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Assessment of Environmental Consequences in a Mine Tailings Dam Using the Fuzzy Similarity Aggregation Method

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ABSTRACT

Wastes generated from the processing of metallic minerals contain significant amounts of heavy metals. Mine tailings dams, particularly those associated with metal mines, are major sources of pollution that pose potential risks to both the environment and human health. Therefore, it is essential to identify the potential consequences associated with mine tailings dams to mitigate or eliminate their environmental risks. This paper aims to assess and prioritize the environmental consequences of the tailings dam at the Qaleh Zari copper mine in Iran. To achieve this, fuzzy probabilities of consequences were calculated using the Similarity Aggregation Method (SAM) within a fuzzy environment. The results indicate that dust dispersion and air pollution are among the most probable environmental consequences posed by the mine tailings dam. Consequently, appropriate control measures must be implemented to prevent and manage dust dispersion from the tailings dam area. The results of this study support the development of practical policies and control measures to protect the environment surrounding the mine tailings dam.

KEYWORDS

Mine tailing dam, environmental consequences, Similarity Aggregation Method, Qaleh Zari copper mine

I. INTRODUCTION

Mines play a significant role in the economy of any country. Therefore, proper planning in the exploitation of mineral resources is essential to generate appropriate added value across various economic sectors. Although mining offers numerous social and economic benefits, its destructive and long-term impacts on the environment and public health cannot be overlooked. Mineral processing, particularly in metal mines, can produce large quantities of waste containing heavy metals. If this waste is released into the environment without proper control, it can cause widespread ecosystem pollution. Tailings dams are constructed to manage, collect, and store mine waste and wastewater generated from mineral processing activities. However, hazardous pollutants in the waste and acidic drainage stored in tailings dams have the potential to cause significant environmental harm (Kossoff et al., 2014; Darban et al., 2018; Garcés et al., 2025).

The concentration of elements in tailings from mineral processing often exceeds the permissible limits set by regulatory standards. Such tailings dams represent significant environmental concerns associated with mining activities. (Adewuyi et al., 2024). Mineral wastewater resulting from heavy metal leaching contains toxic substances that, by infiltrating the environment surrounding the dam, cause pollution of water, soil, and air, ultimately threatening land and natural resources (Zhao et al., 2023; Rahimdel and Aryafar, 2024). Therefore, assessing and prioritizing the environmental impacts of mining tailings dams is a critical concern associated with these structures.

Currently, numerous researchers have evaluated the adverse effects of mining tailings dams. Liu et al. (2015) investigated the risk of contamination of Beijing's drinking water source from the Zhangjiakou tailings dam in China. The water pollution risk analysis in this study identified one contaminated source and two catchments with the highest risk of contamination. Additionally, the most hazardous sources of contamination were also identified. Vaezi and Jowdat Saidabad (2017) investigated the potential for pollutant leakage from the abutments of the Songun copper mine tailings dam in Iran. The study utilized water sampling results, chemical analyses of the samples, and assessments of the permeability of the abutment rock mass and riverbed. According to the findings, there is no risk of leakage at the current dam level; however, with increasing hydraulic pressure, leakage may occur, necessitating the implementation of special precautions. Kheirkhah et al.,

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(2020) studied the environmental risks associated with the tailings dam of the Songun copper mine (Iran) were assessed using the FMEA method. In this study, the potential consequences of the tailings dam were categorized into three groups: physico-chemical, biological, and socio-economic. Subsequently, the risk of each consequence was evaluated. According to the results, landscape risks, seismic risks, and noise pollution risks were identified as the consequences with the highest risk scores, respectively. Nišić (2021) evaluated the risk of dam failure at a copper and gold mine in western Yugoslavia. This study assessed the probability of dam failure by examining the safety factor, predicting various dam failure and flood flow scenarios, and analyzing the consequences of failure, including human casualties, extent of damage, and the overall impact assessment. Based on the findings, the risk of dam failure was determined to be moderate and acceptable.

In another study, Zheng (2022) analyzed the risk of tailings dam failure by combining the Decision-Making Trial and Evaluation Laboratory (DEMATEL) method with the Modified Interpretive Structural Model (MISM). The factors influencing tailings dam failure were evaluated from four perspectives: personnel, management, environment, and system. DEMATEL was employed to examine the relationships among these factors and to identify key causal elements. Additionally, the MISM method was used to classify the causal factors and determine the interrelationships among risk factors. The study concluded that system risk is the most significant factor influencing dam failure. Furthermore, investigating dam height and seepage line depth is essential to enhance dam stability. Gao et al. (2025) proposed a comprehensive evaluation index system for assessing dam failure risk during operation. The risk evaluation model was based on the fuzzy comprehensive evaluation method. This model was applied and analyzed at the Shouyun iron mine and its tailings pond in Beijing, China. Based on the research findings, preventive measures and scientific controls were proposed and discussed across four key areas: personnel risk prevention and control, inherent risks of tailings ponds, environmental risks, and management risks.

The Qaleh Zari copper mine generates substantial amounts of mineral waste daily in the form of slurry. This slurry, produced by the mineral processing facilities, contains high concentrations of heavy metals, including copper, lead, and zinc. Given the potential for these wastes to impact a large area, it is essential to assess the environmental risks associated with the tailings dam. However, limited research has been conducted to identify and classify the environmental hazards of the tailings dam at the Qaleh Zari mine. The present study aims to identify and prioritize the environmental consequences of the Qaleh Zari copper mine tailings dam using the Similarity Aggregation Method (SAM). Reviewing the paper mentioned above revealed that the application of SAM in identifying the most probable environmental consequences of mine tailings dams, with a focus on assessing the probability of these consequences, has not been reported. SAM is a technique for aggregating fuzzy expert opinions by considering the degree of consensus, with the goal of assessing the probability of events occurring under conditions of uncertainty. Traditional prioritization methods often struggle to aggregate diverse individual opinions into a single comprehensive view. Fuzzy sets address this issue by mimicking human reasoning (Omidvar and Niroomand 2015). This approach first creates a fuzzy surface (a gradual change) based on fuzzy membership functions for evaluation, then calculates the sum of opinions, ultimately providing a more reliable output compared to classical methods.

II. Research Methodology

In this study, fuzzy logic and the Similarity Aggregation Method (SAM) were employed to assess the probability of occurrence of various environmental consequences associated with the Qale Zari copper mine tailings dam. This method calculates the probability of events by considering both the relative importance of experts and the degree of consensus among their opinions. Triangular and trapezoidal fuzzy numbers are the most commonly used fuzzy numbers. In this study, trapezoidal fuzzy numbers (as shown in Table 1) were utilized because they can represent opinions over a broader range, thereby providing a more accurate depiction of uncertainties (Abbasi Shureshjani et al., 2024; Rani and Dhanasekar, 2025).

Table 1. Linguistic variable terms and their corresponding trapezoidal fuzzy numbers (Ramzali et al., 2015)

Linguistic scale	Fuzzy number
Very Low (VL)	(0,0,0.1,0.2)
Low (L)	(0,0.1,0.2,0.3)
Medium Low (ML)	(0.2,0.3,0.4,0.5)
Medium (M)	(0.4,0.5,0.5,0.6)
Medium High (MH)	(0.5,0.6,0.7,0.8)
High (H)	(0.7,0.8,0.8,0.9)
Very High (VH)	(0.8,0.9,1,1)

Since expert opinions can vary due to factors such as experience and education level, it is necessary to calculate the weight of each expert in the first step. To achieve this, each expert's characteristics are assigned numerical scores according to Table 2.

The steps of the SAM method for evaluating the probability of each event are described as follows (Guo et al., 2020):

Step 1. Calculation of the Degree of Similarity in Experts' Opinions

In the first step of the SAM method, the degree of similarity between experts' opinions is calculated. To achieve this, the experts' opinions are compared pairwise. Suppose the values $\widetilde{R_u} = (a_1, a_2, a_3, a_4)$ and $\widetilde{R_v} = (b_1, b_2, b_3, b_4)$ are standard trapezoidal fuzzy numbers representing the opinions Eu and Ev. In this case, the similarity degree between these two fuzzy numbers ($S(\widetilde{R_u}, \widetilde{R_v})$) is obtained using the following equation.

Table 2. Classification of experts and their corresponding scores (Guo et al., 2020)

Parameter	Classification	Score
Professional position	Manager	10
	Academic professor	8
	Engineer	6
	Technician	4
	Worker	2
Work Experience	> 30	10
	21-30	8
	16-20	6
	11-15	4
	< 5	2
Education level	Ph.D.	10
	Master	8
	Bachelor	6
	Diploma	4
	School level	2
Age	> 50	8
	41-50	6
	31-40	4
	< 30	2

$$S(\widetilde{R_u}, \widetilde{R_v}) = 1 - \frac{1}{4}\sum_{i=1}^{4} | a_i - b_i| \tag{1}$$

Step 2. Calculation of the Degree of Relative Agreement Among Experts' Opinions

The degree of agreement between experts' opinions ($WA(E_u)$) and the degree of relative agreement between experts' opinions ($RA(E_u)$) are calculated using Eq.s (2) and (3), respectively.

$$A(E_u) = \frac{\sum_{\substack{v=1 \\ u\neq v}}^{M} W(E_v).S(\widetilde{E_u}, \widetilde{E_v})}{\sum_{\substack{v=1 \\ u\neq v}}^{M} W(E_v)} \tag{2}$$

$$RA(E_u) = \frac{WA(E_u)}{\sum_{u=1}^{M} WA(E_u)} \tag{3}$$

In this relation, $W(E_u)$ and $W(E_v)$ represent the weights of experts Eu and Ev, respectively, and M denotes the total number of experts. It is necessary to provide an explanation that for each expert, the degree of importance ($W(E_u)$) is calculated by considering the weighting scores of expert factors ($WS(E_a)$) as follows:

$$W(E_u) = \frac{WS(E_u)}{\sum_{u=1}^{M} WS(E_u)} \tag{4}$$

Step 3. Calculation of the agreement coefficient between experts' opinions

The coefficient of agreement between experts' opinions is calculated using the following equation.

$$CC(E_u) = \beta.w(E_u) + (1-\beta).RA(E_u) \tag{5}$$

In this equation, the coefficient β is the relaxation factor, with a value ranging between zero and one. This coefficient plays a crucial role in balancing the degree of relative agreement (RA) and the importance weight (W) assigned to each expert. Since β indicates the relative importance of the expert's weight versus the degree of agreement among experts, its value should be determined by the decision maker based on their preferences.

Regarding Hsu and Chen (1996), the relaxation factor is a critical parameter in balancing the relative degrees of agreement and the importance weight (W) assigned to an expert. This factor is determined by decision-makers based on their preferences and serves as an appropriate measure to evaluate the relative value of an expert's opinion. A higher relaxation factor increases the influence of the expert's agreement. In this study, the coefficient β was set to 0.5 to ensure that the weight of the experts and their collective agreement were equally represented in the calculations.

Step 4. Calculation of the total of experts' opinions

The final fuzzy number (overall fuzzy number) is calculated by aggregating the experts' opinions using Eq. (6).

$$\tilde{E} = \sum_{u=1}^{M} CC(E_u).\tilde{E}_u \tag{6}$$

Step 5. Defuzzification of Expert Judgments

The purpose of defuzzification is to convert a fuzzy set of theories (FST) into a fuzzy possibility score (FPS). Various methods are used for defuzzification, including the Center of Area (COA) and Center of Gravity (COG) methods, the Center of Maxima (COM) method, the Center of Sums (COS) method, and the Center of Average Weighted Centers method (Sugeno and Kang, 1986). In this paper, the CoA fuzzification technique is used according to the following equation to defuzzify two fuzzy numbers (a_1, a_2, a_3, a_4) and (b_1, b_2, b_3, b_4).

$$X^* = \frac{1}{3}\frac{(a_4+a_3)^2 - a_4a_3 - (a_1+a_2)^2 + a_1a_2}{a_1+a_2+a_3+a_4} \tag{7}$$

Step 6. Converting fuzzy possibility to fuzzy probability

To convert fuzzy possibility into fuzzy probability, the relationship presented by Onisawa (1988) is employed, as shown in the following equations.

$$Pr = \begin{cases} \frac{1}{10^k}, & FPS \neq 0 \\ 0, & FPS = 0 \end{cases} \quad (8)$$

$$k = \left[\left(\frac{1 - FPS}{FPS}\right)\right]^{\frac{1}{3}} \times 2.301 \quad (9)$$

Where, Pr is the failure probability, FPS is the crisp failure possibility, and k is a constant representing the safety criterion based on the lower bound of the error rate and the error rates of a routine.

III. Results and discussion

The Qaleh Zari copper mine is located 180 km southwest of Birjand in South Khorasan Province, Iran, adjacent to the village of Qaleh Zari. The deposit is of the vein type, with vein widths ranging from 0.5 to 7 meters and slopes between 80 and 85 degrees. Mining is conducted using the underground storage method. The Qaleh Zari copper mine processing plant operates with a nominal capacity of 450 tons per day to concentrate copper ore. Mineral processing is performed by flotation, and the effluent from the drum filter is discharged into the tailings dam after clarification and removal of suspended particles. Since significant amounts of mine drainage are produced daily in the form of slurry, and this effluent is released onto the plain, affecting a wide area, there is a risk of its infiltration into the lower soil layers and contamination of groundwater in the region. Consequently, this poses a threat to the physical environment of the mining area, including vegetation, wildlife, and mine workers.

This section evaluates the potential environmental consequences associated with the tailings dam using the SAM approach. Initially, the most significant environmental consequences related to the tailings dam were identified through a literature review of scientific reports and expert judgment. These consequences include the potential for landslides around the dam (Q1), slope instability (Q2), risk of flooding due to increased tailings volume (Q3), dam erosion (Q4), changes in surface water flow direction (Q5), changes in groundwater flow direction (Q6), wind-driven dust dispersion and air pollution (Q7), unpleasant odors from the tailings dam (Q8), sedimentation and settling of tailings (Q9), soil contamination in the dam area (Q10), surface water contamination (Q11), groundwater contamination (Q12), animal mortality and threats to wildlife (Q13), loss of wildlife habitat (Q14), degradation of aquatic ecosystems (Q15), noise pollution (Q16), pollution and threats to agricultural soil (Q17), damage to mining facilities and buildings (Q18), creation of an undesirable landscape (Q19), and threats to the health and safety of indigenous populations (Q20).

To determine the probability of occurrence for each environmental consequence of the mine tailings dam, questionnaires were developed and distributed to a group of experts, including seven specialists from the Qaleh Zari copper mining and processing unit. It is noted that previous studies on the optimal number of experts involved in group decision-making indicate that the ideal group size ranges from 3 to 8 individuals (Emmerling and Rooders 2022; Hashmi et al., 2023). Upon collecting the completed questionnaires, the weight of each expert was calculated based on the indicators presented in Table 2. Fuzzy numbers corresponding to linguistic terms were then identified and used to compute fuzzy probabilities, as detailed in the second part of the article.

To assess the probability of risk occurrence, the first step involved calculating the degree of similarity among the experts' opinions for each risk. Subsequently, the degree of relative agreement, the coefficient of agreement between the experts' opinions, and the final fuzzy number representing the aggregated opinions were computed using Eq.s (3), (5), and (6), respectively. The overall fuzzy numbers corresponding to each risk are presented in Table 3. After defuzzifying these fuzzy values using Eq. (7), the fuzzy probability numbers were determined through Eq.s (8) and (9). The values of fuzzy possibilities and fuzzy probabilities are displayed in Table 4 and Fig. 1, respectively.

According to the results, the seven environmental consequences of the mine tailings dam with the highest probability are wind, dust dispersion, and air pollution (Q7); creation of an undesirable landscape in the area (Q19); tailings sedimentation and settling (Q9); unpleasant odor from the tailings dam (Q8); dam erosion (Q4); soil contamination in the dam area (Q10); and threats to the health and safety of indigenous people (Q20). These results are inconsistent with previous study conducted on the environmental risk analysis of the Qaleh-Zari copper mine (Rahimdel and Aryafar, 2024). The dispersion of dust particles containing toxic metals significantly negatively impacts the lives of residents living near the tailings dam. To control and reduce dust, it is necessary to implement protective layers and surface coatings, construct wind barriers, and establish a green belt and buffer zone between the residential area adjacent to the mine and the tailings dam. These measures not only reduce dust dispersion into the surrounding environment but also improve the landscape of the mine tailings dam. Additionally, selecting a suitable location for constructing the mine tailings dam while adhering to environmental requirements—such as proper insulation of the dam floor to prevent wastewater from penetrating deep into the soil—is another essential control measure to mitigate the environmental risks associated with mine tailings dams.

Table 3. General fuzzy numbers related to each risk

Q1	(0,0,0.1,0.2)	Q6	(0,0,0.1,0.2)	Q11	(0.089,0.163,0.204,0.304)	Q16	(0.221,0.305,0.377,0.477)
Q2	(0.015,0.03, 0.115, 0.215)	Q7	(0.715,0.815,0.83,0.915)	Q12	(0,0,0.1,0.2)	Q17	(0.088,0.176,0.188,0.288)
Q3	(0,0,0.1,0.2)	Q8	(0.415,0.515,0.529,0.629)	Q13	(0,0,0.1,0.2)	Q18	(0.025,0.051,0.125,0.225)
Q4	(0.436,0.536,0.607,0.707)	Q9	(0.474,0.574,0.649,0.749)	Q14	(0,0,0.1,0.2)	Q19	(0.537,0.637,0.696,0.796)
Q5	(0.074,0.148,0.171,0.274)	Q10	(0.273,0.376,0.423,0.523)	Q15	(0,0,0.1,0.2)	Q20	(0.342,0.442,0.456,0.556)

Table 4. The defuzzified failure possibilities for each environmental consequence

Q1	0.0752	Q6	0.0752	Q11	0.1843	Q16	0.2857
Q2	0.0752	Q7	0.8671	Q12	0.0752	Q17	0.2000
Q3	0.0961	Q8	0.5593	Q13	0.0752	Q18	0.1362
Q4	0.5378	Q9	0.6900	Q14	0.0752	Q19	0.7585
Q5	0.2289	Q10	0.4662	Q15	0.0752	Q20	0.4593

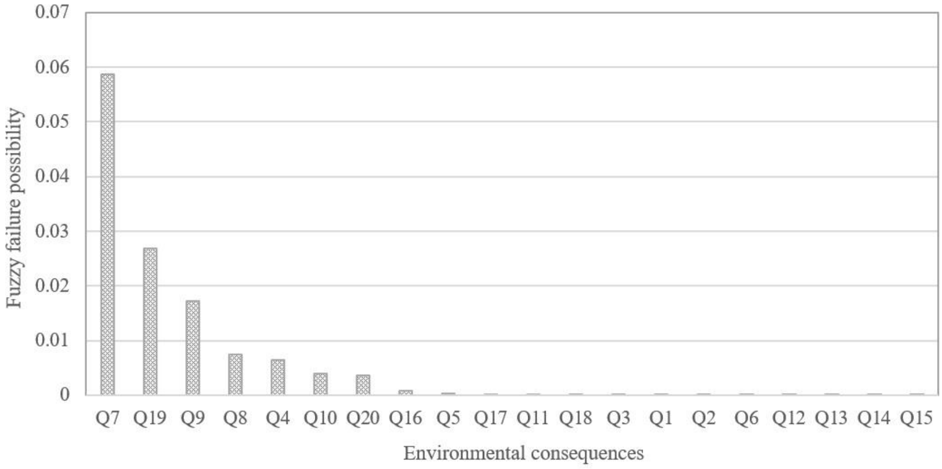

Fig. 1. Fuzzy probability values for each environmental consiquences

IV. CONCLUSIONS

Mining operations generate large volumes of tailings, which often contain hazardous pollutants. The accumulation of mineral tailings during extraction, along with effluents from mineral processing stored in tailings dams, poses a significant threat to natural resources. This paper evaluates the probability of environmental consequences associated with the tailings dam at the Qaleh Zari copper mine. Twenty potential consequences were identified, and the likelihood of each was assessed and analyzed using the fuzzy Similarity Aggregation Method. The results indicate that dust dispersion and air pollution, driven by wind and the unfavorable landscape of the area, represent the environmental consequences with the highest probability of occurrence. Consequently, it is essential to construct wind barriers and establish a buffer zone between the tailings dam and its surrounding environment. The findings of this study provide a valuable framework for evaluating and prioritizing environmental consequences related to tailings dams, thereby aiding in the reduction or elimination of critical risks.

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