



## Multi-criteria analysis for the selection of advanced oxidation technologies in the treatment of emerging pollutants

Análisis multicriterio para la selección de tecnologías avanzadas de oxidación en el tratamiento de contaminantes emergentes

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### ABSTRACT

#### Keywords:

Advanced oxidation processes,  
Multi-criteria analysis,  
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emerging pollutants,  
pharmaceutical compounds.

Although there is technical information on the efficiency of Advanced Oxidation Technologies (TAOs) at the laboratory level, in some cases at the pilot level and few on a large scale, it is not easy to make a selection of the most appropriate technology for effluent in particular, since the choice of technology depends on the characteristics of the contaminated water. Through the application of the multi-criteria analysis technique, this article proposes a scale of TAOs for the complementary treatment of water contaminated with CE. The alternatives chosen were technologies with peroxide application (H<sub>2</sub>O<sub>2</sub>), Ozone (O<sub>3</sub>) and Fenton processes (Fe/H<sub>2</sub>O<sub>2</sub>), the evaluation criteria were electrical energy consumption (EEO) level of technological maturity, complexity of design / operation and cost of operation. The advanced oxidation technology most recommended by the AHP is ozone and peroxide / UV with a difference of 8.6% in the frequency in the evaluation of the criteria. For the AHP-TOPSIS methodology, peroxide / UV is the key technology over ozone with a 31.4% difference in the frequency of selection.

### RESUMEN

#### Palabras clave:

Procesos de oxidación avanzados.  
Análisis multicriterio.  
Aguas residuales.  
Contaminantes emergentes.  
Compuestos farmacéuticos.

A pesar de que existe información técnica sobre la eficiencia de las tecnologías avanzadas de oxidación (TAOs) a nivel de laboratorio, en algunos casos a nivel piloto y pocos a gran escala, no es fácil hacer una selección de la tecnología más apropiada para un efluente en particular, puesto que la selección de la tecnología depende de las características del agua contaminada. A través de la aplicación de la técnica de análisis multicriterio, este artículo propone una escala de TAOs para el tratamiento complementario de aguas contaminadas con CE. Las alternativas elegidas fueron las tecnologías con aplicación de peróxido (H<sub>2</sub>O<sub>2</sub>), Ozono (O<sub>3</sub>) y procesos Fenton (Fe/H<sub>2</sub>O<sub>2</sub>), los criterios de evaluación fueron consumo de energía eléctrica (EEO, por sus siglas en inglés) nivel de madurez tecnológica, complejidad del diseño/operación y costo de operación. La tecnología avanzada de oxidación más recomendada por el AHP es el ozono y el peróxido/UV con una diferencia de 8.6% en la frecuencia en la evaluación de los criterios. Para la metodología AHP-TOPSIS, el peróxido/UV es la tecnología clave sobre el ozono con una diferencia de 31,4 % en la frecuencia de la selección.

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## Introduction

At present, conventional treatments for water purification and wastewater treatment in Colombian cities are inadequate for a large number of new organic and inorganic pollutants, produced both by industrial activities and by the daily life of human beings [1]. These substances can have a high toxic potential, which carries a risk to ecosystems and human health, for which they have been classified by the authorities of countries of the European Union, USA and Australia with the name of Emerging Contaminants or Contaminants of concern emerging (EC) [2].

In recent years, advanced oxidation technologies (TAOs) have shown their effectiveness in the treatment (degradation and mineralization) of this type of pollutants and their derivatives; The literature shows that results at the laboratory, pilot-scale, and in some cases large scale are promising in the treatment of this class of substances [3]. Therefore, in the short and medium-term, it is expected to be implemented in the sector of basic sanitation of domestic water and the treatment of industrial wastewater since the concern about the effects of these pollutants will raise new goals in environmental legislation in the world [4] - [6].

For the implementation of new technologies and / or processes in water treatment, it is necessary to evaluate multiple technical, environmental, social, and economic factors, for this reason, selection methods are required that allow taking into account the relationships between the variables that are identified as important criteria for making a decision [7].

Multi-criteria Analysis (MCDA) is a tool that in recent years has taken a boom in the analysis of information, for decision-making and the development and implementation of engineering projects, as it allows obtaining qualitative and quantitative relationships between technical variables, economic, environmental and social that were not previously taken into account when selecting a certain technology [8], [9].

Few publications have been found that relate the use of multi-criteria tools for the selection and evaluation of TAOs [8] - [11] and these reports show that the studies carried out using this tool on TAOs require a high degree

of specificity.

The MCDA has been used to evaluate various decisions, in the case of the selection of TAOs for the treatment of CE in real wastewater, reports have been found that collect different criteria and factors, which depend on the very purpose of the selection; In addition to technical factors, economic, environmental and social factors are involved to establish rankings of technologies. The most important results in the application of the MCDA in this class of technologies are presented below.

Teodosiu et al. 2018 [12] presents a complete review on the selection of technologies for the treatment of emerging pollutants with special emphasis on pilot plants and industrial-scale units, taking into account technical, economic, and environmental aspects, as well as data on occurrence, and effects on health. An excellent review is made on aspects of the analysis of decision tools and life cycle analysis

Fast et al. 2017 [7] present a critical evaluation of TAOs in the treatment of EC, with data from the literature and a holistic analysis of the processes, propose the use of engineering, environmental, social, and economic parameters and establish a ranking of technologies for the treatment of CE. The list in descending order is:  $H_2O_2/O_3$ ,  $O_3$ ,  $O_3/UV$ ,  $H_2O_2/UV$ ,  $Fe/H_2O_2$  (FENTON) and  $TiO_2$ .

Bui et al. 2016 [8] carry out a study of the application of TAOs in the treatment of pollutants on a large scale, they carry out a comparative study of TAOs with other technologies (adsorption, membrane reactors) from a technical, legislative, and economic point of view. The use of coupled technologies is proposed due to the complexity of the problem and they follow the use of adsorption with activated carbon and ozone as the most accessible and fastest implementation methodology.

Meng, Zhu, and Yu [13] report the use of MCDA analysis to establish a classification of 36 pollutants and thus establish relations with the EC of the official list of China and thus establish a response to emergencies due to contamination.

Sudhakaran, Lattemann, and Amy [10], present a MCDA study for water purification, they use weightings

of the factors and criteria based on the opinion of experts from academia, the productive sector, and companies in the sector. In addition to the technical-economic criteria, they involve the carbon footprint as a parameter for comparing technologies. According to the weightings used, it is estimated that the combination of technologies is the best option for the treatment of water contaminated with EC.

Meng, Qu, and Yu [14] present a study for the selection of technologies for the treatment of wastewater from the paper industry. The study proposes the use of four criteria, the effect of the process, cost-benefit ratio, processing time, and sustainability; ten indices were established by AHP according to the availability of techniques in the region.

In this work, a methodology is proposed for the classification of advanced oxidation technologies that can be used according to the type of emerging compounds present in wastewater through the use of multi-criteria analysis techniques.

## Methodology

**AHP methodology.** It is a decision technique proposed by T.L. Saaty (1977, 1980) who use a hierarchical structure prioritizes the alternatives of a problem based on a series of criteria or variables, making pairwise comparisons of elements of the same level of the hierarchy concerning each criterion of the higher level, this methodology It is used to solve problems in which there is a need to prioritize different options and later decide which is the most convenient option [15]. The general process of the AHP model is:

1. Establish a decision hierarchy. In this, the goal or objective to be achieved is located at the highest level, At the next level in descending order, the criteria and sub-criteria in which the decision-maker justifies transforms and argues their preferences, finally at the last level of the hierarchy the alternatives are located, which are the set of possible options defined on which the decision will be made (Figure 6.1).
2. Peer comparisons. This analytical process uses binary comparisons through the use of matrix theory, establishing priorities between the elements of one level, with respect to an element of the next higher level. Trials

can be guided by scientific and technical information, and that given by the experience and knowledge of the decision-making group. Each person expresses their opinion, assigning a numerical value that measures the intensity of the opinion.

The AHP compares  $n$  elements,  $C_1 \dots C_n$ , denoting the relative weight (priority or significance) of  $C_i$  with respect to  $C_j$  for the reason  $a_{ij}$ . Such comparisons are located in a square matrix of order  $n$  that must meet certain restrictions:  $a_{ij} = 1 / a_{ji}$ , for  $i$  different from  $j$  and  $a_{ii} = 1$  for all  $i$ . Such a matrix is a reciprocal matrix. With these values, the necessary matrices must be generated to perform the pair-by-pair comparisons of the different levels of the defined hierarchy.

3. Matrix consistency. Its consistency index IC (own) is compared with the consistency index of a reciprocal matrix of the same order whose elements have been randomly determined. This value is called a random index RI and its values are previously determined according to the order of each matrix.

4. Determine the overall priority order of the alternatives. After determining the priority of the elements of each level, the weighted sum method is applied, calculating the total priorities associated with each alternative, which represent their importance with respect to the goal. [16].

*Model AHP-TOPSIS.* It is the combination of the AHP and TOPSIS methods that, in this case, allows evaluating the alternatives according to the bibliographic data found of these, the use of the AHP method allows establishing the level of importance that the criteria of the alternatives will have in the making of decision combining with the TOPSIS technique that is used to order the alternatives and prioritize them.

The TOPSIS method consists of the comparison of alternatives, facing the dilemma of working under the premise of the ideal alternative, with the anti-ideal, or with a mixture of the two. The general process of the TOPSIS model is:

1. Construction of the decision matrix: This matrix contains the alternatives that will be evaluated based on the criteria and the vector of associated weights, which in this case are those found by the AHP method, then the matrix is normalized and weighted.

2. Determine the ideal negative and positive solution.

3. Calculate distance measurements and relative proximity.

Criteria to be evaluated for the selection of TAOs. MCDA studies for technology selection indicate a wide possibility of criteria and sub-criteria to be established. Table 1 shows the selection of technical criteria (with financial evaluations) evaluated under the same conditions and elaborated in the use of TAOs, based on the information available in the treatment of EC in real waters.

**Table 1.** Technical criteria for selection of TAOs in real water treatment.

PROCESS	Design / Operation Complexity	Technological Maturity Level (TRL)	EEO Energy Consumption (kWh/m <sup>3</sup> )	Operation cost (Euros/m <sup>3</sup> )
H <sub>2</sub> O <sub>2</sub> / UV	low	Half	0.7 - 2.28	0.12 - 0.18
Ozone	half	high	0.33 - 0.5	0.25 - 0.56
Fenton	high	Half	2 - 10	0.19 - 0.36

As can be seen, the technical criteria and operating costs are key to determining the possibility of implementing technology on an industrial scale and therefore achieving its implementation in real waters. [17] - [25].

The criteria selected for the evaluation of TAOs are described below, as a first approximation in the establishment of a selection scale from the technical point of view, operating costs, and degree of maturity.

**Electric Power Consumption - EEO (kWh/m<sup>3</sup>).** This parameter is defined as the electrical energy consumption in KWh required to degrade a pollutant by an order of magnitude in a cubic meter of water. It is widely used for the comparison of technologies as it takes into account the energy consumption for low concentration pollutants such as emerging pollutants [26] - [30].

**Operation cost.** This parameter takes into account the costs associated with the consumption of chemicals associated with each of the processes and which are decisive in the feasibility of applying OATs [31].

**Plant Design / Operation Complexity.** This parameter is related to the ease of implementation of TAOs at different scales. Heuristic rules are used to determine the high value, the medium or low complexity of plant operation and unit operation [32], [33].

**Technological Maturity Level (TRL).** The Technological

Maturity Level or TRL (Technology Readiness Level) for its acronym in English is one of the methodologies to know the implementation status and the scale of use of a technology [34], [35]. There are not many reports of the use of this parameter in the selection of TAOs, but it is well known that both Ozone and UV-based technologies have a high TRL compared to emerging technologies such as photo catalysis. Thus, this parameter allows establishing viable application options in a given period of time [36], [37].

## Results and Discussion

### *AHP analysis development*

As a result of the development of the AHP analysis, the criteria weights were found through 14 surveys conducted with experts (university researchers, industry engineers) with extensive experience in TAOs and the application of wastewater treatments, surveys, and profiles of the respondents are in Annex 2. A matrix is developed with the geometric averages of the experts' opinion (Table 2) and the iterations of this matrix for each criterion result in the criteria's priority eigenvector (Table 3).

**Table 2.** Matrix resulting from expert opinion.

Criterion	Complexity	C Level of maturity	Energy Costs (EEO)	Operating costs
Complexity	1	4/7	1/3	1/3
Level of maturity	1 3/4	1	3/5	7/9
Energy consumption EE0	2 7/9	1 2/3	1	1 1/2
Costs Operation.	3 1/6	1 2/7	2/3	1

**Table 3.** Expert matrix eigenvector

Criteria	Eigenvector
Energy Costs (EEO)	37.4%
Costs Operation	29.4%
Level of maturity	21.6%
Complexity	11.6%

The matrix of experts shows that energy costs and operating costs are decisive for the selection of technologies, this is to be expected since these aspects determine the feasibility of implementing a new technology [38]–[40]. On the other hand, technological maturity is a new criterion used for the selection of TAOs and very little has been reported so far [41] - [43]

The development of the prioritization matrix of the alternatives was developed with the values found in the literature normalized and iterated by each of the alternatives, Table 4, thus resulting in the prioritization of the TAOs.

According to the results, ozone is the most recommended technology with 47%, followed by peroxide with 35% and finally Fenton with 18%. These results could be following what was stated by some researchers who recommend this type of technology for water treatment [44][26][45] [46].

**Table 4.** Result matrix of alternatives, criteria vector and solution

Alternatives Matrix					Vector Criteria
	Complexity	M level	EE/0	Cost operation.	
H2O2/UV	0.582	0.285	0.162	0.558	* 0.116
Ozone	0.309	0.498	0.770	0.122	0.216
Fenton	0.109	0.217	0.068	0.320	0.374
					0.294

  

H2O2/UV	35%
Ozone	47%
Fenton	18%



## Development of the AHP-TOPSIS Analysis

The development of the AHP-TOPSIS method was carried out using the criteria prioritization vector produced by the AHP method developed with the expert surveys (Table 5.), also, the values reported in the literature were used, which were normalized as shown in Table 5 and weighted to find the positive and negative solution vectors to find the distances to the solutions and the solution vector  $R_i$  (Table 6.).

Table 5. Normalized criteria matrix

Normalized Matrix				
Criteria				
Alternatives	Complexity	Level of maturity	Energy Costs (EEO)	Cost operation
<b>Weight</b>	12%	22%	37%	29%
<b>H<sub>2</sub>O<sub>2</sub>/UV</b>	0.16903	0.45750	0.24048	0.29297
<b>Ozone</b>	0.50710	0.76250	0.06700	0.79101
<b>Fenton</b>	0.84520	0.45750	0.96835	0.53710

Table 6. Solution of TAOs priorities

	$R_i$
<b>H<sub>2</sub>O<sub>2</sub>/UV</b>	0.775
<b>Ozone</b>	0.695
<b>Fenton</b>	0.172

Sensitivity Analysis: To determine the stability of the solution, a sensitivity analysis is performed for both methodologies, varying the starting conditions by modifying the weights of the criteria with 35 different scenarios (Table 7).

Table 7. Evaluation scenarios for the sensitivity analysis

Scenario (%)	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	
Criteria																			
Complexity	25	100	0	0	0	50	50	50	0	0	0	15	15	15	15	15	15	10	
Level of maturity	25	0	100	0	0	50	0	0	50	50	0	25	25	50	50	25	10	15	
EEO Energy Costs	25	0	0	100	0	0	50	0	50	0	50	10	10	10	25	50	50	50	
Cost of operation	25	0	0	0	100	0	0	50	0	50	50	50	50	25	10	10	25	25	
Scenario (%)	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35		
Criteria																			
Complexity	10	10	10	10	10	50	50	50	50	50	50	25	25	25	25	25	25		
Level of maturity	15	25	25	50	50	15	15	10	10	25	25	50	50	10	10	15	15		
EEO Energy Costs	25	50	15	25	15	25	10	25	15	10	15	15	10	15	50	50	10		
Cost of operation	50	15	50	15	25	10	25	15	25	15	10	10	15	50	15	10	50		

**AHP methodology analysis.** The 35 scenarios are evaluated by repeating the steps, the main result continues to be ozone technology as the first alternative to be used in water treatment. This can be observed by reviewing the

frequency with which this technology is repeated in the first place of the 35 scenarios.

Table 8 shows the results of all the scenarios and the last column of this shows the frequency with which each of the treatments is presented in the first place of the prioritization columns, thus ozone with a percentage of 54.3% followed by Peroxide which ranked first at 45.7% and Fenton with 0%.

Table 8. Results of the scenarios for AHP.

Scenario%	1	2	3	4	5	6	7	8	9	10	11	12
Peroxide / UV	39,7	58,2	28,5	16,2	55,8	43,3	37,2	57	22,4	42,1	36	43,5
Ozone	42,5	30,9	49,8	77	12,2	40,4	53,9	21,6	63,4	31	44,6	35
Fenton	17,8	10,9	21,7	6,8	32	16,3	8,9	21,4	14,2	26,9	19,4	21,5

  

Scenario%	13	14	15	16	17	18	19	20	21	22	23	24
Peroxide / UV	45,4	38,5	32,6	29,5	33,6	32,1	42	29,4	43,3	32,5	36,4	43
Ozone	30,9	40,3	50	56,8	51,2	52,1	36	55,9	33,2	49,7	42,6	43,4
Fenton	23,7	21,2	17,4	13,7	15,2	15,8	22	14,7	23,5	18,4	21	13,6

  

Scenario%	25	26	27	28	29	30	31	32	33	34	35	frec
Peroxide / UV	48,9	44,4	48,3	46,2	44,2	36,8	38,8	47,7	33,9	32,5	48,3	45,7
Ozone	33,7	41,5	35	37,4	40,7	45,4	42,1	30,4	53	54,9	29	54,3
Fenton	17,4	14,1	16,7	16,4	15,1	17,8	19,1	21,9	13,1	12,6	22,7	0

**AHP-TOPSIS methodology analysis.** The 35 scenarios were evaluated, in this case, the peroxide / UV technology occupies the first place with a 65.7% frequency followed by ozone with 34.3% and Fenton with 0%. (Table 9).

Table 9. Results of the scenarios for AHP-TOPSIS

Scenario%	1	2	3	4	5	6	7	8	9
Alternatives									
Peroxide / UV	0,76 0	1	0	0,8	1	0,689	0,851	1	0,675
Ozone	0,62 7	0,5	1	1	0	0,574	0,740	0,36	1
Fenton	0,17 6	0	0	0	0,5	0	0	0,26	0
Scenario%	10	11	12	13	14	15	16	17	18
Alternatives									
Peroxide / UV	0,62 0	0,836	0,86 0	0,78 1	0,535	0,575	0,767	0,812	0,799
Ozone	0,38 0	0,644	0,47 8	0,33 6	0,578	0,796	0,866	0,772	0,779
Fenton	0,39 4	0,214	0,31 4	0,39 1	0,230	0,080	0,051	0,120	0,121
Scenario%	19	20	21	22	23	24	25	26	27
Alternatives									
Peroxide / UV	0,83 4	0,766	0,77 7	0,56 7	0,536	0,860	0,883	0,881	0,904
Ozone	0,48 0	0,848	0,38 7	0,77 6	0,616	0,618	0,484	0,605	0,510
Fenton	0,32 1	0,076	0,37 8	0,11 9	0,221	0,058	0,151	0,085	0,146
Scenario%	28	29	30	31	32	33	34	35	Freq
Alternatives									
Peroxide / UV	0,81 9	0,817	0,57 3	0,56 4	0,889	0,816	0,805	0,864	65,7%
Ozone	0,52 7	0,566	0,69 2	0,63 5	0,382	0,803	0,824	0,334	34,3%
Fenton	0,09 6	0,064	0,08 7	0,13 3	0,336	0,073	0,050	0,354	0

## Conclusions

Technologies based on the use of ozone and peroxide / UV are classified by the MCDA methods as appropriate technologies for the treatment of wastewater.

The advanced oxidation technology most recommended by the AHP is ozone and peroxide / UV with a difference of 8.6% in the frequency in the evaluation of the criteria

For the AHP-TOPSIS methodology, peroxide / UV is the key technology over ozone with a 31.4% difference in the frequency of selection.



The Fenton process is not the best option under the criteria evaluated by both AHP and AHP-TOPSIS

The use of the criterion of technological maturity in the evaluation of technologies is constituted as a new indicator in the multi-criteria analyzes used to classify TAOs.

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