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Selection of the Optimum Active Treatment Technology for Acid Mine Drainage (AMD) Using Analytic Hierarchy Process

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The increasing number of proposed technologies for the active treatment of acid mine drainage (AMD) raises a problem for decision-makers during the selection process. Selecting the optimum treatment technology requires extensive analysis to determine the best possible treatment based on multiple and often conflicting criteria. The introduction of multi-decision criteria analysis (MCDA) provides a systematic approach to problem-solving based on both quantitative and qualitative data. In this study, analytic hierarchy process (AHP) as an MCDA tool was used to select the optimum treatment option for AMD in a local copper mining site in the Philippines. Three treatment technologies were found to be the most applicable – a combination of Conventional Lime Neutralization and Sulfidogenic Bioreactor (CLN + SB), High-Density Sludge (HDS) Process, and a combination of Two-Step Neutralization Ferrite Formation and Sulfidogenic Bioreactor (TSNFF + SB). Three criteria – technical, economic, and environmental – and eight sub-criteria were used to evaluate and analyze the three alternatives systematically. The overall ranking of the alternatives was TSNFF + SB > HDS > CLN + SB. However, sensitivity analysis showed that HDS was the most stable treatment technology when equal weights were given for each criterion. Implications from this study could provide a more reliable information for possible technology adoption to sustainably address problems on AMD which is one of the leading global environmental problems today.

1. Introduction

Despite its small size, the Philippines is considered to be the fifth most mineralized country in the world in terms of gold, copper, nickel, and chromite. As of 2020, it was estimated that the Philippine mining industry contributed ₱102.3 10^9 to the Gross Domestic Product (GDP) (Department of Environment and Natural Resources (DENR), 2020). However, despite its positive impact on the economy, the production of acid mine drainage (AMD) due to extensive mining has caused detrimental effects on the environment. AMD occurs when pyrite and other sulfide minerals are exposed to air, microbial activities, and water. It is estimated that one mole of pyrite can produce at most 16 moles of hydronium ions, making the surrounding environment highly acidic. To this day, several treatments, both active and passive, have been studied and done to combat the negative impacts of AMD. One of the most common active treatments done on AMD is chemical neutralization which involves the addition of high pH materials like limestone or lime to AMD to raise and neutralize its pH and precipitate heavy metals (Naidu et al., 2019). Due to the increase in the number of treatment technologies available, selecting the best treatment technique would require extensive analysis to determine the best possible treatment for a specific mine site.

Typically, the optimum treatment technology selection process will require the assessment of different factors and multiple criteria. The introduction of multi-decision criteria analysis (MCDA) as a tool for decision-making eases the burden to decision-makers on the selection process of the optimum technology (Roy, 2010). As of today, different MCDA methods are developed and used for selecting treatment technologies (Cinelli et al., 2021). One of which is the analytic hierarchy process (AHP). AHP is an MCDA tool that was developed by Saaty

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(1987) in the 1970s. AHP can incorporate both qualitative and quantitative factors in the development of the decision structure in order to help decision-makers choose the best option amongst the alternatives presented in the model (Chan et al., 2019). In AHP, the decision structure is arranged in a hierarchical manner. The first level is comprised of the goal, followed by the sub-levels of criteria and sub-criteria, and the last level is composed of the feasible alternatives (Sitorus et al., 2019). After the development of the hierarchical structure, a pairwise comparison of the criteria and sub-criteria is done and results are aggregated to come up with the priority weights (Calabrese et al., 2019).

To this day, not much has been reported on the utilization of MCDA techniques on technology selection for AMD treatment specifically for copper mine sites. Therefore, this study aims to select the optimum active treatment technology for AMD amongst the three alternatives: 1) the combination of conventional lime neutralization and sulfidogenic bioreactor; 2) high-density sludge (HDS) process; 3) the combination of two-step neutralization ferrite formation proposed by Igarashi et al. (2020) and sulfidogenic bioreactor. The study aims to compare the individual performance of each alternative according to a set of criteria and sub-criteria and employ the AHP for the evaluation of the best alternative.

2. Methodology

The following steps were done to determine the global priority weights of alternatives using AHP as described by Saaty (1987):

Step 1: The decision structure was developed in a hierarchical manner. The topmost level contained the goal. The second level represented *n* criteria with respect to the goal. Each criterion can have multiple sub-criteria which were placed below the secondary level. The final level of the hierarchical structure defined a discrete set of *m* alternatives where m ≥ 2.

Step 2: A pairwise comparison matrix was constructed using Saaty's fundamental 9-point scale and its linguistic equivalents are shown in Table 1. The decision-makers were asked to do a pairwise comparison of the criteria with respect to the goal, the sub-criteria with respect to the criteria, and the alternatives with respect to the sub-criteria using the linguistic terms.

Table 1. Saaty's fundamental 9-point scale and linguistic equivalent

Linguistic Term	Numerical Value
Absolutely more importance (AMI)	9
Very high importance (VHI)	7
High importance (HI)	5
Slightly more importance (SMI)	3
Equally importance (EI)	1
Slightly low importance (SLI)	1/3
Low importance (LI)	1/5
Very low importance (VLI)	1/7
Absolutely low importance (ALI)	1/9

Step 3: The consistency check was done using the threshold of the Consistency Ratio (CR) value of 15 % as shown in Eq(1)

$$CR = \frac{CI}{RI} \tag{1}$$

where CI is the Consistency Index. This was computed using Eq(2).

$$CI = \frac{\lambda_{max} - n}{n - 1} \tag{2}$$

where λ_{max} is the eigenvalue of the matrix and *n* is the number of criteria. The Random Index (RI) was obtained based on the number of criteria (Kieu et al., 2021)

Step 4: Aggregation of individual priorities (AIP) was the method used to aggregate the individual preferences of each decision-maker. Weighted arithmetic mean was applied to obtain the local priority weights of each criterion, sub-criterion, and alternative. The weight of the judgments of each decision-maker was obtained based on their confidence level in answering the pairwise comparison survey as shown by the score function, $S(\omega_e)$, in Table 2 below. It is assumed that a decision-makers have their weight representing their confidence level in giving their judgments in the pairwise comparison. The value of the weight coefficient, ω_e, of each decision-maker was obtained by normalizing the score function using Equation 3 below.

Table 2. Confidence level weights and corresponding score function

Level of Confidence	$S(\omega_e)$
1	0.006
2	0.063
3	0.200
4	0.441
5	0.810

$$\omega_e = \frac{S(\omega_e)}{\sum_{e=1}^{a} S(\omega_e)} \tag{3}$$

The local priority weights, $\overline{w}_j^s$, of the criteria, sub-criteria, and alternatives were computed using Equation 4 below:

$$\overline{w}_j^s = \frac{1}{a}\sum_{i=1}^{a}\left(\overline{w}_j^s\right)_i \tag{4}$$

Step 5: The global priority weights of the sub-criteria with respect to the criteria, W_{SG}, were computed using Equation 5.

$$W_{SG} = W_{CG} W_{SC} \tag{5}$$

where W_{CG} is the matrix containing the importance weights of the criteria with respect to the goal and W_{SC} is the local priority weight of the sub-criteria with respect to the criteria.
The global priority weights of each alternative with respect to the sub-criteria, W_{AG}, were computed using equation 6 as shown below:

$$W_{AG} = W_{SG} W_{AC} \tag{6}$$

where W_{SG} is the matrix containing the importance weights of the sub-criteria with respect to the criteria and W_{AC} is the local priority weight of each alternative with respect to the criteria.
Step 6: The idealized scores were also computed to show the relative intensity of the preference for the alternatives. This was done by dividing the global priority weights of the alternatives with the highest global priority weight obtained for all the alternatives. In this case, the most preferred alternative will have a value of 1.0 and the other less preferred alternatives will have a value from [0-1]. This is shown by equation 7 below:

$$W_{idealized\ score} = \frac{W_{AG}}{W_{AG_{max}}} \tag{7}$$

A sensitivity analysis was performed by changing the criteria weights of the three main criteria. Several cases were presented to compare the global weights of each alternative using different scenarios. Table 3 below shows the summary of the case scenarios that were used in the sensitivity analysis.

Table 3. Summary of cases with varying criteria weights used for the sensitivity analysis

	Weighting
Case 1	50% C1; 25% C2; 25% C3
Case 2	25% C1; 50% C2; 25% C3
Case 3	25% C1; 25% C2; 50% C3
Case 4	50% C1; 50% C2; 0% C3
Case 5	0% C1; 50% C2; 50% C3
Case 6	50% C1; 0% C2; 50% C3
Case 7	Equal Weights

3. Results and Discussion

Figure 1 below shows the decision structure used in the study. The topmost level contains the goal which is to select the optimum active AMD treatment technology for copper mine sites. Levels 2 and 3 show the defined criteria and sub-criteria, respectively. And the lowest level shows the treatment alternatives that were chosen.

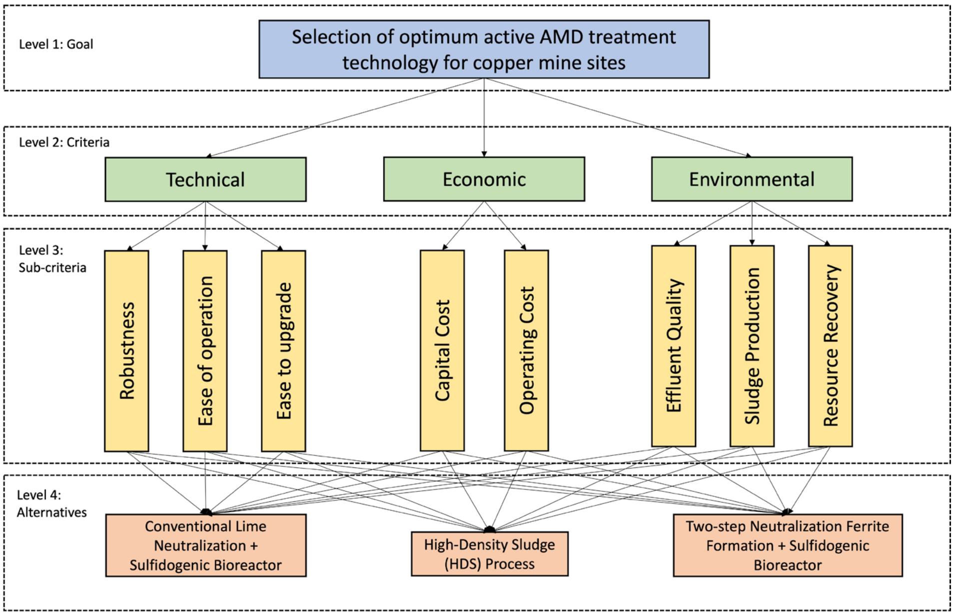

Figure 1. The decision structure for the selection of optimum active treatment technology for AMD in copper mine sites

3.1 Quantitative Analysis

The data for the capital cost (CAPEX), operating cost (OPEX), effluent quality, sludge production, and resource recovery were obtained from literature reviews. In the estimation of the CAPEX, values were obtained from past literatures and inflation rates were also considered. To calculate the OPEX, different assumptions were made to come up with a generalized method of quantifying the total expenses such as the acidity of AMD, flowrate, acid per year, annual volume processed, and total operating hours. The effluent quality considered the sulfates, manganese, and copper removal of each alternative. The quantitative data of the sub-criteria in terms of economic and environmental aspects were normalized to obtain performance scores in such a way that a higher performance value is more desired. This was also done to make each score comparable with each other. Table 4 below shows the normalized score of each alternative with respect to the quantitative sub-criteria.

Table 4. Normalized scores of each alternative with respect to quantitative sub-criteria

Alternatives	CAPEX	OPEX	Effluent Quality	Sludge Production	Resource Recovery
CLN + SB	0.2890	0.2649	0.3157	0.0790	0.5000
HDS	0.4825	0.4043	0.3644	0.1317	0.0000
TSNFF + SB	0.2285	0.3307	0.3199	0.7892	0.5000

The highest local priority weight in terms of CAPEX, OPEX, and effluent quality was obtained by HDS at 0.4825, 0.4043, and 0.3644. This is attributed to the fact that HDS is less complex to build and operate unlike the other two treatment alternatives. On the other hand, the highest local priority weight for sludge production was obtained by the combination of two-step neutralization ferrite formation and sulfidogenic bioreactor. The novel two-step neutralization ferrite formation offered at most 90% and 84% sludge reduction compared to conventional lime neutralization and HDS, respectively. For the sludge production of the sulfidogenic bioreactor, it was assumed that the sludge deposited was processed under flash smelting, hence, producing no additional sludge after the secondary treatment.

3.2 Qualitative Analysis

A total of seven responses were obtained from experts – 5 from the academe and 2 from the industry. Table 5 below shows the global priority weights of the sub-criteria with respect to the criteria. The global priority weight of each sub-criterion was obtained using Equation 5. Results showed that the highest priority was given to S6: Effluent Quality followed by S8: Sludge Production. The high global weights for the sub-criteria under C3: Environmental Aspect can be attributed to its high criteria priority weight. As seen in Table 4, C3 completely dominates the other two criteria based on the importance level given by the decision-makers.

Table 4. Weights of the criteria with respect to the goal and sub-criteria with respect to criteria

Alternatives	Weight	Sub-criteria	Local Priority Weight	Global Priority Weight
C1	0.2536	S1	0.54778	0.1348
		S2	0.27308	0.0672
		S3	0.17914	0.0441
C2	0.2202	S4	0.51389	0.0985
		S5	0.48611	0.0932
C3	0.5262	S6	0.49933	0.2807
		S7	0.19256	0.1083
		S8	0.30811	0.1732

Table 5 below shows the overall and idealized score of the alternatives. The results of the overall score and the idealized scores for each alternative were computed using Equations 6 and 7.

Table 5. Overall score and idealized score of each alternative

Alternatives	Overall Score	Idealized Score
CLN + SB	0.2765	0.7585
HDS	0.3518	0.9180
TSNFF + SB	0.3717	1.0000

Results showed that the most preferred treatment option is TSNFF + SB followed by HDS. The least preferred treatment option is CLN + SB. Even though HDS obtained the highest scores in the sub-criteria for technical and economic aspects, as well as in effluent quality for environmental aspect as shown in Table 4, it received the lowest global weight in sludge production and resource recovery. This can be attributed to the significantly higher sludge production of HDS in comparison with TSNFF + SB and CLN+SB. The sulfidogenic bioreactor as a secondary treatment option for the TSNFF provided higher heavy metal and sulfate removal. Moreover, it also contributed to the resource recovery which is absent for HDS. To summarize, the global priority weight of TSNFF + SB is largely attributed to the high priority weights given for C3: Environmental Aspect specifically S8: Sludge Production.

3.3 Sensitivity Analysis

Sensitivity analysis was employed on the results obtained to check its robustness. Figure 2 below shows the results obtained from the sensitivity analysis using the several cases presented in Table 3.

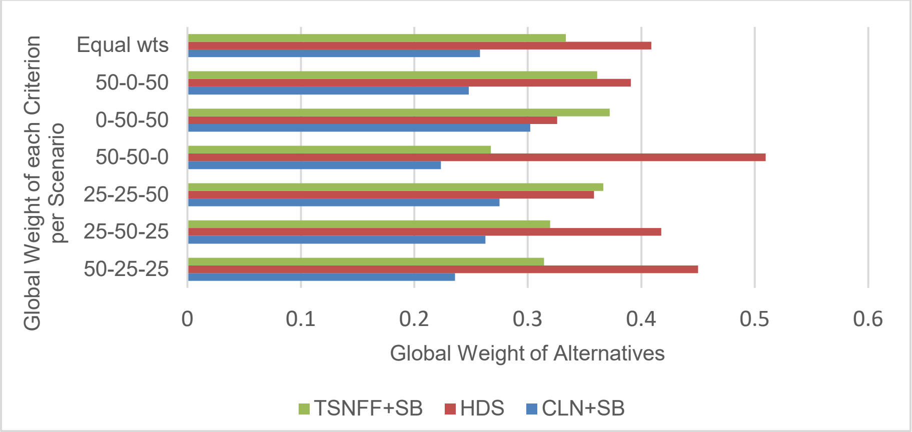

Figure 2. Overall score of the three alternatives for each case scenario of criteria weights

From Figure 2, it can be concluded that the most stable alternative is HDS. At Case 3: 25 – 25 - 50 and Case 4: 0-50 - 50, TSNFF + SB only slightly overtook HDS. However, Figure 2 shows a significant gap between the weights of HDS and TSNFF+SB when high priority was given to C2: technical aspect. The sensitivity analysis showed that while TSNFF + SB increase with increasing weight in environmental aspect, it only partially dominates HDS when the priority weights are at 25 % C1; 25 % C2; 50 % C3. It also confirmed that the performance of HDS, when evaluated under the environmental aspect, is lower than TSNFF + SB. Moreover, the sensitivity analysis showed that HDS is the most stable alternative among the other two when equal weights were given for each criterion.

4. Conclusion

Acid mine drainage (AMD) is one of the most serious and costly environmental threats today. To achieve a sustainable treatment option, the technology should not only consider the technical aspect but also the economic and environmental aspects. Thus, a need for a generalized framework for the selection of the optimum active treatment technology for AMD is needed. In this study, the analytic hierarchy process (AHP) was used to determine the optimum active treatment technology to address problems related to AMD. A total of seven responses were obtained from decision-makers. The results of the analysis gave an overall ranking of TSNFF + SB > HDS > CLN + SB. TSNFF + SB dominated the other two alternatives when evaluated on its capability to produce low sludge. It can be concluded that the high score given for TSNFF + SB is mainly attributed to the high global priority weight given for C3: Environmental Aspect. To further check the robustness of the results, sensitivity analysis was employed. Contrary to the initial results, the sensitivity analysis showed that HDS is the most stable treatment alternative when equal weights were given to each criterion. Moreover, the sensitivity analysis also demonstrated a significant weight difference between HDS and TSNFF + SB when a higher priority weight was given to C2: Technical Aspect. Overall, the use of AHP to determine the optimum treatment option to address AMD in copper mine sites can be used to determine the effect of the varying distribution of the weights among the three criteria during the selection process.

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References

Calabrese, A., Costa, R., Levialdi, N., Menichini, T., 2019, Integrating sustainability into strategic decision-making: A fuzzy AHP method for the selection of relevant sustainability issues, Technological Forecasting and Social Change, 139(November 2018), 155–168. doi: 10.1016/j.techfore.2018.11.005.

Chan, H. K., Sun, X., Chung, S. H., 2019, When should fuzzy analytic hierarchy process be used instead of analytic hierarchy process?, Decision Support Systems, 125(July), 113114, doi: 10.1016/j.dss.2019.113114.

Cinelli, M., Spada, M., Kim, W., Zhang, Y., & Burgherr, P., 2021, MCDA Index Tool: an interactive software to develop indices and rankings. Environment Systems and Decisions, 41(1), 82–109, doi: 10.1007/s10669-020-09784-x.

Department of Environment and Natural Resources (DENR)., 2020, DENR-MGB: PH mining sector contributes ₱102.3B to GDP; allots ₱379B for environmental programs in 2020 <denr.gov.ph/index.php/news-events/press-releases/2935-denr-mgb-ph-mining-sector-contributes-102-3b-to-gdp-allots-379b-for-environmental-programs-in-2020> accessed 08.02.2022.

Igarashi, T., Herrera, P. S., Uchiyama, H., Miyamae, H., Iyatomi, N., Hashimoto, K., & Tabelin, C. B., 2020, The two-step neutralization ferrite-formation process for sustainable acid mine drainage treatment: Removal of copper, zinc and arsenic, and the influence of coexisting ions on ferritization, Science of the Total Environment, 715, 136877, doi: 10.1016/j.scitotenv.2020.136877.

Ishizaka, A., Labib, A., 2011, Review of the main developments in the analytic hierarchy process, Expert Systems with Applications, 38(11), 14336–14345, doi: 10.1016/j.eswa.2011.04.143.

Kieu, P. T., Nguyen, V. T., Nguyen, V. T., Ho, T. P., 2021, A spherical fuzzy analytic hierarchy process (Sf-ahp) and combined compromise solution (cocoso) algorithm in distribution center location selection: A case study in agricultural supply chain, Axioms, 10(2), 1–13, doi: 10.3390/axioms10020053

Naidu, G., Ryu, S., Thiruvenkatachari, R., Choi, Y., Jeong, S., Vigneswaran, S., 2019, A critical review on remediation, reuse, and resource recovery from acid mine drainage, Environmental Pollution, 247, 1110–1124, doi: 10.1016/j.envpol.2019.01.085

Roy, B., 2010, Two conceptions of decision aiding. International Journal of Multicriteria Decision Making, 1(1), 74–79 <ideas.repec.org/a/ids/ijmcdm/v1y2010i1p74-79.html> accessed 18.12.2021

Saaty, R. W., 1987, The analytic hierarchy process—what it is and how it is used, Mathematical Modelling, 9(3–5), 161–176, doi: 10.1016/0270-0255(87)90473-8

Sitorus, F., Cilliers, J. J., Brito-Parada, P. R., 2019, Multi-criteria decision making for the choice problem in mining and mineral processing: Applications and trends, Expert Systems with Applications, 121, 393–417, doi: 10.1016/j.eswa.2018.12.001