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Selection of the Best Waste water Treatment System with Mercury in Gold Mining, Applying Analytic Hierarchy Process.

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Abstract : An application of the Analytic Hierarchy Process is presented below to select the best system of wastewater treatment with mercury (Hg), product of artisanal gold mining and small - scale (AGMSS) developed in Colombia. The Analytic Hierarchy Process has been used in several studies for the selection of alternative wastewater treatment and is a methodology that allows presenting the best alternative from the technical, environmental, economic and social terms, representing an important issue before designing and implementing any wastewater treatment plant in each particular sector. The analysis was applied in a case study in the municipality of Segovia, Antioquia`s department, allowing found that under the conditions of the mining activity in this municipality as well as the selection criteria taken into account, the most suitable tertiary treatment is the bioadsorption.
Keywords: hierarchical analysis, artisanal, gold mining, small - scale, mercury treatment.

I. Introduction

The Analytic Hierarchy Process (AHP) is a theory that can combine human perception, interest and experience to prioritize options in complex situations. It is useful for managing multiple objectives, criteria and alternatives in the making-decision process. In particular, the application of AHP considers socio -cultural and environmental objectives which have been recognizedat the same importance as the economic objective in the selection of optimal alternative wastewater treatment[15,23,12,6].

On the other hand, the need to implement systems for efficient treatment for the removal of mercury (Hg) spill by Artisanal Gold Mining Small Scale (AGMSS) in Colombia, is evident from the inappropriate use of this heavy metal in the amalgamation gold in the sector, which accordingto the National Overview of the Artisanal Gold Mining and Small Scale[13], has generated in the country the discharge of mercury into the environment (discharges and emissions) has become up to 298.2 tons/year. This discharge value exceeds by 34.6% the calculated data in the inventory of mercury releases of 2009 (103 Tons/Year) [14] and 50% in the value reported in the study by[4] (150 Ton/Year).

That is obviously the tendency to increase downloads, which is mainly due that the use of mercury for the benefit of gold is extended. This is attributed to the easy use of these inputs, the cheaper cost compared to other methods and the availability of these compounds even in the most remote regions as well as the high percentage of illegal mining activity[9]. This reality has not allowed regulations on the use of mercury in the country, such as Law No. 1658 of 2013 [21], are met properly.

Thus, it is important to carry out a selection process suitable for the treatment of contaminated with mercury by AGMSSwater technologies, considering social, environmental and economic aspects, helping really this technologies to beapplied by miners who implemented the activity of artisanal gold mining and small - scale in the country.

In this study was implemented a selection process of the suitable treatment of the contaminated water with mercury by AGMSSthrough the application of the Analytic Hierarchy Process (AHP for its acronym in English), which is a selection model of alternatives useful for managing multiple objectives, criteria and alternatives in the decision - making process. The AHP helps analysts to organize the critical aspects of a problem similar to a family tree hierarchical structure. The aim of using this method is to identify the preferred alternative and also determine a ranking of alternatives when all the decision criteria are considered simultaneously[12].

The AHP method was first introduced by[22], in which the analytic hierarchy process was studied through planning, priority setting and resource allocation. After this, there are numerous studies in the literature that uses the AHP to different decision - making problems related to Wastewater Treatment Systems. For example, [6]they used the AHP approach to selecting the best treatment of wastewater for electroplating workshops in Iran, and[15,2], they conducted a study where the Analytic Hierarchy Process -AHP- applied to a real decision problem on the election of the wastewater treatment technology more sustainable for small cheese factories in Italy.

Several technologies have been applied to the treatment of liquid effluents containing Hg and other heavy metals which are commonly classified in physicochemical (adsorption, ion exchange, membrane processes, advanced oxidation and chemical precipitation) and biological (phytoremediation, bioaccumulation, biomineralization, biotransformation and bioadsorption)[19,24,18,1].

The objective of this article is to show the results of the study executed on the application of the AHP methodology in selecting the contaminated waters treatment with mercury by AGMSS in Colombia, looking at technical, social, environmental andeconomic aspects. Applying and validating the model in the AGMSSactivity in the municipality of Segovia department of Antioquia, belonging to the Antioqueño Northeast where in total there are between 15,000 and 30,000 artisanal gold miners[4], and others, 2011).

II. Methodology

According to[12], the general procedure for selecting the best treatment according to AHP model usually consists of the following steps:

1. Identify the alternatives of treatment.
2. Identify the important selection criteria and decide on the criteria used to evaluate alternatives.
3. Evaluate alternatives and select the most appropriate.

Based on this, below detailed the developed AHP methodology as follows:

1. Alternatives tertiary treatment.

To consider tertiary treatment processes for the removal of heavy metals such as mercury and efficiency related to strike up gold mining, it was executed a fieldwork in order to have primary information on the AGMSSactivity developed in the Segovia municipality of Antioquia department, and on the other hand, a literature review and a visit to companies that sell industrial wastewater treatment systems was performed. Data analysis and related surveys were used to determine the efficiency of processes.

In this case, based on the characteristics of the AGMSS effluent in the municipality of Segovia, it was established that the treatment system selected must comply with the following parameters:

a. Remove mercury concentrations: between 552 mg/L and 6118 mg/L
b. Number of total solids to try: between 1,065 mg/L and 5.015 mg/L

Therefore, whatever the selected tertiary treatment, pre treatment is essential, since a high water quality input is required to allow the proper functioning of technologies removal of heavy metals.

In this sense, the proposed treatment system, consisting in each case of a pretreatment through Neutralization with reagents (Cal, calcium carbonate, sodium hydroxide, sodium bicarbonate or ammonium hydroxide) for pH neutralization; followed by a clarifier to separate the effluent sludge and finally a tertiary treatment for the removal of mercury, considered as the last step of the system, treatment and final disposal of tailings or mining sludge. It is expected to contaminants associated in the process as Cyanide and metal sulphides can also be removed by the treatment system (Table 1).

Table 1. Treatment systems evaluated. Source: own elaboration.

No.	**Treatment system**			
	1	**2**	**3**	**4**
1	**Neutralization**	**Clarification**	PRE-FILTRATION. Ion exchange.	**Treatment and disposal of mining tailings**
2			Chemicalprecipitation- Flocculation	
3			Adsorption on activated charcoal obtained from a variety of carbonaceous materials including wood, carbonized pulp, peat and lignite.	
4			PRE-FILTRATION. Inverse osmosis	
5			Biological process in the bioreactor	
6			Biosorption with material from algae, bacteria, fungi or plant material	
7			Phytoremediation, from plants are captured the metal ions.	
8			PREFILTRATION-Nanotechnology	
9			Electrocoagulation	

2. Selection criteria or variables.

In this case, the contributions of authors initially were considered as[23,12,15], who pose technical, socioeconomic and environmental criteria for selection of wastewater treatment, which can be applied, in the specific context of the AGMSS.

So, of a total of 24 initial criteria, we finally selected 13 to which interested parties (owners of 20 respondents miners' strike up, representatives of the Mayor of Segovia, the Government of Antioquia and the Autonomous Regional Corporation of Antioquia - CORANTIOQUIA-), were assigned a higher score. These criteria are described in *Table 2*.

Table 2 Selection criteria used in the study according to the literature review and the perception of stakeholders. Source:[23,12,15].

Appearance	No.	Criterion	Description
Technical	1	System reliability	Possibility of achieving adequate performance for a specific period of time under specific conditions.
	2	Technology easy to build and install	Compatibility with existing processes level of automation and operational familiarity with the process.
	3	Type of materials for operation	Determine the complexity of the materials and equipment required for system construction.
	4	Mercury removal efficiency	Determine the degree of removal of mercury present in the AGMSS waste water
	5	Replicability system	Simple design. The participation of technical experts should be required only for early implementations. Since then, the technology must be easily replicated elsewhere without relying on specific expertise.
Socioeconomic	6	Initial construction costs	Monetary costs for system construction
	7	Annual cost of operation and maintenance	Costs related to the management of the treatment system
	8	Labor required	Determine the required personnel and the ability of this, for the operation and maintenance stage
	9	Social acceptability	Determine how technology is accepted by the affected community.
Environmental	10	Continuity ease of operation and maintenance	Determine whether the system can provide continuity of ease of operation and maintenance over the life of the same
	11	Possibility of recirculation water	The alternative should be able to reuse treated wastewater in the process of the AGMSS
	12	Increase in the quantity and or toxicity of the sludge generated	Establish whether technology increases the quantity and/or toxicity of the sludge generated in the process.
Normative	13	Compliance with environmental regulations	Determine the value of mercury removal with respect to the permissible limit for discharges of mercury, established by Decree 1594 of 1984 [16], which is 0.02 mg / l.

3. Analytical Hierarchy Process.

The phases for carrying out the process of AHP were as follows:

a. Hierarchytree.

From the hierarchy tree was performed a graphical representation of the problem in terms of the overall objective, the decision criteria and alternatives (Fig. *1)*.

Fig.1 Tree hierarchies. Source: [22]

Weighting criteria.

For the determination and qualification of the selection criteria they were taken into account perceptions of stakeholders, in this case in the Segovia municipality. Surveys were made to the owners of 20 strikes up and the representatives of the Mayor of Segovia, Antioquia Government and CORANTIOQUIA. In these surveys, they were scored the level of importance assigned on each one of the evaluation criteria in accordance to the fulfillment of the objective. From this information, the weight given by the scale of pair wise comparisons (Table 3) was performed, obtaining the paired criteria matrix (Table 4).

Table 3 Scale for paired comparisons. Source:[22]

Intensity	**Definition**
1	Equally important
3	Moderate importance of one over another
5	Strong or essential importance
7	Very strong or demonstrable importance
9	Extremely important
2,4,6,8	Intermediate values or commitment
Reciprocal or inverse	For reversecomparison

Table 4 Matrix paired of comparison criteria. Source: [5]

	Criterion 1	**Criterion 2**	**Criterion 3**
Criterion 1	1		
Criterion 2		1	
Criterion 3			1

Subsequently, in order to compare the weights of the criteria evaluated, the matrix was normalized. This is to ensure that all data were the same numerical order[10].

Finally, the eigenvector matrix of criteria, which represents the relative importance of the criteria compared in each matrix, was calculated. This step was carried out from the calculation of the average of the elements of each row of criteria obtained in the standard matrix.

c. Alternative weighting vs. criteria.

At this stage, it push throughoutthe construction of the comparison alternatives matrix based on each criterion analyzed (Table 5).

Table 5 Paired alternative matrix with criteria. Source: (Da Silva, 2014)

Criterion N	Alternative 1	Alternative 2	Alternative 3
Alternative 1	1		
Alternative 2		1	
Alternative 3			1

This assessment was also carried out by pair wise comparison scale for preferences (see Table 3). The assessment was given on the basis of scientific and technical information gathered in the literature review. Finally, eigenvectors of each array were calculated from the normalization of the matrix and the average of this with the same methodology used for the paired comparison matrix criteria.

d. Proportion of consistency.

In order to ensure consistency of results, was measured in each matrix comparison criteria and among alternative, the proportion of consistency (PC) (for approved must be less than 10%), using Equation (1)[12]:

$$PC = IC \div IA \qquad \textbf{(1)}$$

Where: PC = Proportion of Consistency; IC = Consistency Index and IA = Random Index.

Consistencies index (IC) is equal to Equation (2):

$$IC = \frac{\lambda_{Max} - n}{n-1} \qquad \textbf{(2)}$$

Where: $\ddot{e}_{Max}$ = Average values of each matrix eigenvector and n = size of the matrix.

The random index (IA) is a consistency index of a random matrix. Indices for various random n, are shown in Table 6.

Table 6 Indexes random average consistency (IA) for various n Source: [12]

Matrix size (n)	2	3	4	5	6	7	8	9	10	11	12	13
Random Index IA)	0	0.5	0.9	1.12	1.24	1.32	1.41	1.45	1.49	1.51	1.48	1.56

e. Final score.

With the above steps, an eigenvector of the criteria and an eigenvector from each matrix of alternatives from which a unified matrix of eigenvectors alternatives criterion formed was obtained. Finally both matrices are multiplied, giving the weighing or weights of the alternatives according to all criteria and its importance. The final column vector indicated the weighting of each alternative and thus allowed to choose the best.

I. Discussion

The results obtained with the implementation of the process of hierarchical analysis in this study allowed to establish that the information provided by interested parties in specific municipality where you perform the AGMSS activity, you can get to establish the alternative or alternatives of wastewater treatment with mercury most successful considering technical, economic, environmental and social aspects. Whereupon, it ensures that the technology is applied in a specific context, taking into account the population, the environment and at the same time be simple and inexpensive to maintain.

In this case, given the complexity of the problem of the use of this metal in the AGMSSof the Segovia municipality; reported Hg concentrations (up 6118 mg Hg/L) and other pollutants associated with the beneficiation process; and the characteristics of the mining population, which would last responsible for implement treatment systems and improvements in its processes, the best technology that can be applied to remove mercury before being discharged is the bioadsorption as tertiary treatment, with 21% of favorability.

This occurs, considering the relevance of the selection criteria was strongly influenced by the perception of stakeholders, represented mainly by the owners of the strike up, in the sense of accepting the implementation of a treatment system provided and when the costs of installation, operation and maintenance of the technology were affordable to them and ease of installation and operation, factors which in the bioadsorption has advantages over other methods analyzed.

In this context, the bioadsorption using natural polymers, obtained from various sources of biological origin such as vegetable waste, algae, and fungi cultures of microorganisms, is presented as an efficient and low cost alternative. Considering that obtaining the bioadsorbent material is economic, since little treatment is required for use, it is abundant in nature or is a byproduct of industrial and agricultural operations. Also, being a technique that used material of biological origin which may be inactivated or inert, the toxicity problem is eliminated, not only caused by the dissolved metals but also by adverse operating conditions; in addition to the economic component maintenance, including the fact that the supply of nutrients and the ability to regenerate by relatively simple treatments for later use not be necessary.

Other important criteria such as efficiency and system reliability also obtained a high weighting for bioadsorption technology, as have been reported efficient removal of Hg levels (90-98%)[7,20].

Also, the characteristics of the mining effluent where expected significant concentrations of other pollutants such as zinc and cyanide, makes the bioadsorption one of the best alternatives, as this process continues acting under a wide range of physicochemical conditions (temperature, pH and presence of other ions) and has high capacity retention ion (bioadsorption capacities up to 384 mg Hg/g of bioadsorbent, reported in the checked history) [25]. However, specific research is needed to remove mercury with bioadsorbents easy to collect or produce in mining areas.

II. Conclusions and Recommendations

The application of the AHP methodology for the complex problem of the selection of the treatment wastewater process with mercury performed from AGMSS it has been made in this study, for the first time. This methodology showed that for a real case, the procedure is easy to use and understand by experts and stakeholders.

Thus, the selection of alternatives considering technical, economic, social and environmental criteria, in the context of the AGMSS activity in the Segovia municipality, allowed to have primary information for the construction thereof, as well as verify and validate the relevance of the information required for structuring and validation, while results of its application were obtained in a real situation, seeking the implementation of any system selected treatment really carried out by artisanal gold miners and small scale in the country.

In this case, it was established that the best technology that can be applied to remove mercury before being discharged is the bioadsorption as tertiary treatment, with 21% favorability. However, it should be noted that these results will be influenced by perceptions of the stakeholders, which in each case should set your

preferences in order to ensure that alternative proposals meet the expectations of these and are actually applied by artisanal and small - scale gold miners in the process.

It is recommended to validate other models for making decisions documented in the literature and also used for selection of wastewater treatment, such as decision - making methodology based on multiple attributes scenarios[11] CINARA Institute methodology[8] and assessment tool Best Available Technology[3] among others.

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