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INTEGRATING A MULTI-FRAME STUDY ON THE ENVIRONMENTAL SUSTAINABILITY STRATEGIES OF MINING-INDUCED-DUST USING PESTLE ANALYSIS

Dust generated during mining operations presents a critical challenge for both occupational health and environmental well-being. Existing literature shows that the assessment of dust generated by mining is addressed from technical and health viewpoints, which results in a limited scope of analysis. To address this issue, this study adopts a broader perspective by evaluating external environmental factors influencing dust management through the PESTLE analysis framework. By encompassing political, economic, social, technological, legal, and environmental dimensions, it offers a comprehensive perspective on dust management, its impacts, and relevant control policies. To gather relevant data, a survey was conducted among individuals with over five years of experience in the mining sector to obtain their perspectives. Our findings indicate a clear consensus among participants regarding the necessity of increased budget allocation for dust control in the mining sector, with an average score exceeding 4.5/5. There's also strong agreement that evaluating mining dust is crucial for strategic planning and promoting sustainable mining practices. However, the survey results reveal uncertainty in technological and legal aspects, with average scores around 3/5. Professionals believe that dust control technologies currently used in mining are behind those in other industries. Furthermore, a significant portion still faces knowledge gaps regarding legal regulations. This highlights critical areas where further investment and comprehensive information are needed. The insights will help strategic planners identify gaps in technology and regulation. By focusing efforts on improving knowledge, technological capacity, and regulatory frameworks, resources can be better allocated to enhance dust control measures and support sustainable mining practices.

Keywords: Mining dust; pm; PESTLE analysis; strategic planning; environmental sustainability

1. Introduction

Mining activities generate substantial amounts of dust at every stage of operation [1-3]. The emitted dust can cause respiratory diseases, cardiovascular problems [4-6], as well as allergic and

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irritative reactions [5,7]. Mineral dust produced during mining operations can lead to long-term, irreversible health conditions [8,9]. In addition to its health impacts, dust can impair photosynthesis in plants, contaminate water sources, and significantly reduce the efficiency of machinery [10,11]. It also poses a critical threat to occupational safety by reducing visibility, necessitating strict control measures [12-14]. The wide-ranging impacts of mining dust may have both direct and indirect long-term consequences for an organisation, as it influences worker health and safety, equipment lifespan, environmental alignment, and overall operational performance. In 2024, the number of mining operation licenses in Türkiye reached 9,873, while exploration licenses totalled 4,403 [15]. According to statistics published by the General Directorate of Mining and Petroleum Affairs, there were 7,186 active mining workplaces in Türkiye in 2023, employing 143,504 workers. Moreover, data from the European Union's Mining and Quarrying Statistics for 2022 indicate that there were 17,033 mining enterprises across EU member states, employing around 371,000 people [16]. A comparison of these figures shows that Türkiye operates a mining sector that is approximately one-third the size of the EU's in terms of both the number of enterprises and workers. This reveals not only the significant scale of Türkiye's mining industry but also its strong growth potential, especially when considering the high number of existing operation licenses. With 143,504 workers in Türkiye and 371,000 in the EU directly exposed to mineral dust hazards, the scale of risk is substantial. In a sector that directly affects such a large population, the need for strategic planning around mining dust management becomes an unavoidable necessity. Considering the wide-ranging and lasting impacts of mining dust on the large number of affected workers, the PESTLE analysis, recognised for its multi-frame analytical approach, offers a powerful lens to identify the challenges and guide sustainable solutions. The PESTLE analysis (Political, Economic, Socio-cultural, Technological, Legal, and Environmental) is a tool in long-term strategic planning, offering a multi-dimensional perspective for examining complex issues. It helps identify priority areas for investment and assess the sustainability of policies. Research on mining dust has primarily focused on its technical and health dimensions, PESTLE's strength lies in its ability to incorporate factors beyond these limited areas. Its perspective provides a deeper understanding of environmental implications, enhancing strategic decision-making. It streamlines the identification of critical factors, aids in developing action plans, and facilitates setting performance-driven goals [17].

In this study, an integrated multi-frame approach by utilising PESTLE analysis through a survey methodology was employed to examine environmental sustainability strategies concerning mining-induced dust. The survey participants were selected from professionals with extensive experience in the sector; given their responsibilities across political, economic, socio-cultural, and environmental areas, their views are considered well-informed and reliable. Consequently, the survey method was selected as the most suitable means to capture a refined and comprehensive synthesis of expert perspectives. The survey method, along with its descriptive statistical evaluation, internal consistency, and reliability analyses, as well as a thorough examination and interpretation of the respondents' answers, is systematically detailed in the subsequent sections.

2. Literature review

Mining engineering is recognised as one of the oldest branches of engineering. Since ancient times, the mining industry has experienced two major turning points, industrialisation and mechanisation, followed by technological advancements emerging after the 1960s. In the last century, the mining sector has entered a new phase of transformation, characterised by strategic planning, environmental considerations, and sustainability concepts. Accordingly, numerous novel analytical approaches have been incorporated into the literature over the past fifty years to evaluate mining activities. Among these, the PESTLE analysis stands out as a powerful tool demonstrating a central role in strategic planning and efforts to gain advantage. Originating from Aguilar's [18] environmental scanning approach, the PESTLE framework, with its six components, was developed post 1980s and gained widespread adoption during the 1990s. This analysis is widely employed to examine macro-environmental factors relevant to strategic planning and to assess their potential impacts [19-21].

PESTLE analysis is a highly effective tool and widely utilised in strategic planning and decision-making processes across a diverse range of sectors such as construction, economics, and textiles. For instance, Zavvari et al. [22] offer valuable insights into the factors influencing decision-making on robotics adoption in construction organisations in New Zealand, underlining the tool's relevance in technology-driven transitions. Nunes et al. [23] employed PESTLE analysis to conduct a comprehensive multi-dimensional evaluation of alternative energy sources within the textile sector, demonstrating its applicability in sustainability-focused energy strategies. In the context of post-conflict industrial recovery, Kondratenko et al. [24] proposed a practical roadmap for implementing an adaptive management system in Ukraine's manufacturing sector through the lens of PESTLE analysis. Ulubeyli and Kazanci [25], on the other hand, highlighted how macroeconomic conditions shape the dynamics of the green building industry, emphasising the analysis's utility in environmentally driven development. Furthermore, Lopez-Dominguez and Levya [26] presented a case study illustrating how political, economic, social, and technological factors collectively influence the food industry, thereby underscoring PESTLE's capacity to capture complex external forces across diverse value chains.

In the mining sector, the growing use of PESTLE analysis reveals its expanding influence across subfields and operational contexts. Tibilov et al. [27], for example, applied PEST analysis to guide strategic and long-term decision-making for project development at the Nivensky mine, highlighting its role in resource-based project planning. Expanding on this strategic perspective, Wu et al. [28] integrated PEST with SWOT analysis to identify internal and external factors hindering the advancement of green mining practices, ultimately contributing to the formulation of more effective sustainability strategies. Espinolla et al. [29] further demonstrated the method's value in examining technological and environmental developments in deep-sea mining, employing bibliometric and PESTEL analyses to evaluate implications for sustainable development. Domaracká et al. [30] combined PEST and SWOT analyses to assess both the external environment and customer relations of mining companies, offering a more holistic view of organisational positioning. In a similar vein, Basu et al. [31] evaluated the impacts of corporate social responsibility practices in an Australian gold mining operation through PESTEL analysis, showcasing its utility in assessing the broader societal dimensions of mining activities. Finally, Bak et al. [32] investigated the structural factors affecting Poland's raw materials sector using PESTEL analysis, revealing the key dynamics shaping industrial growth and sectoral transformation.

In addition to its applications across various sectors, PESTLE analysis has also been employed in the field of air quality, offering valuable insights into the broader environmental and policy-related dimensions of pollution control. For example, Gheibi et al. [33] conducted a comprehensive analysis emphasising the dominant role of economic factors in managing urban air pollution. Similarly, Kokkinos and Nathanail [34] applied a PESTEL-based fuzzy cognitive mapping approach in the context of Greece, aiming to reduce CO_2 emissions from urban mobility and thereby improve air quality. Mendoza et al. [35] examined carbon capture strategies from 2007 to 2018 using PEST analysis, considering political, economic, social, and technological dimensions of emission mitigation.

Air pollution is a critical global health issue, linked to as many as 8.8 million deaths annually, most of which result from cardiovascular conditions aggravated by poor air quality [36]. The mining sector, in particular, stands out as one of the industries with the highest levels of dust exposure [3,37]. Given this context and the fact that PESTLE analysis has been increasingly adopted in recent years to address complex sector-specific challenges, it has emerged as a widely accepted and methodologically robust framework within the academic literature. Taking into account the prevalence and effectiveness of PESTLE analysis, as well as the identified gaps in the literature related to this specific research area, the current study adopts PESTLE as its primary analytical approach.

3. Methods

Within the scope of this study, a structured questionnaire was administered to sector professionals, specifically mining engineers with a minimum of five years of professional experience, to evaluate both the perceived importance and the current level of impact of PESTLE analysis factors.

A five-point symmetric 'Likert' scale was employed for this evaluation [36] where the response options were defined as follows: 1: Strongly Disagree; 2: Disagree; 3: Neutral (Neither agree nor disagree); 4: Agree; 5: Strongly Agree. Participants were asked to evaluate a series of statements categorised under each PESTLE dimension, as outlined below:

3.1. Question on Political Aspect (P)

Q1.P: The assessment of dust generated by mining activities provides strategic guidance for planning and sustainable mining policies.
Q2.P: Improvements are needed in dust control measures related to mining activities.
Q3.P: The research and development budgets allocated nationally and globally for the investigation and enhancement of dust mitigation technologies in mining are sufficient.

3.2. Question on Economical Aspect (E)

Q4.E: The investment and operational costs of dust control systems (e.g., filters, water spraying systems, enclosed production units) in the mining sector are high.
Q5.E: A greater budget should be allocated for dust mitigation in the mining industry.

3.3. Question on Socio-cultural Aspect (S)

Q6.S: The mining sector is adequately aware of dust and its associated impacts.
Q7.S: Local communities have concerns regarding dust generated by mining activities.
Q8.S: Local communities have corporate social responsibility expectations related to dust control.

3.4. Question on Technological Aspect (T)

Q9.T: Dust control technologies used in the mining sector are comparable in adequacy to those applied in other industries.

Q10.T: Current technologies for dust control in mining sufficiently meet the sector's operational needs.

Q11.T: The technologies used in personal protective equipment (PPE) for dust exposure in mining are adequate.

3.5. Question on Legal Aspect (L)

Q12.L: I am sufficiently informed about national and international regulations regarding dust from mining activities.

Q13.L: Protective measures against dust are adequately implemented in the mining sector.

Q14.L: National and international standards on dust emissions from mining operations are sufficient.

3.6. Question on Environmental Aspect (E)

Q15.En: Dust from mining activities has adverse effects on the environment, including vegetation, water resources, and air quality.

Q16.En: Among the environmental impacts of mining activities, dust ranks among the most significant.

The responses were analysed using descriptive statistical methods. For this purpose, arithmetic mean, standard deviation, coefficient of variation (percentage standard deviation), and variance values were calculated and interpreted as key descriptive statistics.

Among these indicators, the mean serves as a measure of central tendency for quantitative data and was calculated using the formula shown in Eq. (1) below:

$$\underline{x} = \frac{1}{n}\left(x_1 + x_2 \ldots + x_n\right) = \frac{1}{n}\sum_{i=1}^{n} x_i \tag{1}$$

Where $\underline{x}$ is the arithmetic mean value, and n is the total number of observations.

Standard deviation is a measure of data dispersion, defined as the square root of the variance. It is calculated using Eq. (2). The percentage standard deviation is computed with Eq. (3), and the variance is calculated using Eq. (4).

$$s = \sqrt{\frac{1}{n-1}\sum_{i=1}^{n}(x_i - \underline{x})^2} \tag{2}$$

$$s(\%) = \frac{x}{s} \cdot 100 \tag{3}$$

$$v = \frac{1}{n-1}\sum_{i=1}^{n}(x_i - \underline{x})^2 \tag{4}$$

Where, S is the standard deviation, n is the number of data points in the sample, and $\underline{x}$ is the arithmetic mean value of the sample.

Descriptive statistics have limited reliability in survey evaluations due to their sensitivity to extreme values. Therefore, in this study, internal consistency reliability analysis was performed using Cronbach's Alpha to analyse the survey data more robustly. The calculation of Cronbach's Alpha is based on Eq. (5) [38].

$$\alpha = \left(\frac{k}{k-1}\right)\left(\frac{\sigma_y^2 - \sum\sigma_i^2}{\sigma_y^2}\right) \tag{5}$$

Where, α is the Cronbach's Alpha coefficient, k denotes the number of items (questions) on the scale, σ_y^2 is the variance of the total test scores (the variance of the sum of all items), σ_i^2 is the variance of each item (question) (i = 1, 2, ..., k) and $\sum\sigma_i^2$ is the sum of the variances of all items. The scale presented in TABLE 1 is used to interpret the obtained Cronbach's Alpha value [38].

TABLE 1

Cronbach's Alpha value evaluation scale

α value	Evaluation
≥0.90	Excellent
0.80-0.89	Very good
0.70-0.79	Acceptable
0.60-0.69	Marginal
<0.60	Not reliable

A non-parametric statistic, Kendall's Coefficient of Concordance (W), is used to measure the degree of agreement among multiple evaluators who rank or rate a set of items. It quantifies the overall consensus within the group, where higher values indicate stronger concordance. In this study, Kendall's W was applied to evaluate the consistency of expert judgments across the survey items, providing an objective measure of internal agreement [39,40].

4. Results and discussion

In the study, a total of 16 questions were presented to 24 experts in mining operations to gather their views on political, economic, socio-cultural, technological, legal, and environmental aspects of the topic, to shed light on future strategies. TABLE 1 presents the question numbers according to their content, along with the mean scores, standard deviations, coefficient of variation (% Std. Dev.), and variance values of the participants' responses to each question. These indicators reveal the degree of consistency in the participants' answers and the concentration level of the overall trend, while the variance value serves as a parameter used in calculating Cronbach's

Alpha to assess the homogeneity and reliability of the survey. The mean values reflect the general tendency of participants' responses to the respective questions, whereas the standard deviation provides information on the dispersion of the answers.

TABLE 1

Summary of descriptive statistics for participant responses

Question No	Question Content	Mean Value	Std. Deviation	Std. Deviation (%)	Variance
1.P	Political	4.4	0.65	14.80	0.43
2.P		4.9	0.28	5.74	0.08
3.P		1.9	0.78	40.46	0.60
4.E	Economical	2.6	1.06	40.21	1.11
5.E		4.6	0.50	10.83	0.25
6.S	Socio-Cultural	1.9	0.83	43.29	0.69
7.S		4.6	0.73	15.94	0.53
8.S		4.5	0.66	14.76	0.43
9.T	Technological	2.2	0.95	42.91	0.91
10.T		3.0	0.98	32.60	0.96
11.T		3.0	0.98	32.60	0.96
12.L	Legal	3.2	0.98	30.45	0.95
13.L		2.2	0.92	42.32	0.84
14.L		2.8	1.03	37.53	1.07
15.En	Environmental	4.3	0.76	17.57	0.58
16.En		3.2	1.09	34.43	1.19
Cronbach's Alpha (α) : 0,96					

Some questions in the survey were presented using a reverse-coded scale. In other words, for certain questions, a response value of 5 indicated the most negative condition, whereas for others, the value 1 represented the most negative condition. This approach aims to assess whether the survey was completed thoughtfully rather than carelessly or without reading. In the reverse-coded questions, the values were recoded as follows: 1 corresponds to 5, 2 corresponds to 4, 4 corresponds to 2, and 5 corresponds to 1. The questions with reverse coding in this survey are numbers 3, 6, 9, 10, 11, 12, 13, and 14.

When calculating Cronbach's alpha, the reverse-coded responses were converted back to their corresponding values on the standard scale. Following these adjustments, the Cronbach's alpha coefficient was calculated as 1.07, indicating excellent internal consistency. According to this value, the scale is considered highly reliable.

During the reliability analysis, all reverse-coded items were converted to their corresponding values on the standard scale to ensure accurate data coding. Cronbach's alpha was then recalculated using a Statistical Tool [41]. After this correction, the revised Cronbach's alpha value was found to be 0.96, indicating excellent internal consistency and acceptable reliability of the scale.

A detailed evaluation of the survey results is presented in the subsequent sections of the article. The percentage distribution of responses for each question, along with the average scores, are grouped and reported separately for each category. During the interpretation of participants' average responses, values above 3.5 and below 2.5 were considered indicative of consensus. Survey legends are ordered from the most frequently given response to the least, from top to bottom.

4.1. Political Analysis

To identify insights related to strategic planning approaches, the distribution of professionals' responses to the relevant questions is presented in Figs. 1a-1c.

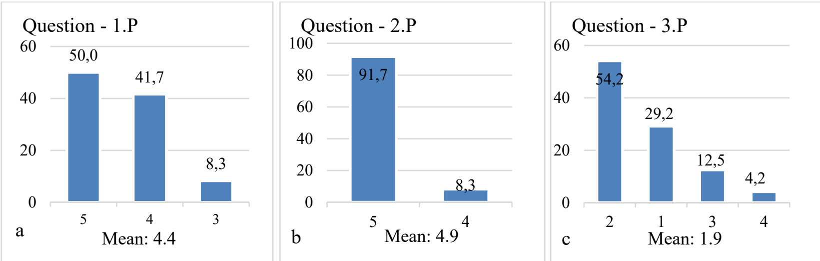

Fig. 1. Proportional distribution of survey responses for the political aspect
(a: Response to Question 1.P; b: Response to Question 2.P; c: Response to Question 3.P)

According to the survey analysis, professionals expressed strong agreement, with an average score of 4.4/5 that assessing dust generated by mining activities serves as a strategic guide for planning and sustainable mining practices (Question 1.P). In addition, all participants agreed, with an average score of 4.9 out of 5, that improvements are needed regarding dust-related issues in mining operations (Question 2.P), and that the current research budget allocated in Türkiye and globally is insufficient (Question 3.P). These findings suggest a consensus among professionals that there is a clear need for improvement in strategic planning related to dust management in the mining sector. Furthermore, the shared view that improvements are urgently needed, coupled with the perception that current R&D funding is inadequate, highlights specific areas where strategic planning should be strengthened.

4.2. Economical Aspect

In this section, the following questions were asked to assess the role of dust control measures within the economics of the mining sector. The distribution of professionals' responses to these questions is presented in Figs. 2a-2b.

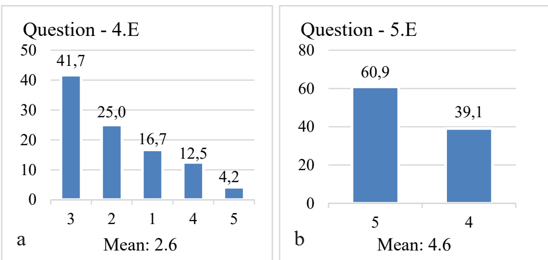

Fig. 2. Proportional distribution of survey responses for the economic aspect
(a: Response to Question 4.E; b: Response to Question 5.E)

The professionals participating in the survey disagreed with the notion that the investment and operational costs of dust control systems (such as filters, water spraying systems, and enclosed production) are high in the mining sector (Question 4.E), with an average of 2.6/5 score. However, there was strong consensus, reflected by an average score of 4.6/5, that a larger budget should be allocated for dust mitigation efforts in the mining industry (Question 5.E). These results highlight the necessity of incorporating dust mitigation efforts into long-term strategic frameworks, reinforcing their importance not only from a health and environmental perspective but also from a financial and operational standpoint.

4.3. Socio-Cultural Aspect

To understand the perceptions of people living in mining areas regarding mine-related dust, the proportional distribution and mean scores of professionals' responses to the related questions are presented in Figs. 3a-3c.

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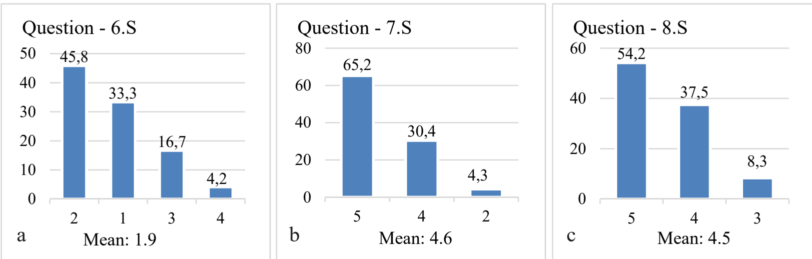

Fig. 3. Proportional distribution of survey responses for the socio-cultural aspect (a: Response to Question 6.S; b: Response to Question 7.S; c: Response to Question 8.S)

Analysis of the survey responses indicates a strong consensus among professionals that the mining sector lacks sufficient awareness regarding dust and its associated impacts (Mean: 1.6/5) (Question 6.S). Additionally, there is agreement that local communities have significant concerns about dust generated by mining activities (Mean: 4.6) (Question 7.S), and that they hold clear expectations for corporate social responsibility initiatives related to dust management (Mean: 4.5/5) (Question 8.S).

These results highlight the need for stronger internal awareness in the mining sector about dust-related risks. At the same time, community concerns and expectations for social responsibility show that dust management is not only a technical issue but also a social one. Strategic plans should include training, communication, and community-based dust control actions to support long-term project success.

4.4. Technological Aspect

In order to assess the current state of dust control technologies and whether these technologies meet the needs of the sector, the proportional distribution and mean values of professionals' responses to the relevant questions are presented in Figs. 4a-4c.

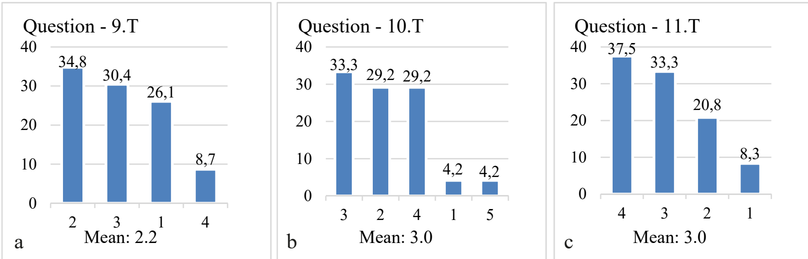

Fig. 4. Proportional distribution of survey responses for the technological aspect
(a: Response to Question 9.T; b: Response to Question 10.T; c: Response to Question 11.T)

Based on the survey responses, professionals believe that dust control technologies used in the mining sector are less advanced compared to those employed in other industries (Question 9.T). Regarding the effectiveness of current technologies in meeting the sector's specific needs (Question 10.T), and the adequacy of personal protective equipment technologies used for dust exposure (Question 11.T), responses were generally neutral.

It is noteworthy that responses across all three questions under the technological aspect largely centred around the neutral (neither agree nor disagree) point (mean score ≈ 3), suggesting either uncertainty or a lack of sufficient information among professionals concerning the current state of technology in the sector.

4.5. Legal Aspect

To assess professionals' views on the current legal regulations regarding dust control in the mining sector, the proportional distribution and average scores of their responses to the following questions are presented in Figs. 5a-5c.

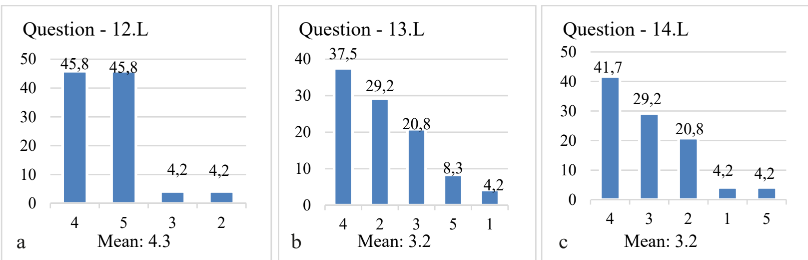

Fig. 5. Proportional distribution of survey responses for the legal aspect
(a: Response to Question 12.L; b: Response to Question 13.L; c: Response to Question 14.L)

According to the survey results, 45.9% of participants reported having sufficient knowledge of national and international regulations related to dust generated by mining activities, responding with a score of 4 or 5, while 29.2% were uncertain, and 25.1% indicated they lacked such knowledge (Question 12.L). This suggests that approximately half of the respondents are aware of the issue, but a significant portion still faces knowledge gaps or uncertainty.

Regarding protective measures against dust in the mining sector, participants generally agreed that these measures are insufficiently implemented, with an average score of 2.2 out of 5 (Question 13.L). Additionally, the belief that national and international standards for dust emissions in mining activities are adequate is not widely held, with an average score of 2.8 out of 5 (Question 14.L).

4.6. Environmental Aspect

Regarding the environmental impacts of mining activities, the following survey questions focused specifically on the effects of dust were posed to the target group. The proportional distribution and mean scores of participants' responses to these questions are presented in Figs. 6a-6b.

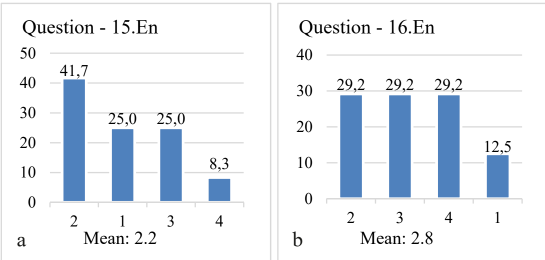

Fig. 6. Proportional distribution of survey responses for the environmental aspect
(a: Response to Question 15.En; b: Response to Question 16.En)

Participants overwhelmingly agreed (mean score: 4.3 out of 5) that dust generated by mining activities has negative impacts on the environment, including vegetation, water resources, and air quality (Question 15.En). However, they did not widely perceive dust as the most significant among the various environmental impacts caused by mining, with a moderate mean score of 3.2 out of 5 (Question 16.En).

As shown in the charts, the experts' responses were generally consistent across the items. Since the majority of participants provided similar ratings and the response variance was relatively low, Kendall's coefficient of concordance (W) was applied as a non-parametric measure to assess the internal consistency of the expert evaluations. The obtained Kendall's coefficient of concordance (W = 0.61) further confirms a substantial level of agreement among participants.

5. Conclusions

This study offers crucial insights into dust management in the mining sector, highlighting its complex and multifaceted nature, which includes technical, political, economic, socio-cultural, technological, legal, and environmental dimensions. The findings reveal strong consensus among professionals on environmental impacts, socio-cultural concerns, policies, and economic investments related to mining dust. However, uncertainties remain in technological capabilities and legal frameworks, highlighting critical gaps that require further attention.

In this context, recent global research trends provide a valuable perspective on future directions in dust management and environmental monitoring. Modern dust-control systems increasingly focus on preventive surface treatments, such as super-hydrophobic coatings, and AI- and IoT-based real-time monitoring that enable dynamic and data-driven operational decisions [42-44]. The adoption of AI-based monitoring frameworks enhances pollutant detection accuracy and predictive analytics capabilities, providing actionable insights for environmental management and policy development [45,46]. Furthermore, UAV-based photogrammetry and LiDAR technologies are being widely applied in mining and construction for high-resolution assessment of dust emissions, volumetric analysis, and atmospheric monitoring [47-49]. These developments collectively reflect the global transition toward intelligent, automated, and data-informed dust-control strategies, aligning closely with the future direction of sustainable mining operations.

In light of both the present findings and these emerging global trends, mining companies are advised to adopt interdisciplinary strategies, invest more in advanced dust control technologies, strengthen community-focused communication, and ensure full compliance with regulations. Such integrated efforts are essential to enhance dust management effectiveness and promote sustainable mining practices.

To address existing uncertainties and strengthen dust control measures, future research could explore reducing the uncertainties found in the technological and legal areas. This can be achieved through targeted field studies and investigations covering different mining activities, such as mineral processing and mining methods. Expanding similar studies across different regions and conducting long-term environmental impact assessments will further support informed decision-making and strategic planning in the sector. Additionally, participants' feedback offers valuable insights. They emphasised that mining dust can be controlled through personal protective equipment, site watering, and dust suppression systems in facilities, and called for increased dust monitoring by relevant authorities. Furthermore, it was stressed that environmentally friendly practices should be driven not only by legal requirements but also by a sense of responsibility towards future generations.

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