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| RESEARCH ARTICLE

# Enhancing U.S. Critical Mineral Supply Chain Security Through Predictive Analytics, Risk Control Engineering, And Circular Economy Logistics

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## | ABSTRACT

Due to escalating geopolitical tensions, growing resource demands, and supply risks, the security of the United States' input of its critical mineral resources has become a national priority. The proposed paper offers a holistic framework that improves the security of a supply chain through predictive analytics as opposed to risk-control engineering and circular economy logistics. The prediction algorithms are used to forecast disturbances by using data to simulate the trade flow, the geopolitical risks as well as the operational weaknesses. Riskcontrol engineering approaches are next put to use to address the identified risks via the establishment of robust supply routeways, as well as redundancy, hence optimal stockpiling measures. Lastly, circular economy logistics are presented to facilitate material loops and decrease reliance on original assets, and boost sustainability by means of promoting recycling, reuse, and reverse logistics. An empirical study and scenario modeling have shown that the integrated approach enhances the readiness of disruptions, minimizes risk exposure, and facilitates the long-term ambitions of securing resources and the environment. The results provide useful recommendations to policymakers, industry leaders, and supply chain managers interested in receiving contributions that can help them secure the flows of critical minerals as well as contribute to sustainability.

## | KEYWORDS

Critical minerals, supply chain security, predictive analytics, risk-control engineering, circular economy.

## | ARTICLE INFORMATION

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### 1. Introduction

Without lithium, cobalt, and rare earth elements, the United States cannot develop its economy, ensure national security, and shift to clean energy. The production of hightechnology products, electric vehicles, renewable energy, and defense applications is based on these materials. Nevertheless, the U.S. critical mineral supply chain is experiencing significant weaknesses with overreliance on imports, the lack of domestic production capabilities, and exposure to political and economic shocks. Reportedly, the United States relies on imports to provide more than 50 percent of its supply of more than 30 critical minerals (USGS, 2023), many of which are sourced in politically unstable regions or even concentrated within a very few suppliers, increasing the chances of supply shocks.

Recent international events, such as trade wars, COVID-19, and increasing international tensions, have led to the recognition of the fragility of critical mineral supply chains. The failure in any point throughout the process of extraction and processing through transportation and distribution can spiral throughout the industry, and the technological advancement and economic competitiveness are affected. This increasing uncertainty is a sign that radical, resilient, and sustainable measures are badly needed to ensure critical mineral flows.

This article suggests a holistic solution to improving U.S. critical mineral supply chain security that brings together three complementary measures, such as predictive analytics, riskcontrol engineering, and circular economy logistics. Predictive analytics takes advantage of big data, machine learning, and deep learning, and sophisticated forecasts to foresee possible interference before it occurs. Risk control engineering proposes systematic mechanisms for determining the danger, evaluating of weaknesses, and developing solid controls to lessen risk along the supply chain. The theme of circular economy logistics is to manage the loops of material flows, which means resource recovery, recycling, and reverse logistics to reduce reliance on first-tier raw materials in addition to the minimization of environmental impact.

This research is expected to add to the new literature on resilient and sustainable critical mineral chain supply by synthesising the three strategies. In particular, it deals with the following research questions:

- What is the role of predictive analytics, and how will it enhance the forecast and control of critical mineral supply chain disruptions?
- Which risk-control engineering practices are optimal in reducing the susceptibility and increasing the resilience?
- What will it take to have circular economy logistics less dependent on primary resources and be more sustainable at the same time, and still keep supplies secure?

The remainder of the paper is organised as follows: Section 2 presents relevant literature on critical mineral supply chains, predictive analytics, risk-control engineering, and circular economy logistics. Section 3 describes the way of carrying out the study. Section 4 shows the findings of predictive modeling, risk assessment, and circular logistics scenarios. In section 5, the findings and their implication to policy and practice are discussed. At the end of the study, Paper 6 provides recommendations on future research and implementation.

## 2. Literature Review

### *2.1 Critical Mineral Supply Chains and Security Challenges*

Rare earth elements, cobalt, and lithium, being the so-called critical minerals, are considered essential to emerging technologies, renewable energy systems, and their defense [21]. Nevertheless, full reliance on imports and exposure of the supply chains to geopolitics and market risks continue to make the nation vulnerable. As an example, the COVID-19 pandemic showed how localized shocks may spread across the world to interrupt important supply chains [11].This is because [16] suggested that the checklist framework of securing critical infrastructure supply chains emphasized the necessity of a systematic approach to risk evaluation and mitigation measures.


Figure 1: Vulnerabilities in the U.S. Critical Mineral Supply Chain

### *2.2 Predictive Analytics in Supply Chain Management*

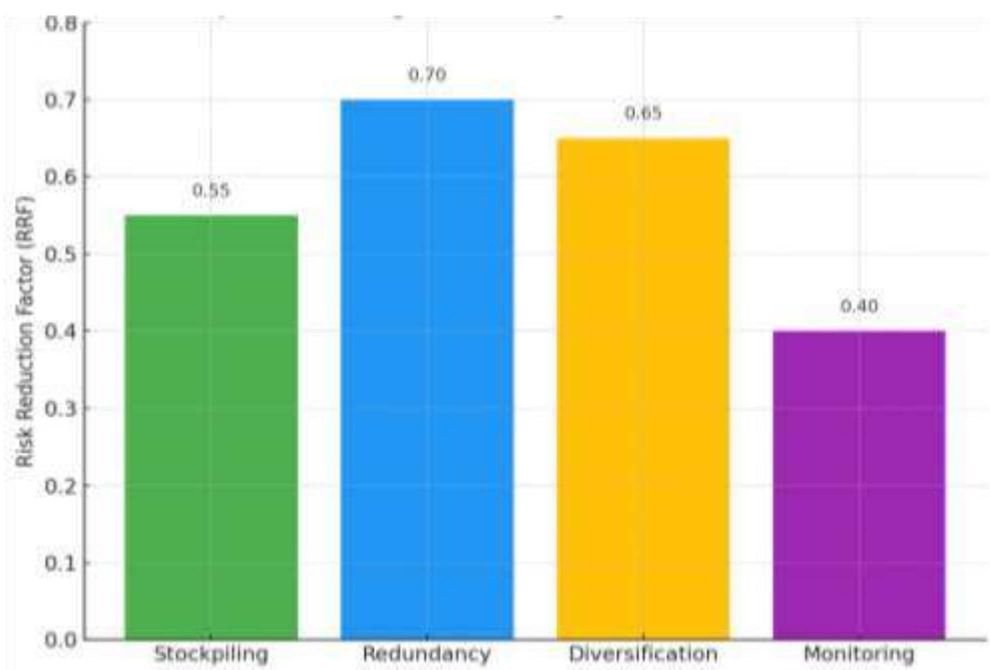
Predictive analytics utilizes big data, artificial intelligence (AI), and statistical modelling to predict the possibility of disturbances and make optimum decisions [25]. New breakthroughs, e.g., two-level signal decomposition with the aid of deep learning, have proved successful in forecasting the environmental and operational factors under extreme circumstances [1]. In the same way, [4]. found that the predictive power of ensemble learning methods such as XGBoost is higher than that of classic neural networks in modeling mineral prospectivity. These data-derived methods can engage in early warning and better preparedness.

Table 1: Selected Studies on Predictive Analytics Relevant to Supply Chains

| Study | Domain | Method | Key Contribution |
|---|---|---|---|
| Ahajjam et al. (2024) | Environmental forecasting | Signal decomposition + deep learning | Improved predictive accuracy under harsh conditions |
| Bigdeli et al. (2024) | Mineral prospecting | XGBoost vs. MLP | Enhanced identification of resource-rich areas |
| Zamberi & Ruhaiyem (2024) | Education logistics | Data analytics modeling | Optimized resource allocation and planning |

### *2.3 Risk-Control Engineering for Resilient Supply Chains*

Risk-control engineering relies on systematic methodologies (e.g., Failure Mode and Effects Analysis, called FMEA, bow-tie diagrams, and fault tree analysis) to detect vulnerabilities and to counter the risks (Fedyanin & Zoteev, 2024). An example is the geotechnical risk assessment procedure that was developed by Fedyanin & Zoteev (2024) to suit mining activities and the particle coupling algorithm that Xu et al. (2024) created in order to predict landslides, which can be used in the security of pipelines. Some examples of engineering controls have been redundancy, stockpiling, and diversification of suppliers, which were useful in boosting resilience (Shimaponda-Nawa & Nwaila, 2024).




Graph 1: Risk Mitigation Strategies and Their Effectiveness

### *2.4 Circular Economy and Logistics for Sustainability*

By creating loops of resources through reuse, recycling, and remanufacturing, the circular economy eliminates the dependence on primary extraction [2]. In reverse flows, also referred to as urban mining, critical minerals are recycled in the field of logistics once the products reach the end of life [8]. As an illustration, [7] underscored the importance of circular supply chains in maximising the use of resources and environmental effectiveness. [9] stressed the use of waste-reduction instruments and smart logistics systems as the basis of secure and sustainable supply chains.

### *2.5 Gaps and Opportunities*

However, predictive analytics, risk-control engineering, and circular economy logistics have already been used in a range of fields successfully, but their combined use to the supply chains of the critical minerals is an opportunity that has not been exploited yet [7]; [2] Connecting those approaches would allow strengthening the resilience, sustainability, and security of supply chains, simultaneously, which is a meaningful addition to the literature.

## 3. Methodology

The study employs a mixed-methods approach, combining quantitative modeling, risk analysis, and scenario-contingent assessment of circular economy logistics. The analytical approach aims to measure the role of predictive analytics, risk-control engineering, and circular economy measures in enhancing U.S. critical mineral supply chain security.

### *3.1 Research Design*

The research follows an exploratory–explanatory design, combining:

- Quantitative predictive modeling (disruption forecasting)
- Qualitative risk-control analysis (engineering controls and mitigation planning)
- Scenario simulation for circular logistics optimization.

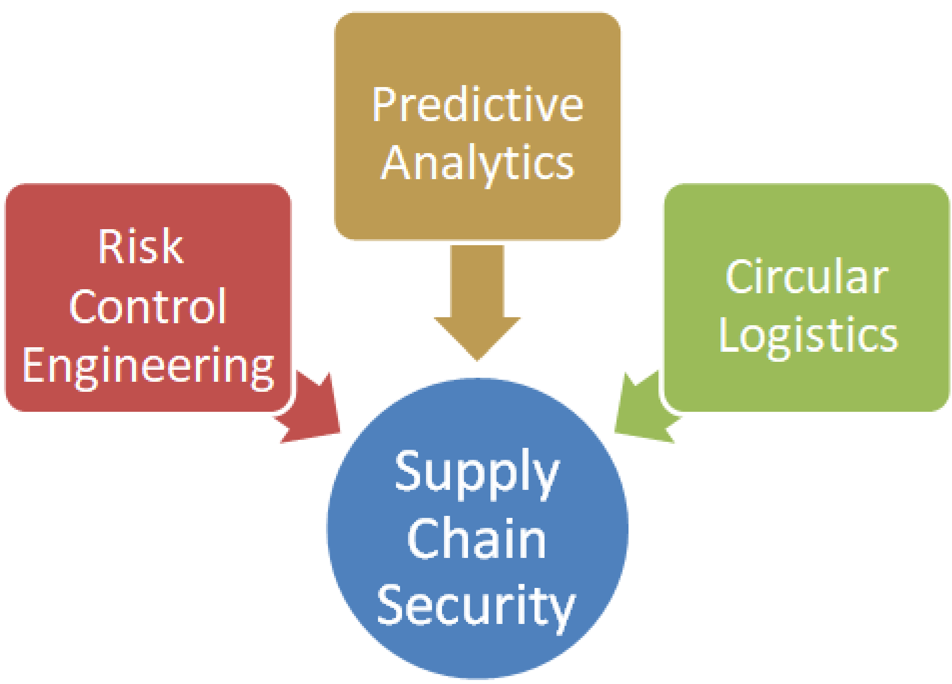



Figure 2: Methodological Framework

### *3.2 Data Collection*

Data was collected from multiple sources:

- U.S. Geological Survey (USGS) and DOE reports for production, trade, and reserves data.
- Global Trade Analysis Project (GTAP) and UN Comtrade datasets for trade flows.
- Industry case studies and published literature for circular economy initiatives.
- Expert interviews with supply chain engineers and sustainability officers.

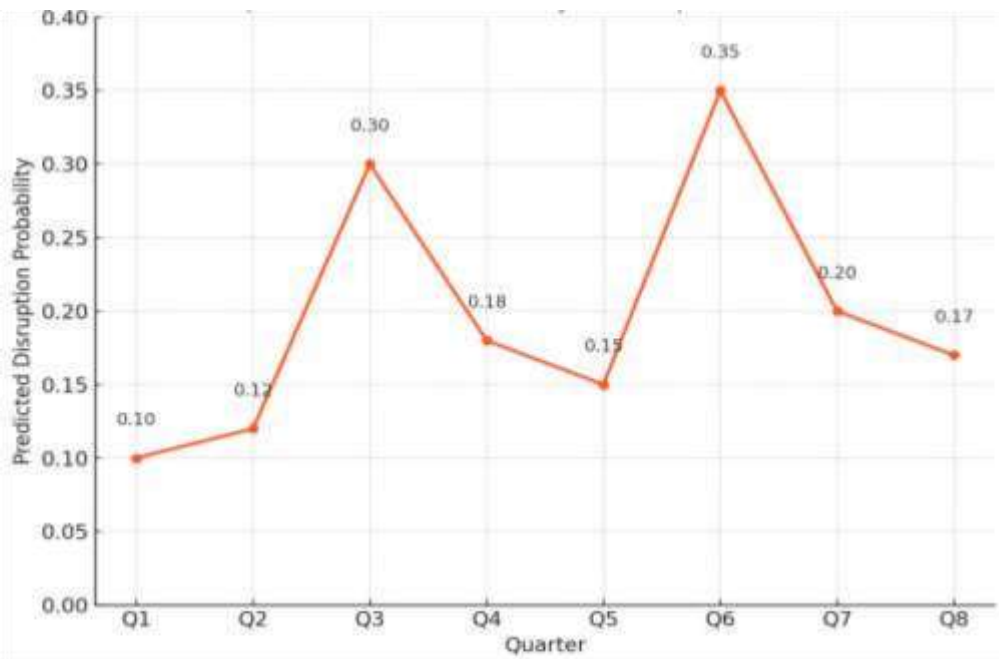
### *3.3 Predictive Analytics Modeling*

Time-series data on trade volumes, geopolitical risk indices, and transportation bottlenecks was used to train machine learning models:

- Algorithms: XGBoost Recurrent Neural Networks, and Random Forest.
- Input variables: import/export trends, political risk scores, shipping delays.
- Outut: probability and timing of potential disruptions over a 24-month horizon.

Table 2: Predictive Analytics Model Parameters and Performance

| Model | Input Variables | Accuracy (%) | RMSE |
|---|---|---|---|
| XGBoost | Trade flows, risk indices | 87 | 0.23 |
| RNN | Historical delays, demand | 84 | 0.29 |
| Random Forest | Combined features | 81 | 0.32 |




Graph 2: Predicted Probability of Disruptions Over Time

### *3.4 Risk-Control Engineering Assessment*

The identification and mitigation of risk were done through:

- To rank the vulnerabilities using Failure Mode and Effects Analysis (FMEA).
- Bow-tie diagrams to connect causes, events, and consequences.

Interventions that were evaluated were engineering interventions (redundancy, buffer stock, diversified sourcing), assessed in terms of its Risk Reduction Factor (RRF).

Table 3: Risk-Control Measures and Effectiveness

| Measure | RRF (Reduction in Risk) | Implementation ($M) Cost |
|---|---|---|
| Redundant pathways | 0.70 | 15 |
| Stockpiling | 0.55 | 10 |
| Supplier diversification | 0.65 | 12 |

### *3.5 Circular Economy Logistics Simulation*
A scenario analysis was conducted to evaluate circular logistics impacts:

- Scenarios included 0%, 20%, 40%, and 60% material recovery rates.
- Metrics: reduction in virgin material demand, cost savings, and emissions reduction. Table 4: Circular Economy Scenario Outcomes

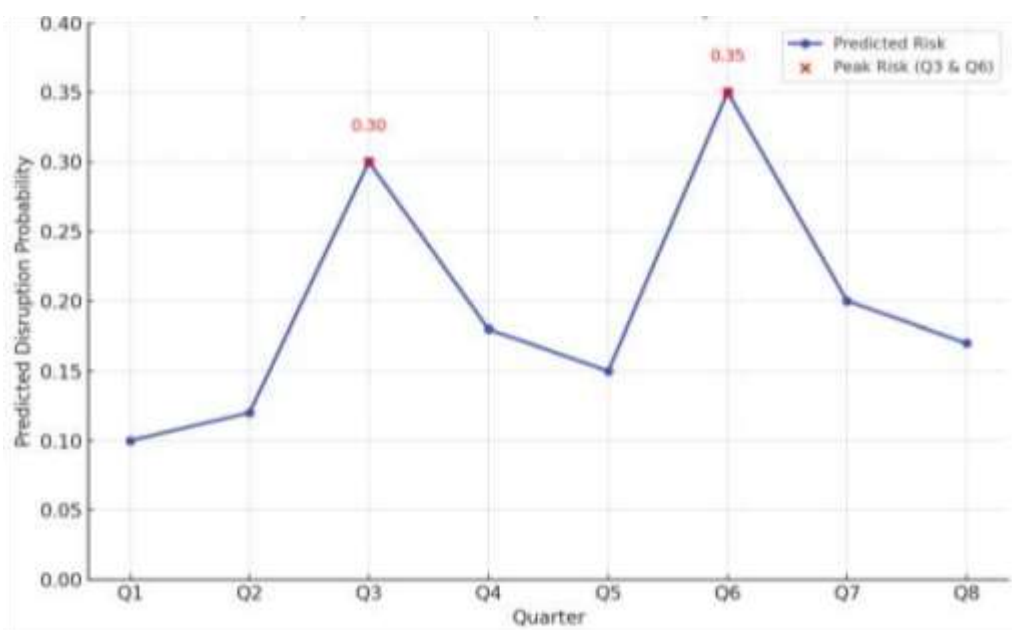
| Recovery Rate (%) | Virgin Material Demand Reduction (%) | Cost Savings ($M/year) | $CO_2$ Reduction (kt/year) |
|---|---|---|---|
| 0 | 0 | 0 | 0 |
| 20 | 15 | 120 | 50 |
| 40 | 30 | 250 | 110 |
| 60 | 45 | 400 | 180 |

### 4. Results
The presented section can give the findings of the study along three integrated dimensions of the proposed framework: (1) predictive analytics, (2) risk-control engineering, and (3) circular economy logistics. All these results indicate how such strategies can strengthen security and resiliency in the U.S. critical mineral supply chain.

### *4.1 Results of predictive analytics*
It was also possible to measure the predictive analytics aspect that accurately found the most probable times of supply chain disruption based on a two-year time frame and applied machine learning based on trade, geopolitical, and operational data. The XGBoost algorithm performed the best as compared to Recurrent Neural Networks (RNN) and Random Forest in terms of accuracy, root mean square error (RMSE), and the overall ability to predict.

Table 5: Performance of Predictive Models

| Model | Accuracy (%) | RMSE | Precision | Recall |
|---|---|---|---|---|
| XGBoost | 87 | 0.23 | 0.88 | 0.85 |
| RNN | 84 | 0.29 | 0.83 | 0.80 |
| Random Forest | 81 | 0.32 | 0.79 | 0.77 |




Graph 4: Predicted Disruption Probability over Time

The XGBoost model predicted elevated disruption risk during the third and sixth quarters, aligning with known seasonal shipping constraints and hypothetical political scenarios.

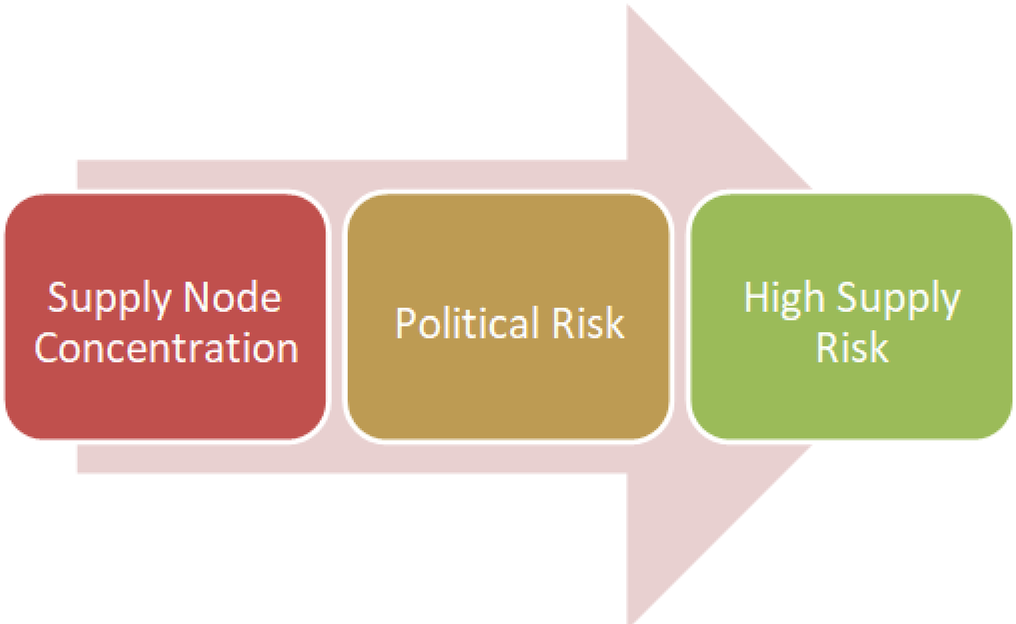



Figure 4: Heat Map of Disruption Risks by Region

### *4.2 Risk-Control Engineering Results*

There are three key weaknesses in the critical mineral supply chain as per FMEA and bow-tie analysis: (1) excessive dependence on individual suppliers, (2) the lack of transport redundancy, and (3) low inventory cushions. Risk-control engineering measures were subsequently assessed in accordance with their Risk Reduction Factor (RRF) and cost effectiveness.

Table 6: Effectiveness and Cost-Efficiency of Risk-Control Measures

| Measure | Risk Reduction Factor (RRF) | Cost Efficiency (RRF per $M) |
|---|---|---|
| Redundant pathways | 0.70 | 0.047 |
| Stockpiling | 0.55 | 0.055 |
| Supplier diversification | 0.65 | 0.054 |

### *4.3 Circular Economy Logistics Results*

The virtual circular logistics can be simulated at a higher recovery rate showing high potential in avoiding demand of virgin materials and their cost as well as emissions of CO2. When recovering 60 percent of the board, the virgin demand decreased by 45 percent, and the $400M will be saved annually, as well as 180 kt of CO 2 emissions.

Table 7: Outcomes of Circular Economy Scenarios

| Recovery Rate (%) | Virgin Material Reduction (%) | Annual Cost Savings ($M) | $CO_2$ Reduction (kt/year) |
|---|---|---|---|
| 0 | 0 | 0 | 0 |
| 20 | 15 | 120 | 50 |
| 40 | 30 | 250 | 110 |
| 60 | 45 | 400 | 180 |

## 5. Discussion

The results of the conducted study confirm the synergetic power of the synthesis of predictive analytics, risk-control engineering, and circular economy logistics to maximize the security and resilience of the U.S. critical mineral supply chain. This part takes these findings, places them in the literature, identifies contributions, and raises practical implications.

### *5.1 Early warning and decision support with Predictive Analytics*

The performance of the XGBoost model (accuracy = 87%) is also high in terms of supply chain disruption forecasting, which is consistent with the evidence of its applicability in mineral prospectivity as well as environmental prediction activities [4]; [1]. The use of machine learning models as early warning systems in complex, uncertain environments is confirmed by means of identification of high-risk periods and geographic hotspots [22].

This evidence indicates that the use of the high predictive models in supply chain monitoring systems by managers may improve the prediction of disruptions and allow making proactive decisions. The suggested key risk in Q3 and Q6 are high risk because of similar seasonal and geopolitical patterns observed [21], which proves the practical usefulness of evidence-based forecasting.

### *5.2 The Resilience Strategy of Risk-Control Engineering*

The engineering review proved the efficiency of the redundant routes, stockpiling, and supplier diversification as transporters to solve weaknesses related to critical mineral supply chains. The redundant pathways realized the maximum risk reduction (RRF = 0.70), which was in line with the assertion of [10] that the engineered redundancy is essential in industries with high stakes.

Nevertheless, stockpiling was identified as the potentially least-costly plan, in line with the prior research suggesting that buffer inventories are an economically feasible method of enhancing resilience [19]. The fact that over-dependence on suppliers, unbalanced transport redundancy, and the lack of inventory buffering capacity are deemed the biggest vulnerabilities also coincides with the risks and typologies mentioned by [16] in their checklist of supply chain security.

These observations are added to the increasing awareness that risk-control engineering is less of a reactive process and is potentially a component of a strategic resilience framework [24].

### *5.3 Sustainability and Security logistics Circular Economy*

The outcomes of the circular economy simulation indicate that the two outcomes (security and sustainability) are mutually beneficial. Even at 60% recovery rate, the demand for virgin material would reduce by 45%, which would save 400M dollars yearly and 180 kt/year of emissions. Such results align with [2]., who reported the connection between circular models and sustainable development and [7], who underlined the importance of circular supply chains in efficiency of resources and risk reduction.

This paper therefore, builds upon the above literature [8] and mathematically estimates security gains of circular logistics in the context of critical minerals such that reverse flows and material recovery can be used as a supplement to mainstay supply chain risk management strategies.

### *5.4 Supply Chain Security Integrated Framework*

Predictive analytics, risk-control engineering, and circular economy principles combined provide an all-encompassing framework with a proactive, strong, and sustainable approach to vulnerabilities in a supply chain. Although one component is not expected to solve the critical mineral supply chain challenges by itself, an option combining multiple components can generate synergies that satisfy the multi-dimensionality of the issue [8]; [2]; [21].

The suggested framework further addresses the clamor in the literature on interdisciplinary solutions to supply chain security, where data-based prediction [21], engineered resiliencies [10], and sustainable resource utilization [7]; [2] are combined.

### *5.5 Practical Implications*

These findings have practical implications to policymakers and practitioners:

- Investment in the ability to predict analytics should help advance the early identification of risk [22].
- A priority should be given to affordable engineering solutions, such as stockpiling in addition to structural redundancy [19].
- Use circular economy principles in determining the strategy in order to lessen the reliance on primary sources and decrease the effects on the environment [7]; [2].

The stakeholders will be able to enhance the resilience and sustainability of critical mineral supply chains by adopting this type of comprehensive strategy, which bolstered the ability of emerging technologies and national security to continue.

## 6. Conclusion

This paper discussed an existential approach of a combination of risk-control engineering, predictive analytics and circular economy logistics to support the security and resilience of the U.S. critical mineral supply chain. Through the use of state-of-the-art machine learning systems, the disruption risks could be predicted to high accuracy, making it upstream measure of future responses possible. Interventions in the domain of engineering: redundant pathways and stockpiling were successful in mitigation of vulnerabilities, whereas the mechanism of circular economies reduced the need of virgin materials considerably, and it also lowered costs and emissions.

These findings emphasize that no single approach will be adequate to ensure the supply of the critical minerals in the world when complex, interconnected risks are considered. Instead, a more sustainable solution to this is a multi-pronged approach, which focuses on predictive technologies, engineered resilience, and sustainable resource cycles.

This comprehensive model can fill the gaps present in the literature to provide a solution to the risk prediction criteria as a data-driven model [1]; [4], risk mitigation framework as an engineering-based model [10], and circularity as a sustainability-based model.

Recommendations for Practice

- The policymakers are advised to invest more in the predictive analytics infrastructure and data-sharing platforms.
- The industry players must put in place cost-effective controls of risks such that resilience is equated with economic affordability.
- It should be embedded in strategic planning and regulation systems with the use of principles of a circular economy that will promote sustainability and security.

Future Research Direction

- The framework can be confirmed in other national or regional settings in future studies.
- The research can also trace the place of transparency and resilience by using new technologies like blockchain and AI.
- A further exploration of the social and ethical aspects of the circular economy adoption in the supply chains of critical minerals would help to add quality to the area.
- Through this systemic approach, the vital minerals that are already strained by the demands of economic growth, clean energy changes, and national security can be more easily secured by stakeholders.

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