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Photochemical treatments (UV/H_2O_2, UV/O_3 and UV/H_2O_2/O_3) and inverse osmosis in wastewater: Systematic review

Angeles Amaro-Soriano [1], Fernando Hernández-Aldana [1, †] and Antonio Rivera [2, *]

[1] Postgraduate in Environmental Sciences from the Institute of Sciences, Meritorious Autonomous University of Puebla, Mexico.
[2] Research Center in Microbiological Sciences of the Institute of Sciences, Meritorious Autonomous University of Puebla, Mexico.
† In Memory of Dr. Fernando Hernandez-Aldana

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Abstract

Every year, the bodies of water receive millions of cubic meters of wastewater from municipal, industrial, agricultural or livestock discharges, treated in an inadequate way or without treatment. The objective of this study was to carry out a systematic review of the frequency of use and effectiveness of the main photochemical processes and the complementation with other treatments such as it is reverse osmosis, used in different types of wastewater effluents. We searched multiple electronic databases (2010-2021), using a stepwise searching approach, supplemented with hand searching. *In vitro* or *in vivo* English language publications, original studies, and reviews were included. The database was made up of a total of 100 articles that met the minimum selection criteria, of which 25 articles the maximum scores for analysis. These articles report the improvement in the elimination of pollutants when the treatments are used together and not individually, in relatively short times ranging from 30 minutes of radiation to 8 minutes of exposure to the treatments. Regarding the type of water that was treated, most of the articles report the decontamination of natural wastewater, that is, from the industry without treatment. The percentages calculated to identify research opportunities or gaps in relation to photochemical processes (UV/H_2O_2/O_3). As proposed some authors, if any value of the percentage of pre-selected articles (PAA %) is less than the value of the percentage of failure (MAPAA %), a research opportunity is revealed not addressed by the literature. Based on the percentage results, it is observed that there are no gaps with respect to the photochemical processes or that there are possibly no updates reported in the literature yet.

Keywords: Wastewater; Depuration; Treatments; Systematic review

1. Introduction

The planet is covered by 70% of water, however, only 2.5% is fresh water accessible to humans. It is found in rivers, lakes, underground deposits and only a part is usable for human consumption without special treatments [1].

According to the United Nations (2018), about 2.1 billion people do not have access to basic water and sanitation services, affecting 40% of the world's population and 6 out of 10, or 4.5 billion, lack of safe sanitation. In Mexico 24 million lack sewerage. In addition, there are many water bodies, surface and underground, contaminated, and overexploited, which could increase due to the fact that 80% of untreated wastewater generated by human and industrial activity is discharged in rivers and seas. By 2050, it is estimated that 25% of the population will be affected by the shortage of water intended for human consumption [2].

* Corresponding author: Antonio Rivera
Centro de Investigaciones en Ciencias Microbiológicas del Instituto de Ciencias, Benemérita Universidad Autónoma de Puebla.

Water body's each year receive millions of cubic meters of wastewater either from municipal, industrial, agricultural or livestock discharges, treated in an inadequate way or without treatment. The treatments that are applied consist of a set of physical, biological and chemical operations, with the purpose of eliminating the greatest amount of pollutants before their discharge, so that the levels of contamination that remain in the treated effluents meet the legal limits. Existing and can be assimilated naturally by the receiving channels [3].

Over time, different studies have been carried out on the difficulty of conventional treatments to remove or chemically transform many of the pollutants, since tertiary treatments are not implemented in wastewater treatment, with the aim of being able to reuse the treated water, it is resorting to the search for new efficient alternatives for the treatment of wastewater, currently Advanced Oxidation Processes (POA) are proposed as an option for the treatment of water that present contaminants that are difficult to biodegrade, where the radical Hydroxyl (● OH) acts as the main oxidative agent and demonstrates an efficiency in the elimination of bacteria harmful to humans [4].

Some of the treatments that are most frequently reported in the literature are those implemented with ultra violet light such as UV/hydrogen peroxide (UV/H_2O_2), UV/ozone (UV/O_3) and UV/hydrogen peroxide/ozone (UV/H_2O_2/O_3) which are efficient technologies in the oxidation of organic matter and even the complete mineralization of some pollutants, also reducing the Chemical Oxygen Demand (COD), toxicity and the Total Organic Carbon (TOC) in the water [5].

One of the main evidences within scientific investigations are systematic reviews, which constitute an essential tool to synthesize the available scientific information, increase the validity of individual studies and identify areas of uncertainty where deeper investigations are required [6]. The objective of this study was to carry out a systematic review of the frequency of use and effectiveness of the main photochemical processes (UV/H_2O_2, UV/O_3, UV/H_2O_2/O_3) and the complementation with other treatments such as it is reverse osmosis, used in different types of wastewater effluents in which rivers and waters simulated in the laboratory stand out, in Latin American countries and the world.

2. Material and methods

The construction of this work was focused on a systematic review, the bibliographic compilation and relevant scientific information on advanced oxidation technologies (PAO) specifically of photochemical treatments that include hydrogen peroxide and ozone (UV/H_2O_2, UV/O_3 and UV/H_2O_2/O_3), as well as the use of reverse osmosis applied in Mexico and other countries of the world for the elimination of pollutants and removal of the bacterial load in different types of industrial, agricultural, municipal wastewater and not municipal.

2.1. Bibliographic search procedure

A literature review was carried out in the following databases: Scielo, Redalyc, NCBI, Science Direct, Scopus and Dialnet. Considering the following keywords: wastewater, reverse osmosis, wastewater treatment. Limiting to the last decade of publication: 2010-2021. The selected information was taken from scientific articles giving priority to experimental research.

2.2. Bibliographic selection

During the bibliographic review, the aforementioned keywords were used, adding to the search the following words: UV/hydrogen peroxide (UV/hydrogen peroxide), (H_2O_2/UV), UV/ozone (UV/ozone) (O_3/UV), UV/hydrogen peroxide/ozone (UV/hydrogen peroxide/ozone) (H_2O_2/O_3/UV) Advanced oxidation process, emerging pollutants, UV/waste water (UV/wastewater treatment).

For the fulfillment of the proposed objectives, during the preselection of the bibliography the following criteria were taken: 1) documents containing the points of interest, 2) local and international articles, 3) types of wastewater, 4) type of treatment applied, 5) positive and negative results of the use of the treatments and their constant updating. Likewise, works that contained UV treatments with other components that were not hydrogen peroxide or ozone were excluded.

Based on the work done by Jurado *et al*., (2017) [8], each article was assigned a selection criterion and a relevance value from 0 to 5 (Table 1), documents containing the points of interest were selected for review and assignment by average. Simple arithmetic of the total score, of which documents with scores of 4 and 5 were chosen for the analysis and discussion, considering them as those that best met the objective of this study.

Table 1 Relevance value for article selection

Criteria number	Description	Score
1	Studies of wastewater from rivers and treatment plants	1.5
2	Wastewater studies using simulated waters in the laboratory	1
3	Studies that perform treatments with only one of the photochemical processes (UV/H_2O_2 and UV/O_3) and reverse osmosis. With the aim of eliminating organic or persistent pollutants and bacteria present	1
4	Studies that use both photochemical processes ($UV/H_2O_2/O_3$) to eliminate organic or persistent pollutants and bacteria present	1.5
5	Studies with experimental methodologies and results treated statistically	1.5

Subsequently, the percentage of articles that meet each of the criteria was calculated, as proposed by Gómez *et al*., (2014) [7] and Jurado *et al*., (2017) [8]:

First, the average of the criteria was calculated using the following equation:

$$PAA\%(n) = \left(\frac{T}{TA}\right) \times 100$$

Where:

PAA%: percentage of shortlisted articles that meet the nth selection criteria.

T: total of shortlisted articles that meet the nth selection criteria

TA: total of shortlisted articles

n: number of selection criteria (1,2,3 or 4)

Next, the average of the percentages was calculated using the equation:

$$APPA\% = \frac{PPA\%(1) + PPA\%(2) + ..PPA\%(n)}{TC}$$

Where:

APPA%: average of percentages of questions or selection criteria

PAA% (n): percentage of articles that respond to the questions or criteria of the nth section.

TC: total number of questions or selection criteria.

Finally, the average of the percentages was divided by 3, to obtain a percentage of break, minimum or limit, using the following equation:

$$MAPAA\% = \frac{APPA\%}{3}$$

Where:

MAPAA%: percentage of break, minimum or limit

APPA%: average of percentages of questions or selection criteria.

2.3. Bibliographic analysis

After the preselection of the articles that contained any of the criteria for their review and their subsequent assignment of utility for this work, a next phase of analysis was carried out.

Univariate and multivariate studies were carried out to compare the use and frequency of the main photochemical decontamination techniques (UV/H_2O_2, UV/O_3 and $UV/H_2O_2/O_3$) and their usefulness in the elimination of bacterial load, organic pollutants and emerging, as well as its percentage of use in our country and in the world.

For the multivariate analysis, different coding was carried out (Table 2), this to establish a characterization of all the documents studied.

Table 2 Classification encodings

Classification	Code	Description
Treatments	1	UV/H_2O_2
	2	UV/O_3
	3	$UV/H_2O_2/O_3$
	4	Inverse osmosis
Pollution removal	1	Consider organic pollutants
	2	Consider emerging pollutants
Bacterial load	1	Does not consider cause-disease
	2	Consider cause-disease
Effluent type	1	Consider rivers
	2	Consider wastewater treatment plant
	3	Consider other effluents
	4	Simulated waters in laboratory

3. Results

3.1. Bibliographic selection

The bibliographic search showed a total of 150 documents, most of them refer to reports of the efficiency of photochemical processes that include hydrogen peroxide (UV/H_2O_2) and ozone (UV/O_3), as well as the results of the degradation of pollutants. Fifty articles that did not meet the selection criteria were excluded, being review articles, postgraduate thesis, conference abstract and the inclusion of other treatments different from those studied. The database was made up of a total of 100 articles that met the minimum selection criteria, of which 25 reached the maximum scores for analysis.

3.2. Bibliographic analysis

In the last decade, various studies have been reported regarding photochemical treatments that include hydrogen peroxide and ozone or the combination of both (H_2O_2/O_3), the number of articles reported by year and country was analyzed (Figure 1), considering only countries with a number of articles greater than one.

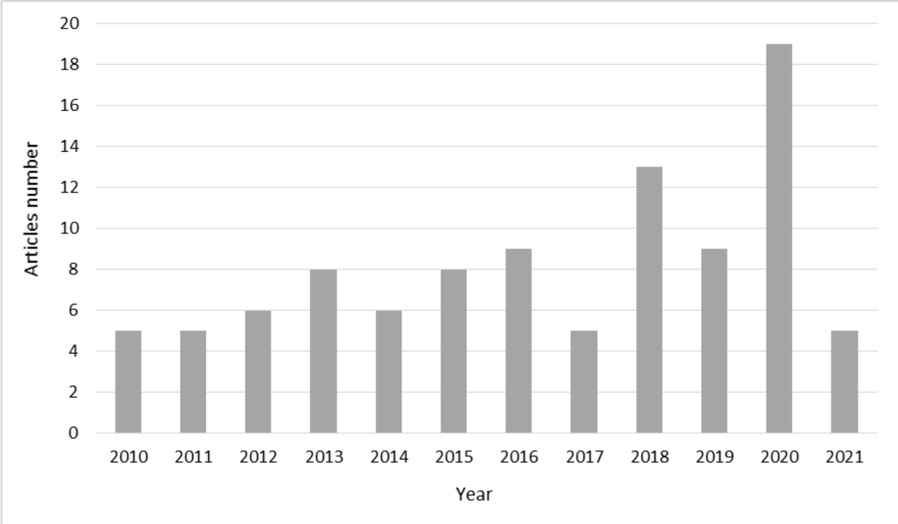

Figure 1 Number of publications referring to photochemical treatments in recent years

Regarding the largest number of publications by country, China stands out with 17, Brazil 13, Colombia 10, Germany 6 and Canada 5, for Mexico 3 were reported. According to the years of publication, a trend in recent years is observed (2015 to date) in the use and updating of photochemical treatments as an alternative for wastewater treatment, with 2020 being the year with the highest report on its implementation.

A trend was found for the greater use of photochemical processes using hydrogen peroxide with a total of 48 articles, likewise the use of the combination of both processes reported a total of 32 articles, not being the same case for ozone and reverse osmosis processes with only 10 items, respectively. In addition, a classification was made of the published works and the different aqueous matrices that are used, resulting in the greater use of simulated waters in the laboratory for their treatment with photochemical processes, in addition, it is reported that most of the contaminants treated were emerging pollutants and their derivatives.

Table 3 shows 25 articles with their score according to the established criteria, the photochemical treatment applied, and the type of wastewater treated. It is observed that the highest scores were obtained by the studies that used the combination of hydrogen peroxide and ozone treatments, showing conclusions about its effectiveness of 80-100% in the elimination of various pollutants such as the presence of drugs, phenols, toxic of oil, among others and in some cases the decrease of bacteria. And only two articles with UV/H_2O_2 treatment managed to obtain scores of 4.5 and 5 respectively and be considered for their analysis. In addition, two articles that have the use of photochemical processes plus the implementation of reverse osmosis obtained the minimum selection scores, concluding a degradation of 48% of the pollutants.

These articles report the improvement in the elimination of pollutants when the treatments are used together and not individually, in relatively short times ranging from 30 minutes of radiation to 8 minutes of exposure to the treatments. Regarding the type of water that was treated, most of the articles report the decontamination of natural wastewater, that is, from the industry without treatment.

Table 3 Application of photochemical treatments in different types of wastewater

Photochemical treatment	Wastewaster type	Treatment efficiency	Source	Reference
$UV/H_2O_2/O_3$	Yamuna river with high wastewater	Effective in the degradation of trihalomethane precursors (THM) in wastewater with 12 minutes of treatment	4.5	[9]
$UV/H_2O_2/O_3$	Drinking water and wastewater effluents	Phenolic and olefinic UV filters efficiently removed by O_3 treatment with specific doses of <0.5 mg O_3/mg DOC for ~100% removal	4.5	[10]

$UV/H_2O_2/O_3$	Tertiary municipal wastewater	The $UV/H_2O_2/O_3$ process is an efficient method against micro pollutants	4.5	[11]
$UV/H_2O_2/O_3$	Grey waters	The highest COD removal in the process was 92%	5	[12]
UV/H_2O_2	Hospital laundry wastewater	The mean COD and surfactant removal efficiencies were 60.3% and 98%, respectively. However, the treatment was not effective in reducing color and haze	5	[13]
$UV/H_2O_2/O_3$	Water from naphtha sweetening processes	UV/H_2O_2 increases the degradation rate of phenol (150-200%) $UV/H_2O_2/O_3$ is a very efficient process for degrading toxic organic compounds in wastewater from oil refining	4.5	[14]
$UV/H_2O_2/O_3$	Alkylbenzene industrial wastewater	A maximum reduction in TCOD was 58, 53 and 49%, respectively for the $UV/H_2O_2/O_3$, UV/O_3 and UV/H_2O_2 processes	4.5	[15]
$UV/H_2O_2/O_3$	Agroindustrial wastewater	99% total organic carbon (TOC) removal. It can be used for irrigation in accordance with legal limits	5	[16]
$UVc/O_3/H_2O_2$ UVc/H_2O_2 and O_3/H_2O_2	Aquaculture wastewater	100% inactivation of bacteria present with $UVc/O_3/H_2O_2$ and UVc/H_2O_2, requiring 20 and 80 minutes for the inactivation of *Vibrio* spp. and total culturable bacteria, respectively	4.5	[17]
UV/H_2O_2 and inverse osmosis	Wastewater treatment plant	48% removal of BPA, the rejection efficiency of the membrane ranged from 60% to 84%	4.5	[18]
UV/H_2O_2	Sanandaj Water Treatment Plant	Increasing the concentration of H_2O_2, time and the decrease of the initial concentration	5	[19]
$UV/H_2O_2/O_3$	Leachate treatment plant	DOM removal efficiency, in COD, TOC and color equipment	4.5	[20]
$UV/H_2O_2/O_3$	Underground water	The formation of bromate, a potentially carcinogenic by-product of ozonation, could be significantly reduced	4.5	[21]
$UV/H_2O_2/O_3$	Wastewater from the gas field	Achieved degradation of most of the organic matter of ML-GFW (wastewater from gas fields)	4.5	[22]
$UV/H_2O_2/O_3$	Residual water treatment plant	Complete removal of gemfibrozil and a maximum of 80% removal of ibuprofen were achieved using an ozone dose of 1.5 mg/L	4.5	[23]
$UV/H_2O_2/O_3$	Wastewater treatment pilot plant	Effective removal of trace organic compound, ranging from 21% to more than 99% degradation	4.5	[24]
$UV/H_2O_2/O_3$	Sewage produced at the South Baghdad power station	20 minutes was the best exposure time with removal percentages of 89.79%, 83.33% and 70% for oil, COD and TOC, respectively	4.5	[25]

$UV/H_2O_2/O_3$	Lake Zurich and Lake Greifensee Sewage effluent from Dubendorf (Switzerland) Lake Jonsvatnet(Norway)	The use of O_3/H_2O_2 increased the micro-pollutant transformation rate and reduced bromate formation by 70%	4.5	[26]
UV/H_2O_2 and inverse osmosis	Brackish water	Microbial biofilm formation after UV/H_2O_2 pretreatment was significantly lower than that obtained after control and UV pretreatments	5	[27]
$UV/H_2O_2/O_3$	Textile water	In 240 minutes of irradiation time, all color was removed using 1% H_2O_2 dose and COD removal was 78.4%	4.5	[28]
$UV/H_2O_2/O_3$	Textile water	$UV/H_2O_2/O_3$ with 30 minutes duration, was the most effective method. UV/H_2O_2 duration of time in 10 minutes was the least effective method	4.5	[29]
$UV/H_2O_2/O_3$	Pharmaceutical industry waters	Without the application of additional factors, the process is not very effective, transferring the fate of the antibiotics to the environment	5	[30]
$UV/H_2O_2/O_3$	Raw hospital wastewater	Effective for the removal of COD, it was found that the interaction between the concentration of O_3 and the dose of H_2O_2 is the most important factor that affects the performance of the process	5	[31]
$UV/H_2O_2/O_3$	Seawater	Produces high levels of downtime	4.5	[32]
$UV/H_2O_2/O_3$	Wastewater treatment plant	Removal efficiencies> 85% for 20 of 21 organic micropollutants, *E. coli* and enterococci decreased to values below the levels allowed for drinking water, even if stored for 3 days	4.5	[33]

Of the articles included, 5 of them correspond to the year 2020 of publication, followed by the years 2014, 2018 and 2019 with 4 articles reported. Indicating small jumps between the reports on the use and/or efficacy of photochemical treatments ($UV/H_2O_2/O_3$).

Table 4 shows the percentages calculated to identify research opportunities or gaps in relation to photochemical processes ($UV/H_2O_2/O_3$). As proposed by Gómez *et al.*, (2014) [7] and Jurado *et al.*, (2017) [8] if any value of the percentage of pre-selected articles (PAA %) is less than the value of the percentage of failure (MAPAA %), a research opportunity is revealed not addressed by the literature.

Table 4 Percentages calculated for the identification of gaps

Indicator [%]	Calculated value [%]
PAA	C1= 100
	C2=65
	C3=40
	C4=100
APPA	76
MAPAA	25

Based on the percentage results, it is observed that there are no gaps with respect to the photochemical processes or that there are possibly no updates reported in the literature yet.

4. Discussion

As in any research study, the presence of errors in data extraction can invalidate the results of a systematic review. It is of the almost importance to get as many primary studies on the question of interest as possible. This is to minimize random error and bias. If studies are omitted, bias can be introduced if the sample finally selected is not representative. Two decisions must be made at this point: in relation to the restriction or not of the language of publication and in relation to the inclusion or exclusion of studies not published in medical journals. Regarding language, the most frequent for pragmatic reasons is to include only publications in English and in the native language of the author of the systematic review. However, the available data indicate that the quality of the research is not necessarily related to the language of publication [34].

Access to water, sanitation and hygiene is a fundamental right, yet billions of people around the world continue to face enormous difficulties in accessing the most basic services on a daily basis. Water treatment involves a set of physical, chemical, and biological operations, which are used to eliminate water pollution. The objective is to obtain a water that is suitable for the use that is going to be given to it for human or animal consumption, irrigation, industrial use, etc. Water treatment is essential for people to have access to better quality water. According to data from the World Health Organization, 3 out of 10 people in the world lack access to safe drinking water and available at home, and 6 out of 10 lack safe sanitation [1].

This means that, according to the World Health Organization report "Progress in Drinking Water, Sanitation and Hygiene", the 2030 Agenda for Sustainable Development recognizes that safe water, effective sanitation and adequate hygiene are factors that influence other sustainable development goals related to health, nutrition, education or gender equality. Sustainable development goal number 6 is to ensure the availability and sustainable management of water and sanitation for all by 2030 [35].

Different works corroborate the efficiency of electrochemistry and photocatalysis to eliminated biological and chemical pollutants, which increases water quality. The combination of these processes, as a preliminary treatment, followed by a biological process, is very promising from an economic point of view. However, the strategy of coupling these systems is not a universal solution. Chemical, biological, and kinetic studies should always be carried out for all kinds of compounds and wastewater to ensure that the pretreatment process favors their compatibility with a biological subsequent treatment [36].

Wastewater treatments by photochemical catalysis strategies offer a possibility of profitable and environmentally friendly wastewater treatment, in addition to the fact that photocatalysis is a non-selective technology, which can lead to the recovery of wastewater containing different pollutants [37, 38].

In the last decade, a large number of studies have been reported on photochemical treatments that include hydrogen peroxide and ozone or the combination of both (H_2O_2/O_3), in which several authors agree that the use of ultraviolet radiation is profitable for water treatment systems given that it does not produce toxic waste, the contact time is short and with relatively simple equipment to operate [39].

More publications stand out in China, followed by Latin American countries such as Colombia and Brazil. According to the years of publication, there is a trend of the last six years in the use and updating of photochemical treatments as an alternative for wastewater treatment, with the year 2020 being the highest report of its implementation. It could be deduced that the use of these treatments is an efficient technology in degradation and have applications in different sectors, however, a disadvantage is that trained personnel are required to handle the treatments, which could be justifying that the countries where more its use is reported in China [40].

There is a trend towards the greater use of photochemical processes using hydrogen peroxide, likewise the use of the combination of both processes reported a total of 32 articles, not being the same case for the processes with ozone and reverse osmosis with only 10 articles, respectively. Which could be because hydrogen peroxide and UV processes are widely known by various researchers for the best removal of organic matter. However, as mentioned by Grijalva *et al.*, (2020) [39], disadvantages have been reported regarding the use of these treatments and it is that due to the composition of the water they cannot be used with high levels of suspended solids, turbidity, color or organic matter. , since these substances can reduce or absorb ultraviolet radiation and disinfection efficiency.

A classification was made of the published works and the different aqueous matrices that are used, resulting in the greater use of simulated waters in the laboratory for their treatment with photochemical processes, in addition, it is reported that most of the treated pollutants were emerging pollutants and its derivatives. Although it would be expected that the reports were mostly on organic pollutants, since these interact with hydroxyl radicals by three mechanisms that make their elimination possible. Furthermore, the increase in the reporting of emerging pollutants is mainly due to the increasing amounts of these compounds in water sources and the fact that other commonly applied disinfection processes were unable to eliminate them [5].

Table 4 shows the investigations with their score according to the established criteria, the photochemical treatment applied, and the type of wastewater treated. It is observed that the highest scores were obtained by the studies that used the combination of hydrogen peroxide and ozone treatments, showing conclusions about its effectiveness of 80-100% in the elimination of various pollutants such as the presence of drugs, phenols, toxic of oil, among others and in some cases the decrease of bacteria. And only two articles with UV/H_2O_2 treatment managed to obtain scores of 4.5 and 5, respectively, and be considered for their analysis. In addition, two articles that have the use of photochemical processes plus the implementation of reverse osmosis obtained the minimum selection scores, concluding a degradation of 48% of the pollutants. However, investigations that have been carried out in recent years, report in relation to the feasibility of costs and energy consumption that reverse osmosis requires less energy consumption, which presents an advantage over the rest of the processes, it can also be used in brackish water like seawater [39].

Likewise, these articles report the improvement in the elimination of pollutants when the treatments are used together and not separately, in relatively short times ranging from 30 minutes of radiation to 8 minutes of exposure to the treatments. Regarding the type of water that was treated, most of the articles report the decontamination of natural wastewater, that is, from the industry without treatment. To which the researchers make the recommendation to carry out other types of studies such as chemical, physicochemical, toxicological, to know the state of lotic systems [41]. It is also highlighted that, in the types of treated water, water resulting from pharmaceuticals and hospitals are found using UV processes in combination, however, it is reported that the use of ozone alone is an effective disinfectant against pathogens and viruses in the wastewater, as well as an economically viable treatment for the removal of antibiotics and other organic pollutants [42].

The calculated percentages are presented to identify research opportunities or gaps in relation to photochemical processes (UV/H_2O_2/O_3). Since the development of the photochemical processes used for the decontamination of wastewater has been gradual from the first years in which they were used until the 90s when the scientific community began to address decontamination issues and propose the option of using these procedures [43]. As proposed by Gómez *et al*., (2014) [7] and Jurado *et al*., (2017) [8], if any value of the percentage of pre-selected articles (PAA%) is less than the value of the percentage of failure (MAPAA%), a research opportunity is revealed not addressed by the literature.

Based on the percentage results, it can be inferred that there are no gaps with respect to the photochemical processes or that there are possibly no updates reported in the literature yet. What is currently reported in the literature is the use of heterogeneous photocatalysis processes with titanium dioxide and it is the procedure with the greatest interest among researchers, because in several cases it uses electricity as an ecological source of energy, in addition to profitability and simplicity of operation [44].

In relation to the percentages obtained from pre-selected articles (PAA%), if the results are exceeded 50%, the criterion will reach greater attention in the coming years, in accordance with this, almost all the criteria exceed it, not being the case of the criterion no. 3, studies that perform treatments with only one of the photochemical processes (UV/H_2O_2 and UV/O_3) and/or reverse osmosis.

5. Conclusion

According to the bibliographic analysis, one hundred articles were identified, in which UV/hydrogen peroxide/Ozone (UV/H_2O^2/O_3) and reverse osmosis treatments are evidenced as the most efficient for the removal of organic pollutants and few when it comes to emerging pollutants. The use of treatments worldwide reveals a trend of their use in countries such as China and Latin America, demonstrating the little use and/or ignorance of these treatments in the wastewater of Mexico. In addition to a tendency to use technologies in the early stages of their development with other components.

Compliance with ethical standards

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Disclosure of conflict of interest

The authors declare that there are no conflicts of interest.

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