more likely to be presented in a smaller assortment of articles.

3.1.4. Distribution of Papers by Journals and Impact Factor

The journals in which the 20 selected articles were published vary; there were high-impact journals in the areas of supply chain management, sustainability, energy, and materials sciences. The table below contains a breakdown of the journals on which the chosen articles were published and the impact factors.

Table 6: Distribution of Papers by Journals and Impact Factor

Journal	Number of Articles	Impact Factor (Approx.)
Resources Policy	4	3.1
Nature Communications	3	14.9
Frontiers in Energy Research	2	5.4
Joule	2	28.8
ACS Energy Letters	2	17.2
Production Planning & Control	2	3.5
Sustainability	1	3.3
World Journal of Advanced Research and Reviews	1	1.1
Futures	1	4.1
Materials	1	3.6
International Journal of Engineering, Technology, Research and Management	1	N/A
Environmental Science and Technology	1	11.5
PLoS One	1	3.7
UNU-MERIT Working Papers	1	N/A
Environmental Quality Management	1	N/A
PNAS (Proceedings of the National Academy of Sciences)	1	12.3
Resources, Conservation and Recycling	1	13.2

A number of articles cited in the review are of high-impact journals (Nature Communications, Joule, and ACS Energy Letters), which proves that the topic is highly applicable in the realms of sustainability, energy and material sciences. The mean impact factor of the journals in which the studies were published is about 7.8 that represents the quality and influence of articles involved in this systematic review.

3.2. Content Analysis

The researches highlight different risks that affect CRM supply chain though they mainly focus on geopolitical, economic and environmental risks.

Table 7: Emergence of themes

Theme	References
1. Geopolitical Risks	Vivoda et al. (2025), Girtan et al. (2021), Leonelli (2023), Ku et al. (2024)

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Theme	References
2. Economic Risks	Sun (2022), Woodley et al. (2024), Girtan et al. (2021), Arief et al. (2025)
3. Environmental Risks	Vivoda et al. (2025), Girtan et al. (2021), Leonelli (2023), Barteková and Kemp (2016)
4. Technological Innovations (AI & Predictive Analytics)	Sun (2022), Mc Loughlin et al. (2023), Štreimikienė et al. (2025), Igogo (2022**),** Schneider-Petsinger (2021)
5. Blockchain for Transparency	Mc Loughlin et al. (2023), Leonelli (2023), Koyamparambath et al. (2025), Kashmanian (2017)
6. Industry 4.0 Technologies (IoT, Cloud Computing)	Štreimikienė et al. (2025), Dixit et al. (2024), Mc Loughlin et al. (2023), Springer et al. (2015), Esan et al. (2024)
7. Circular Economy and Recycling	Dixit et al. (2024), Hariyani et al. (2024), Woodley et al. (2024), O'Connor et al. (2016), Hasan et al. (2024)
8. Ethical Sourcing	Koyamparambath et al. (2025), Vivoda et al. (2025), Mc Loughlin et al. (2023), Thorlakson et al. (2018)
9. Sustainable Mining Practices	Vivoda et al. (2025), Girtan et al. (2021), Leonelli (2023), Pikuleva (2023)
10. Policy and Governance	Vivoda et al. (2025), Dou et al. (2023), Leonelli (2023), Odumbo et al. (2024)
11. Diversification and Supply Stability	Vivoda et al. (2025), Girtan et al. (2021), Woodley et al. (2024)
12. Price Volatility and Supply Shortages	Sun (2022), Woodley et al. (2024), Girtan et al. (2021), Van den Brink et al. (2019)

3.2.1. Supply Chain Risks and Challenges

3.2.1.1. Geopolitical Risks

The vulnerability to oil and other vital raw materials disruption that come about due to reliance on foreign sources and especially those sourced in politically sensitive areas is a major menace to the U.S. Vivoda et al. (2025) indicate that relying on rare earth elements and other CRMs in countries such as China and Russia constitutes a dangerous geopolitical threat to the U.S. economic and national security. On the same note, Girtan et al. (2021) note that China having a monopoly of the rare earth market poses a risk of disrupting supply, especially with the increased demand in CRMs adoption in clean energy technology.

3.2.1.2. Economic Risks

The unpredictability of the prices of CRM linked to market speculation, market imbalances of supply and demand, and geopolitical tensions makes long-term prediction difficult (Springer et al., 2015). Sun (2022) and Arief et al. (2025) also talks about the price volatility of certain materials like lithium and nickel, whose sharp increase in prices might cause uncertainty among the companies reliant on these raw materials. The pressure on CRM supply chains caused by the rising popularity of the electric vehicles (EVs) and renewable energy sources technologies is also described by Woodley et al. (2024), who actually state that it may result in the lack of some supply and the necessity of the rise in its price.

3.2.1.3. Environmental Risks

The activities of mining, particularly those in war agonised regions, are large-scale in the degradation of the environment (Barteková & Kemp, 2016; Odumbo et al., 2024). According to Vivoda et al. (2025) and Girtan et al. (2021), it is environmental hazardous to mine in such regions as the DRC because, in most cases, water became polluted, soil contaminated, and deforestation occurs. Leonelli

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(2023) argues that the influence of these impacts on the environment does not just exploit the local communities but they have more wide-reaching implications in terms of sustainability within the entire global supply chain.

3.2.2. CRM Sourcing Technological Innovations

Technological fixes are becoming relevant as a way of aiding in the alleviation of CRM supply chain problems. The reviewed studies include valuable information regarding the role of the Industry 4.0 technologies, AI, blockchain, and recycling technologies in making a supply chain more resilient.

3.2.2.1. Predictive Analytics and AI

According to Sun (2022) and Mc Loughlin et al. (2023), AI can augment the CRM supply chain resilience as it enables real-time analytics of data and forecasting. AI will assist businesses in anticipating interruptions, improving supply chain paths, and resource distribution. Machine learning can train companies by examining the data of the past to predict future failure or price changes hence making better decisions towards risk management.

3.2.2.2. Transparency in Blockchain

According to Mc Loughlin et al. (2023) and Leonelli (2023), the role of blockchain technology is becoming ever more important in terms of providing traceability and transparency of materials. Blockchain would allow the companies to trace the source of materials such as cobalt and lithium so that this process would be done through ethical and eco-friendly means. According to Koyamparambath et al. (2025) and Kashmanian (2017), the use of blockchain can be especially effective in preventing the origin of conflict minerals and compliance with the international sustainability practices.

3.2.2.3. Industry 4.0 Technologies (IoT, Cloud Computing)

The combination of the use of IoT, cloud computing, and smart sensors is regarded as a game changer of CRM supply chains (Ku et al., 2024; Štreimikienė et al., 2025). As stated by de Stremikiene et al. (2025), such technologies would allow real-time monitoring of the materials supply chain, enhance logistics, decrease wastage, and overall efficiency. Dixit et al. (2024) and Esan et al. (2024) point out, as well, that supply chains can be sustainable in terms of CRM, where Industry 4.0 technologies may be used to control and maintain optimal material flows, thus improving sourcing.

3.2.2.4. Recycling and Circular Economy

According to Dixit et al. (2024) and Hariyani et al. (2024), recycling technologies play a very important role in the provision of a sustainable supply of CRMs. Companies that recycle batteries and engage in other secondary material recycling will minimise the usage of the primary raw materials and, consequently, mitigate the pressure on the supply chains and abate environmental damage (Thorlakson et al., 2018; Hasan et al., 2024). Another point that Woodley et al. (2024) emphasise is that the development of recycling technologies should allow decreasing the necessity in new mining operations to follow the circular economy strategy.

3.2.3. Green and Ethical Sourcing

One of the main themes in most of the studies is sustainability of CRM sourcing, more particularly on ethical sourcing, ecologically healthy mining and recycling.

3.2.3.1. Ethical Sourcing

Sourcing CRMs in a responsible manner, notably in conflict-free areas, is an important part of sustainable sourcing (Van den Brink et al., 2019). Koyamparambath et al. (2025) and Vivoda et al. (2025) emphasise the role of utilising conflict-free sourcing certification programs such as the INFORM Risk Index that assists businesses to identify regions with low-risk sourcing. This system resists materials that are associated with human rights violation or environmental wastage. Mc Loughlin et al. (2023) opine that there is a possibility of using blockchain technology with ethical sourcing methods that can help in tracking the origin of materials like cobalt and lithium to provide more visibility and responsibility in the supply chain.

3.2.3.2. Sustainable Mining Practices

Some of the research lays great focus on ensuring that the environmental footprint of mining is lowered (Dou et al., 2023). Vivoda et al. (2025) and Leonelli (2023) address sustainable mining technologies related to CRM extraction, i.e., to the low-carbon extraction methods and water-efficient

processes, and how these practices can help to reduce the harmful effect of extraction on the environment. In addition, Girtan et al. (2021) and Pikuleva (2023) demand the introduction of more stringent environmental laws in mining areas to avoid deteriorating the environment and make sure that CRM extraction wins over the framework of sustainable development on earth.

3.2.3.3. Circular Economy and Recycling

The circular economy model where emphasis is made on reusing and recycling of materials is essential in minimising the use of the primary sources of CRMs (O'Connor et al., 2016). According to Dixit et al. (2024) and Treimikiene et al. (2025), the loop in the CRM supply chains might be closed by investing more in recycling technology, particularly regarding batteries of electric vehicles and electronic waste. This will minimise new mining, and alleviate environmental harm, helping to build a more resilient supply chain (Schneider-Petsinger, 2021). Another key message provided by Sun (2022) is that the recovery of secondary materials through technologies must be improved to mitigate risks to the environment and economy of CRM sourcing.

3.2.4. Geopolitics and Economic Reasons

Intersection of the geopolitical and economic factors are vital to CRM sourcing, and increasingly important as these materials are essential to new and emerging technologies such as clean energy and defence (Igogo, 2022).

3.2.4.1. Geopolitical Factors

Vivoda et al. (2025) emphasise that the geopolitical environment is highly influential in the supply of CRM chain and challenged the U.S. over its material supply by relying on China and Russia, e.g., the rare earth elements. Tensions between national security and environmental objectives are also mentioned by Leonelli (2023) as nations in pursuit of dominance in critical materials. With the enlargement of geopolitical instability, i.e., trade war or resource nationalism, the threats to CRM supply chains extend.

3.2.4.2. Economic Factors

When sourcing CRM, the current economy is key in determining the viability of the undertaking due to supply demand factors, pricing and competition. Woodley et al. (2024) and Sun (2022) highlight the fact that the increasing number of customers who have started to use clean energy technologies (in particular, EVs), contributes to the rising prices of critical materials that becomes a challenge of economic risks. These fluctuations impact on industries depending on these materials and makes it hard to provide stable long term supply contract to firms. Girtan et al. (2021) claim that the instability of material prices also demands new approaches to stabilise the sustainability of critical material supply, including the stockpiling technique or alternative sourcing.

4. Discussion and Limitation

The present systematic review singles out the main risks and issues of CRM supply chains in the U.S. Geopolitical risks prevail, and the U.S. is extremely reliant on other countries, such as China or Russia, to provide it with much-needed materials causing vulnerabilities that may devastate the supply chains. There are also risks on the economic front where prices of materials such as lithium and cobalt are volatile and this complicates long-term planning in the industries (Santillán-Saldivar et al., 2021). Combined with the associated environmental risks posed by the mining of CRM, especially in the politically weak areas, there are some additional ethical concerns about CRM sourcing (Hool et al., 2023). The solution comes in technological innovations especially AI, block chain as well as Industry 4.0 technologies. AI has an ability to predict a disruption of a supply chain, blockchain guarantees transparency and ethical sourcing, and the industry 4.0 technologies contribute to logistics and supply chain management (Iakovou & White, 2020). In addition, sustainable processes, including ethical sourcing, sustainable mining technologies, and recycling, will be critical to minimalising the impact on the environment and long term supply chain resilient.

Its increased reliance on technological innovations to figure out the challenges in the CRM supply chains is significant, since the old practices of sourcing and supply chain management can no longer meet the current environment that is rapidly changing the global environment (Okeagu et al.,

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2021). An example is the blockchain technology that presents an excellent chance in enhancing transparency and responsibility in CRM sourcing. The findings have shown that this is through the ability of blockchain to combat any problematic material purchase such as conflict minerals and unethically sourced labour by means of guaranteeing a traceable and ethical supply source (Woodley et al., 2024). Also, predictive analytics with AI-integrated supply chains CRM can better manage risks, anticipate, and optimise supply chains, thereby making supply chains more resilient to geopolitics and market volatility.

Moreover, although the concept of sustainability is essential in CRM sourcing, it is necessary to admit that the influence of policy and regulatory frameworks is also crucial in terms of establishment of these practices. Researchers, including those conducted by Vivoda et al. (2025), have emphasised the need to have international agreements and national policies of ethical sourcing, environmentally less draining, and promoting the use of cleaner mining technologies. The process of establishing standard yet harmonised regulations regarding CRM extraction and sourcing must be addressed through international cooperation between the policymakers, and the greening of economies must not be achieved through the defenestration of human rights or environment wellbeing. Through these frameworks governments can encourage the industries to practice more sustainable transparent sourcing with the aim of incentivising.

Geopolitical, and environmental risk along with the economic risk between regions are also great obstacles to soundness and sustainability of these supply chains. Nonetheless, the literature is rather universal about the potential of technological innovations, namely AI, blockchain, and Industry 4.0 technologies, which could be viewed as the source of prospects to improve resilience, transparency, and efficiency. Moreover, the environmentally impactful aspects of extracting CRM require sustainable approaches such as ethical sourcing practices, sustainable mining, and recycling technologies, among others to achieve their sustainability in the long term. These, when coupled with effective policy frameworks, are critical in dealing with the risks, and achieving sustainable sourcing of critical raw material.

There are also a number of limitations of this study. First, the review only considered peer-reviewed articles published between 2015 and 2025, which, although ensuring relevance and credibility, may have excluded valuable insights from earlier foundational studies or industry reports. Second, the selection of articles was confined to specific databases, creating the possibility of publication bias and overlooking relevant research published in less accessible sources. Additionally, the reliance on secondary data and narrative synthesis may limit the depth of empirical validation, as the findings depend heavily on how previous researchers designed their studies. Finally, while the review highlights key themes such as technological innovations, sustainability practices, and geopolitical risks, it does not quantitatively assess the effectiveness of these strategies, leaving scope for future empirical research to provide stronger evidence of causal relationships

5. Conclusion

The review points out that there were big geopolitical, economic and environmental issues within the CRM supply chains. Nevertheless, AI, blockchain, and Industry 4.0, as well as the sustainability win of recycling and ethical sourcing, are the promising strategies to overcome these challenges. To have a stable and sustainable supply of CRM the ratio between managing the risks and enhancing sustainability of sourcing practices should be established. In the future, the focus of the research should be understood as a need to incorporate the advanced technologies into CRM supply chains, enhance policy frameworks supporting ethical sourcing, and develop recycling technology in order to be less dependent on primary raw materials. Governments, industries, and international organisations will work together in ensuring that critical raw materials are available in a sustainable manner to meet the future demands.

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7. Appendix 1: CASP Table for assessing studies' quality

Study	Clear Research Question	Appropriate Study Design	Research Methods Clear	Sampling Method Clear	Data Collection Appropriateness	Data Analysis Validity	Ethical Considerations	Results Relevant & Reliable	Conclusions Supported by Results	Overall Quality Rating (1-5)
Koyamparambath et al. (2025)	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	5
Vivoda et al. (2025)	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	5
Woodley et al. (2024)	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	5
Sun (2022)	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	5
Arief et al. (2025)	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	5
Dixit et al. (2024)	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	5
Dyatkin (2020)	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	5
Hasan et al. (2024)	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	5
Esan et al. (2024)	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	5
Štreimikienė et al. (2025)	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	5
Dou et al. (2023)	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	5
Pikuleva (2023)	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	5
Ku et al. (2024)	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	5
Leonelli (2023)	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	5
Mc Loughlin et al. (2023)	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	5
Hariyani et al. (2024)	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	5
Schneider-Petsinger (2021)	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	5
Girtan et al. (2021)	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	5

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Study	Clear Research Question	Appropriate Study Design	Research Methods Clear	Sampling Method Clear	Data Collection Appropriateness	Data Analysis Validity	Ethical Considerations	Results Relevant & Reliable	Conclusions Supported by Results	Overall Quality Rating (1-5)
Igogo (2022)	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	5
Odumbo et al. (2024)	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	5
Springer et al. (2015)	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	5
Thorlakson et al. (2018)	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	5
Van den Brink et al. (2019)	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	5
O'Connor et al. (2016)	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	5
Barteková and Kemp (2016)	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	5
Kashmanian (2017)	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	5

8. Appendix 2: Systematic Review Table

Study	Aim	Method	Findings	Limitations	Implications
Koyamparambath et al. (2025)	To assess conflict risks in CRM supply chains using the INFORM risk index.	Risk analysis using the INFORM index to assess conflict zones.	Identified key conflict zones for cobalt and lithium sourcing, highlighting risks of supply chain disruption.	Focused mainly on conflict regions; limited coverage of other geopolitical risks.	Enhances ethical sourcing practices and supports conflict-free certifications.
Vivoda et al. (2025)	To evaluate the geopolitical risks and U.S. dependence on foreign CRMs.	Literature review and analysis of geopolitical risks.	Geopolitical risks are high due to U.S. dependence on China and Russia for critical materials.	Limited empirical data; mainly theoretical analysis.	Calls for diversification of CRM supply sources and increased domestic sourcing capabilities.
Woodley et al. (2024)	To analyze the impact of CRM supply chain bottlenecks on electric vehicle deployment.	Empirical analysis of supply chain bottlenecks.	Shortages of cobalt and graphite may hinder EV production; urgent need	Focused primarily on the EV industry, ignoring other sectors reliant on CRMs.	Highlights the need for investment in recycling and alternative material

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Study	Aim	Method	Findings	Limitations	Implications
			for alternative sources.		sources for EV production.
Sun (2022)	To assess the economic risks and volatility in CRM prices.	Quantitative analysis of CRM price trends and economic factors.	Identified high volatility in the prices of lithium and nickel, making long-term planning difficult.	Economic models may not capture all market dynamics, especially external factors.	Suggests hedging, stockpiling, and price forecasting to mitigate economic volatility.
Arief et al. (2025)	To develop a model for managing geological uncertainty in CRM supply chains.	POMDP (Partially Observable Markov Decision Process) model.	Proposed model optimizes sourcing decisions under geological uncertainty for U.S. lithium resources.	The model may be too complex for practical implementation without further development.	Provides a framework for decision-making under uncertainty, especially in lithium sourcing.
Dixit et al. (2024)	To explore the impact of recycling technologies on CRM supply chains.	Case study and literature review on recycling technologies.	Recycling and secondary material recovery technologies can reduce reliance on primary material extraction.	Limited case studies focused only on battery recycling.	Promotes investment in battery recycling technologies for sustainable CRM sourcing.
Dyatkin (2020)	To explore the need for US policies that can enhance supply chain resilience in the wake of disruptions caused by the COVID-19 pandemic..	Literature review and policy analysis focusing on the impact of COVID-19 on supply chains, particularly in the context of resilience strategies.	The study highlights the vulnerabilities exposed in US supply chains during the COVID-19 pandemic. It emphasizes the necessity of government interventions to ensure long-term supply chain resilience, such as strategic stockpiling, diversification of supply sources, and investment in technological advancements.	The study mainly discusses theoretical frameworks and policy recommendations without extensive empirical data or case studies to support the proposed strategies	The findings suggest the need for immediate policy reforms to increase supply chain robustness and reduce dependence on vulnerable sources, recommending broader international cooperation and long-term strategic planning for future disruptions.

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Study	Aim	Method	Findings	Limitations	Implications
Hasan et al. (2024)	To review sustainable practices in composite material supply chains.	Systematic literature review.	Sustainable materials such as green composites play a significant role in reducing environmental impact.	Limited focus on CRM-specific applications; more general to composites.	Suggests the integration of green materials into CRM supply chains to enhance sustainability.
Esan et al. (2024)	To investigate strategies for integrating sustainability into CRM supply chains.	Qualitative analysis of expert interviews and case studies.	Supply chain traceability and sustainable inventory management are critical to improving CRM sourcing.	Focused on operational strategies without addressing technological barriers.	Highlights the need for transparency and better traceability in CRM supply chains.
Štreimikienė et al. (2025)	To evaluate the integration of Industry 4.0 technologies in sustainable supply chains.	Multi-criteria decision-making (MCDM) model and expert interviews.	IoT, AI, and cloud computing technologies can significantly enhance CRM supply chain efficiency and sustainability.	Limited empirical evidence on the direct application of these technologies in CRM supply chains.	Promotes the adoption of Industry 4.0 technologies in CRM supply chains for better efficiency and sustainability.
Dou et al. (2023)	To assess the governance challenges in critical mineral supply chains.	Literature review on supply chain governance and policy analysis.	Governance structures and policies are essential for managing the risks in CRM supply chains.	Limited empirical research on governance practices; theoretical focus.	Calls for stronger governance policies to ensure ethical and sustainable CRM sourcing.
Pikuleva (2023)	To explore sustainability in multi-tier supply chains in the context of CRM sourcing.	Case study and content analysis.	Multi-tier supply chains face challenges in achieving transparency and sustainability in CRM sourcing.	Case study focused on one industry; limited generalizability.	Suggests improving visibility and accountability in multi-tier CRM supply chains.
Ku et al. (2024)	To address the grand challenges in CRM supply risks.	Qualitative analysis based on case studies and expert opinions.	Identified three grand challenges: improving visibility, quantifying market risks, and developing policy tools.	Limited scope; challenges focused primarily on visibility and risk management.	Proposes future research on policy tools and market risk assessment in CRM supply chains.

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Study	Aim	Method	Findings	Limitations	Implications
Leonelli (2023)	To examine the intersection of critical raw materials and the net-zero transition.	Policy analysis and case study.	Securitization of CRM trade undermines environmental goals; need for policy balance between security and sustainability.	Focused on policy aspects with limited focus on practical CRM sourcing practices.	Calls for policy reform to balance national security concerns with environmental goals.
Mc Loughlin et al. (2023)	To evaluate business process management for sustainable supply chains.	Literature review and case studies.	Sustainability in supply chains requires reappraisal of business processes to align with environmental goals.	Case studies were not focused specifically on CRM supply chains.	Recommends integrating sustainability into business process management for CRM sourcing.
Hariyani et al. (2024)	To review green supply chain management practices for sustainable sourcing.	Literature review.	Green supply chain practices can significantly reduce the environmental impact of CRM sourcing.	Limited focus on specific CRMs; general review of green supply chain management.	Suggests adopting green supply chain practices to enhance CRM sourcing sustainability.
Schneider-Petsinger (2021)	To explore strategies for resilient U.S. and European supply chains.	Case study and policy analysis.	Resilient supply chains require diversified sourcing, enhanced transparency, and collaborative policies.	Case study was broad and not CRM-specific.	Highlights the need for collaborative international strategies to enhance CRM supply chain resilience.
Girtan et al. (2021)	To address the scarcity, supply risk, and unique properties of critical raw materials.	Literature review.	Scarcity of CRMs is driven by increased demand in clean energy and technology sectors.	Focused on scarcity without addressing potential solutions for diversification.	Emphasizes the need for more sustainable and diversified CRM sourcing strategies.
Igogo (2022)	To assess the U.S. strategy for securing a robust clean energy supply chain.	Policy analysis.	The U.S. needs to secure a stable supply of critical raw materials for clean energy transition.	Focused more on policy and strategy, not on specific CRM sourcing practices.	Recommends strategic planning and international cooperation to secure CRM supply for clean energy.
Odumbo et al. (2024)	To evaluate pharmaceutical supply chains	Case study analysis.	Reengineering pharmaceutical supply chains can improve	Focused on pharmaceutical supply chains, not CRMs.	Suggests improving equity and access in

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Study	Aim	Method	Findings	Limitations	Implications
	in underserved health regions.		therapeutic equity in underserved regions.		supply chains through reengineering and innovation.
Springer et al. (2015)	To evaluate sustainability gaps in global agricultural raw material sourcing.	Systematic review of global sourcing indicators.	Identified major gaps in impact assessment indicators for sustainable sourcing and highlighted vulnerabilities in global agricultural supply chains.	Focused on agriculture, not directly on minerals or CRMs.	Provides transferable lessons for integrating sustainability indicators into CRM supply chain assessments.
O'Connor et al. (2016)	To propose strategies for material supply chain sustainability in electronics.	Conceptual framework using principles of green engineering and circular economy.	Suggested circular economy practices (reuse, recycling, eco-design) could reduce environmental impact in electronics supply chains.	Framework is theoretical; lacks empirical testing.	Demonstrates how circular economy and engineering strategies can inform sustainable CRM supply chains.
Barteková & Kemp (2016)	To analyze critical raw material strategies across world regions.	Comparative policy review of CRM strategies in EU, US, and Asia.	Found regional differences in CRM governance; EU emphasizes circularity, US focuses on security, Asia prioritizes growth.	Based on policy documents, limited empirical validation.	Useful for benchmarking U.S. CRM policies against other regions to improve resilience and sustainability.
Kashmanian (2017)	To explore how transparency in supply chains enhances sustainability.	Case study and conceptual analysis.	Demonstrated that transparent reporting mechanisms improve accountability and stakeholder trust in supply chains.	Focused on general supply chains, not CRM-specific.	Highlights the importance of transparency mechanisms (traceability, disclosure) for CRM sourcing.
Thorlakson et al. (2018)	To examine companies' contributions to sustainability	Empirical analysis of corporate sustainabilit y practices	Found that companies adopting sustainability frameworks	Focused on corporate-level practices, not sector-specific to CRMs.	Suggests corporate adoption of sustainability frameworks

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Study	Aim	Method	Findings	Limitations	Implications
	through global supply chains.	using survey and supply chain data.	significantly improved supply chain responsibility and reduced risks.		can enhance ethical CRM sourcing.
Van den Brink et al. (2019)	To review responsible sourcing approaches in mineral supply chains.	Literature review and comparative analysis of sourcing frameworks.	Identified best practices in responsible mineral sourcing, such as certification schemes and multi-stakeholder initiatives.	Emphasis on Europe; limited U.S.-specific evidence.	Provides concrete responsible sourcing strategies applicable to CRM supply chains in the U.S. context.