

AHP-BASED WEIGHTING APPROACH FOR RISK ASSESSMENT AND PRIORITIZATION IN PAKISTAN'S COAL SUPPLY CHAIN

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Abstract

This study investigates the risks and mitigation strategies associated with Pakistan's coal supply chain, focusing on enhancing its resilience and sustainability. The research uses a mixed-methods approach, combining qualitative and quantitative data collection techniques, such as conducting semi-structured interviews and a structured survey questionnaire, involving 120 stakeholders. Data was analysed quantitatively using SPSS. Ranking and prioritizing of identified risks were done using Analytical Hierarchy Process (AHP) based weighting approach. High priority weighting shows that the quality factors (0.134-0.154) and the time factors (0.104-0.135) are more important. The most important individual risk factors are total moisture (0.154) and lead time (0.135). Furthermore, the study shows that the weak infrastructure, geopolitical instability, regulatory issues, and environmental issues like pollution and carbon emissions are the main concerns in the coal supply chain in Pakistan. Technology improvements, including energy-efficient machines and mining technology, were seen as important contributors to the improvements in the supply chain. The findings of the study corroborate previous studies and bring to the fore issues that are specific to Pakistan including the effect of policy fluctuations and geopolitical tensions in the region. The study highlights the importance of strategic investments in infrastructure, sustainable practices, technological innovation, and collaboration among stakeholders to improve the resilience of the coal supply chain and support the nation's energy security and economic development.

INTRODUCTION

Coal has been a key factor in economic development and is a key source of energy in both developed and developing countries. It is extensively used for generation of electricity and other industrial applications. Pakistan has large coal reserves which can play a significant role in the country's energy sector (Botha & Badenhorst-Weiss, 2019). However, Pakistan has not been able

to make the best use of its coal reserve to meet its energy deficit and dependency on imported fuels (Li et al., 2020).

Availability and relatively low cost of coal are the most common reasons given for the importance of coal in Pakistan. Coal is playing an increasingly significant role in the national energy mix, providing energy for industry and power generation. The coal supply chain, however, has a

number of risks associated with it, ranging from efficiency and reliability, to sustainability. Efficient operation, underdeveloped infrastructure, mismanagement, uncertainties regarding regulations, environmental compliance issues, and technical limitations remain key challenges in the supply chain's functioning. Such problems can lead to operational expenses, delays, and even impacts on coal availability, which in turn can affect the performance of the supply chain (Belov et al., 2020).

Coal supply chain refers to various stages involved in the supply of coal, such as coal extraction, processing, transportation, storage, and distribution. It is important for these stages to be well coordinated so that coal supply can be continuous and the operational efficiency is maintained. However, disruptions that occur at any point in the supply chain can have a downstream impact on activities, and impact the overall reliability of the supply chain. These are also exacerbated by policy misalignments, resource shortages, and infrastructure constraints in developing countries like Pakistan.

Existing literature has considered supply chain risks in various industrial and geographical settings and pointed out the relevance of risk management practices in enhancing supply chain resilience. However, empirical studies on this particular issue of coal supply chain in Pakistan are still limited. Much of the existing research has focused on technical, environmental and/or operational issues, and holistic assessments that include multiple risk dimensions have been limited in scope and from the perspective of key stakeholders. Thus, no specific evidence exists in Pakistan on the relative importance of different risk factors to coal supply chain performance in the country.

This research gap should be addressed to inform decision-making and formulating policy. Thus, this research is focused on identification, evaluation and prioritization of the major risks of coal supply chain in Pakistan through the weightage method of AHP. The research also aims to identify the key drivers of supply chain performance and to identify key areas where strategies can be aligned to improve supply chain

resiliency, sustainability and long term energy security within the sector.

LITERATURE REVIEW

Importance of an energy supply chain for coal is very significant to provide energy security, industrial development, and employment. In developing economies, coal supply chains, however, are often vulnerable to operational, environmental, regulatory and technological issues, which can have a negative impact on their performance. A lack of infrastructure and administrative issues and technical inefficiencies can make supply chains more vulnerable and less resilient.

The coal supply chain involves multiple inter-dependent steps such as mining, processing, transportation, storage and delivery to end-users like power plants, industrial facilities etc. Effective coordination between these stages is key to On-Time, On-Quality, and On-Cost (OTOQOC) supply. The coal supply chain is complex and vulnerable to many risk factors, as it relies on a significant amount of infrastructure, regulatory control and environmental compliance. Therefore, the challenges of logistics management, risk reduction and sustainability are gaining relevance both in academia and industrial practice (Han & Um, 2024; Pooe & Mathu, 2011).

The starting point of the supply chain is the extraction and production from the mining sites. The extraction can be surface mining, where the overlying rocks are removed, e.g. open cast or strip mining, or underground mining. The choice of mining method has a direct impact on production costs, quality of coal, efficiency of the work, the environment and safety of the workers. After the extraction, the coal is usually subjected to a series of processing steps, including crushing, washing, and blending, to enhance its quality and meet the needs of users (He et al., 2020).

Transportation is one of the most important elements in the supply chain of coal. Coal transportation in many countries including Pakistan is mostly by road and rail. The principle of rail transportation is considered to be more efficient, thus preferred for long-haul and high volume transport. Railways, however, do need a

significant amount of investment in infrastructure – in the track, loading and unloading stations and the maintenance operations. Few or inadequate transportation facilities can be a major factor in logistics costs and delivery delay.

The management of supplies and stocks also plays a role in the supply chain performance. The quality of the coal may decline during long storage due to environmental exposure, moisture fluctuation and handling operations. So, the storage facility should be properly designed and equipped with monitoring systems to minimize the wastage, reduce risk of self combustion and maintain the coal quality. Appropriate inventory control practices can reduce uncertainty due to demand fluctuations, reduce holding costs and prevent stockouts (Kamiński et al., 2017).

The modern coal industry is concerned with environmental sustainability. The coal mining, transport and utilization process are responsible for air pollution, water pollution, land degradation and GHG emissions (Gopinathan et al., 2023). The emissions from coal operations can cause considerable impacts on both environmental sustainability and human health (He et al., 2020). Consequently, there has been a growing push by regulatory bodies to have organizations adopt cleaner technologies and meet environmental standards. Limited enforcement and capital investment in pollution control technologies, as is common in emerging economies like Pakistan, can worsen environmental issues.

Technology is an important enabler for making coal supply chains more efficient, safe and resilient. Use of modern mining machinery, automation, digital communication systems, and advanced logistics practices can help minimize risks and maximize productivity in operations. According to Benalcazar et al. (2017) the current mining technology can lead to reduced operational downtime and improved safety performance, which would increase the reliability of the supply chain.

The performance of coal supply chain also can be significantly influenced by the time-related risks. Equipment failures, delays and poor scheduling procedures and maintenance work may affect the continuity of supply and cost of operation. Poor maintenance planning raises the risk of disruption and supply chain vulnerability, Spear (2014) pointed out. Therefore, well-coordinated maintenance management and scheduling are crucial to reducing delays and smooth coal supply. Existing empirical evidence on the resilience strategies of the coal supply chain in Pakistan is limited, though there are studies that have analysed supply chain risks in various industry sectors and sustainability issues. The current research is more on specific problems such as the environmental impact, the mining process or logistic problems. The few comprehensive investigations that exist do not cover a holistic perspective on operational, regulatory, environmental, technological, social, quality related and time-related risks from a stakeholder perspective.

There is a lack of research on this subject in literature that has led to the need for a context specific and structured analysis of risk in the coal supply chain in Pakistan. However, in the present study, an AHP based weighing approach is used to identify, assess and prioritize the factors affecting the coal supply chain performance. The study's inclusion of stakeholder voices and a multi-faceted approach to risk adds to the broader understanding of the threats to Pakistan's coal supply chain, and offers a starting point for effective risk reduction measures.

METHODOLOGY

The methodology adopted in this study is illustrated in Figure 1. The research was designed to identify, evaluate, and prioritize the key risks affecting Pakistan's coal supply chain through a systematic and structured approach.

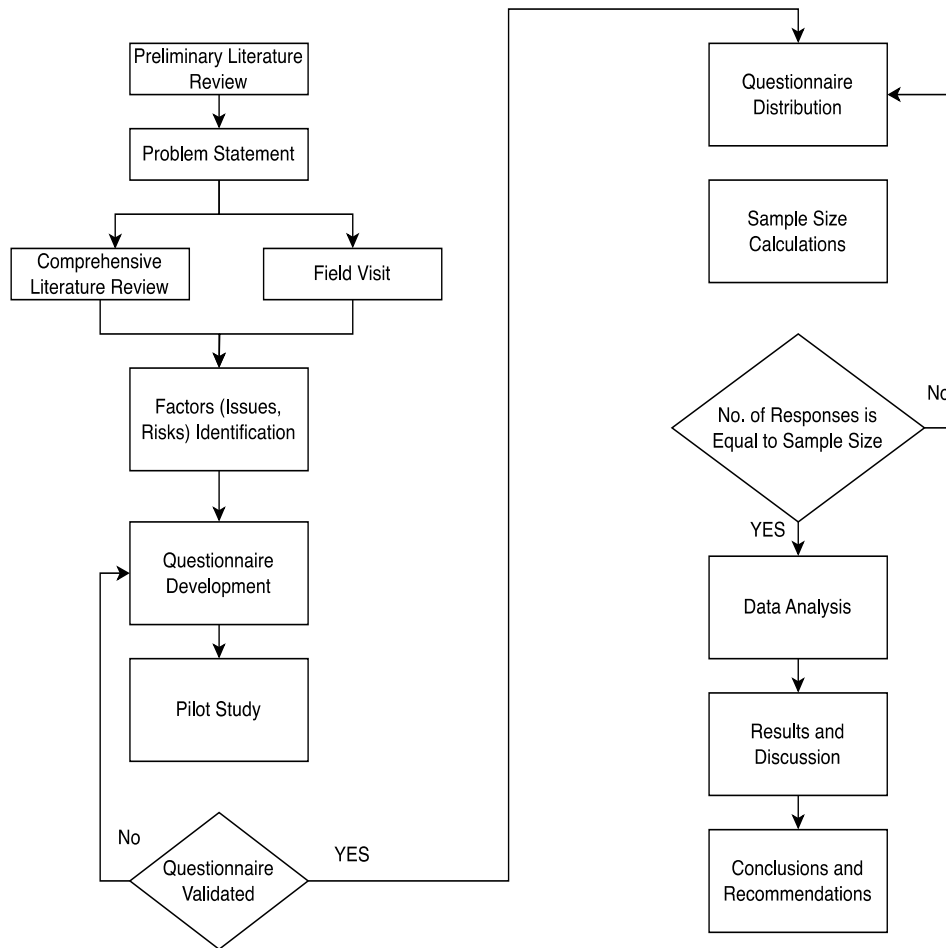


Figure 1. Research Methodology

3.1 Research Design

This study used mixed-methods research design which included both qualitative and quantitative methods. First, an exhaustive literature review was carried out to understand the important factors affecting the performance of the coal supply chain. A few studies, industry reports and policy documents were reviewed to define the research framework and create a preliminary list of risk factors.

A number of field visits have been made and consultations were held with industry practitioners and stakeholders in the coal supply chain to enhance the validity and relevance of the factors identified. The feedback received in these interactions has been taken into account in the

final design of the questionnaire and no duplicate and overlapping factors found.

A finalised questionnaire was then sent to the selected respondents from a variety of stakeholder groups linked to the coal supply chain in Pakistan. Data collected were analyzed with SPSS and an AHP based weighting approach was used to arrive at the relative importance of the risk factors identified.

3.2 Sample Size Determination

The sample size for the study was determined using Slovin's formula, which is commonly applied when the population size is large and the characteristics of the population are not fully known. The formula is expressed as:

$$n = \frac{N}{1 + Ne^2} \quad 1$$

Where:

n = Required sample size

N = Population size

e = Margin of error

For this study, the population was assumed to be infinite and the margin of error was taken as 10% (e = 0.10). Based on Slovin’s formula, the minimum required sample size was calculated to be 100 respondents. To improve the reliability and representativeness of the findings, data were collected from 120 respondents, which exceeded the minimum sample size requirement.

3.3 Selection of Risk Factors

Typically, sustainability evaluations are made with the help of the three bottom lines: economic performance, environmental performance and social performance. This paper, however, broadened this traditional approach by introducing technological, timeliness and quality dimensions given the operational features of coal supply chains.

The factors were selected after a thorough literature search of previous research and industry reports. Table 1 shows the identified categories and references to support them.

Table 1: Literature-Based Identification of Risk Assessment Categories

References	Economic	Environmental	Social	Technology	Time	Quality
Botha & Badenhorst-Weiss (2019)	✓		✓		✓	
Belov et al. (2020)	✓	✓		✓		
Han & Um (2024)	✓	✓		✓	✓	
He et al. (2020)	✓	✓		✓		✓
Gopinathan et al. (2023)		✓	✓			
Pooe & Mathu (2011)	✓		✓		✓	
Benalcazar et al. (2017)				✓	✓	
Kamiński et al. (2017)					✓	✓
Russo & Camanho (2015)	✓			✓		
Spear (2014)				✓	✓	
Li et al. (2020)	✓	✓		✓		
Zhou et al. (2025)	✓			✓	✓	
Present Study	✓	✓	✓	✓	✓	✓

The selected categories were kept due to their relevance to the activities in the coal supply chain, their frequency in the literature and their potential impact on the performance of the supply chain. These dimensions integrate to give a full picture of the risks of Pakistan's coal supply chain.

3.4 Factor Screening & Categorization

A comprehensive literature search was conducted on the topic of risk factors in coal supply chains, sustainability, logistics and risk management. A list of 73 risk related items were generated at first from past studies and industry sources. These

encompassed a wide variety of operational, environmental, technological, economic, quality, social and time aspects related to coal performance in the coal supply chain.

The identified items were discussed with industry and stakeholders and field visits were conducted to ensure clarity and avoidance of duplication. Established a streamlined list of 49 distinct risk factors, where similar and overlapping items were combined.

The validated risk factors were then further classified into 20 general risk factors, which were assigned to the broad themes of the risks. These overall factors were then grouped into six major risk dimensions: Economic factors, Environmental factors, Social factors, Technological factors, Time-related and Quality-related factors. This hierarchical structure helped

to apply the weighing approach using AHP and allowed the prioritization of the identified risks systematically.

3.5 Research Framework

The proposed methodology consists of four major stages:

Literature review and industry consultation to identify risk factors.

Field visits and feedback from stakeholders for Validation and refinement of factors.

Structured questionnaires and semi-structured interviews to gain primary data.

Data analysis and prioritization of risk factors in SPSS and weightage by AHP method.

The framework provides for the integration of the perceptions of the stakeholders and quantitative analysis in the risk assessment process.

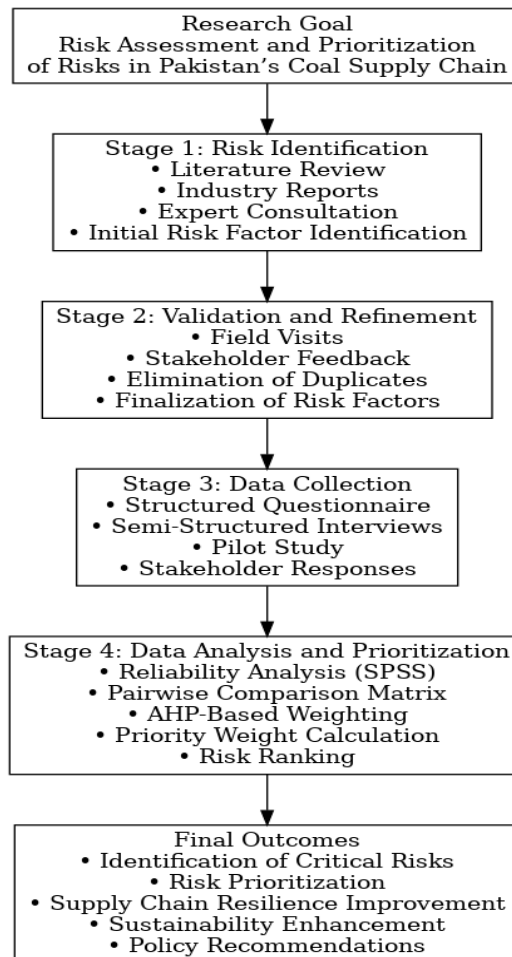


Figure 2. Research Framework

The outcomes of this methodology provide a structured basis for identifying critical risk areas and establishing priorities for improving the resilience and sustainability of Pakistan's coal supply chain.

4. DATA COLLECTION

Structured questionnaires and semi-structured interviews were used to gather the data required for this study. The data collection techniques, such as quantitative and qualitative, helped in understanding the risks and challenges in the coal supply chain in Pakistan.

The target groups were representatives of various stakeholders directly or indirectly involved with coal supply chain activities. Representatives from the mining industry, logistics service providers, government departments, environmental groups and local communities impacted by coal operations were part of these groups. A broad spectrum of stakeholder perspectives were captured both during the data collection process as well as at the conclusion of the process.

Semi-structured interviews were selected to gain a detailed understanding of concerns of the coal supply chain on operational, environmental, regulatory and technological matters. The interviews lasted approximately 45 minutes to one hour and provided a wealth of qualitative information which helped to supplement the quantitative analysis.

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The questionnaire was mainly close ended, on a 5-point Likert scale (1 being least significant and 5 being most significant). The survey instrument was designed to measure the perception of stakeholders on the importance of the various risk factors and effectiveness of potential risk mitigation strategies. The format ensured that responses were consistent and comparable for all of the respondent groups.

A preliminary investigation of the questionnaire was carried out with 10 individuals to test the clarity, relevance and comprehensiveness of the questionnaire before the full-scale survey. The feedback from the pilot phase led to some minor changes to the wording and structure of the questions, as well as the design of the overall questionnaire. This helped to enhance the reliability and validity of the instrument used for the survey.

The finalized questionnaire was then sent out via online and paper medium. There were 120 completely filled-in responses received and analysed. The respondents comprised the key stakeholders of coal supply chain in Pakistan. Table 2 shows the demographic characteristics of respondents.

Table 1 Demographic Profile of Respondents

Category	Frequency	Percentage%
Mining Company Employees	42	35
Logistics Providers	30	25
Government Officials	24	20
Local Community Members	24	20
Total	120	100%

The demographic distribution shows that key stakeholders in coal supply chain operations participate and are balanced. This helps to support the trustworthiness of the results and offers a thorough analysis of the threats and concerns that are experienced by the industry.

4.1 Reliability Analysis

Reliability of the questionnaire was assessed using the widely used internal consistency measure namely Cronbach's Alpha. Cronbach's Alpha evaluates how well the items on a survey are measuring the same thing and if they generate the

same results. The coefficient can be between 0 and 1, with higher scores reflecting the greater reliability and internal consistency of the survey items (Tavakol & Dennick, 2011).

The mathematical expression for Cronbach’s Alpha is presented below:

$$\alpha = \frac{N \times \bar{C}}{\bar{V} + (N - 1) \times \bar{C}}$$

The reliability of the questionnaire was determined by calculating Cronbach's Alpha on SPSS software. Analysis was conducted to check if the questionnaire items, that were meant to measure coal supply chain risk assessment, were measuring the intended dimensions across the board.

Reliability Statistics

Cronbach's Alpha	Cronbach's Alpha Based on Standardized Items	N of Items
.941	.941	73

Figure 1. SPSS Reliability Reports

The reliability analysis validated the questionnaire and demonstrated that the questionnaire had a satisfactory internal consistency, making it appropriate for statistical analysis and risk prioritization.

were gathered and analyzed to find out the relative importance of the identified factors. The results were then used to develop a weighting system based on the AHP to define the priority of each factor in the overall risk assessment model.

5. DATA ANALYSIS

The collected data was analyzed qualitatively and quantitatively to give an overall picture about the risks in the coal supply chain of Pakistan. By combining these strategies, key risk factors were identified, and the relative importance of these factors was evaluated systematically.

The qualitative analysis was based on summarizing the key themes and concerns that were identified from stakeholder interviews. All the answers were meticulously analyzed and segmented based on the key parameters of the coal supply chain such as economic, environmental, technological, quality, social and time related parameters. The results were used as a context for quantitative analysis and used to validate the relevance of the selected risk factors.

The data analyzed quantitatively was analyzed by the Statistical Package for Social Sciences (SPSS). The responses to the structured questionnaire

5.1 AHP-Based Weighting Approach

The Analytical Hierarchy Process (AHP) is a multi-criteria decision-making method that can be used to evaluate and prioritize multiple criteria in a complex decision-making environment (Zhou et al., 2025). The approach is to structure the decision problem in a hierarchy of a goal, a set of evaluation criteria, a set of sub-criteria and a set of alternatives. The factors are then compared one by one and the weights obtained in the process reflect their relative importance to the overall objective (Russo & Camanho, 2015).

Based on the identified coal supply chain risk factors, an AHP-based weighting method was selected for prioritizing these factors. The answers received from the stakeholders were consolidated for each factor and then the pairwise comparison matrix was built. The final matrix allowed the relative weights and priorities of the identified risk factors to be established.

A hierarchical structure was established for the analysis and is shown in Figure 4.

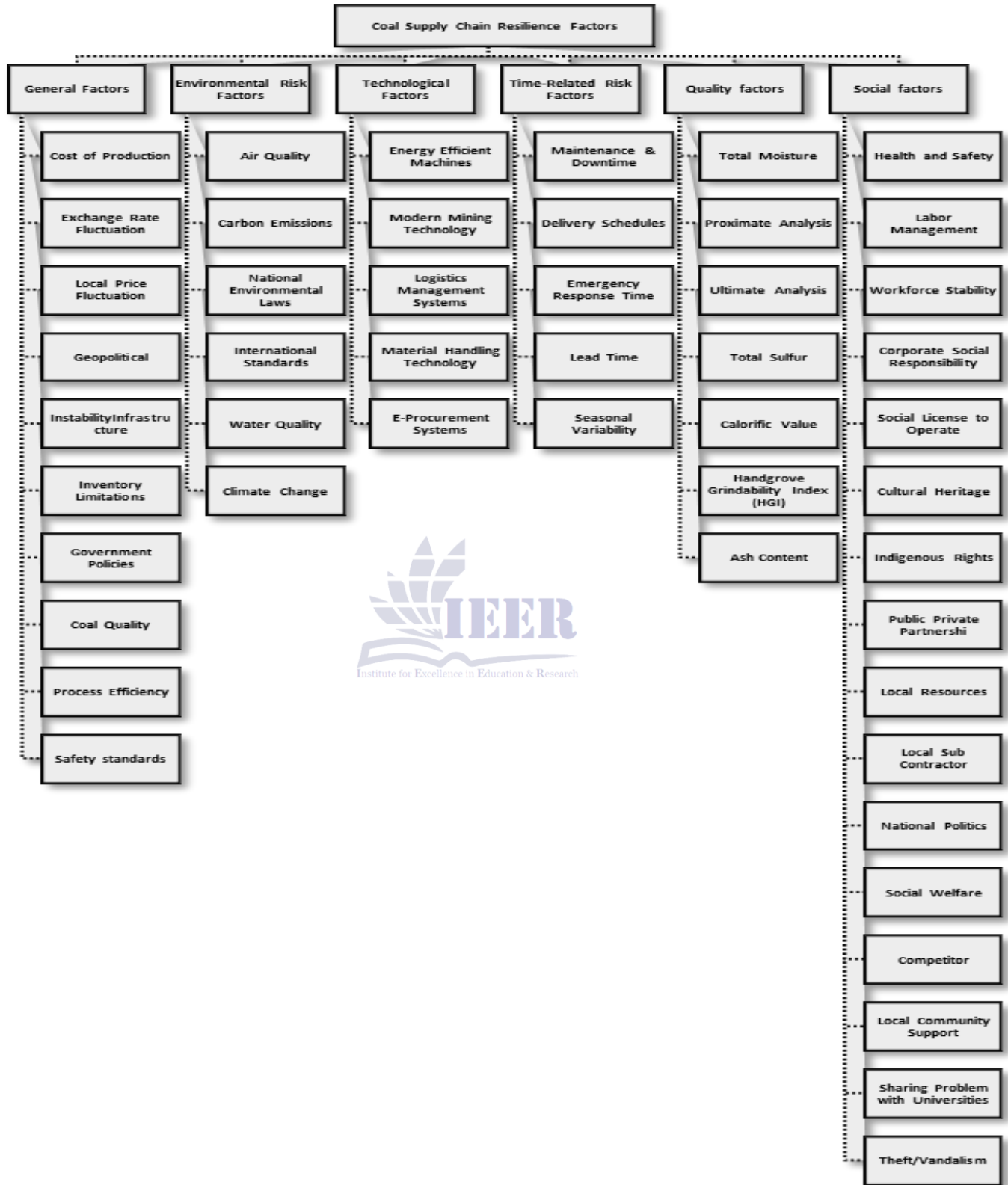


Figure 2 : Hierarchical structure of factors and sub-factors

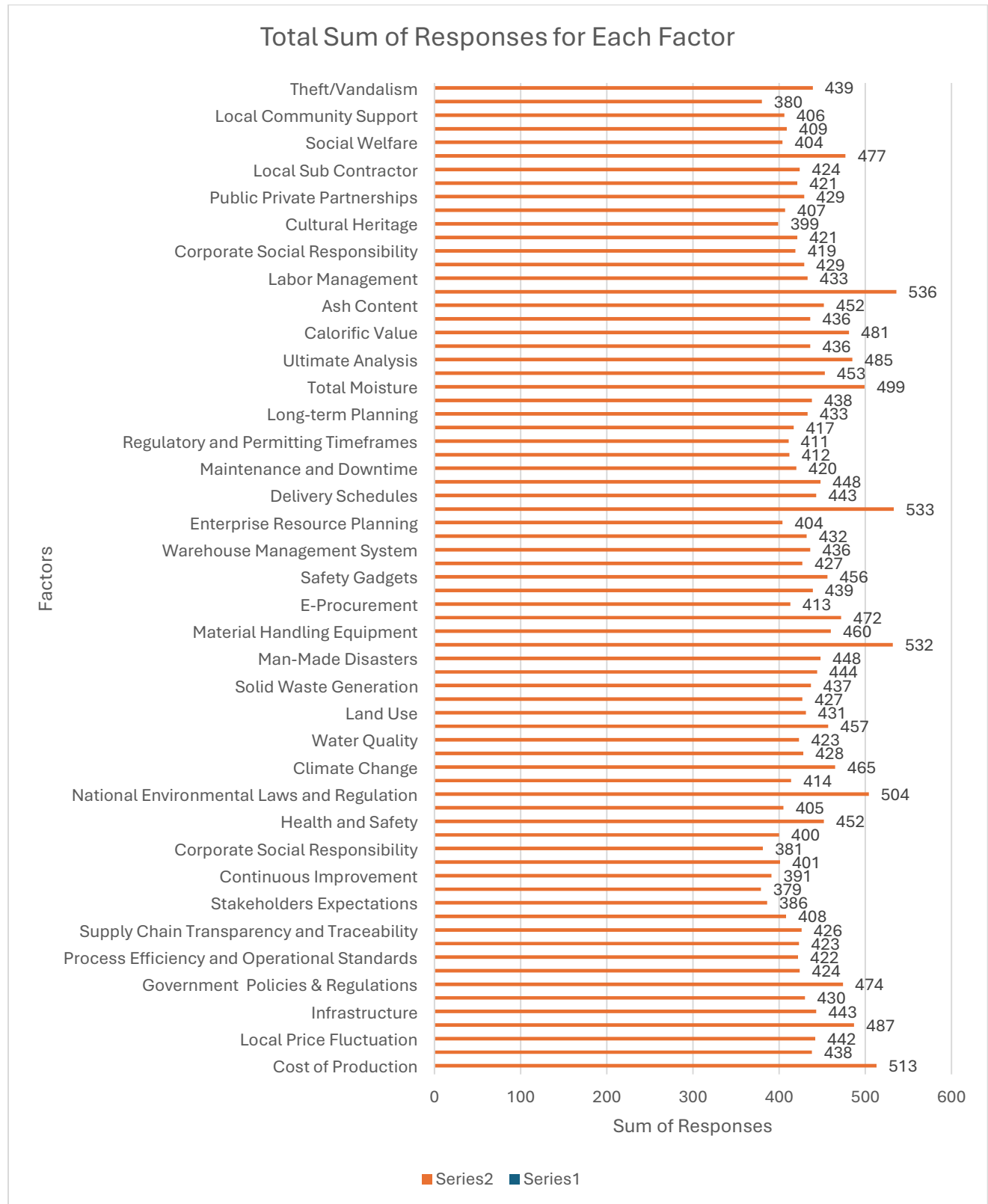


Figure 5: Total Sum of Responses

The framework is composed of the overall goal of coal supply chain risk assessment, multiple risk dimensions and related factors. This is a hierarchical structure and gives a systematic way to compare each factor.

5.2 Development of the Pairwise Comparison Matrix

The first step in the quantitative analysis was to total up the answers that were received from all the respondents for each factor identified. These aggregated values were then used to build the

matrix of comparisons between the two. The relative comparison values were obtained using Equation 4.

$$a_{ij} = \frac{S_i}{S_j}$$
$$a_{12} = \frac{513}{438}$$
$$a_{12} = 1.17$$

The resulting pairwise comparison matrix is presented in Table 5.

Table 5: Pairwise Comparison Table



	Cost of Production	Exchange Rate	Local Price Fluctuation	Geopolitical Instability	Infrastructure	Inventory Limitations	Government Policies	Coal Quality and Consistency	Process Efficiency and Operational Standards	Safety and Compliance Standards	Supply Chain Transparency and Traceability	Customer Expectations	Stakeholders Expectations	Innovation	Continuous Improvement	Local Community Engagement	Corporate Social Responsibility	Digital Communication	Health and Safety	Outsourcing	Row Sum	Eigen Values	
sum of response values	513	438	442	487	443	430	474	424	422	423	426	408	386	379	391	401	381	400	452	405			
Cost of Production	1.00	1.17	1.16	1.05	1.16	1.19	1.08	1.21	1.22	1.21	1.20	1.26	1.33	1.35	1.31	1.28	1.35	1.28	1.13	1.07	1.12	24.22	0.06
Exchange Rate	0.85	1.00	0.99	0.90	0.99	0.92	0.92	1.03	1.04	0.00	1.03	1.07	1.13	1.16	1.12	1.09	1.15	1.10	0.97	1.08	1.09	19.65	0.05
Local Price Fluctuation	0.86	1.01	1.00	0.91	1.00	1.03	0.93	1.04	1.05	1.04	1.04	1.08	1.15	1.17	1.13	1.10	1.16	1.11	0.98	1.09	1.09	20.87	0.05
Geopolitical Instability	0.95	1.11	1.10	1.00	1.10	1.13	1.03	1.15	1.15	1.15	1.14	1.19	1.26	1.28	1.25	1.21	1.28	1.22	1.08	1.20	1.20	23.00	0.06
Infrastructure	0.86	1.01	1.00	0.91	1.00	1.03	0.93	1.04	1.05	1.05	1.04	1.09	1.15	1.17	1.13	1.10	1.16	1.11	0.98	1.09	1.09	20.92	0.05
Inventory Limitations	0.84	0.98	0.97	0.88	0.97	1.00	0.91	1.01	1.02	1.02	1.01	1.05	1.11	1.13	1.10	1.07	1.13	1.08	0.95	1.06	1.06	20.30	0.05
Government Policies & Regulations	0.92	1.08	1.07	0.97	1.07	1.10	1.00	1.12	1.12	1.12	1.11	1.16	1.23	1.25	1.21	1.18	1.24	1.19	1.05	1.17	1.17	22.38	0.06
Coal Quality and Consistency	0.83	0.97	0.96	0.87	0.96	0.99	0.89	1.00	1.00	1.00	1.00	1.04	1.10	1.12	1.08	1.06	1.11	1.06	0.94	1.05	1.02	20.02	0.05
Process Efficiency and Operational Standards	0.82	0.96	0.95	0.87	0.95	0.98	0.89	1.00	1.00	1.00	0.99	1.03	1.09	1.11	1.08	1.05	1.11	1.06	0.93	1.04	1.04	19.93	0.05
Safety and Compliance Standards	0.82	0.97	0.96	0.87	0.95	0.98	0.89	1.00	1.00	1.00	0.99	1.04	1.10	1.12	1.08	1.05	1.11	1.06	0.94	1.04	1.04	19.97	0.05
Supply Chain Transparency and Traceability	0.83	0.97	0.96	0.87	0.96	0.99	0.90	1.00	1.01	1.01	1.00	1.04	1.10	1.12	1.09	1.06	1.12	1.07	0.94	1.05	1.05	20.11	0.05
Customer Expectations	0.80	0.93	0.92	0.84	0.92	0.95	0.86	0.96	0.97	0.96	0.96	1.00	1.06	1.08	1.04	1.02	1.07	1.02	0.90	1.01	1.01	19.27	0.05
Stakeholders Expectations	0.75	0.88	0.87	0.79	0.87	0.90	0.81	0.91	0.91	0.91	0.91	0.95	1.00	1.02	0.99	0.96	1.01	0.97	0.85	0.95	0.95	18.23	0.05
Innovation	0.74	0.87	0.86	0.78	0.86	0.88	0.80	0.89	0.90	0.90	0.89	0.93	0.98	1.00	0.97	0.95	0.99	0.95	0.84	0.94	0.94	17.90	0.04
Continuous Improvement	0.76	0.89	0.88	0.80	0.88	0.91	0.82	0.92	0.93	0.92	0.92	0.96	1.01	1.03	1.00	0.98	1.03	0.98	0.87	0.97	0.97	18.46	0.05
Local Community Engagement	0.78	0.92	0.91	0.82	0.91	0.93	0.85	0.95	0.95	0.95	0.94	0.98	1.04	1.06	1.03	1.00	1.05	1.00	0.89	0.99	0.99	18.93	0.05
Corporate Social Responsibility	0.74	0.87	0.86	0.78	0.86	0.89	0.80	0.90	0.90	0.90	0.89	0.93	0.99	1.01	0.97	0.95	1.00	0.95	0.84	0.94	0.94	17.99	0.04
Digital Communication	0.78	0.91	0.90	0.82	0.90	0.93	0.84	0.94	0.95	0.95	0.94	0.98	1.04	1.06	1.02	1.00	1.05	1.00	0.88	0.99	0.99	18.89	0.05
Health and Safety	0.88	1.03	1.02	0.93	1.02	1.05	0.95	1.07	1.07	1.07	1.06	1.11	1.17	1.19	1.16	1.13	1.19	1.13	1.00	1.12	1.12	21.34	0.05
Outsourcing	0.79	0.92	0.92	0.83	0.91	0.94	0.85	0.96	0.96	0.96	0.95	0.99	1.05	1.07	1.04	1.01	1.06	1.01	0.90	1.00	1.00	19.12	0.05
																					Sum	40.150	1.00

The matrix shows the relative comparisons between the factors identified, and forms the basis for assigning priority weights to the factors. After the matrix was constructed, the number in each row was added together to get the row totals. The row sums were then normalized to determine the relative importance of each factor.

5.3 Determination of Priority Weights

The Pairwise comparison matrix was used to determine priority weights, which were normalized by the sum of the rows on the matrix. The normalized values are used to indicate the proportion of each component of the coal supply chain risk assessment framework.

Priority weights have been calculated for the general factors and are presented in Table 6.

Table 2 Priority Weight of general factors

Factors	Priority Weights
Cost of Production	0.0603
Exchange Rate	0.0489
Local Price Fluctuation	0.0519
Geopolitical Instability	0.0572
Infrastructure	0.0520
Inventory Limitations	0.0505
Government Policies & Regulations	0.0557
Coal Quality and Consistency	0.0498
Process Efficiency and Operational Standards	0.0496
Safety and Compliance Standards	0.0497
Supply Chain Transparency and Traceability	0.0500
Customer Expectations	0.0479
Stakeholders Expectations	0.0453
Innovation	0.0445
Continuous Improvement	0.0459
Local Community Engagement	0.0471
Corporate Social Responsibility	0.0448
Digital Communication	0.0470
Health and Safety	0.0531
Outsourcing	0.0476

The results show that there are different degrees of significance of the identified factors. The higher the priority weight, the more influence the factor has on the performance of the coal supply chain,

and the lower the priority weight, the less the influence of the factor within the decision framework.

5.4 Eigenvalue Computation

The eigenvalue approach was used for determining final priority weights. The pairwise comparison matrix was multiplied an iterative process until the matrix converged. In every iteration, row sums and total sums were calculated and respectively eigenvalues were found.

The first iteration consisted of processing the initial pairwise comparison matrix to get a set of

eigenvalues. After a second application in the same manner, the resulting matrix was used for the third application. A succession of iterations was used to get eigenvalues which were compared to see the convergence. This was repeated until successive eigenvalues were close, which meant that the results were stable and converged.

Table 7 gives the calculation involved in the iterative eigenvalue method.

Table 3 Eigen Values Calculations

Factors	Iteration 1		Iteration 2		Eigen Values Difference
	Row Sum	Eigen Values	Row Sum	Eigen Values	
Cost of Production	483.249	0.06033	192335	0.06033	0
Exchange Rate	391.972	0.04894	156006	0.04894	0
Local Price Fluctuation	416.367	0.05198	165715	0.05198	0
Geopolitical Instability	458.757	0.05727	182587	0.05727	0
Infrastructure	417.309	0.0521	166090	0.0521	0
Inventory Limitations	405.063	0.05057	161216	0.05057	0
Government Policies & Regulations	446.511	0.05574	177713	0.05574	0
Coal Quality and Consistency	399.411	0.04986	158967	0.04986	0
Process Efficiency and Operational Standards	397.527	0.04963	158217	0.04963	0
Safety and Compliance Standards	398.469	0.04975	158592	0.04975	0
Supply Chain Transparency and Traceability	401.295	0.0501	159716	0.0501	0
Customer Expectations	384.339	0.04798	152968	0.04798	0
Stakeholders Expectations	363.614	0.0454	144720	0.0454	0
Innovation	357.02	0.04457	142095	0.04457	0
Continuous Improvement	368.324	0.04598	146594	0.04598	0
Local Community Engagement	377.745	0.04716	150343	0.04716	0
Corporate Social Responsibility	358.904	0.04481	142845	0.04481	0
Digital Communication	376.803	0.04704	149968	0.04704	0
Health and Safety	425.787	0.05316	169464	0.05316	0
Outsourcing	381.513	0.04763	151843	0.04763	0
Total Sum	8009.98	1	3187994	1	0

The results validate the successful convergence of the eigenvalues, which shows stability of the priority weights calculated. The weights were then used to rank and prioritize the identified coal supply chain risk factors.

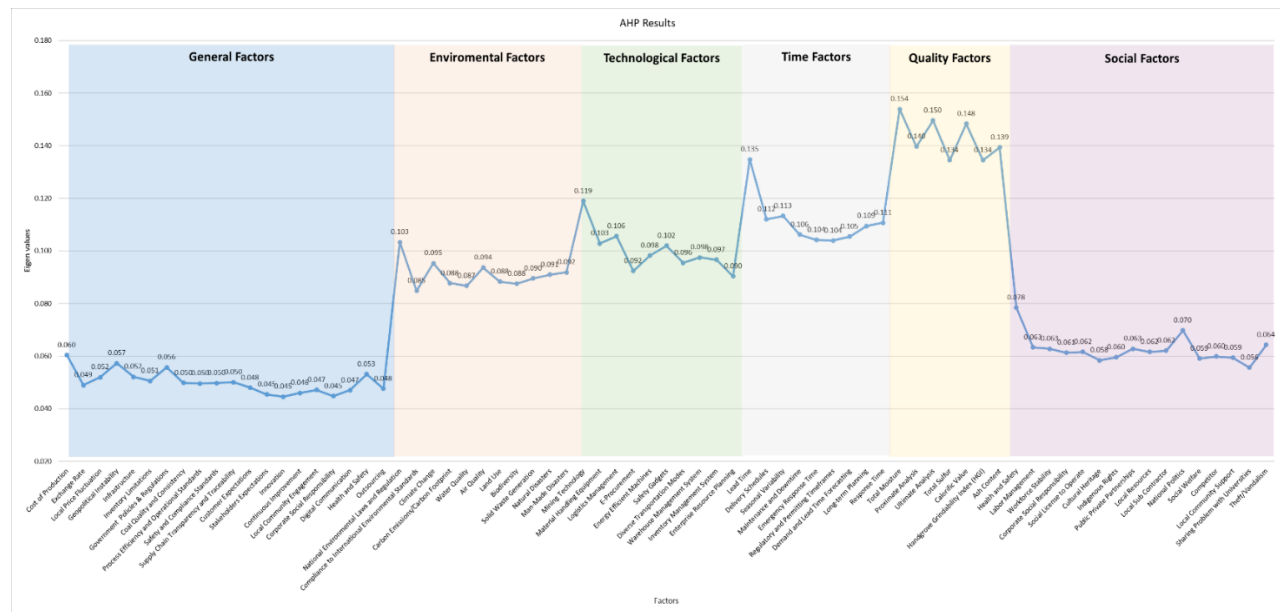
The results of the AHP-based weighting analysis offer a structured approach to assessing the relative importance of various risk dimensions and lend a support to designing risk mitigation plans for the coal supply chain in Pakistan.

RESULTS

The identified risk factors associated with the coal supply chain in Pakistan have been analysed through a weighting analysis based on AHP

(Analytical Hierarchy Process) to determine the relative importance of the risk factors. This analysis resulted in priority weights for the factors considered under the general, environmental, technological, time-related, quality-related and social dimensions. The resulting weights give a quantitative context for the relative importance of the different risk factors in the whole decision making process.

The results show that there is a clear difference in the significance attributed to the different factors and sub-factors. The priority weights resulted from the AHP-based weighting analysis are shown in figure 6.



innovation in mining operations, logistics management and equipment use, have a significant influence on enhancing supply chain effectiveness and resilience.

The environmental factors listed were assigned priority weights between about 0.085 and 0.103. This suggests that sustainability and regulatory compliance are relevant areas for the management of the coal supply chain and that environmental matters are still relevant. Within this category, weights assigned to factors reflecting environmental performance (i.e., air quality, carbon emissions, and environmental regulations) were comparatively high.

The priority weights for the social factors ranged from around 0.056 to 0.070. They are lower than values of the quality, time and technological categories but they show the importance of the stakeholder engagement, community relations, workforce related aspects as well as social responsibility in coal supply chain operations.

The general factors got priority weights varying from 0.045 to 0.060. These factors showed relatively lower influences in the entire decision structure as compared to the other categories. However, cost of production, government policies and regulations, geopolitical instability and health and safety still played their part in the overall risk assessment framework.

The results also show that the identified risk factors do not equally affect the performance of the coal supply chain. Rather, the prioritization process shows that there is a clear difference between the very influential and the relatively less influential factors. The increased weighting of the quality and time-related factors reflect the need to maintain product quality, operational efficiency and responsiveness across the coal supply chain.

In general, the AHP based weighing analysis method has been used to structure the identified factors and made a quantitative basis for discussion and interpretation of the risks to the coal supply chain of Pakistan

DISCUSSION OF RESULTS

This study identified different interconnected risks in the supply chain of coal in Pakistan and how they affect the efficiency, reliability and

sustainability of the supply chain. The prioritization results resulting from the AHP based weighting approach clearly show that the various risk factors are not equally important for the performance of the supply chain. Rather, some factors have a much greater influence, and thus need a higher level of managerial and policy attention.

It is one of the most significant findings that quality-related factors are of great importance. The findings show that the most important weights were assigned to the dimensions of quality for all categories with the individual dimension of Total Moisture being the most important. The discovery underlines the significance of coal quality control throughout the supply chain, as fluctuations in coal quality can have tangible impacts on operational efficiency, combustion performance, transportation needs, and customer satisfaction. The fact that quality-related aspects are included shows that stakeholders are very focused on the reliability of the supply chain, which is ensured through the maintenance of the standards of coal. Another key concern was time-related issues. The transportation, processing and delivery delay was one of the highest weightings from all factors evaluated, and it has a significant impact on the effectiveness of the coal supply chain. As Pakistan relies heavily on long-distance transportation systems between mining regions and industrial consumers, as well as power generation plants, any delays could lead to operational disruptions and raise the total cost of supply chain systems. The results corroborate Spear (2014) who highlighted the role of maintenance planning and operational scheduling in reducing the interruptions in the supply chain.

The findings also show that technology has a significant impact on enhancing supply chain resilience. The weights assigned to the factors within the technological category were comparatively higher for mining technology, equipment utilisation, logistics management and operational innovation. The results showed that the technological modernization can play a significant role in minimizing inefficiency in operations and improving the overall performance of the supply chain. These findings align with the

findings from Benalcazar et al., (2017) who found that modern technology and advance operational practices help in reducing downtime, increasing safety and boosting the reliability of the supply chain.

Environmental factors were also noted as key drivers of the risks in the coal supply chain. The respondents showed a significant interest in factors relating to air quality, carbon emissions, environmental laws and sustainability needs. The results are similar to the previous studies that have pointed out the environmental impacts of coal mining, transportation, and consumption activities (He et al., 2020; Gopinathan et al., 2023). Stakeholders are becoming ever more aware of the need to balance the energy security goals with environmental sustainability obligations, as evidenced by the increased focus on environmental compliance.

Infrastructure-related issues were one of the main problems that arose among the general factors. The transportation network is a key component of Pakistan's coal supply chain, playing a crucial role in transporting coal from the mining regions to the consuming centres. Road, railway and storage infrastructure, logistics constraints can cause delays, cost and supply disruption. The result is consistent with that of Poee and Mathu (2011) who reported infrastructure deficiencies as a significant constraint on achieving an efficient coal supply chain in developing economies.

Government policies and regulatory framework were also observed as influencing factors on the performance of supply chains. Stakeholders in coal supply chain activities may experience operational challenges due to changes in policy and regulatory uncertainty, and administration overlaps. This finding aligns with a number of other studies that have found a need for policy stability and regulatory clarity in order to promote long-term investment and supply chain performance.

Despite the fact that the social factors have lower weights than the other categories (quality, time, technological dimensions), they are still relevant factors in the risk assessment framework. Some of the attributes that create social acceptance and business continuity are workforce stability,

community involvement, corporate social responsibility and stakeholder expectations. Without taking these into account, resistance from local communities, labour issues and reputation issues can be expected, which can adversely affect the supply chain.

Overall, these findings suggest that the operational, technological, environmental, regulatory and social factors are the challenges of the coal supply chain in Pakistan. The results indicate that the processes of quality assurance and time management are the most important and should be given special focus, while infrastructure development, technological modernization, environmental compliance and policy stability are all key supporting factors to improve the resilience of the supply chain.

The findings can be used to guide policy makers and practitioners in the focus on investing in the transportation infrastructure, the adoption of modern mining technologies, quality monitoring systems and maintenance management practices. Furthermore, adequate regulatory framework and environmental management can enhance the reliability, sustainability and competitiveness of the Pakistan's Coal value chain. Stakeholders can contribute to build resilience of supply chains and contribute to the national energy security and economic development goals by addressing these priority areas.

CONCLUSION

The main objective of this study was to identify, evaluate and prioritize risks associated with the coal supply chain in Pakistan by applying AHP based weighting method. As coal becomes a significant component of Pakistan's energy mix, it is critical to understand the factors that impact the performance of the coal supply chain to ensure a reliable energy supply, optimize energy operations, and facilitate the country's economic development in the long run.

The results show that various factors in the coal supply chain in Pakistan are economic, environmental, technological, quality, time and social factors. These dimensions can be further categorized into factors related to quality, which proved to be the most influential one, and among

these the weight of the total moisture was the highest. Second, time-related factors were identified, with Lead Time and operational responsiveness being of particular importance in ensuring the uninterrupted coal supply. Other factors related to technology, environment and infrastructure also were identified as significant in rating the overall performance of the supply chain. It also indicates that despite significant progress, infrastructure bottlenecks, regulatory uncertainty, environmental issues and operational inefficiencies remain to be a concern in the fragility and performance of Pakistan's coal value chain. Meanwhile, the other side of the equation, technology, better maintenance systems and quality management systems provide great tools for increasing supply chain reliability and decreasing risks on the operations side.

This is an attempt to add to the existing body of knowledge by structuring the assessment of coal supply chain risks in Pakistan. The research also integrates stakeholder views and uses a stakeholder-based prioritisation framework, based on AHP, to aid decision makers in prioritising the risk factors and facilitate evidence-based decision making. These results provide a valuable reference for policy makers, industry practitioners and supply chain managers for improving supply chain resiliency and sustainability.

Strategic investments in transportation infrastructure, modern mining and logistics technologies, effective quality control measures and development of stable regulatory frameworks are pointed out from a practical standpoint. Improvements in the operational performance, enhancing resilience of the coal supply chain and meeting the national energy security goals can be achieved through the action of the priority areas. Overall, the study offers a comprehensive framework of the key risk issues of coal supply chain in Pakistan, and lays a foundation for further investigation and policy development for enhancing the sustainability and competitiveness of the coal sector in Pakistan.

FUTURE RESEARCH DIRECTIONS

The current study has given an insight about the risks that are faced by the coal supply chain in

Pakistan; however, there are several opportunities for further studies. Longitudinal research designs may be used in future studies to investigate the changes in risk priorities over time, as they are affected by changes in market conditions, regulatory frameworks, technological and environmental needs.

Comparative studies on various energy supply chains (oil, natural gas, and renewable energies) can lead to a wider understanding of the risk and resilience strategies across the energy supply chain. Comparative analysis between regions or countries also could be useful for determining context-specific issues and best practices to be translated to the coal industry in Pakistan.

In the future, the researchers would like to apply more sophisticated analysis methods such as: Interpretive Structural Modeling (ISM), DEMATEL, Fuzzy AHP, and integrated multi-criteria decision-making approaches to explore the inter-relationships and causal effects of risk factors. These would give a greater insight into the interdependency and interactions affecting the performance of the coal supply chain.

Furthermore, future studies could involve a broader and more varied group of actors beyond those mentioned, such as energy regulators, transportation agencies, environmental groups, and investors. These results should be expanded to include a larger number of stakeholders, to make them more comprehensive and generalizable.

New fields of research are also emerging with the focus on sustainability and digital transformation. Future research could focus on the use of Industry 4.0 technologies, artificial intelligence, digital supply chain platforms, Internet of Things (IoT) and predictive analytics to increase the efficiency, transparency and resilience of coal supply chains.

Last, some case studies, simulation models or optimization techniques might be used to assess the success of the chosen risk mitigation strategies and policy interventions in the future. This study could be useful to guide the decision makers for the reinforcement of coal supply chain and long term energy security and sustainable industrial development.

REFERENCES

- Belov, G., Boland, N. L., Savelsbergh, M. W. P., & Stuckey, P. J. (2020). Logistics optimization for a coal supply chain. *Journal of Heuristics*, 26(2), 269–300. <https://doi.org/10.1007/s10732-019-09435-8>
- Botha, A., & Badenhorst-Weiss, J. A. (2019). Risk management in a bulk coal export logistic chain: A stakeholder perspective. *Journal of Transport and Supply Chain Management*, 13. <https://doi.org/10.4102/jtscm.v13i0.424>
- Frish, S., Talmor, I., Hadar, O., Shoshany, M., & Shapira, A. (2025). Enhancing consistency of AHP-based expert judgements: A new approach and its implementation in an interactive tool. *MethodsX*, 14. <https://doi.org/10.1016/j.mex.2025.103341>
- Li, J., Wang, L., & Tan, X. (2020). Sustainable design and optimization of coal supply chain network under different carbon emission policies. *Journal of Cleaner Production*, 250. <https://doi.org/10.1016/j.jclepro.2019.119548>
- Rooshdi, R. R. R. M., Majid, M. Z. A., Sahamir, S. R., & Ismail, N. A. A. (2018). Relative importance index of sustainable design and construction activities criteria for green highway. *Chemical Engineering Transactions*, 63, 151–156. <https://doi.org/10.3303/CET1863026>
- Russo, R. D. F. S. M., & Camanho, R. (2015). Criteria in AHP: A systematic review of literature. *Procedia Computer Science*, 55, 1123–1132. <https://doi.org/10.1016/j.procs.2015.07.081>
- Tavakol, M., & Dennick, R. (2011). Making sense of Cronbach's alpha. In *International journal of medical education* (Vol. 2, pp. 53–55). <https://doi.org/10.5116/ijme.4dfb.8dfd>
- Zhou, Y., Guo, M., Hao, J., Xu, W., & Wu, Y. (2025). Multidimensional Risk Assessment in Sustainable Coal Supply Chains for China's Low-Carbon Transition: An AHP-FCE Framework. *Sustainability* (Switzerland), 17(13). <https://doi.org/10.3390/su17135689>
- Gopinathan, P., Subramani, T., Barbosa, S., & Yuvaraj, D. (2023). Environmental impact and health risk assessment due to coal mining and utilization. *Environmental Geochemistry and Health*, 45(10), 6915–6922. <https://doi.org/10.1007/s10653-023-01744-z>
- Han, N., & Um, J. (2024). Risk management strategy for supply chain sustainability and resilience capability. *Risk Management*, 26. <https://doi.org/10.1057/s41283-023-00138-w>
- He, G., Zhou, L., Dai, Y., Dang, Y., & Ji, X. (2020). Coal Industrial Supply Chain Network and Associated Evaluation Models. *Sustainability*, 12(23), Article 23. <https://doi.org/10.3390/su12239919>
- Kamiński, J., Saługa, P. W., & Benalcazar, P. (2017). The storage location problem in a coal supply chain: Background and methodological approach. *Gospodarka Surowcami Mineralnymi - Mineral Resources Management*; 2017; Vol. 33; No 1.
- Pooe, D., & Mathu, K. (2011). The South African coal mining industry: A need for a more efficient and collaborative supply chain. *Journal of Transport and Supply Chain Management*, 5(1), Article 1. <https://doi.org/10.4102/jtscm.v5i1.80>
- Yang, C., Zheng, X., Dai, C., Li, D., Liu, L., Fang, L., Tian, H., Shao, T. and Zhang, J., 2025. Risk assessment of coal supply chain based on analytic hierarchy process and fuzzy comprehensive evaluation. *Heliyon*, 11(4), e42629. <https://doi.org/10.1016/j.heliyon.2025.e42629>