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Hierarchical Modeling of Barriers to Sustainable Development in the Mining Industry of Pakistan: An ISM and MICMAC-Based Approach

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Mining contributes to economic development but relies on finite and non-renewable resources, posing sustainability challenges. Achieving long-term economic stability and environmental preservation requires a balanced approach that integrates effective resource management with sustainable development strategies. However, sustainable development in mining is complex, as it faces multiple barriers related to governance, economic, structural, and environmental challenges. This study applies Interpretive Structural Modeling (ISM) to explore these barriers and analyze their interdependencies. Data was collected from the literature and analyzed through expert opinions via a structured questionnaire, and an ISM-based model was developed to determine the hierarchical structure of these barriers. The MICMAC (Cross Impact Matrix Multiplication Applied to Classification) analysis further classifies barriers based on their driving and dependence power, providing insights into their relative importance within the system. Findings reveal that all thirty-two barriers influence the sustainability process, with some controlling as a key driving force while others function as dependent factors. Lack of top management commitment and lack of enforcement of rules and regulations emerge as the most influential barriers due to high driving power and low dependence. The absence of autonomous barriers indicates that all identified factors significantly affect the sustainable development of mining. The hierarchical ISM-based model emphasizes the necessity for targeted interventions at different barrier levels. This research contributes to sustainability efforts by offering a structured approach to understanding barrier interrelationships, aiding policymakers and industry stakeholders in formulating effective strategies for responsible and sustainable mining practices.

Keywords: Sustainable Mining Development, Finite resource, Barriers, Interpretive Structural Modeling, MICMAC Analysis.

Introduction:

Mining significantly contributes to a country's economic growth; however, its resources are limited and non-renewable. The depletion of these resources heightens societal concerns about maintaining a balance between natural resource use and economic growth [1]. This ongoing depletion has given rise to sustainable development as a strategy to safeguard future needs [2][3]. Sustainability has been defined in many ways. For instance, the United Nations report "Our Common Future" defined it as a progression that meets present needs without affecting the potential of future generations to meet their necessities [2][3]. It has emerged as a global priority, gaining attention from countries and industries worldwide [3]. Sustainability comprises environmental, economic, and social components, and balancing these aspects to achieve sustainable development is challenging [4]. The mining industry is confronted with these challenges, along with concerns related to resource depletion [5]

The growing awareness of sustainable development is drawing attention to the mining sector. This highlights the need for addressing its unsustainable practices that can adversely affect local communities and ecosystems. However, minerals are essential for sustainable development, as improving the quality of life requires a steady supply of minerals while also prioritizing environmental protection [3]. Researchers and policymakers are exploring ways for the industry to align with sustainable development objectives, aiming to balance economic benefits with responsible resource management and social equity. Variations in sustainable development approaches arise as countries develop customized strategies for planning, implementation, and governance that reflect their unique contexts [6]. Accordingly, experts agree that a range of approaches is essential to address the diverse regional conditions.

In developed countries, strategies for sustainable mining often focus on reducing environmental impacts, engaging local communities, and ensuring economic feasibility [7]. However, in developing countries like Pakistan, factors such as political instability, lack of technologies, and poor regulatory frameworks need to be considered, other to the primary factors of sustainability [2]. Other risk factors, such as deforestation, water contamination, and labor rights violations, have also been identified in various studies on sustainable mining practices [8]. Considering the multifaceted risks associated with sustainable mining, this study intends to explore and analyze the main barriers that hinder its implementation. To address these challenges, it also proposes potential pathways. This study contributes by applying Interpretive Structural Modeling to analyze the hierarchical structure and driving-dependence power of barriers to sustainable mining. As prior studies are focused on individual barriers, they highlight their interconnections to support more effective and informed policy making. The research findings are intended to help policymakers, mining companies, and stakeholders in assessing important driving factors and overcoming major barriers to enhance sustainable mining strategies, particularly in developing countries with limited resources.

Literature Review:

Several studies have been conducted to assess the sustainable development of mining, but as it is a continuous process and the target has not been achieved yet, especially in developing countries, due to numerous challenges. For instance, Author[9] identified that the mining sector has limited integration between sustainable development goals and environmental, social, and governance principles, key progress areas, and emphasized the need for stronger SDGs alignment, transparent ESG disclosure, and protection of sensitive zones to ensure meaningful sustainability outcomes. A multi-criteria decision-making (MCD) method was employed to assess the fundamental challenges to sustainability in the African mining sector and reported that over-exploitation, lack of trained labor, unstable power sources, insufficient infrastructure, and political instability contribute to mineral depletion [10]. Similarly, a sustainable development model was formulated to assess the optimal balance between capital and natural resources depletion, using a nested constant elasticity of substitution (CES) production function to allow flexible substitution [11]. Author[12] conducted interviews with experts and analyzed reports for the identification of challenges faced in the Brazilian mining sector and reported that the negative environmental impact is the major sustainability challenge. A methodology involving expert interviews was employed to identify environmental and organizational-level barriers to technology adoption, which are critical for the successful implementation of new technologies and the long-term sustainability of the mining industry [1]. The fuzzy synthetic evaluation approach was applied, and as a result, eight categories of risk factors, including operational, organization, economic, health, environmental, political, socio-cultural, and natural, were identified that affect sustainable mining in Pakistan [13]. The Folchi technique, based on the multicriteria decision-making (MCDM) method, was utilized to evaluate the sustainability of an open-pit mine by assessing the main factors and their effects [14]. The study found the most important sustainability factors in the Angouran Lead and Zinc Mine, an open pit in Iran, are biodiversity, surface water, water and air quality, and human health and safety. Author[15] utilized the Acropolis DSS, an innovative decision support system grounded in multi-criteria and multi-attribute analysis, to integrate sustainable development challenges into mining project decisions, assisting stakeholders in addressing pivotal issues. Similarly, numerous researchers have identified a range of barriers related to the research topic. A consolidated list of the most common barriers/challenges to sustainable development is presented in Table 1.

Table 1. Barriers/Challenges to Sustainable Development

Core Barriers	Sub-Barriers and assigned code	Sources
Environmental Barriers	Land degradation (B1)	[8], [16], [17]
	Air Pollution (B2)	[9][1]
	Improper waste management (B3)	[18][19]
	Deforestation (B4)	[20][21]
Economic Barriers	High operational costs for sustainable technologies (B5)	[1][12][22][23]
	Fluctuating commodity prices (B6)	[20][24]
	Challenges in adopting the circular economy (B7)	[7][25][26]
	Prioritizing short-term profits over long-term sustainability (B8)	[22][25][27]
	Resource depletion affects investments in sustainability (B9)	[28][11][1][29]
	Lack of investment in sustainable technologies (B10)	[20][30]
Technological Barriers	Outdated mining technologies for sustainable development (B11)	[1][12][17][25][27]
	Lack of technical expertise for introducing new technologies (B12)	[31][32]
	Lack of skilled force to operate modern technologies (13)	[5][33]
	Inadequate infrastructure for technology deployment (B14)	[34][35]
	Reluctance to adopt innovation due to uncertainty or lack of awareness (B15)	[36][37][38]
	Lack of investment in research and development for innovation and local and local adaptation of sustainable mining technologies (B16)	[35][38][39][40]
Societal Barriers	Community resistance and conflict over land use (B17)	[9][41][42]
	Local community employment issues (B18)	[16][25]
	Poor working standards and health and safety issues (B19)	[43][44]
	Limited local economic benefits (B20)	[14][30][45]
	Lack of community engagement in decision making (B21)	[16][46][47]
	Lack of awareness about sustainable mining practices (B22)	[9][17][1][22]
	Social inequity and displacement (B23)	[1][48]
	Inadequate provision for community-based training (24)	[46][1][17][22]
Regulatory and Policy Barriers	Inconsistent Global Standards for Sustainable Mining (25)	[16][49]
	Geopolitical Instability (26)	[2][31]
	Corruption and lack of transparency (27)	[9][50]

Core Barriers	Sub-Barriers and assigned code	Sources
	Slow permitting and approval of sustainability processes (28)	[50][22]
	Lack of commitment by top management to initiate sustainability efforts (29)	[9][27][31]
	Lack of enforcement of rules and regulations (30)	[9][17][21]
	Inadequate adoption of sustainability into the mining planning process (31)	[17][22][1]
	Limited engagement of stakeholders in sustainable processes (32)	[9][41][48]

Method and Material:

This study employed a qualitative approach, utilizing Interpretive Structural Modeling (ISM) through Smart ISM 2.0 software to examine and structure the interrelationship among barriers identified in the sustainable development of mining. The research systematically analyzed how the barriers influence one another, providing a structured framework for understanding the challenges faced by sustainability in the mining industry.

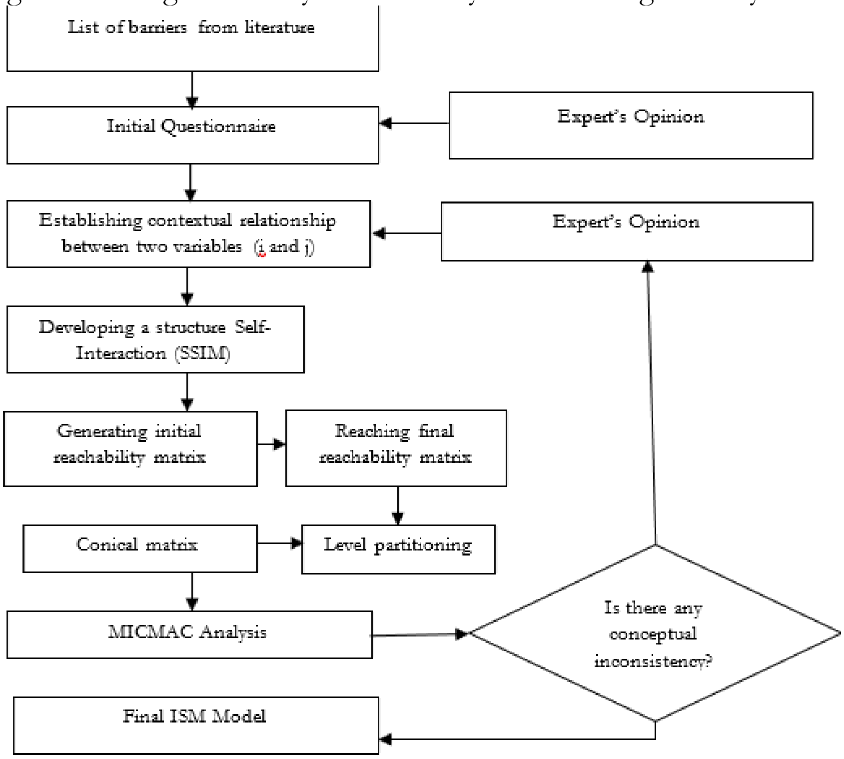

Figure 1. Methodology and ISM Process Flowchart [51]

Interpretive Structural Modeling is a process for identifying the relationships among factors that affect the system under investigation and structuring them into a systematic model using both textual and graphical representations [52]. It was established by Warfield in 1974 to analyze the intricate socio-economic system [53]. ISM has the benefit of prioritizing variables while also delineating their interrelationships, distinguishing it from methodologies such as AHP, TOPSIS, and DEMATEL, which concentrate exclusively on prioritization [54][55]. The ISM process is initiated by identifying the elements impacting a problem and thereafter utilizes a collaborative, group-oriented approach to problem-solving [54]. Relevant factors for the system are usually found by a literature review and are then refined, excluded, or selected depending on expert judgment.

To overcome the constraints of ISM in evaluating the driving and dependent power of variables, the MICMAC approach is employed to accurately describe these relationships [56]. The integrated ISM-MICMAC methodology has been utilized to assess the driving and dependent power as well as the interrelationships among the identified barriers concerning sustainable development in mining [53][57]. The results affirm substantial challenges to sustainable development and enhance understanding of their dynamic relationships, providing valuable insights for addressing these challenges in developing contexts.

Data Collection:

In the context of this study, the barriers impeding the sustainable development of mining were initially identified through a literature review. In the first phase, a questionnaire was developed, and the identified barriers were verified by three PhD academicians and three industry experts with more than fifteen years of experience. In the second phase, the questionnaire data was analyzed by four Ph.D academicians and fifteen experts from the mining industry with not least fifteen years of experience. The literature suggests that the ISM studies do not require a large sample size of respondents [53][57]. The number of experts varies from a few to many, but the experience of the experts is highly focused on, with a minimum of ten years in the relevant industry [56][58]. Experts' opinions were utilized to identify the linguistic relationship between each pair of barriers through a questionnaire based on ISM rules. The linguistic relationship that was chosen by most experts was considered for further study.

Data Analysis and Results:

Structured Self-Interaction Matrix:

The textual relationship between the barriers was obtained through experts' opinions and presented in Table 2. The common four symbols V, A, X, and O denote the directional relationship between barriers x and y, with x indicating the variables in the row and y indicating the variables in the column [51]. The directional relationships are the following:

V – variable x has a direct effect on variable y.
A – variable y has a direct effect on variable x.
X – variables x and y affect each other.
O – Variables x and y have no direct effect on each other.

The results reveal that B10 and B12 have the highest number of V symbols row-wise, and B29 and B30, followed by B24, with the most A symbols column-wise indicate factors that strongly influence others, reflecting a strong influence on the other barriers, as the columns with more A symbols correspond to rows with more V symbols across the matrix.

Table 2. Structural Self-Interaction Matrix (SSIM)

Variable	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32
B1		O	A	V	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O
B2			A	A	O	O	O	O	O	O	O	O	O	O	O	O	O	O	V	O	O	O	O	O	O	O	O	O	O	O	O	O
B3				O	O	O	O	O	O	A	A	O	O	O	O	O	O	O	A	O	O	O	O	O	O	O	O	O	A	A	O	O
B4					O	O	O	O	O	O	O	O	O	O	O	A	O	O	O	O	O	O	O	O	O	O	O	O	A	A	O	O
B5						O	O	V	O	V	V	O	O	O	V	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O
B6							V	V	O	V	O	O	O	A	V	O	O	O	O	O	O	O	O	O	A	O	O	O	O	O	O	O
B7								V	O	O	O	V	O	A	V	O	O	O	O	O	O	O	O	O	A	O	O	O	O	O	O	O
B8									O	A	O	O	O	O	O	A	O	O	O	V	O	O	O	A	O	O	O	O	A	A	V	V
B9										V	O	O	O	O	O	V	O	O	O	V	O	O	O	V	O	O	O	O	O	O	O	O
B10											V	A	V	V	X	A	O	O	V	V	O	V	O	A	O	A	O	A	A	A	O	O
B11												A	O	A	A	V	O	O	O	O	O	O	A	A	O	O	O	O	A	A	A	A
B12													V	V	V	V	O	O	O	O	O	O	O	A	A	A	A	O	A	O	V	O
B13														O	O	O	O	O	V	O	O	A	O	O	O	O	O	O	O	O	O	O
B14															A	O	O	O	O	O	O	O	O	A	O	O	O	O	A	A	A	O
B15																V	O	O	O	O	O	V	A	A	A	A	A	O	A	O	O	A
B16																	O	O	O	O	O	O	O	O	O	O	O	O	A	O	O	O
B17																		O	O	O	X	O	A	O	O	O	A	O	A	A	O	A
B18																			A	A	O	V	O	O	O	O	O	O	A	A	O	O
B19																				X	O	O	O	O	O	O	O	O	A	O	O	O
B20																					O	O	O	O	O	O	O	O	A	A	O	O
B21																						O	A	A	O	O	A	O	A	O	O	A
B22																							O	O	O	O	O	O	A	O	O	O
B23																								O	O	O	O	O	A	O	O	A
B24																									A	A	O	O	A	O	A	O
B25																										O	O	O	O	O	V	O
B26																											X	V	O	O	O	V
B27																												V	O	A	O	O
B28																													A	A	A	A
B29																														X	V	V
B30																															V	V

B31																															V
B32																															

Table 3. Initial Reachability Matrix (IRM)

Variables	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	Driving Power
B1	1	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2
B2	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	2
B3	1	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	3
B4	0	1	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2
B5	0	0	0	0	1	0	0	1	0	1	1	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	5
B6	0	0	0	0	0	1	1	1	0	1	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	5
B7	0	0	0	0	0	0	1	1	0	0	0	1	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	4
B8	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	1	1	4
B9	0	0	0	0	0	0	0	0	1	1	0	0	0	0	0	1	0	0	0	1	0	0	0	1	0	0	0	0	0	0	0	0	5
B10	0	0	1	0	0	0	0	1	0	1	1	0	1	1	1	0	0	0	1	1	0	1	0	0	0	0	0	0	0	0	0	0	10
B11	0	0	1	0	0	0	0	0	0	0	1	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	3
B12	0	0	0	0	0	0	0	0	0	1	1	1	1	1	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	8
B13	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	2
B14	0	0	0	0	0	1	1	0	0	0	1	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	4
B15	0	0	0	0	0	0	0	0	0	1	1	0	0	1	1	1	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	6
B16	0	0	0	0	0	0	0	1	0	1	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	3
B17	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	3
B18	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	1	0	0	0	0	0	0	0	0	0	0	2
B19	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	1	0	0	0	0	0	0	0	0	0	0	0	0	4
B20	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	1	0	0	0	0	0	0	0	0	0	0	0	0	3
B21	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	2
B22	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	2
B23	0	0	0	0	0	0	0	0	0	0	1	0	0	0	1	0	1	0	0	0	1	0	1	0	0	0	0	0	0	0	0	0	5
B24	0	0	0	0	0	0	0	1	0	1	1	1	0	1	1	0	0	0	0	0	1	0	0	1	0	0	0	0	0	0	0	0	8
B25	0	0	0	0	0	1	1	0	0	0	0	1	0	0	1	0	0	0	0	0	0	0	0	1	1	0	0	0	0	0	1	0	7
B26	0	0	0	0	0	0	0	0	0	1	0	1	0	0	1	0	0	0	0	0	0	0	0	1	0	1	1	1	0	0	0	1	8
B27	0	0	0	0	0	0	0	0	0	0	0	1	0	0	1	0	1	0	0	0	1	0	0	0	0	1	1	1	0	0	0	0	7
B28	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	2

B29	0	0	1	1	0	0	0	1	0	1	1	1	0	1	1	1	1	1	1	1	1	1	1	1	0	0	0	1	1	1	1	1	22
B30	0	0	1	1	0	0	0	1	0	1	1	0	0	1	0	0	1	1	0	1	0	0	0	0	0	0	1	1	1	1	1	1	15
B31	0	0	0	0	0	0	0	0	0	0	1	0	0	1	0	0	0	0	0	0	0	0	0	1	0	0	0	1	0	0	1	1	6
B32	0	0	0	0	0	0	0	0	0	0	1	0	0	0	1	0	1	0	0	0	1	0	1	0	0	0	0	1	0	0	0	1	7
Dependence Power	2	3	6	5	1	3	4	9	1	12	12	7	4	8	13	6	7	5	6	7	7	5	3	6	1	2	3	7	2	2	6	6	

Table 4. Final Reachability Matrix (FRM)

Variables	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	Driving Power
B1	1	1*	1*	1	0	0	0	0	0	0	0	0	1*	0	0	0	0	1*	1*	1*	0	1*	0	0	0	0	0	0	0	0	0	0	9
B2	1*	1	1*	1*	0	0	0	0	0	0	0	0	1*	0	0	0	0	1*	1	1*	0	1*	0	0	0	0	0	0	0	0	0	0	9
B3	1*	1	1	1*	0	0	0	0	0	0	0	0	1*	0	0	0	0	1*	1*	1*	0	1*	0	0	0	0	0	0	0	0	0	0	9
B4	1*	1	1*	1	0	0	0	0	0	0	0	0	1*	0	0	0	0	1*	1*	1*	0	1*	0	0	0	0	0	0	0	0	0	0	9
B5	1*	1*	1*	1*	1	1*	1*	1	0	1	1	1*	1*	1*	1	1*	1*	1*	1*	1*	1*	1*	1*	1*	0	0	0	1*	0	0	1*	1*	26
B6	1*	1*	1*	1*	0	1	1	1	0	1	1*	1*	1*	1*	1	1*	1*	1*	1*	1*	1*	1*	1*	1*	0	0	0	1*	0	0	1*	1*	25
B7	1*	1*	1*	1*	0	1*	1	1	0	1*	1*	1	1*	1*	1	1*	1*	1*	1*	1*	1*	1*	1*	1*	0	0	0	1*	0	0	1*	1*	25
B8	1*	1*	1*	1*	0	1*	1*	1	0	1*	1*	1	1*	1*	1*	1*	1*	1*	1*	1	1*	1*	1*	1*	0	0	0	1*	0	0	1	1	25
B9	1*	1*	1*	1*	1	1*	1*	1*	1	1	1*	1*	1*	1*	1*	1	1*	1*	1*	1	1*	1*	1*	1	0	0	0	1*	0	0	1*	1*	26
B10	1*	1*	1	1*	0	1*	1*	1	0	1	1	1*	1	1	1	1*	1*	1*	1	1	1*	1	1*	1*	0	0	0	1*	0	0	1*	1*	25
B11	1*	1*	1	1*	0	1*	1*	1*	0	1*	1	1*	1*	1*	1*	1	1*	1*	1*	1*	1*	1*	1*	1*	0	0	0	1*	0	0	1*	1*	25
B12	1*	1*	1*	1*	0	1*	1*	1*	0	1	1	1	1	1	1	1	1*	1*	1*	1*	1*	1*	1*	1*	0	0	0	1*	0	0	1	1*	25
B13	1*	1*	1*	1*	0	0	0	0	0	0	0	0	1	0	0	0	0	1*	1	1*	0	1*	0	0	0	0	0	0	0	0	0	0	9
B14	1*	1*	1*	1*	0	1	1	1*	0	1*	1	1*	1*	1	1*	1	1*	1*	1*	1*	1*	1*	1*	1*	0	0	0	1*	0	0	1*	1*	25
B15	1*	1*	1*	1*	0	1*	1*	1*	0	1	1	1*	1*	1	1	1	1*	1*	1*	1*	1*	1	1*	1*	0	0	0	1*	0	0	1*	1*	25
B16	1*	1*	1*	1*	0	1*	1*	1	0	1	1*	1*	1*	1*	1*	1	1*	1*	1*	1*	1*	1*	1*	1*	0	0	0	1*	0	0	1*	1*	25
B17	1*	1*	1*	1	0	0	0	0	0	0	0	0	1*	0	0	0	1	1*	1*	1*	1	1*	0	0	0	0	0	0	0	0	0	0	11
B18	1*	1*	1*	1*	0	0	0	0	0	0	0	0	1*	0	0	0	0	1	1*	1*	0	0	0	0	0	0	0	0	0	0	0	0	9
B19	1*	1*	1	1*	0	0	0	0	0	0	0	0	1*	0	0	0	0	1	1	1	0	1*	0	0	0	0	0	0	0	0	0	0	9
B20	1*	1*	1*	1*	0	0	0	0	0	0	0	0	1*	0	0	0	0	1	1	1	0	1*	0	0	0	0	0	0	0	0	0	0	9
B21	1*	1*	1*	1*	0	0	0	0	0	0	0	0	1*	0	0	0	0	1*	1*	1*	1	1*	0	0	0	0	0	0	0	0	0	0	11
B22	1*	1*	1*	1*	0	0	0	0	0	0	0	0	1	0	0	0	0	1*	1*	1*	0	1	0	0	0	0	0	0	0	0	0	0	9
B23	1*	1*	1*	1*	0	1*	1*	1*	0	1*	1	1*	1*	1*	1	1	1	1*	1*	1*	1	1*	1	1*	0	0	0	1*	0	0	1*	1*	25

B24	1*	1*	1*	1*	0	1*	1*	1	0	1	1	1	1*	1	1	1	1*	1*	1*	1*	1	1*	1*	1	0	0	0	1*	0	0	1*	1*	25
B25	1*	1*	1*	1*	0	1	1	1*	0	1*	1*	1	1*	1*	1	1	1*	1*	1*	1*	1*	1*	1*	1	1	0	0	1*	0	0	1	1*	26
B26	1*	1*	1*	1*	0	1*	1*	1*	0	1	1*	1	1*	1*	1	1	1*	1*	1*	1*	1*	1*	1*	1	0	1	1	1	1	0	1*	1	27
B27	1*	1*	1*	1*	0	1*	1*	1*	0	1*	1*	1	1*	1*	1	1	1	1*	1*	1*	1	1*	1*	1*	0	1	1	1	1	0	1*	1*	27
B28	1*	1*	1*	1*	0	1*	1*	1*	0	1	1*	1*	1*	1*	1*	1*	1*	1*	1*	1*	1*	1*	1*	1*	0	0	0	1	0	0	1*	1*	25
B29	1*	1*	1	1	0	1*	1*	1	0	1	1	1	1*	1	1	1	1	1	1	1	1	1	1	1	0	1*	1*	1	1	1	1	1	29
B30	1*	1*	1	1*	0	1*	1*	1	0	1	1	1*	1*	1	1*	1*	1	1	1*	1	1*	1*	1*	1*	0	1*	1	1	1	1	1	1	29
B31	1*	1*	1*	1*	0	1*	1*	1*	0	1*	1	1*	1*	1	1*	1*	1*	1*	1*	1*	1*	1*	1*	1	0	0	0	1	0	0	1	1	25
B32	1*	1*	1*	1*	0	1*	1*	1*	0	1*	1	1*	1*	1*	1	1	1	1*	1*	1*	1	1*	1	1*	0	0	0	1	0	0	1*	1	25
Dependence Power	32	32	32	32	1	21	21	21	1	21	21	21	32	21	21	21	23	32	32	32	23	32	21	21	1	4	4	21	2	2	21	21	

Table 5. Level Partitioning (LP)

Variables (Mi)	Reachability Set R(Mi)	Antecedent Set A(Ni)	Intersection Set R(Mi)∩A(Ni)	Level
1	1, 2, 3, 4, 13, 18, 19, 20, 22	1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14, 15, 16, 17, 18, 19, 20, 21, 22, 23, 24, 25, 26, 27, 28, 29, 30, 31, 32	1, 2, 3, 4, 13, 18, 19, 20, 22	1
2	1, 2, 3, 4, 13, 18, 19, 20, 22	1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14, 15, 16, 17, 18, 19, 20, 21, 22, 23, 24, 25, 26, 27, 28, 29, 30, 31, 32	1, 2, 3, 4, 13, 18, 19, 20, 22	1
3	1, 2, 3, 4, 13, 18, 19, 20, 22	1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14, 15, 16, 17, 18, 19, 20, 21, 22, 23, 24, 25, 26, 27, 28, 29, 30, 31, 32	1, 2, 3, 4, 13, 18, 19, 20, 22	1
4	1, 2, 3, 4, 13, 18, 19, 20, 22	1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14, 15, 16, 17, 18, 19, 20, 21, 22, 23, 24, 25, 26, 27, 28, 29, 30, 31, 32	1, 2, 3, 4, 13, 18, 19, 20, 22	1
5	5	5	5	4
6	6, 7, 8, 10, 11, 12, 14, 15, 16, 23, 24, 28, 31, 32	5, 6, 7, 8, 9, 10, 11, 12, 14, 15, 16, 23, 24, 25, 26, 27, 28, 29, 30, 31, 32	6, 7, 8, 10, 11, 12, 14, 15, 16, 23, 24, 28, 31, 32	3
7	6, 7, 8, 10, 11, 12, 14, 15, 16, 23, 24, 28, 31, 32	5, 6, 7, 8, 9, 10, 11, 12, 14, 15, 16, 23, 24, 25, 26, 27, 28, 29, 30, 31, 32	6, 7, 8, 10, 11, 12, 14, 15, 16, 23, 24, 28, 31, 32	3
8	6, 7, 8, 10, 11, 12, 14, 15, 16, 23, 24, 28, 31, 32	5, 6, 7, 8, 9, 10, 11, 12, 14, 15, 16, 23, 24, 25, 26, 27, 28, 29, 30, 31, 32	6, 7, 8, 10, 11, 12, 14, 15, 16, 23, 24, 28, 31, 32	3
9	9	9	9	4

10	6, 7, 8, 10, 11, 12, 14, 15, 16, 23, 24, 28, 31, 32	5, 6, 7, 8, 9, 10, 11, 12, 14, 15, 16, 23, 24, 25, 26, 27, 28, 29, 30, 31, 32	6, 7, 8, 10, 11, 12, 14, 15, 16, 23, 24, 28, 31, 32	3
11	6, 7, 8, 10, 11, 12, 14, 15, 16, 23, 24, 28, 31, 32	5, 6, 7, 8, 9, 10, 11, 12, 14, 15, 16, 23, 24, 25, 26, 27, 28, 29, 30, 31, 32	6, 7, 8, 10, 11, 12, 14, 15, 16, 23, 24, 28, 31, 32	3
12	6, 7, 8, 10, 11, 12, 14, 15, 16, 23, 24, 28, 31, 32	5, 6, 7, 8, 9, 10, 11, 12, 14, 15, 16, 23, 24, 25, 26, 27, 28, 29, 30, 31, 32	6, 7, 8, 10, 11, 12, 14, 15, 16, 23, 24, 28, 31, 32	3
13	1, 2, 3, 4, 13, 18, 19, 20, 22	1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14, 15, 16, 17, 18, 19, 20, 21, 22, 23, 24, 25, 26, 27, 28, 29, 30, 31, 32	1, 2, 3, 4, 13, 18, 19, 20, 22	1
14	6, 7, 8, 10, 11, 12, 14, 15, 16, 23, 24, 28, 31, 32	5, 6, 7, 8, 9, 10, 11, 12, 14, 15, 16, 23, 24, 25, 26, 27, 28, 29, 30, 31, 32	6, 7, 8, 10, 11, 12, 14, 15, 16, 23, 24, 28, 31, 32	3
15	6, 7, 8, 10, 11, 12, 14, 15, 16, 23, 24, 28, 31, 32	5, 6, 7, 8, 9, 10, 11, 12, 14, 15, 16, 23, 24, 25, 26, 27, 28, 29, 30, 31, 32	6, 7, 8, 10, 11, 12, 14, 15, 16, 23, 24, 28, 31, 32	3
16	6, 7, 8, 10, 11, 12, 14, 15, 16, 23, 24, 28, 31, 32	5, 6, 7, 8, 9, 10, 11, 12, 14, 15, 16, 23, 24, 25, 26, 27, 28, 29, 30, 31, 32	6, 7, 8, 10, 11, 12, 14, 15, 16, 23, 24, 28, 31, 32	3
17	17, 21	5, 6, 7, 8, 9, 10, 11, 12, 14, 15, 16, 17, 21, 23, 24, 25, 26, 27, 28, 29, 30, 31, 32	17, 21	2
18	1, 2, 3, 4, 13, 18, 19, 20, 22	1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14, 15, 16, 17, 18, 19, 20, 21, 22, 23, 24, 25, 26, 27, 28, 29, 30, 31, 32	1, 2, 3, 4, 13, 18, 19, 20, 22	1
19	1, 2, 3, 4, 13, 18, 19, 20, 22	1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14, 15, 16, 17, 18, 19, 20, 21, 22, 23, 24, 25, 26, 27, 28, 29, 30, 31, 32	1, 2, 3, 4, 13, 18, 19, 20, 22	1
20	1, 2, 3, 4, 13, 18, 19, 20, 22	1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14, 15, 16, 17, 18, 19, 20, 21, 22, 23, 24, 25, 26, 27, 28, 29, 30, 31, 32	1, 2, 3, 4, 13, 18, 19, 20, 22	1
21	17, 21	5, 6, 7, 8, 9, 10, 11, 12, 14, 15, 16, 17, 21, 23, 24, 25, 26, 27, 28, 29, 30, 31, 32	17, 21	2
22	1, 2, 3, 4, 13, 18, 19, 20, 22	1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14, 15, 16, 17, 18, 19, 20, 21, 22, 23, 24, 25, 26, 27, 28, 29, 30, 31, 32	1, 2, 3, 4, 13, 18, 19, 20, 22	1
23	6, 7, 8, 10, 11, 12, 14, 15, 16, 23, 24, 28, 31, 32	5, 6, 7, 8, 9, 10, 11, 12, 14, 15, 16, 23, 24, 25, 26, 27, 28, 29, 30, 31, 32	6, 7, 8, 10, 11, 12, 14, 15, 16, 23, 24, 28, 31, 32	3
24	6, 7, 8, 10, 11, 12, 14, 15, 16, 23, 24, 28, 31, 32	5, 6, 7, 8, 9, 10, 11, 12, 14, 15, 16, 23, 24, 25, 26, 27, 28, 29, 30, 31, 32	6, 7, 8, 10, 11, 12, 14, 15, 16, 23, 24, 28, 31, 32	3
25	25	25	25	4
26	26, 27	26, 27, 29, 30	26, 27	4
27	26, 27	26, 27, 29, 30	26, 27	4

28	6, 7, 8, 10, 11, 12, 14, 15, 16, 23, 24, 28, 31, 32	5, 6, 7, 8, 9, 10, 11, 12, 14, 15, 16, 23, 24, 25, 26, 27, 28, 29, 30, 31, 32	6, 7, 8, 10, 11, 12, 14, 15, 16, 23, 24, 28, 31, 32	3
29	29, 30	29, 30	29, 30	5
30	29, 30	29, 30	29, 30	5
31	6, 7, 8, 10, 11, 12, 14, 15, 16, 23, 24, 28, 31, 32	5, 6, 7, 8, 9, 10, 11, 12, 14, 15, 16, 23, 24, 25, 26, 27, 28, 29, 30, 31, 32	6, 7, 8, 10, 11, 12, 14, 15, 16, 23, 24, 28, 31, 32	3
32	6, 7, 8, 10, 11, 12, 14, 15, 16, 23, 24, 28, 31, 32	5, 6, 7, 8, 9, 10, 11, 12, 14, 15, 16, 23, 24, 25, 26, 27, 28, 29, 30, 31, 32	6, 7, 8, 10, 11, 12, 14, 15, 16, 23, 24, 28, 31, 32	3

Table 6. Conical Matrix (CM)

Variables	1	2	3	4	13	18	19	20	22	17	21	6	7	8	10	11	12	14	15	16	23	24	28	31	32	5	9	25	26	27	29	30	Driving Power	Level
B1	1	1*	1*	1	1*	1*	1*	1*	1*	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	9	1
B2	1*	1	1*	1*	1*	1*	1	1*	1*	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	9	1
B3	1*	1	1	1*	1*	1*	1*	1*	1*	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	9	1
B4	1*	1	1*	1	1*	1*	1*	1*	1*	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	9	1
B13	1*	1*	1*	1*	1*	1*	1	1*	1*	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	9	1
B18	1*	1*	1*	1*	1*	1	1*	1*	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	9	1
B19	1*	1*	1	1*	1*	1	1	1	1*	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	9	1
B20	1*	1*	1*	1*	1*	1	1	1	1*	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	9	1
B22	1*	1*	1*	1*	1	1*	1*	1*	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	9	1
B17	1*	1*	1*	1	1*	1*	1*	1*	1*	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	11	2
B21	1*	1*	1*	1*	1*	1*	1*	1*	1*	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	11	2
B6	1*	1*	1*	1*	1*	1*	1*	1*	1*	1*	1*	1	1	1	1	1*	1*	1*	1	1*	1*	1*	1*	1*	1*	0	0	0	0	0	0	0	25	3
B7	1*	1*	1*	1*	1*	1*	1*	1*	1*	1*	1*	1*	1	1	1*	1*	1	1*	1	1*	1*	1*	1*	1*	1*	0	0	0	0	0	0	0	25	3
B8	1*	1*	1*	1*	1*	1*	1*	1	1*	1*	1*	1*	1*	1	1*	1*	1	1*	1*	1*	1*	1*	1*	1	1	0	0	0	0	0	0	0	25	3
B10	1*	1*	1	1*	1	1*	1	1	1	1*	1*	1*	1*	1	1	1	1*	1	1	1*	1*	1*	1*	1*	1*	0	0	0	0	0	0	0	25	3
B11	1*	1*	1	1*	1*	1*	1*	1*	1*	1*	1*	1*	1*	1*	1*	1	1*	1*	1*	1	1*	1*	1*	1*	1*	0	0	0	0	0	0	0	25	3
B12	1*	1*	1*	1*	1	1*	1*	1*	1*	1*	1*	1*	1*	1*	1	1	1	1	1	1	1*	1*	1*	1	1*	0	0	0	0	0	0	0	25	3
B14	1*	1*	1*	1*	1*	1*	1*	1*	1*	1*	1*	1	1	1*	1*	1	1*	1	1*	1	1*	1*	1*	1*	1*	0	0	0	0	0	0	0	25	3
B15	1*	1*	1*	1*	1*	1*	1*	1*	1	1*	1*	1*	1*	1*	1	1	1*	1	1	1	1*	1*	1*	1*	1*	0	0	0	0	0	0	0	25	3
B16	1*	1*	1*	1*	1*	1*	1*	1*	1*	1*	1*	1*	1*	1	1	1*	1*	1*	1*	1	1*	1*	1*	1*	1*	0	0	0	0	0	0	0	25	3
B23	1*	1*	1*	1*	1*	1*	1*	1*	1*	1	1	1*	1*	1*	1*	1	1*	1*	1	1	1	1*	1*	1*	1*	0	0	0	0	0	0	0	25	3
B24	1*	1*	1*	1*	1*	1*	1*	1*	1*	1*	1	1*	1*	1	1	1	1	1	1	1	1*	1	1*	1*	1*	0	0	0	0	0	0	0	25	3

B28	1*	1*	1*	1*	1*	1*	1*	1*	1*	1*	1*	1*	1*	1*	1	1*	1*	1*	1*	1*	1*	1*	1	1*	1*	0	0	0	0	0	0	0	25	3
B31	1*	1*	1*	1*	1*	1*	1*	1*	1*	1*	1*	1*	1*	1*	1*	1	1*	1	1*	1*	1*	1	1	1	1	0	0	0	0	0	0	0	25	3
B32	1*	1*	1*	1*	1*	1*	1*	1*	1*	1	1	1*	1*	1*	1*	1	1*	1*	1	1	1	1*	1	1*	1	0	0	0	0	0	0	0	25	3
B5	1*	1*	1*	1*	1*	1*	1*	1*	1*	1*	1*	1*	1*	1	1	1	1*	1*	1	1*	1*	1*	1*	1*	1*	1	0	0	0	0	0	0	26	4
B9	1*	1*	1*	1*	1*	1*	1*	1	1*	1*	1*	1*	1*	1*	1	1*	1*	1*	1*	1	1*	1	1*	1*	1*	1	1	0	0	0	0	0	26	4
B25	1*	1*	1*	1*	1*	1*	1*	1*	1*	1*	1*	1	1	1*	1*	1*	1	1*	1	1	1*	1	1*	1	1*	0	0	1	0	0	0	0	26	4
B26	1*	1*	1*	1*	1*	1*	1*	1*	1*	1*	1*	1*	1*	1*	1	1*	1	1*	1	1	1*	1	1	1*	1	0	0	0	1	1	1	0	27	4
B27	1*	1*	1*	1*	1*	1*	1*	1*	1*	1	1	1*	1*	1*	1*	1*	1	1*	1	1	1*	1*	1	1*	1*	0	0	0	1	1	1	0	27	4
B29	1*	1*	1	1	1*	1	1	1	1	1	1	1*	1*	1	1	1	1	1	1	1	1	1	1	1	1	0	0	0	1*	1*	1	1	29	5
B30	1*	1*	1	1*	1*	1	1*	1	1*	1	1*	1*	1*	1	1	1	1*	1	1*	1*	1*	1*	1	1	1	0	0	0	1*	1	1	1	29	5
Dependence Power	32	32	32	32	32	32	32	32	32	23	23	21	21	21	21	21	21	21	21	21	21	21	21	21	21	1	1	1	4	4	2	2		
Level	1	1	1	1	1	1	1	1	1	2	2	3	3	3	3	3	3	3	3	3	3	3	3	3	3	4	4	4	4	4	5	5		

Initial Reachability Matrix:

The initial reachability matrix is generated in binary (0 or 1) numbers, substituted with symbols V, A, X, and O in SSIM according to the following rules and presented in Table 3.

If the (i, j) cell block in the SSIM has entry V, insert 1 for (i, j) and 0 for (j, i).
If the (i, j) cell block in the SSIM has entry A, insert 1 for (i, j) and 0 for (j, i).
If the (i, j) cell block in the SSIM has entry X, insert 1 for both (i, j) and (j, i).
If the (i, j) cell block in the SSIM has entry O, insert 0 for both (i, j) and (j, i).

The analysis indicates that the higher influencing barriers are B29 and B30, with driving powers affecting 22 and 15 factors, respectively. While B15, B10, and B11 are highly dependent barriers, influenced by 13 and 12 factors, respectively.

Final Reachability Matrix:

The final Reachability Matrix is derived by applying the transitivity rule, which asserts that if factor A has an association with factor B, and factor B is associated with factor C, then A is naturally connected to C [51]. The conclusive reachability matrix is given in Table 4, with transitivity emphasized as 1*.

The final reachability matrix indicates that, following the application of the transitivity rule, B29 and B30 exhibit the highest driving power, influencing 29 factors either directly or indirectly. They are followed by B31 and B32, each affecting 25 factors across the system, and so on.

Level partition:

The final reachability matrix is partitioned into different sets, namely the reachability set and the antecedent set, as shown in Table 5. The reachability set encompasses each form of variable, including the factors that may facilitate their occurrence. The antecedent set encompasses both a factor itself and those that may contribute to its occurrence [54]. Factors that appear in both the reachability set and the antecedent set make up the intersection set. If the intersection set matches the reachability set, the factors are categorized as level 1in the ISM hierarchical system [57]. The top-level factor will not contribute to the accomplishment of any factor beyond its level. Similarly, the succeeding key factors are identified for the subsequent levels, and the procedure terminates with assigning a level to each factor. The top-level factors, starting from level 1 in Table 5, exhibit minimal influence on other barriers. These are followed by factors distributed across levels 2 to 4 with moderate to high influence. Whereas Level 5 represents the root level of the system, comprising the most influential factors that drive the overall structure. These determined levels are used to develop the ultimate ISM model and digraph. Level partition iterations are provided as supplementary material.

Conical Matrix:

The conical matrix is constructed by grouping factors at the same hierarchical level within the columns and rows of the final reachability matrix (Table 6). The driving power of each factor is determined by the total number of ones in its corresponding column. Subsequently, ranking for both driving and dependence power is performed by assigning the highest ranks to the factors with the greatest number of ones in the relevant rows and columns.

MICMAC Analysis:

MICMAC is a methodology grounded in matrix multiplication principles, designed to evaluate the driving and dependent capabilities of enablers to identify significant drivers within a system [51]. Enablers are classified into four quadrants: Autonomous (Quadrant I), exhibiting weak driving and dependence power, and being relatively disconnected from the system; Dependent (Quadrant II), demonstrating weak driving power but strong dependence power; Linkage (quadrant III), marked by strong driving and dependence power; and Independent (Quadrant IV), possessing driving but weak dependence power [53]. The independent or linked quadrants usually contain key variables, which are frequently important system drivers.

The analysis indicates that each of the 32 identified barriers contributes to the sustainability process. The upper tier of the hierarchy is comprised of barriers B1, B2, B3, B4, B12, B18, B19, B2O, and B22. These are regarded as superficial obstacles that exert little influence on the system. The second tier of the hierarchy comprises barriers B17 and B21. These barriers identified at the second level in the ISM-based model demonstrate significant dependence power while exhibiting minimal driving power, positioning them among the above levels of the hierarchical structure. On the other hand, barriers at the third tier comprising B6, B7, B8, B10, B11, B12, B14, B15, B16, B23, B24, B28, B31, and B32 exhibit high driving and dependence power, which are essential to be considered for careful addressing. The barriers in the 4th tier, including B5, B9, B25, B26, and B27, are characterized by higher driving power with lower dependence power, indicating their influential role within the system. While the barriers at the 5th tier, B29 and B30, are identified as the most significant barriers due to their substantial driving power and minimal dependence. These results are consistent with the findings of previous empirical studies, further validating their critical position within the hierarchical structure [1][38]. The driving power and dependence diagram (Figure 2) clearly illustrates the absence of autonomous barriers within the system. Autonomous barriers, characterized by weak drivers and weak dependents, exhibit minimal impact on the system. Their absence in this study suggests that all identified barriers play a role in the process of sustainable development in mining.

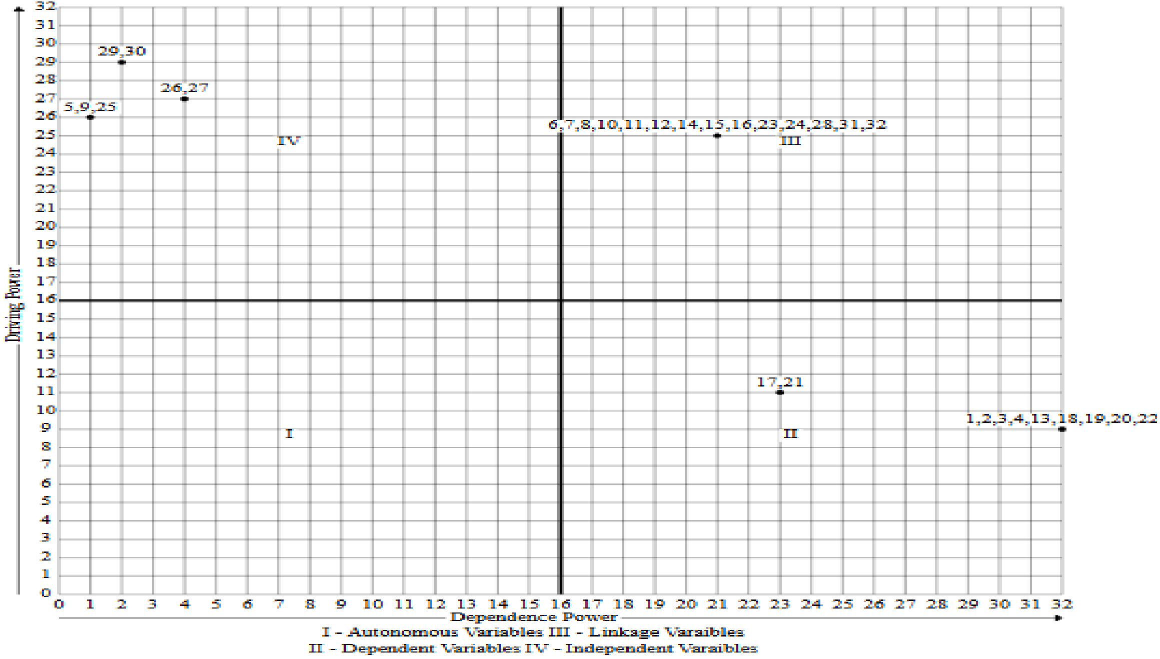

Figure 2. MICMAC Graph

ISM-based Model:

The final ISM-based model illustrating the barriers to sustainable mining development is constructed using the final reachability matrix, level partitioning, conical matrix, and MICMAC analysis, as shown in Figure 3. This model presents a five-level hierarchical structure that clearly illustrates the directional and contextual relationships among the identified barriers. It provides a systematic visualization of how certain barriers influence others, thereby highlighting the driving and dependent factors essential for achieving sustainable mining practices.

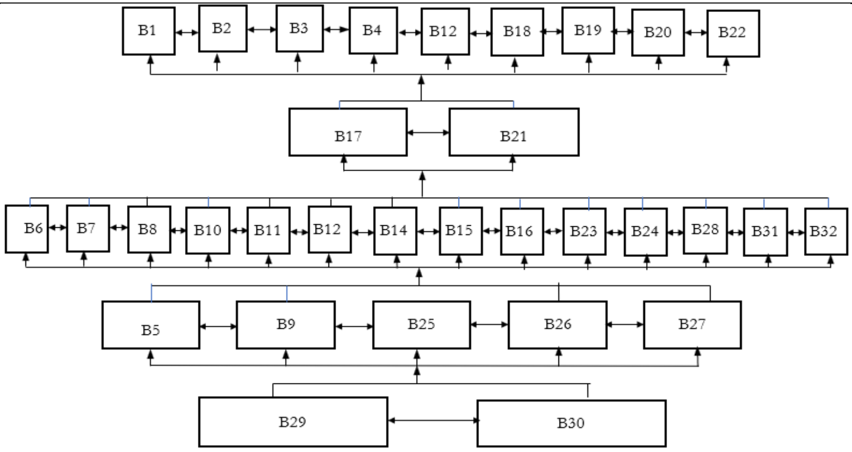

Figure 3. ISM Final Model

Discussion:

The contribution of the mining sector in achieving sustainable development is intrinsically linked to its adherence to economic, environmental, and social standards. It is essential to identify important barriers and analyze how the sector may transition from existing practices to long-term systematic sustainability. Identifying and addressing these constraints are crucial steps towards attaining genuinely sustainable mining practices.

This paper systematically identifies the key barriers and assesses their levels of interconnection by using the ISM method. The findings showed that the lack of top management commitment and a lack of enforcement of rules and regulations are significant barriers to the sustainable development of mining. Strengthening the top management commitment is essential for initiating sustainable development, which is possible by implementing rules and regulations.

Economic barriers significantly affect the sustainable development of mining, posing critical challenges that influence long-term sustainability efforts. High operational costs associated with advanced technologies, regulatory compliance, and environmental obligations often act as disincentives for investment in sustainable practices. Furthermore, inconsistent international standards, governance challenges, and issues such as corruption, lack of transparency, and geopolitical instability collectively impede progress toward achieving long-term environmental, social, and economic sustainability across sectors.

Moreover, resource depletion poses a persistent concern, as declining ore grades increase extraction costs and environmental impacts, making sustainable resource management more difficult. These financial barriers collectively promote unsustainable practices, limiting the mining industry's ability to transition towards sustainable development. Addressing these challenges requires policy interventions, financial incentives, and strategic investments in sustainable technologies to balance economic viability with environmental and social responsibility.

Similarly, fluctuations in commodity prices and challenges in adopting the circular economy further complicate sustainability efforts, as unstable market conditions can deter long-term investments in sustainable infrastructure and environmentally friendly technologies[8]. During periods of low prices, mining firms may cut costs by reducing sustainability initiatives, workforce training, or environmental protection measures. Operational and technological limitations present significant barriers to improving efficiency and advancing sustainability across industries. Additionally, a persistent focus on immediate economic gains often outweighs long-term environmental and social considerations, impeding the adoption of sustainable development practices.

Advancements in sustainable technologies and strengthened regulatory frameworks are important to enhance the industry's long-term sustainability and transparency. The sustainable development of the mining industry is impeded by environmental, structural, and governance-related challenges. Environmental concerns contribute significantly to ecosystem degradation and public health risks. At the same time, weak occupational health and safety standards intensify workplace hazards, compromising social well-being. Socioeconomic tension, including disputes over land use, limited community participation, and unequal distribution of economic benefits, further aggravates societal impacts. Delays in permitting procedures discourage investment in ecologically friendly technologies and make it more difficult to implement sustainability programs. These challenges emphasize the necessity of policy reforms, enhanced stakeholder collaboration, and the integration of sustainable technologies to achieve a balance between economic development and environmental and social responsibilities.

This study has systematically addressed the barriers to sustainable mining development by using an integrative approach such as ISM and MICMAC analysis. The finding will help to provide actionable insights for policymakers and stakeholders, facilitating the design of targeted strategies that not only promote environmentally sustainable practices but also enhance the mining sector's role in national economic development and long-term sustainability. However, some limitations were observed, for example, the barriers have been taken from existing literature and experts' opinions, and have not undergone a statistical procedure due to the unavailability of accurate and comprehensive data.

Conclusion:

This study highlights the critical role of addressing sustainability barriers to promote long-term development in the mining sector of Pakistan, where unregulated resource exploitation poses significant risks to environmental, economic, and social stability. By employing Interpretive Structural Modeling (ISM), the research systematically identified and analyzed key barriers to sustainability, drawing on expert input from mining and environmental domains. The results reveal that weak regulatory enforcement, limited adoption of sustainable technologies, insufficient financial incentives, poor institutional coordination, and lack of stakeholder integration are among the most significant impediments to sustainable mining in Pakistan.

The hierarchical framework developed through ISM offers valuable insights into the interdependencies among these barriers, enabling a deeper understanding of how targeted interventions can generate system-wide improvements. The findings emphasize the need for comprehensive policy reforms, strategic investments in green technologies, capacity building, and stronger governance mechanisms to effectively address sustainability challenges in the sector. This study contributes a structured and context-specific decision-support tool for policymakers and industry stakeholders, facilitating the transition toward a more expand this framework by incorporating dynamic modeling or evaluating the effectiveness of proposed interventions over time.

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