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Optimization of tailings disposal method using fuzzy analytic hierarchy process

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ABSTRACT

Due to the increasing demand for metals, the extractable grade of metal deposits has been decreasing and caused an increase in the amount of tailings. Increase in the volume of tailings requires proper attention to tailings disposal, the establishment of tailings dams, water consumption and prevention of environmental and groundwater pollution. Since tailings disposal consists of many stages such as discharge, thickening technology and location, and transportation, selection of the best disposal method is a complicated task. Nowadays, decision-making methods are widely used and they are very reliable and efficient. Therefore, a model based on fuzzy analytic hierarchy process (AHP) has been developed in this study to optimize tailings disposal method selection. In the model, 21 criteria and a wide range of alternatives have been introduced. The model has been applied to the Sangan Iron Ore Project (SIOP). The concentrator plant of SIOP will produce 75 million tons of tailings during the mine lifetime. Since the current disposal method wastes 1.5 million cubic metres of water annually and the project is located in a dry region, the proposed model has been used to investigate other options and the results show the filtered technique is the best alternative.

Key words | filtered tailings, fuzzy analytic hierarchy process, Sangan Iron Ore Project, tailings disposal, water management

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INTRODUCTION

Water crisis in the present century is a fundamental and global problem. Undoubtedly, water is one of the main bases of industrial development in any country. Due to the fact that Iran is located in an arid to semi-arid region, the importance of the issue is multiplied. The supply of water coming from natural resources cannot fulfill the needs of the industry single-handedly since mineral processing requires 1–2 tons of water to process (concentrate) each ton of minerals. Thereby, this problem gives rise to the inevitable recycling of water, which is done by tailings disposal systems (Watson *et al.* 2010). Hydrological studies in the region indicate that water is the most important and limiting factor for the development of Sangan City. Low air humidity coupled with the low amount of rainfall prevent the creation of permanent surface flows in the area. At the moment, a conventional tailings disposal system is in operation in the Sangan Iron Ore Project (SIOP). As a result, due to a very high rate of water loss, a daily volume of about 4,000 m^3 (52 million cubic metres in the lifetime of project) of water is needed to compensate for the lost water at the tailings disposal site. Due to the climatic conditions of the location of the mine and the high demand of the project for water, the application of a tailings disposal method which minimizes water loss and recycles the water back to the concentrator is essential (Danieli Co. 2008).

In recent years, extensive studies have been carried out on the disposal of tailings and related subjects. Adiansyah *et al.* (2015) showed that existing frameworks for mine tailings management have significant weaknesses. Mine tailings management needs better factors in sustainability considerations. Barrera *et al.* (2015) evaluated the existing tailings management techniques in different tailings dams in Chile and compared different ways of reducing water consumption

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and dam failure prevention methods in seismic areas. Schoenberger (2016) studied the different tailings disposal methods with the aim of sustainable mining from environmental aspects. In the same year, another study reviewed the method of paste tailings disposal in tropical regions, and revealed the benefits of using this technology instead of conventional methods (Liu *et al.* 2016). Today, many mines are thinking about changing their tailings disposal method or using new technologies as an auxiliary system alongside their used thickeners. As can be seen, tailings management and water consumption are both vitally important in sustainable mining; however, the latter seems to be of primary importance. To overcome the shortcomings of tailings management, fuzzy analytic hierarchy process (AHP) has been proposed in the present research to optimize the decision-making procedure in this problem. Fuzzy AHP is one of the most famous and reliable methods among the multi-attribute decision-making (MADM) methods, and which has been widely used over managerial problems (Masoumi *et al.* 2014). Also, MADM techniques have been commonly used in mine management issues, as in Golestanifar & Bazzazi (2010), who applied this method to select a tailings impoundment site. Alavi & Akbari (2011) used the fuzzy AHP method to select suitable vegetation for the rehabilitation of the Sarcheshmeh copper mine. Shahba *et al.* (2017) applied MADM methods for mine waste management. Masoumi *et al.* (2014, 2017, 2018a, 2018b) have employed various MADM methods for mine reclamation project management and geotechnical improvement of embankments.

Since the purpose of this study is to develop a model using fuzzy AHP to select the best tailings disposal procedure among the possible methods, firstly, all the effective criteria and possible alternatives in this field have been identified to form a comprehensive resource, and then a framework based on fuzzy AHP has been proposed to solve the problem. Also, the performance of the method has been examined using a real case study.

MATERIALS AND METHODS

Determination of tailings disposal process alternatives

There are different methods that are mainly used in a whole tailings disposal process. These methods can be generally introduced as follows:

1. Filtered tailings disposal: In this method, materials are thickened to more than 85% by weight (solid weight divided by total weight), which is done by vacuum filters or filter-pressed technologies. The filtered material is transferred to the tailing storage location by the conveyor or a truck (Caldwell & Crystal 2015).
2. Paste disposal: These tailings are produced in special paste thickeners or in thickeners with ultra-high density and transferred by displacement pumps. The paste is a very useful tool for underground mine backfilling. Paste backfilling requires a high pumping pressure to transfer high-density backfill materials into the underground voids. The percentage of solids in this type of tailing is in the range 70–85% (Williams *et al.* 2008; Yilmaz & Mamadou 2017).
3. Thickened tailings disposal: Tailings are thickened by high-density thickeners up to 65–72% by weight of solids. In this case, highly stable tailings are produced for disposal in tailings dams with low segregation and water release. In this method, integrating the design of the thickener, transport system and disposal strategy is really important and the key link between these three disciplines is the rheology of the tailings (Thompson & Moreno 2017).
4. Conventional tailings disposal: Tailings are injected into conventional thickeners with up to 40–60% by weight of solids and transmitted to the dam in slurry form. Tailings particles during disposal go under segregation and a large amount of water is released via storage and accumulates in ponds. The conventional disposal methods require the use of dams, embankments or surface inhibitors as well as the use of cyclones or spigots for storage (Rashidinejad & Raoufsheibani 2004).

It should be noted that the options in this problem are not only classified based on tailings thickening technology, but also the place that they should be kept, discharge methods and transportation form several alternatives. Therefore, all possible alternatives in the tailings disposal process have been gathered in Table 1, which includes their abbreviations. One can combine various options in different steps and form a wide range of alternatives.

As shown in Table 1, the tailings disposal process consists of different parts and each part is divided into different sub-groups. There are various alternatives for tailings disposal; therefore, these could be applied in each

Table 1 | Different parts of the tailings disposal process and their abbreviations

Parts of tailings disposal process	Sub-group	Abbr.
Thickening technology	Conventional thickener	CON
	Paste thickener	PAS
	High-density thickener	TKN
	Filter	FIL
	High-rate and paste thickener	HXS
Thickening place	Concentrator	COR
	Tailings storage facility	TSF
	Concentrator and Facility	CXF
Transportation	Pipe line	PIP
	Truck	TRU
	Conveyor	COV
Discharge	Embankment	EMK
	Cell	CEL
	Paddock	PDK
	Central tailings discharge	CTD

Table 2 | Categorization of effective factors to select the best tailings disposal alternatives

No.	Description	Abbr.	No.	Description	Abbr.
Technical			**Environmental**		
1	Total tailing	tt	14	Biological problems	biop
2	Slurry rheology	reh	15	Ground water pollution	gwp
3	Thickening technology	th	16	Surface water pollution	swp
4	Transportation technology	tr	17	Earth pollution	ep
5	Separate discharge	ds	18	Air pollution	ap
6	Water recovery	wr	**Economic**		
7	Air distance from concentrator	ad	19	Study cost	sc
8	Climate	cl	20	Capital cost	cc
9	Topography	tp	21	Operating cost	oc
10	Geotechnics	geo			
11	Earthquake	eq			
12	Hydrology	hl			
13	Hydrogeology	hgeo			

project regarding the differences in climate, geotechnics, economy, geography, and other criteria.

Determination of effective criteria

Considering previous research and related reports, the most important factors in the case of selecting the best method of tailings disposal in mine projects are as follows:

1. Technical factors
2. Environmental factors
3. Economic factors.

Upon investigating and studying the various tailings disposal methods as well as the various reports related to different projects, the factors have been divided into 21 criteria, which can be seen in Table 2.

Decision-making model based on fuzzy AHP

The AHP method facilitates judgments and calculation preferences using pair-wise comparisons. It is also the best procedure to carry out pair-wise judgment comparisons. Nonetheless, human judgments are commonly imprecise, hence the priorities are not determined by a precise numeric amount. Fuzzy theory was developed by Zadeh to overcome imprecise judgments and preferences. Many of the weighing methods of attributes and alternatives are intellectually carried out by qualitative scales, whereas logical determination of the priorities is difficult for decision-makers in general. Therefore, in order to carry out precise pair-wise judgment comparisons and decision-making, fuzzy sets theory and the AHP method were combined (Masoumi *et al.* 2014).

Considering the use of fuzzy AHP with triangular fuzzy numbers, their mathematical operations are defined as Equations (1)–(3):

$$M_1 + M_2 = (l_1 + l_2,\ m_1 + m_2,\ \ u_1 + u_2) \tag{1}$$

$$M_1 \times M_2 = (l_1 \times l_2,\ m_1 \times m_2,\ \ u_1 \times u_2) \tag{2}$$

$$M_1^{-1} = \left(\frac{1}{u_1},\ \frac{1}{m_1},\ \frac{1}{l_1}\right) \ \&\ M_2^{-1} = \left(\frac{1}{u_2},\ \frac{1}{m_2},\ \frac{1}{l_2}\right) \tag{3}$$

where M is a triangular fuzzy number, $M_1 = (l_1, m_1, u_1)$ and $M_2 = (l_2, m_2, u_2)$, l, m and u are lower, mean and upper limits of a triangular fuzzy number, respectively.

After creating a pair-wise comparison matrix, the synthetic extent value is calculated by Equation (4):

$$S_i = \sum_{j=1}^{m} M_{gi}^{j} \otimes \left[\sum_{i=1}^{n} \sum_{j=1}^{m} M_{gi}^{j}\right]^{-1} \tag{4}$$

S_i is also a triangular fuzzy number; i and k are rows and j is columns.

The next step is to calculate the degree of possibility with Equation (5). Note that to compare S_1 and S_2 it needs both values of V ($S_1 \geq S_2$) and V ($S_2 \geq S_1$)

$$V(S_i \geq S_k) = \begin{cases} 1 \text{ if } \quad m_i \geq m_k \\ 1 \text{ if } l_k \geq u_i \\ \dfrac{l_k - u_i}{(m_i - u_i) - (m_k - l_k)} \text{ otherwise} \end{cases} \quad (5)$$

The degree of possibility for a convex fuzzy number greater than k is then calculated, and the convex fuzzy numbers can be defined by:

$$W_i^{'} = \min V(S_i \geq S_k) \quad (6)$$

for $k = 1, 2, \ldots, n$ and $k \neq i$. Then the normalized weight vector of criteria is given by Equation (7) and finally the ranking of alternatives is given by Equation (8):

$$W_i = \frac{w_i^{'}}{\sum_{i=1}^{n} w_i^{'}}, \quad i = (1, 2, 3, n) \quad (7)$$

$$\begin{aligned} A_1 = (W(A_1 \ \ to \ \ C_1) * W(C_1 \ \ to \ \ Goal)) \\ + (W(A_1 \ \ to \ \ C_2) * W(C_2 \ \ to \ \ Goal)) + \ldots \\ + (W(A_1 \ \ to \ \ C_n) * W(C_n \ \ to \ \ Goal)) \end{aligned} \quad (8)$$

where W is a non-fuzzy number, A is an alternative and Equation (8) should be implemented for all alternatives so they can be comparable, and C is each criterion (Masoumi *et al.* 2018b). Table 3 represents the scale for pair-wise comparison in fuzzy AHP. It should be noted that the numbers used in this table are not the only optimal numbers available and the does not cause any errors in the results as long as the order of the priorities does not change (Akdoğan *et al.* 2015).

The procedure of the tailings disposal decision-making model is presented in Figure 1. It simplifies the understanding of the model procedure.

Table 3 | Triangular fuzzy conversion scale (Akdoğan *et al.* 2015)

Definition	Triangular fuzzy scale	Triangular fuzzy reciprocal scale
Just equal	(1, 1, 1)	(1, 1, 1)
Rather equal preference	(1/2, 1, 3/2)	(2/3, 1, 2)
Weak preference	(1, 3/2, 2)	(1/2, 2/3, 1)
Strong preference	(3/2, 2, 5/2)	(2/5, 1/2, 2/3)
Very strong preference	(2, 5/2, 3)	(1/3, 2/5, 1/2)
Absolute preference	(5/2, 3, 7/2)	(2/7, 1/3, 2/5)

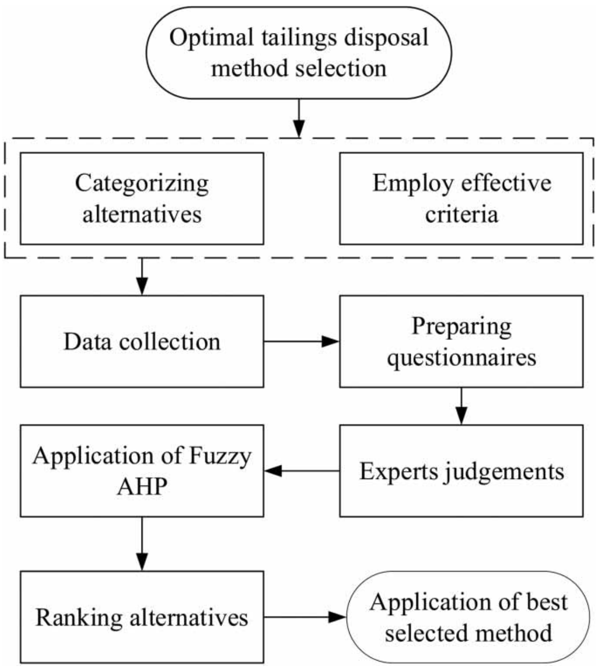

Figure 1 | Tailings disposal decision-making model procedure.

RESULTS AND DISCUSSION

Description of SIOP as a case study

Sangan Iron Ore mines are situated in three adjacent mineral areas on the western, central and eastern sides at longitude 60°16′ E and latitude 34°24′ N, in Khorasan Razavi province (300 km southeast of Mashhad) and 16 km north of Sangan city. The relative humidity of the area in the rainy months is more than 55% (about 57% to 59%) and in dry and non-rainy seasons it drops to about 26% to 28%. The average rainfall has been reported to be about 60 mm per year, which indicates an arid climate in addition to a general lack of moisture and precipitation (Danieli Co. 2008).

The concentration plant is designed with a productivity of 1.3 million tons (based on dry concentrate) per year. Thickeners treat slurry from the factory with a nominal capacity of 3,000 cubic metres per hour. In order to improve the concentration process and achieve a suitable concentration of slurry (density of solids up to 60%), coagulants are added to the thickeners. Conventional thickeners at the concentration plant are shown in Figure 2. The thickener residual slurry is sent to the discharge pump tank and the final tailing is pumped to the tailings dam (Kanikavan Sharq Engineering Co. 2010).

The tailings storage facility (TSF) is located in the south-eastern part of the concentration site. The level of the crown in the first phase is 1,080 m, which after completion of this phase in a 5 year period will be raised in three stages, as at each stage 5 metres is added to the crown height. The ultimate level of the dam is approximately 1,100 m. The total capacity of the disposal cells is 15 million tons (Danieli Co. 2007). Figure 3 shows the operation of the tailings dam in the first phase.

Identification of the applicable alternatives for SIOP

For SIOP, after investigation of different methods from Table 1, five applicable methods are identified. These methods are described in Table 4.

Since the paste disposal method (alternative number 3) and filtered tailings disposal method (alternative number 5) can be implemented in different ways in the present case and each of them has its own characteristics, for more accuracy in choosing and selecting the optimal system, each of these two methods is subdivided into three individual alternatives as shown in Table 5. Also, for the filtered tailings disposal method, the paddock method is considered.

According to Tables 4 and 5, all the applicable strategies for SIOP are finally introduced in an abbreviated form in Table 6 as model alternatives.

Application of decision model to select the best alternative

There is a decision hierarchy in fuzzy AHP problems from goal to alternatives, where criteria are situated between them. As for this research, the first level is the purpose (selection of the best method for tailings disposal), the second level is the criteria and the third level is the alternatives. In Figure 4, the hierarchy structure of the decision-making process used in this project is represented. As shown in this figure, all criteria are directly connected to the goal. On the other hand, every alternative is connected to all criteria, which is their route to the goal. It should be noted that every alternative should have connection to all

Figure 2 | Concentrator and thickeners.

Figure 3 | First phase of tailings dam.

Table 4 | Applicable tailings disposal procedures for SIOP

Alternative number	Disposal method	Evaluating its feasibility to be implemented in Sangan
1	Disposal of the slurry in the valley, using the TSF and surrounding wall (embankment barrier) via down-stream, up-stream and central-line methods.	In the country, there are plenty of TSF for base-metal mines using a retaining wall. Due to the dry weather of the region and the very low precipitation rate versus evaporation, this method is technically possible for SIOP. But because of the flat topography of the region, an integrated embankment is also required.
2	Discharging slurry tailings within consecutive cells with stepwise evacuation of tailings between cells to increase the density and dryness.	This method has been recommended for Sangan by well-known and expert companies.
3	Paste tailings disposal method using a central drain at a relatively flat surface with a floating water accumulation system on the back of a surrounding wall.	Regarding the topography of the area and surface conditions, this method can be used in Sangan.
4	Thickened tailings disposal method, the density of tailing in this method is between the conventional slurry and paste tailings.	This method can be used in Sangan and given the region's conditions and water recovery problems, it should be studied further.
5	Filtered tailings disposal.	The rate of water recovery in this method is very high and given the climatic conditions of this area, it is a good method.

criteria but the authors have avoided drawing these for the other options so as not to cause confusion. In order to achieve the purpose of the research, first of all, the weight of all criteria must be determined (arrows of criteria to the goal). Simultaneously, the weights of the alternatives should be determined in relation to every individual criterion (arrows of alternatives to criterion). At last, in order to determine the final weight of each alternative and rank them based on their importance weights, Equation (8) should be used.

According to the number of the criteria in this model, a total of 22 matrices are formed. The initial matrix is 21×21, which has been used to compare the degree of importance of different criteria in relation to the goal, and

Table 5 | Categorization of paste and filtered tailings disposal methods into subgroups

Main method	Alternative number	Subgroups
Disposal of paste tailings	3-1	Thickening by paste thickener at TSF
	3-2	Thickening by high-rate thickener at the place of concentrator and with paste thickener at TSF
	3-3	Thickening by paste thickener at concentrator
Disposal of filtered tailings	5-1	Filtration at concentrator and transportation of the tailing cake to the depot location by truck
	5-2	Filtration at concentrator and transportation of the tailing cake to the depot location by conveyor
	5-3	Filtration at TSF

Table 6 | Nomination of the alternatives for tailings disposal in the Sangan project

Alternatives	Technique no.
CON-COR-PIP-EMK	1
CON-COR-PIP-CEL	2
PAS-TSF-PIP-CTD	3-1
HXS-CXF-PIP-CTD	3-2
PAS-COR-PIP-CTD	3-3
TKN-COR-PIP-CEL	4
FIL-COR-TRU-PDK	5-1
FIL-COR-COV-PDK	5-2
FIL-TSF-COV-PDK	5-3

21 sets of 9×9 matrices that have been used to compare alternatives in relation to different criteria.

As shown in Table 7 and as expected, the rate of water recycling criteria has the highest level of importance in the selection of tailings disposal method and regarding the importance of environmental issues, and groundwater pollution resources are at second place. The ranking of criteria is also shown in Figure 5 based on their importance weights.

Above, the importance weights of the criteria have been obtained. As mentioned, the procedure should be repeated in order to calculate the importance weights of alternatives regarding every criterion. Finally, to get the final weight of each alternative, the weight of each arrow (in the second

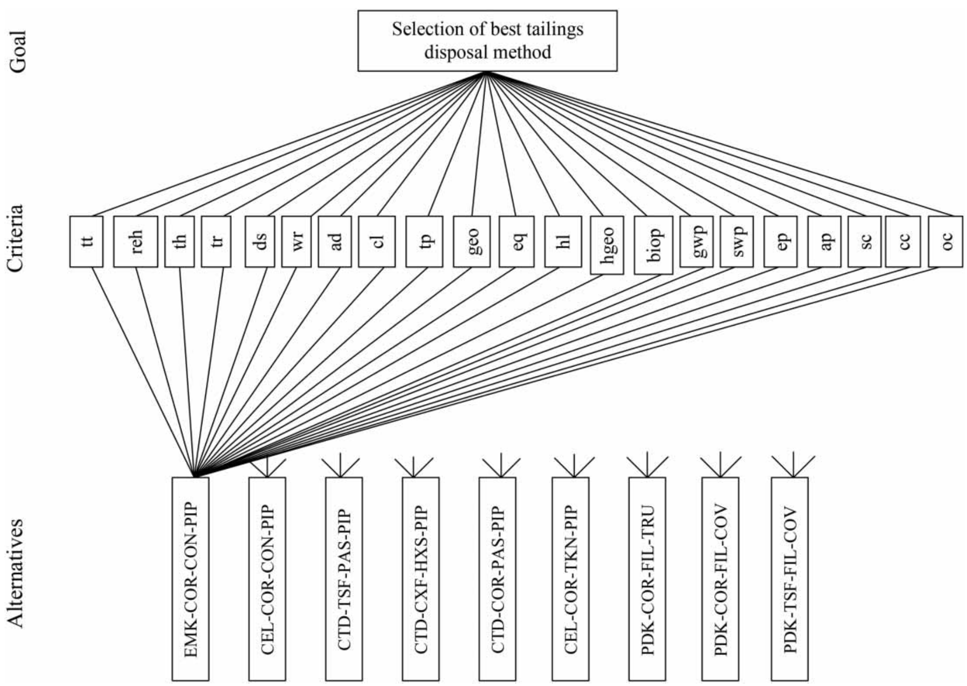

Figure 4 | Hierarchy of decision-making in this research.

Table 7 | Normalized weights of criteria

W_i	Weight of criteria	W_i	Weight of criteria
W_{cl}	0.05332	W_{gwp}	0.05989
W_{tp}	0.05716	W_{swp}	0.05283
W_{geo}	0.03955	W_{ep}	0.04880
W_{eq}	0.05882	W_{ap}	0.0481
W_{hl}	0.04655	W_{sc}	0.00932
W_{hgeo}	0.04523	W_{cc}	0.04264
W_{biop}	0.05003	W_{oc}	0.05157
W_{tt}	0.04553	W_{tr}	0.04593
W_{reh}	0.0499	W_{ds}	0.04399
W_{th}	0.05823	W_{wr}	0.06043
W_{ad}	0.03209		

row of Figure 4) should be multiplied by the weight of its symmetric arrow (in the first row of Figure 4) and the results must be added. This operation has been described with Equation (8). Alternatives' weights are shown in Table 8.

The higher importance weight an alternative has, the better an alternative it is. As shown in Table 8, considering the benefits of the filtered tailings disposal method and also the paste disposal, these methods take priority over the other applicable methods in the SIOP. Their prioritization changes only in terms of their transport system. The method that is currently underway in the project (due to the high water loss and ensuing environmental problems), as well as the high cost of the implementation of the tailings dam, is in the penultimate position. Finally, the filtering option at the concentrator and transferring the tailings cake via the conveyor to the storage site is recommended for the Sangan project.

CONCLUSION

In order to optimize the selection of the most compatible tailings disposal method, a decision-making model based on fuzzy AHP has been developed in this research. The model has introduced various methods as alternatives for tailings disposal. In addition, the most important criteria, which affect choosing the best alternative, have been classified. Finally, SIOP has been used by the model as a case study to assess its performance. Regarding use of the model, the following has been concluded:

1. Due to the disadvantages of the conventional tailings disposal methods (methods 1 and 2 in this project), such as low water recovery, low tailings stabilization and safety, high occupancy and low reconstruction potential, the model properly shows this method has a low score for implementation in the SIOP.
2. Considering the benefits of the filtered tailings disposal method, such as the highest degree of water recovery, better environmental conditions in the storage site, less contamination of groundwater due to the lack of water with tailings and the least penetration and also the faster vegetation stability after reconstruction, as predicted, it was the best option for implementation from technical, economic and environmental points of view

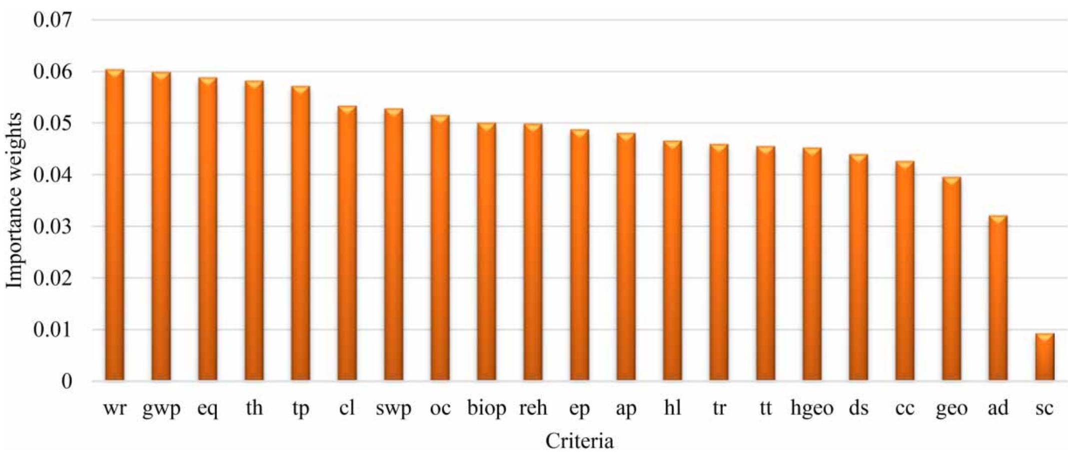

Figure 5 | Rankings of criteria importance weights.

Table 8 | Final weights of alternatives

Alternatives	Technique no.	Final weight
EMK-COR-CON-PIP	1	0.070614
CEL-COR-CON-PIP	2	0.07198
CTD-TSF-PAS-PIP	3-1	0.107417
CTD-CXF-HXS-PIP	3-2	0.099642
CTD-COR-PAS-PIP	3-3	0.09436
CEL-COR-TKN-PIP	4	0.08813
PDK-COR-FIL-TRU	5-1	0.150366
PDK-COR-FIL-COV	5-2	0.1637587
PDK-TSF-FIL-COV	5-3	0.153644

in the SIOP, which has the highest importance weights among the alternatives.

3. One of the most important results of this research is to provide a ranking for effective criteria in the selection of the tailings disposal method for processing, which will be very useful for future studies.

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