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Emerging contaminants as global environmental hazards. A bibliometric analysis

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ABSTRACT

This paper presents a bibliometric analysis of peer-reviewed scientific literature on emerging contaminants published from 2000 through 2019. A total of 4968 documents (among research articles and review papers) collected from Scopus database were analyzed using the VOSviewer 1.6.11 software. According to our results, this topic has been capturing researchers' attention over the years and the latter five years of the analysis timespan corresponds to the period of highest scientific productivity on this subject, when a 70.4% of all analyzed documents were published. United States, China, Spain, Italy and Canada were the top–5 most productive countries in terms of number of published works, while *Science of the Total Environment*, *Chemosphere*, *Environmental Science and Pollution Research*, *Environmental Pollution* and *Water Research* stood out as the journals with the highest number of publications, gathering a 31% of papers and 34% of all citations. According to the frequency of author keywords, the main specific research topic assessed by the researchers are the occurrence of pharmaceuticals and personal care products in wastewater and the removal of such pollutants by the application of adsorption and advanced oxidation processes.

1. Introduction

Emerging contaminants (EC) represent a wide variety of chemical compounds that have been detected in the environment and are sourced from daily anthropogenic practices such as domestic, healthcare, agricultural and industrial processes [1]. Although the occurrence of such compounds in the environment is not necessarily recent, they became more relevant in the world during the last decades thanks to the development of more sensitive analytical technologies that revealed the presence of such pollutants at levels down to parts per trillion in air, soil and water. As well, different studies have ascribed to these compounds some negative impacts on the environment and adverse health effects on animals [2,3].

These pollutants can be pharmaceuticals (veterinary and human drugs), hormones and steroids, disinfection by-products, hygiene and personal care products, surfactants, flame retardants, industrial compounds, household products, agrochemicals (pesticides, fertilizers and growth agents), microplastics, trace metals, nanoparticles, among others [3–5]. All of them have been catalogued as potential hazardous materials of environmental concern as most of them have been proven to alter the quality of natural resources, interfere on the biochemical processes that take place on the environment and affect the health of living species by exerting adverse effects such as endocrine disruption, mutagenesis, carcinogenesis, congenital disorders, etc. [6]. This relevance has stimulated the development of works to study their sources, toxicity, physico-chemical stability, fate and degradation alternatives [7–15].

One of the first and most important steps that made humanity realize about the occurrence of these kind of contaminants and pay attention to their serious effects was the publication of the book *Silent Spring* by the American biologist Rachel Carson in 1962. In that work, Carson questioned the widespread use of the biocide dichlorodiphenyltrichloroethane (mostly referred to as DDT) and other long-lasting poisons for agricultural control programs [16]. Through her work, Carson alerted the serious negative environmental impacts caused by the improper use of pesticides such as

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DDT, the same that was later prohibited in the United States since 1972 for crop applications. In the second part of the twentieth century other researchers also made important contributions that helped increase the global concern towards the environmental presence and effects of other dangerous substances as reported in many studies conducted to fight with asbestos and lead [17,18]. Nowadays the term emerging pollutant or contaminant is the most used to refer to all type of chemical compounds that have been introduced into the environment through any anthropogenic activity and whose detrimental effects on the environment are a matter of concern for humanity. However, the use of the term EC as known today was coined at the turn of the millennium to encompass compounds of any nature recently found in the environment. Henceforth, this term started to gain much more attention and become more frequently used in scientific publications as reflected in Fig. 1. Some alternative synonyms that some authors have also used to refer to specific types of EC, but with a lower frequency, are organic wastewater contaminants (OWC), pharmaceuticals and personal care products (PPCP), endocrine disrupting compounds (EDC), anthropogenic organic compounds (AOC), or persistent organic pollutants (POP), among others. In all cases, they are encompassed within the EC category.

The present study corresponds to a bibliometric analysis of the global research output on EC from 2000 to 2019. This study is pertinent since bibliometric approaches on this topic are still scare. Through this type of analysis is possible to monitor the evolution of scientific output on a specific field during a given period of time providing a snapshot of the research trends in scientific community [19,20,112,113].

This work was conducted with the aim of knowing how the EC issue has captured the attention of the scientific community since two decades ago, when this them was coined. As scientific journals are the main method of communication among scientists, our analysis was carried out from data indexed to Scopus scientific database. Scopus was chosen as source of information as it is catalogued as one of the broadest and more reliable scientific databases on interdisciplinary scientific information [21]. The analysis here presented takes into account the specific subjects of more interest, relationship among journal citations, countries with higher number of publications, and possible future trends of research, etc.

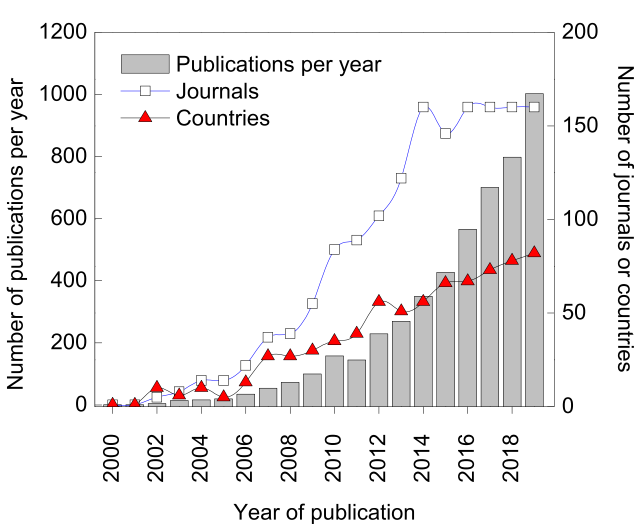

Fig. 1. Evolution of the number of published papers, journals and countries publishing on EC between 2000 and 2019 according to Scopus database.

2. Methods

Data were acquired from Scopus database on November 8, 2019 and comprised records obtained from a systematic search of documents matching the search terms in the fields of article title, abstract and keywords. The search was refined to article and review as document type.

The first search was carried out using the following search syntax: *Emerging* W/2 (*contaminant* OR *pollutant*). So that the query also included the most common ways of referring to EC. Such as, emerging pollutant(s), contaminant(s) of emerging concern, pollutant(s) of emerging concern, emerging organic contaminant(s), emerging organic pollutant(s), emerging environmental concern contaminant(s) and emerging environmental concern pollutant(s). This search was limited to a period between 2000 and 2019, and sub-periods of 2000–2004, 2005–2009, 2010–2014 and 2015–2019, in order to obtain additional information about the publishing activity during each sub-period.

Additional and more specific searches were conducted to evaluate the output on some particular research areas related to EC. In these cases, the searches were carried out within the results obtained in the initial search above mentioned in order to determine research trends and topics of major relevance.

The results of these searches are limited to those works related to compounds that have been classified as EC and indicated as such by the authors. Therefore, this study allows evaluate how the term EC has gained relevance among the scientific community during the last two decades to refer to all pollutants of environmental concern.

The information retrieved from the Scopus database in each search was: (i) citation information, (ii) bibliographical information, (iii) abstract and keywords, (iv) funding details and (v) other information. The software VOSviewer 1.6.11 was used for visualization and data analysis [22].

3. Results and discussion

3.1. Global scientific output related to emerging concern pollutants

Through the search process, a total of 4968 documents (considering research articles and review papers) were obtained from 160 different journals that are indexed in Scopus database, 87% of them correspond to research articles and 12% were published in open access journals. Fig. 1 shows the evolution of the number of papers related to EC published per year from 2000 to 2019, the journals issueing them and countries with their authorship. The growth in number of papers per year has an exponential behavior, which indicates a clear rise on the global output of scientific publishing focused on this topic that has been accelerated over the years. Publications in scientific journals related to pollutants of emerging concern began to become more relevant in the scientific community in the mid-2000s. Before 2004 the number of publications related to this subject in Scopus indexed journals was still scare (corresponding to 0.8% of all output from 2000 to 2019). This result is probably because the term EC was only coined until the turn of the century, although much research had already been carried out on some specific EC between the 60's and 70's, such as lead [23,24], mercury (reviewed by Ref. [25]), asbestos [18], among others contaminants. During the second half of the 2000s there was a considerable growth in interest on EC evidenced by an acceleration in the number of scientific publications per year. Records collected from this period represent a 5.7% of all analyzed works. During the 2010s were given the greatest contributions in scientific literature related to this topic. A 93.5% of the data were published between 2010 and 2019. Additionally, it is noteworthy that the last five years of this period were the most productive in terms of number of publications representing 70.4% of all papers published. Therefore, the decade of 2010 was the moment of blooming of global output on EC research.

Also from Fig. 1, it can be seen an increase in the amount of journals and countries publishing on EC over the years, what evidently is a consequence of the expansion observed on the scientific research output related to EC. During the decade of 2000–2009 emerged new journals and many of them focused on environmental aspects; simultaneously, various countries began to research in this area. The growth in the number of countries conducting studies on EC has been steadily raising while, since 2014, the total number of journals indexed in Scopus that have issued papers on this field per year have not increased. Therefore, the average of papers per journal has augmented over the years. In Table 1 are summarized the number of published papers, journals and publishing countries segmented in four periods: 2000–2004, 2005–2009, 2010–2014 and 2015–2019. Likewise, the ratio of number of papers to number of either journals or publishing countries is shown. The trend indicates that these ratios increase between 2 and 3–fold in magnitude every five years.

The positive trend in the global output related to EC issues is likely due to some important new regulatory frameworks that emerged during the late 1900s and early 2000s, and programs promoting scientific research in the environmental realm, which made governments and scientific community set their sights on the serious issue caused by the presence of EC.

During 1999 and 2000 was carried out by the U.S. Geological Survey one of the most important reconnaissance studies in the history of United States. This survey evaluated the occurrence of pharmaceuticals, hormones and other organic contaminants in different rivers and water streams nationwide [26]. It was detected the presence of pharmaceutical and personal care products in 80% of 139 streams sampled along the country. This work became one of the most cited papers in the field.

After the amendments made in 1996 to the Safe Drinking Water Act, U.S. Environmental Protection Agency (EPA) was directed to publish periodically a list of not yet regulated contaminants that are suspected to occur in water systems [27] and, after a period of monitoring health effects, occurrence and levels of exposure, take the decision whether or not to regulate the compounds on the list. To fulfill this mission, EPA must compile information from the National Academy of Sciences, the National Research Council, the National Drinking Water Advisory Council and the scientific community. Through this program, EPA have conducted and sponsored research to collect enough information on the selected contaminants. This has prompted studies on chemical substances and microbial contaminants among industrial additives, pesticides, disinfection by-products, waterborne pathogens and biological toxins [28].

In Europe, the Water Framework adopted in 2000 by the European Parliament and the Council of the European Union [29] established some guidelines for the sustainable use of waterbodies throughout Europe and to secure drinking water supply for the population. To achieve these objectives, Member States were required to take measures to fight against water pollution and eliminate priority hazardous pollutants from water ecosystems. The list of priority substances is prepared and updated after evaluating extensive data by an advanced setting method. The data are provided by the Scientific Committee on Toxicity, Ecotoxicity and the Environment, Member States, the European Parliament, the European Environment Agency, business organizations and the scientific community. This have spurred Member States to developed extensive research to monitor and control the ocurrence of these compounds in water. The commission sponsors this research projects for the implementation of the European Union policies throughout the continent [30,31].

Other countries have also endeavored to develop and promote programs for environmental protection that have driven the development of research related to the presence of substances that threaten the quality of natural resources. For example, in China, the 10th, 11th and 12th versions of the National Five-Year Plan that were launced in 2001, 2006 and 2011, respectively, were of crucial importance since they led to achievement of great advances in matter of environmental protection. This plans encouraged local goverments and different institutions, as the State Environmental Protection Administration (today known as Ministry of Ecology and Environment) to do a better monitoring of the environment, reinforce the control of pollution, reduce the emission of major contaminants as an essential part of the economic and social development of the state. This has facilitated the expansion of environmental research and initiatives [32,33].

As well, UNESCO has launched several programs to promote scientific research and the sharing of knowledge on water quality, as the International Initiative on Water Quality (IIWQ). IIWQ implements its activities and projects in an interdisciplinary, integrated and cooperative manner aiming to meet global water quality challenges comprising all regions of the world. One of the main programs UNESCO has developed in the framework of IIWQ is the Project on Emerging Pollutants in Water and Wastewater (2014–2018) and the establishment of important networks of collaboration constituted by scientific and policy experts from organizations from different countries that work on water quality priorities and emerging pollutants [34].

3.2. *World largest producers of scientific literature on emerging contaminants*

Fig. 2 shows the countries that generated the largest number of publications during 2000–2019 presented in periods of five years. The data represented correspond to the percentage of publications authored by scientists affiliated to research centers or institutions from each country.

As shown in Fig. 2, over the last two decades, the most prolific countries in terms of authorship of studies related to EC are United States (USA), China, Spain, Italy, Canada, Brazil, Germany, France, United Kingdom (UK) and India.

During the 2000–2004 period (Fig. 2A), only a total of 39 papers on the subject were published by authors from 15 different countries. European countries (56% of mentions as country of author's

Table 1
Global output on emerging pollutants from 2000 to 2019.

	2000–2004	2005–2009	2010–2014	2015–2019
No. journals with publications	27	108	160	160
No. publishing countries	15	43	70	105
No. papers	39	282	1152	3495
No. papers/No. journals	1.4	2.6	7.2	21.8
No. papers/No. countries	2.6	6.6	16.5	33.3

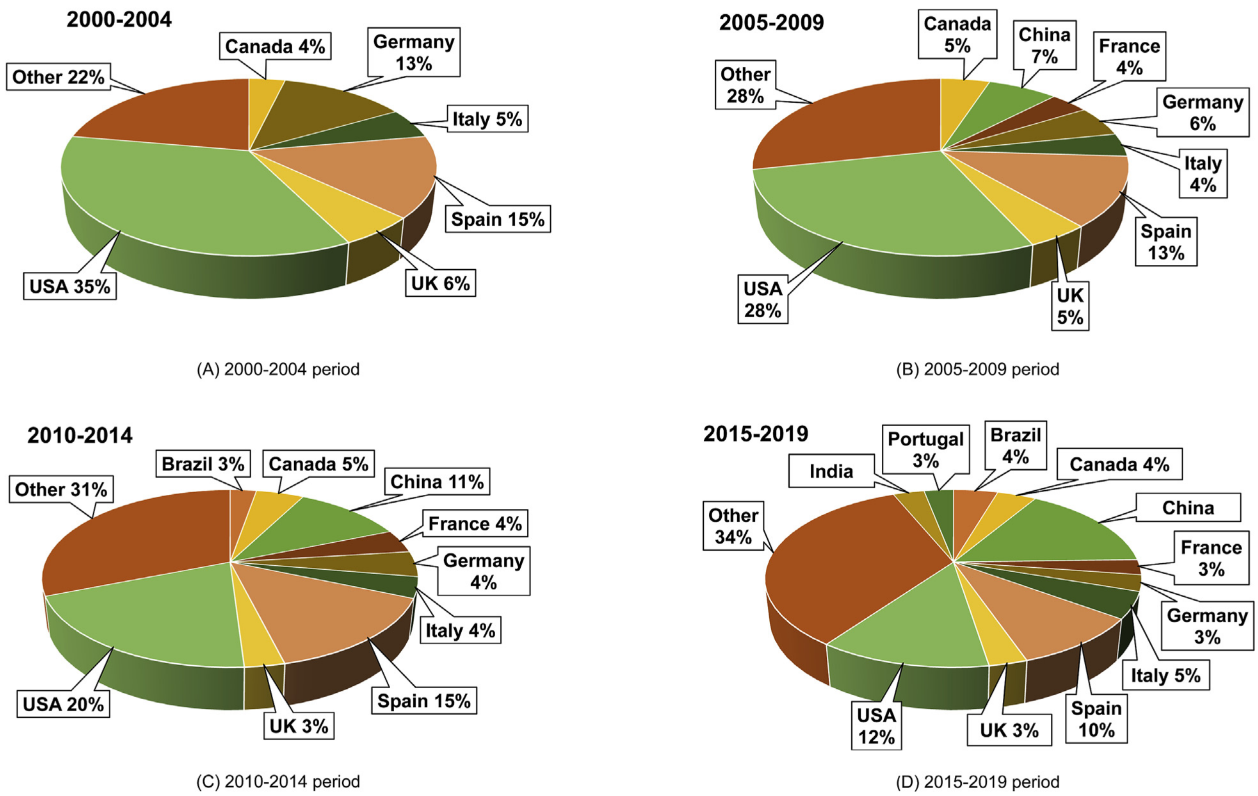

Fig. 2. Leading countries in terms of authorship of scientific papers related to EC published between 2000 and 2019 in Scopus indexed journals.

affiliation) made the highest contribution, being Germany, Italy, Spain and UK the ones with higher number of issued works, followed by North America (39%).

In the 2005–2009 period, authors from 43 countries published a total of 282 scientific documents using the term EC (Fig. 2B). A 30% of such countries have authorship in only 1 paper. A 14% of records were from Asian countries and 2% from South America, but still North America (34%) and Europe (47%) led the publishing.

In the 2010s (Fig. 2C and D), new countries began publishing works related to this topic authoring around a third part of the records. Brazil, India and Portugal were some of the new strongest contributors during this period. In this last decade, Asian countries were credited in 15% of author's affiliation, North America 20%, Europe 40%, South and Central America 6%, Africa 2% and Australia 2%. A total of 4647 papers were published from authors affiliated to institutions of 105 different countries.

Based on the total number of citations (up to November 8, 2019), the research institutions with highest impact on this area during the past two decades were U.S. Environmental Protection Agency (USA), University of California (USA), Universidad de Almería (Spain), University of Chinese Academy of Science (China), Tsinghua University (China), Chinese Academy of Sciences (China), Institución Catalana de Investigación y Estudios Avanzados (Spain), Georgia Institute of Technology (USA), College of Environmental Science and Engineering (China) and University of Florida (USA).

Fig. 3 shows a map of co-authorship analysis that reveals the collaboration networks among countries working on emerging pollutants during 2000–2019.

Of all countries shown in Fig. 3, USA, China and Spain represent the largest nodes in the map. Besides being the most prolific in scientific publishing, they have also made the greatest number of collaborative research with other countries. Other productive countries were Brazil, Germany, Italy and Canada. According to Fig. 3, there are strong collaboration networks among the displayed countries, since almost all of them are linked in the network. Countries located in the outermost areas of the map (such as Ecuador, Qatar, Oman, Palestine or Algeria) have been less productive in this topic and consequently have established weaker international collaboration networks.

The strongest collaborators of USA have been countries from Eastern Asia (such as China, South Korea, Japan and India), Spain, Canada, Germany, Switzerland, The Netherlands and Italy. This country has also co-authored several publications with countries from South America (such as Brazil, Argentina, Colombia and Chile), Mexico and some European countries. Fewer collaborations with countries from Africa and Middle East has been observed.

Spain has conducted investigations with almost all listed European countries, South America (especially with Argentina, Colombia, Costa Rica, Chile and Brazil) and some countries from Asia (as China, Iran, Turkey, Israel and Saudi Arabia). Its closest partners have been USA, UK, Brazil, Mexico, The Netherlands, France and Canada.

China has mostly co-authored papers with Europe, Asia, Australia and North America, but it has collaborated with a much lower frequency with Latin America (only with Mexico and Brazil) and Africa.

Also five important clusters or sub-networks of collaboration can be identified. The most important and productive was mostly formed for Asian countries, USA, UK, Canada and Australia (green); the second in importance was constituted by over 20 countries from Europe (red); the third cluster has eight countries and is formed by Spain, Israel and some Latin American countries (blue); the fourth included five countries from the Middle East (lilac); and the last one is centered in France and included Finland, Iran, Tunisia, Turkey and Ukraine (yellow).

Table 2 shows the number of papers related to EC published by

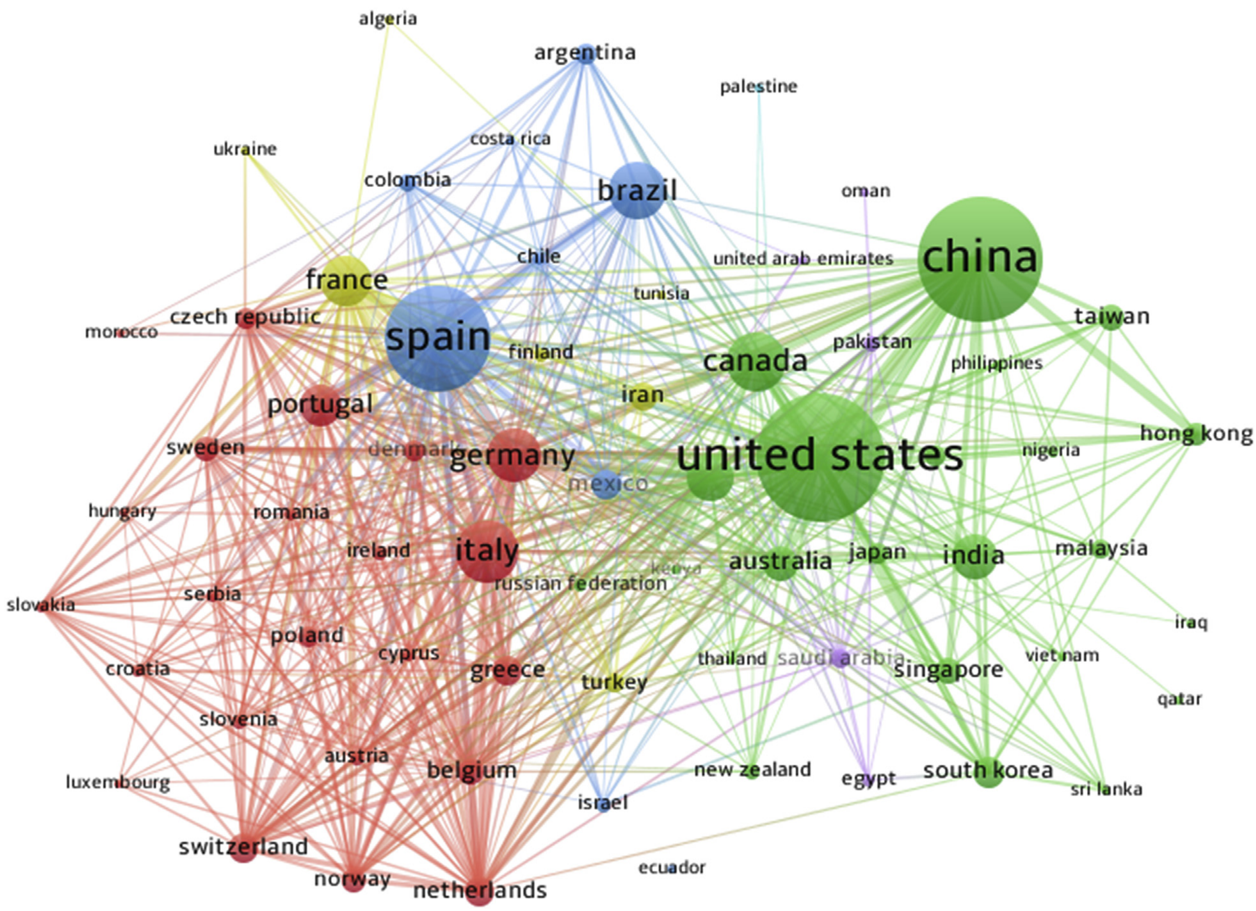

Fig. 3. VOSviewer bibliometric map of global collaboration network among countries researching on emerging pollutants during 2000–2019.

Table 2
Number of total publication and citations for the top-10 leading countries in studies related to EC between 2000 and 2019.

Country	No. of publications	No. of citations	Citations per paper published (avg.)
USA	1072	37747	35.2
China	1025	19934	19.4
Spain	781	26736	34.2
Italy	327	9652	29.5
Canada	304	7585	25.0
Brazil	280	3251	11.6
Germany	252	9649	38.3
France	224	6884	30.7
UK	208	10430	50.1
India	188	2507	13.3

each country during last 20 years and the total number of citations they received as reported in Scopus database on November 8, 2019. This Table also shows the value of the ratio of total citations received to published papers that can be used as an indicator to evaluate the impact of the output published by the most productive countries.

As shown in Table 2, the ratio of citations to number of publications for each country follows the order: UK > Germany > USA > Spain > France > Italy > Canada > China > India > Brazil. This means that, in average, the papers published from UK researchers have had the highest impact within this field and served as reference for other studies that found them relevant. USA, China and Brazil have the highest relative impact of papers in their continents (North America, Asia and South America, respectively).

3.3. Journals and main research topics

According to our literature search, these publications have addressed the problem of EC from an environmental and technical perspective. Accordingly, the journals that concentrate the greatest number of publications in this matter are those of environmental interest. The top–5 Scopus indexed journals with the highest number of citations and number of published papers on EC are Science of the Total Environment, Chemosphere, Environmental Science and Pollution Research, Environmental Pollution and Water Research. These journals gather a 31% of all papers retrieved in our query and 34% of all citations made to papers related to EC by November 8, 2019. The evolution in the number of accepted papers per year for the top–5 journals is shown in Fig. 4A. This is consistent with the growth that these journals have had over the years, as

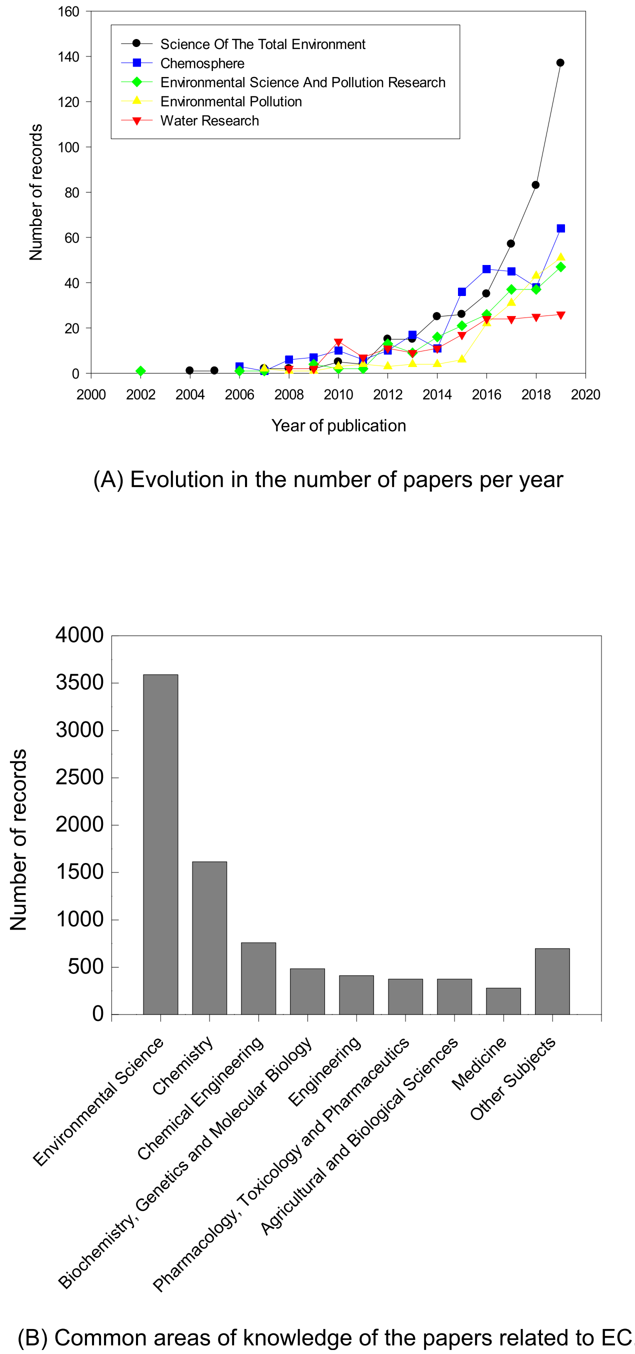

Fig. 4. Dynamic of publishing of works related to EC between 2000 and 2019. (A) Evolution in the number of papers per year for the top−5 journals. (B) Common areas of knowledge of the papers related to EC.

a consequence of the increase in their publishing frequency. During the 20-year period evaluated in this work, Science of the Total Environment has occupied the first place in number of publications per year related to EC. This international multidisciplinary journal currently publishes papers on topics such as the biosphere and anthroposphere every week. The other 4 journals occupying the top positions publish papers biweekly or monthly on topics such as water quality, environmental pollution, environmental engineering and environmental science, and although they have also increased the frequency of their publications, in these cases it has been slower compared to the top−1.

Fig. 4B shows the knowledge areas in which the published papers were classified. Most of the papers were focused on determining the occurrence, detection, seasonality, distribution and negative effects that EC have on the environment and living species; therefore, environmental science was the most common research area cited throughout the papers. This interdisciplinary area integrates many other knowledge fields; therefore, it is transversal in most of the analyzed papers. Another important part of the studies were based on the chemical aspects of pollution: composition, chemical properties, degradation by-products, kinetics, physicochemical stability and analythical methods of detection. A large part of the works has been approached from the perspective of chemical engineering and have focused on the engineering of new materials with tailored properties to be used as catalyst or adsorbents to remove EC, the study of degradation mechanisms, kinetic modeling, determination of reaction parameters, contaminant removal rates and development of oxidation technologies. Papers with a biochemical approach have dealt with bioaccumulation of EC, ecotoxicology, the use of microorganisms, biomass and organic materials in the bioremediation of EC, the study of bacteria with antibiotic resistance, the use of bioremediation in treatment of polluted water and the evaluation of mutagenic effects caused by the exposition to EC. Engineering–focused papers are mainly based on the intensification of new technologies for the treatment of wastewaters, ground water, industrial effluents, sanitary sewage and soil containing recalcitrant contaminants. Also the upscaling of these processes to pilot or industrial scale, evaluation of energy conversion, economic estimations and designing treatment unities. Another part of the papers is related to the determination and monitoring of pharmaceutical and personal care products in the environment and, the evaluation of the effects that a chronic exposure to EC entails. The use of EC in crop activities, consumption of large quantities of water in agricultural fields and their transport to different water streams due to runoff, the recovery of agricultural wastes to develop adsorbents or materials that can be used as catalyst supports have also been topics of great interest. In the medical approach of EC problem there are works mainly related to the routes of exposure to EC, prevalence of diseases derived from a chronic exposure to EC, appearance of infections resistant to conventional antibiotic treatments and health monitoring programs have been studied.

To have a better understanding about how these areas of knowledge were interrelated, and the specific topics of study that were addressed in the papers, a keyword co-occurrence analysis was carried out. To this, the most frequently used author keywords (those cited at least 10 times among all retrieved documents) were analyzed. An amount of 315 keywords met this threshold. The terms emerging (organic) contaminant (or pollutant) and contaminant (or pollutant) of emerging concern, were excluded as they are transversal to all works.

Fig. 5 corresponds to an analysis of co-occurrence of the most used author keywords among the papers published in the 2000–2019 period.

According to the map shown in Fig. 5, pharmaceuticals are the group of EC of highest interest. The node corresponding to the pharmaceuticals is located in the core of the map, which indicates that is transversal to all other topics addressed in research related to EC. The proximity between the nodes corresponding to pharmaceuticals and wastewater means that most of the output related to pharmaceutic compounds is concerning to their occurrence in wastewater, toxicity and risk assessment (red cluster). Another research trend is related to the application of advanced oxidation processes (especially photocatalysis) and adsorption treatment in

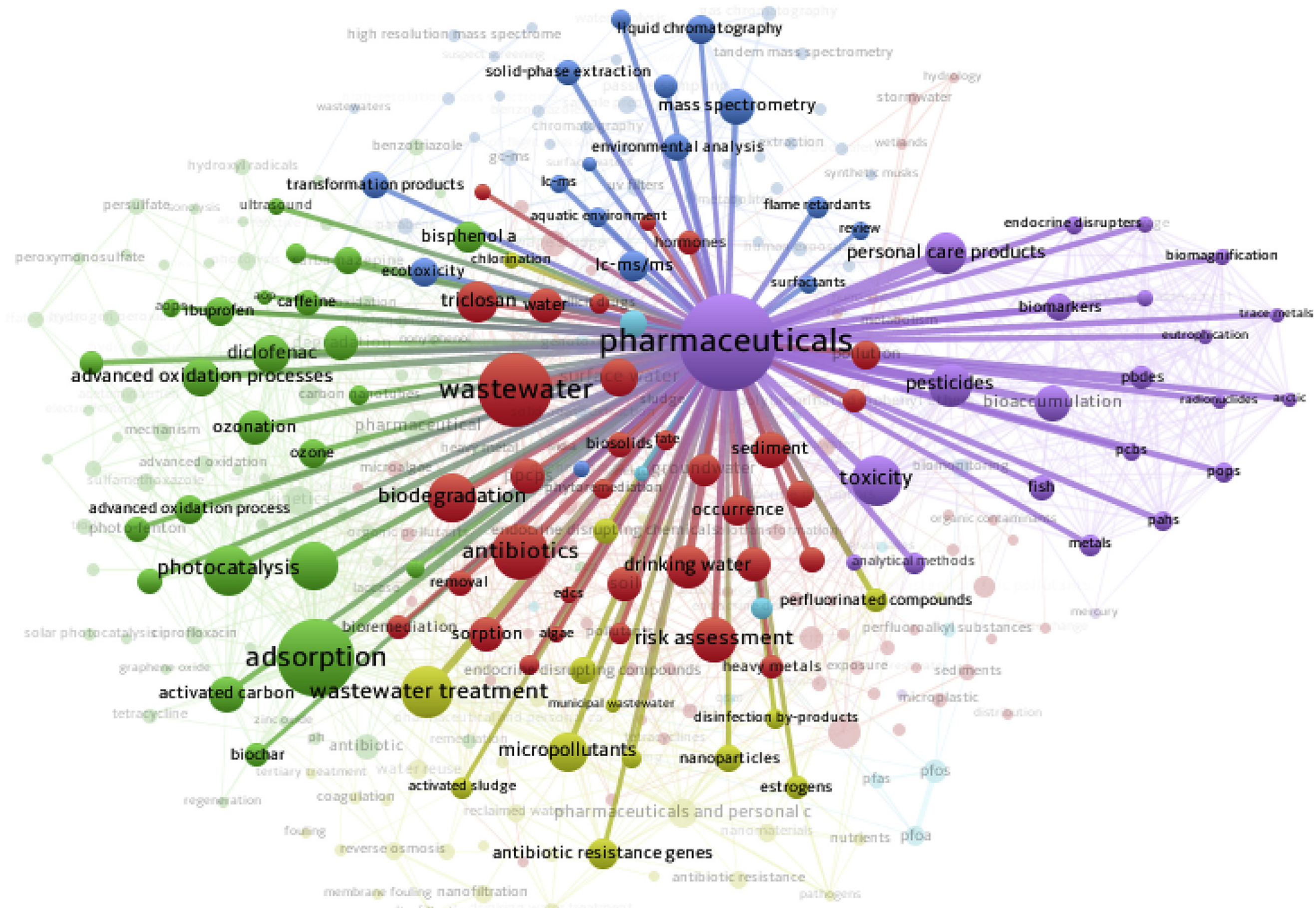

Fig. 5. VOSviewer bibliometric map of most frequently mentioned author keywords on global output on EC from 2000 to 2019.

the removal of pharmaceuticals (green cluster). The purple cluster is likely related to a great output about the monitoring occurrence, fate and effects of other groups of persistent pollutants as pesticides, personal care products, biomarkers, endocrine disrupters, trace metals, polychlorinated biphenyls, polycyclic aromatic hydrocarbons, polybrominated diphenyl ethers, radionuclides, and their effects. The blue cluster in the upper side of the map refers to the published literature in analytical methods to determine EC metabolites and by-products. Finally, the presence of recalcitrant micropollutants in water environments, their effects and removal by advanced processes represents another trend (yellow cluster).

Fig. 6 shows the EC types that have gathered major attention in each country. The trend observed is similar for all the countries shown. This trend is in agreement with the results discussed above regarding the areas of greatest interest worldwide. It is clear that in each country the research related to pharmaceutical and personal care compounds generates the greatest number of publications. The drugs that mostly concentrate the attention of researchers are antibiotics, analgesics and anti-inflammatories. The second group of EC with the highest number of publications are organohalogenated compounds comprising poly and perfluorinated compounds, polychlorinated biphenyls, polybrominated diphenyl ethers, triclosan, DDT, among others. Research related to pollution due to the presence of agrochemicals in nature is also highlighted.

Further analysis was carried out to evaluate the output on the main specific topics found in EC research: pharmaceuticals, wastewater, advanced oxidation processes and adsorption. In all cases there were a considerable increase in number of documents published per year especially during the 2010–2019 period. More than 90% of the documents related to these topics were published as of 2010. The results are discussed below.

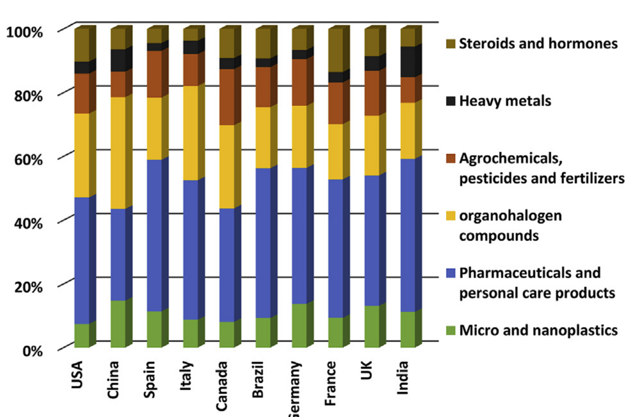

Fig. 6. EC that concentrates the highest number of publications by country.

3.4. Emerging contaminants and pharmaceuticals

Thirty per cent of the publications related to EC indexed in Scopus database are related to pharmaceutics, which are considered as top-priority pollutants and require special attention. There are plenty of pharmaceutical products that can be purchased over the corner without a medical prescription and their consumption has increased together with the global population. Pharmaceuticals enter the environment mainly during their production but also through hospital and domestic wastewaters. Most of them remain unregulated and their impact on living species is under evaluation. It has been found that the main threats due to the presence of pharmaceuticals in the environment are their potential acute and chronic toxicity to the biota, the development of antibiotic resistant microorganisms and endocrine disruption effects on both animals and humans [35,36]. Another aspect of great concern is the presence of metabolites derived from pharmaceuticals, veterinary drugs and pesticides which are reported to reach higher concentrations in water than their parent compounds [37] and are continuously detected in different water environments. Some metabolites are more stable and chemically reactive than their parent compounds thus, in some cases, they turn out to have higher toxicity and cause fatal effects on living beings. Some steroidal drugs, for instance, are attributed to structural alterations in some aquatic organisms [38]. In the same way, people are exposed to different pharmaceuticals' metabolites that might still be present in treated water and jeopardize their health [38].The highest publishers in this field were USA, Spain and China. Based on the most recurring keywords, the most studied pharmaceuticals are carbamazepine, diclofenac, ibuprofen, sulfamethoxazole, triclosan, naproxen, ciprofloxacin, estradiol, atenolol and trimethoprim.

3.5. Emerging contaminants and wastewater

More than a third of the documents indexed in Scopus from 2000 to 2019 on this specific topic were focused on the detection and treatment of EC in wastewater. Researchers from USA, Spain and China were cited as authors in most of these papers. Wastewater streams are primary reservoirs of all kind of EC. According to its origin, wastewater can be classified as domestic or municipal sewage, storm water and industrial effluents. Conventional wastewater treatment plants are not able to completely remove all EC from sewage, then they prevail in their effluents and end up being discharged into natural water streams.

The discharge of untreated industrial wastewater is a major concern in nowadays society. Along with the growth of the world population, which in 2019 surpassed the 7.7 billion figure [39], there has been an increase in industrial production to meet the population's demands and, consequently, the industrial wastewater production has been maximized. In the absence of more efficient wastewater treatment methodologies, the discharge of industrial effluents negatively impacts the environment and deteriorates the quality of the water resource. The composition of industrial wastewaters depends on the branch of industry where their come from. For example, residual effluents generated in the manufacture of pharmaceuticals and drugs contain a mixture of organic compounds whose effects may be diverse as exerting endocrine disrupting effects, developing antibiotic resistant microbes, even cause extinction of some biota or can be transformed into metabolites with higher toxicity [40]. Refinery effluents contain a high variety of phenols, organic solvents and other hydrocarbons depending on the plant configuration and operation. This kind of compounds are extremely toxic, chemically stable and generally are carcinogenic [41]. Electroplating wastewater are sources of significant quantities of heavy metals such as nickel, copper, cadmium and chromium that toxic and detrimental to living organisms [42]. Pulp and paper industries generate sewage containing chlorophenols and acid compounds [43]. Given this panorama, the development of new wastewater treatment technologies is mandatory. Accordingly, many studies have addressed the application of alternative technologies to enhance the removal of EC from wastewater [44].

3.6. Technologies for treatment of emerging contaminants

As most EC and their metabolites and degradation by-products are reported not to be biodegradable and persist in water even after being treated with conventional processes, they tend to bioaccummulate in the environment and eventually enter to the food web [45]. Once released into the environment, EC get dispersed and converted into transformation products which, in some cases, can be even more persistent and toxic than the parent compound [4,37]. Some advanced water treatment technologies have been developed over the time and reported to be efficient to degrade some target EC. These treatments can be classified in phase-changing technologies (such as adsorption and membrane technologies), advanced oxidation processes (commonly abbreviated as AOP) and biological treatments [45].

3.7. Emerging contaminants and advanced oxidation processes

AOP are in essence physicochemical technologies based on the in-situ generation of oxidant species that possess high reactivity toward organic and inorganic matter [46,47]. One of the most powerful oxidizing agents is the hydroxyl radical ($^{\bullet}OH$) thanks to its superior oxidation potential (2.80 V NHE), which is higher than that of other common oxidants such as atomic oxygen (2.42 V), ozone (2.07 V), hydrogen peroxide (1.78 V), perhydroxyl radical (1.70 V), permanganate (1.68 V) or chlorine (1.36 V) [48]. The $^{\bullet}OH$ radical is able to react instantaneously and unselectively with both organic and inorganic compounds at reaction rates in the order of 10^7 and 10^{10} L mol^{-1} s^{-1} [49] and can decompose organic compounds by hydrogen abstraction from certain functional groups, direct electron transfer or radical-radical interactions. Therefore, AOP–based treatments seek to generate a sufficient concentration of $^{\bullet}OH$ radicals that will lead to a complete conversion and mineralization of toxic organic compounds to yield CO_2, H_2O and inorganic acids [50], or at least, convert them into simpler, less toxic or more readily treatable residues. According to our query results, AOP have been successfully applied in the remediation of complex and highly polluted effluents such as the sewage from pharmaceutical, tannery, urban, textile, laboratory, battery manufacturing and hydrocarbon processing industries [51–56] and different air streams [57–59]. In most of the cases, they have been reported to improve the organoleptic and physicochemical properties of the streams treated. The application of AOP in simpler water matrices, as river, distilled or tap water, usually is reported to achieve complete compound transformation; however, it has been found that the effectiveness of these technologies is strongly affected by the composition of the matrix containing the target pollutants. For instance, the presence of a high content organic matter and inorganic ions in some industrial wastewaters leads to the development of competitive reactions between these compounds and the target EC for the in–situ generated oxidizing species exerting an inhibitory effect on the process [60,61].

Fig. 7A shows the most studied AOP according to our search. Percentages shown in this figure have been calculated based on the number of times in which these technologies were used as a treatment method for a target EC in papers published in journals indexed in Scopus database.

According to Fig. 7, photocatalytic oxidation is the most recurrent AOP–based technology evaluated in the treatment of EC. This technology implies the usage of a photoactive semiconductor as catalyst, such as TiO_2, ZnO, WO_3, CuO, among others that can absorb radiation with energy equal or higher than that of their bandgaps; this excites the valence electrons and prompt them to leap up to the

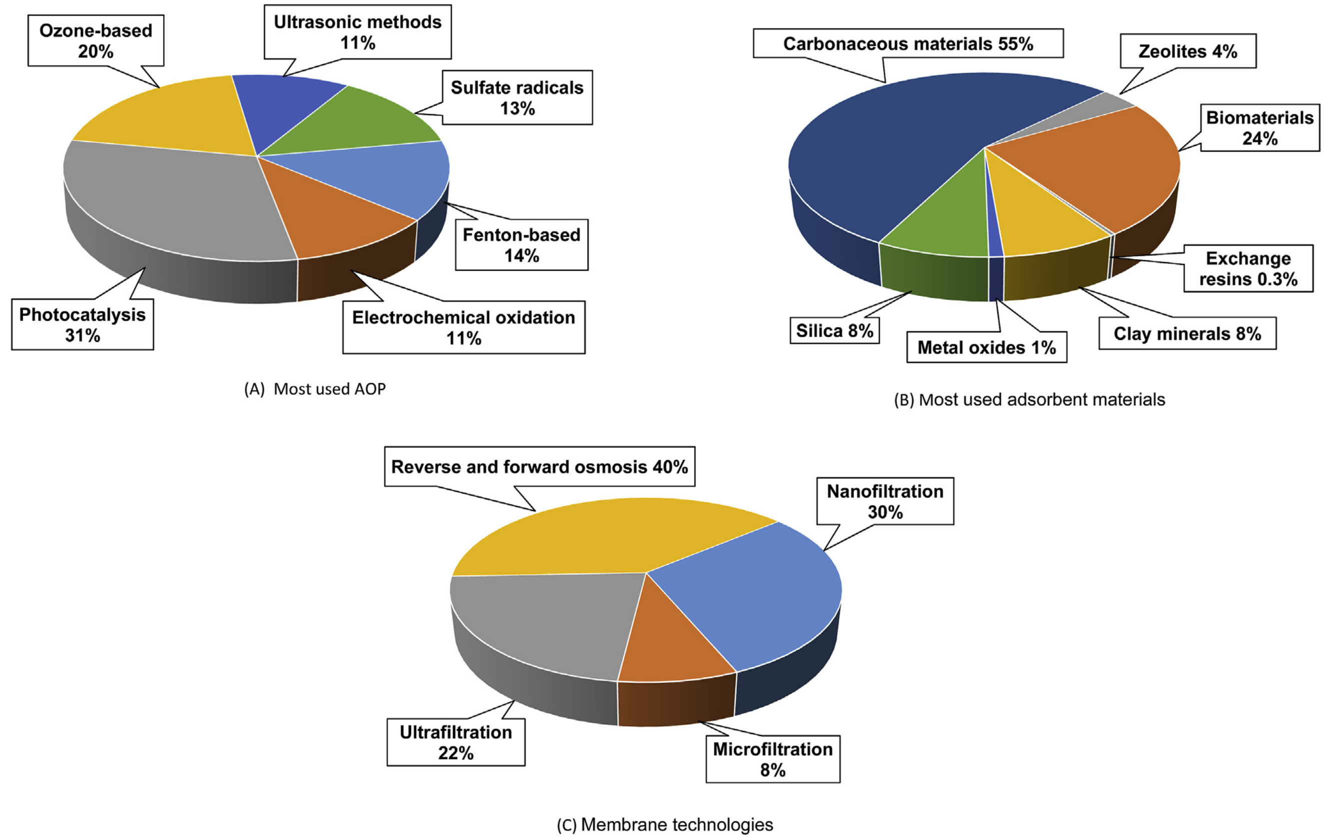

Fig. 7. New technologic approaches for the treatment of EC. Different AOP (A), Most used adsorbent materials (B), Membrane technologies (C).

conduction band, thus generating electron-hole pairs that trigger several redox-type reactions that lead to the formation of oxygen reactive species which participate in the oxidation of the pollutants [62]. The possibility of using solar light as radiation source represents a factor of crucial importance that has boosted interest in this technology over others [63]. A major drawback of this type of technology is the requirement to perform a subsequent stage of separation of the catalyst from the reaction medium (these are usually commercially available as nanoparticles). Therefore, many works have focused on the development of methods to achieve an effective modification, immobilization or support of the semiconductor particles on different substrates in order to allow their recovery of the medium in a simpler way and even their recycling in successive processes [64,65].

Ozone−based technologies have been also widely studied as alternatives to deal with EC. Molecular ozone can selectively decompose organic contaminants by breaking unsaturated bonds and certain functional groups in their structures by electrophilic and nucleophilic attack, but this mechanism usually leads to incomplete compound mineralization. This is because the application of ozone alone can convert the original contaminants into saturated carboxylic acids that have a lower reactivity with ozone [66]. Then, to improve mineralization in ozonation processes are used some agents such a catalyst, radiation, some chemical additives or the combination with other oxidation technologies to promote an accelerated decomposition of ozone to yield active radicals [67]. The use of ozone implies higher operational costs compared to other treatment methods [68].

Fenton processes consist in the decomposition of hydrogen peroxide into reactive oxygen species catalyzed by iron salts. These processes are safe, use environmentally-benign and readily available reagents, and usually require short reaction times [69]. Some of their disadvantages are their narrow optimum pH range of application (from 2.8 to 3.1), the potential generation of iron sludge and the necessity of recovering the used catalyst at the end of the treatment. These aspects can be overcome by the use of separable iron-based solid catalysts which allows to perform the Fenton process in heterogeneous mode that facilitate the separation of the catalyst [67] and also allows carrying out the processes at neutral pH. These processes can also be intensified by using electrochemistry, radiation or increasing the operating temperature [70].

Sulfate-based AOP represent an alternative to hydroxyl radical-based AOP and it is based in the in−situ generation of sulfate radicals ($SO_4^{\bullet -}$) by the degradation of persulfate or peroxymonosulfate salts that are used as radical precursors. The decomposition of such precursors into $SO_4^{\bullet -}$ is accelerated by heat, transition metals, alkali, radiation, ultrasound or heat [71]. Sulfate radicals possess an oxidation potential comparable to $^{\bullet}OH$ radicals (2.5V−3.1V) [72] but reacts more selectively via electron transfer with unsaturated organic compounds, thus the scavenging effect due to the diverse background matrix components that is observed in the case of $^{\bullet}OH$ based AOP is in this case limited [73]. Sulfate precursors are cheap, naturally abundant, and non-toxic [74]. When metals are used to activate persulfate a large amount of metal sludge can be produced and the metal salts also may scavenge sulfate radicals inhibiting the process [75].

Ultrasound−driven technologies are based in the use of ultrasonic waves (from 20 to 10000 kH) that when irradiated in water produce cavitation or implosive collapse of gas micro-bubbles. The bubble collapse generates localized spots with high temperature and pressure, the organic contaminants undergo homolytic bond breaking and water molecules are dissociated into $^{\bullet}OH$ and other reactive oxygen species [76]. Some important drawbacks of these technologies are the inefficient conversion of energy to produce ultrasonic cavitation and the complexity of scaling these processes up to industrial volumes [77].

Finally, electrochemical oxidation (also known as anodic oxidation) generates •OH and other active oxygen species by the electro-oxidation of water molecules on the surface of overvoltage anodes [78]. This technology does not necessarily need the addition of chemical substances; however, some electrodes are not stable, require the subsequent removal of deposits that are formed over their surface and in some cases, the current efficiency to produce •OH is very low [79].

All these AOP have been used in the treatment of different nature EC such as pharmaceuticals (as antibiotics, carbamazepine, diclofenac, sulfamethoxazole, ibuprofen), amides, endocrine disruptors, pesticides, phenols and caffeine. The top-3 countries in research on this field during this period were Spain, China and USA.

3.8. Emerging contaminants and adsorption processes

An extensive research has been conducted on the adsorption of different EC by diverse adsorbents; in fact, adsorption of EC from water represents the application of the greatest interest in the treatment of polluted water. Adsorption is based on the uptake of the pollutants over the surface of a solid material or adsorbent, live (such as algae, fungi or bacteria) or biologically inactive (such some organic or mineral matter) [80,81]. Compared to other pollutant removal techniques, adsorption is simpler, leads to less sludge formation and is considered as a green process of low investment cost [82]. However, as this is a phase-changing technology based on capturing the EC on the surface or pores of a solid material, it does not necessary lead to chemical degradation or transformation of the contaminants and implies a posterior process to dispose or regenerate the used adsorbent. Carbonaceous materials are the preferred adsorbents to remove EC due to their high porosity, large variety of functional groups, tunable surface functionality and large specific surface areas. Besides that, carbon materials are low cost, with high availability and exhibit chemical resistance. The predominant adsorption mechanism that takes place in EC removal using carbons is electrostatic interaction and, in less extent, physisorption, chemisorption and π-electron dispersions [45,83–85]. According to the number of publications on this field, the most studied carbon-based adsorbents are activated carbons (which are the most commonly used by far), charcoal, biochar, carbon nanotubes, graphene and fullerenes.

Some minerals and inorganic materials such as clay, zeolites, MgO nanoparticles, aluminum oxide, silica or ion exchange resins have also exhibited capacity to remove EC from water. Ion exchange resins have been used to remove heavy metals and other toxic ions, additionally in water softening treatments. As well, many synthetic resins possessing great adsorption capacities and improved mechanical properties have been developed [86]. Silica have been highlighted as versatile materials (owing their wide range of natural and synthetic polymorphs). They have been found to be great adsorbents given their chemical stability and inertness, large pore size and high specific surface. It has been reported that silica can be functionalized to improve their affinity toward EC, also it has been possible to synthetize tailored silica–based materials with the desired morphological properties to be used as efficient adsorbents and catalyst supports [87]. Similarly, clay minerals have been used as adsorbents of heavy metals and organic EC. Clays possess high porosity, high surface area and can be pillared to enhance their capability of removing EC and increase their catalytic potential. Natural and modified clays have been effectively used as adsorbents of EC in wastewaters, landfills, oil spills, etc. Some of the most studied clays are montmorillonite, illite, saponite, bentonite, kaolinite and vermiculite [82,88]. Recently, pillared clays are gaining considerable attention because they can be combined with semiconductors to increase their surface area and catalytic activity for the degradation of EC in the application of AOP [45].

Biosorption or bioremediation uses biomass as adsorbents or other materials engineered from biomass. This type of treatments is cheaper than other advanced technologies given the wide range of available biomaterials, and also represents an alternative to dispose agricultural wastes. The use of biomass as adsorbents implies several removal mechanisms such as ion exchanging, complexation reactions, electrostatic interaction and metabolic processes such as intracellular uptake [81,89,90]. Several studies have shown that the use of biosorbents such as bacteria, algae, fungi, plant biomass, chitosan, fruit peels and seeds, lignocellulosic materials, short hemp fibers, shrimp shells, rice or nutshells have a great potential in the removal of heavy metals and other EC [90,91].

Adsorption processes are usually reported to achieve complete removal or percentages very close to 100%; however, the process efficiency is affected by the operating conditions, ratio of solid to liquid, affinity of the adsorbate for the adsorbent surface, contact time, ionic strength and competitive reactions with the background matrix components [84].

Fig. 7B shows the adsorbents most used in the removal of EC according to the results of our query. China, USA and Spain authored the highest number of papers related to the treatment of EC by adsorption processes. These technique has been extensively used to remove contaminants such as diclofenac, carbamazepine, ibuprofen, ciprofloxacin, caffeine, paracetamol, tetracycline, bisphenol A, triclosan and some dyes.

3.9. Emerging contaminants and membranes

Membranes act as selective barriers that allow separating suspended solids and solutes of high molecular weight from a water matrix when subjected to hydrostatic pressure. Membranes can be produced using different materials with tailored features such as hydrophobicity, pore size or surface charge to determine the type of contaminant to be retained [45]. Pollutants separation through membranes is governed by three main mechanisms: steric exclusion (that separates the solutes based on their size), hydrophobic repulsion and electrostatic interactions between the membrane and EC (that leads to the adsorption of EC onto the membrane charged surface) [92]. Microfiltration is useful to separate suspended solids in the range of 100–1000 nm, ultrafiltración to retain particles sized between 5 and 100 nm (such as colloids, viruses, bacteria and large molecules of $\geq$1000 molecular weight) and nanofiltration is capable of separating 1–5 nm sized compounds (and molecules of 300–1000 molecular weight). Reverse and forward osmosis, on the other hand, uses semi-permeable membranes that allows the removal of ion and molecules of 100 molecular weight based on differences in solubility or diffusivity [45,93]. Membranes have been used in a variety of EC. These processes have been extensively applied in the treatment of water achieving high removal percentages of EC and producing high-quality permeates [94]; however, these technologies require additional stages for the treatment of the generated solid sludge containing the retained pollutant. Additionally, the phenomenon of membrane fouling due to the unwanted deposition of material within the membrane leads to a loss of performance [95]. Thus, regular cleaning or some pretreatments are needed to optimize the functionality of membranes [96]. Numerous works have used membrane treatments to remove EC such as endocrine disruptors, pharmaceutics and personal care products with promising results [94].

Fig. 7C compares the membrane technologies used in the treatment of EC according to number of publications.

3.10. Some of the publications with the highest impact

Some of the most relevant papers in terms of number of citations related to EC and published between 2000 and 2019 are listed in Table 3.

Most of the works listed in Table 3 correspond to review papers that became key reference documents in this field because they gathered the main findings of several research works and provided comprehensive insight into the major topics related to EC. In the other hand, the original research articles in Table 3 stand out because they correspond to studies that brought to light the presence of different types of EC in the environment, especially aquatic ecosystems. Some of these works also presented input sources, occurrence, spatial distribution, risks on living species and optional treatment technologies for such pollutants.

The most cited review paper was authored by Pelaez and co-workers and published in 2012. This review provided fundamental state-of-the-art insight into heterogeneous photocatalysis and gave comprehensive information on the TiO_2 structural and electronic properties that made it the benchmark photocatalyst in AOP applications. Also, this review exposed the TiO_2 different synthesis methods, doping strategies and its activity under different light sources in the removal of EC and bacteria [97].

The occurrence of antibiotic resistance genes (ARGs) in the environment was another aspect that attracted the interest of scientific community. ARGs are considered as EC that pose potential risks to human health. Some of the most highlighted works in this topic are quoted below. Pruden and co-workers studied the occurrence of ARGs in different water environments (rivers, irrigation ditches, diary lagoons, recycled wastewater and drinking water plants) in northern Colorado, USA [100]. According to its results, the following trend was observed with respect to ARGs concentrations: dairy lagoon water > irrigation ditch water > urban/agriculturally impacted river sediments. ARGs were also detected in drinking water and recycled wastewater. These alarming results indicated that these water bodies are potential sources to spread these EC to the population. Similarly, Zhu and co-workers investigated the presence ARGs in Chinese swine farms at different stages of the manure processing. According to the results of this study, the unmonitored use of antibiotics and metals has led to an increased abundance of ARGs in farm environments [99].

Works addressing the presence of pharmaceuticals, endocrine disruptors and organic pollutants in aquatic environments still have high impact among scientists. These studies mainly focused on their occurrence and fate in ground and surface water bodies. For instance, the national reconnaissance survey for some selected pharmaceuticals and other EC in ground and surface water resources that are used for drinking water in United States [104] reported the presence of 63 different EC on such water bodies. The most frequently detected compounds were cholesterol, metolachlor, cotinine, β-sitosterol and 1,7-dimethylxanthine in surface water, and tetrachloroethylene, carbamazepine, bisphenol A, 1,7-dimethylxanthine and tri(2-chloroethyl)phosphate in ground water. Likewise, Kasprzyk-Hordern and co-workers investigated the occurrence of 56 target pharmaceuticals, personal care products, endocrine disruptors and illicit drugs in surface waters in South Wales, UK [101]. Pharmaceuticals were the most frequently detected EC, of which antibacterial (trimethoprim, erythromycin and amoxicillin), anti-inflammatories (paracetamol, tramadol, codeine, naproxen, ibuprofen and diclofenac) and antiepileptic drugs

Table 3
Some of the most cited papers by Nov. 8, 2019 in the field of EC.

Title	Authors	Authors' affiliation countries	Publication year/Journal	No. citations
A review on the visible light active titanium dioxide photocatalysts for environmental applications [97]	Pelaez, M. Nolan N.T., Pillai, S.C., Seery, M.K, Falaras, P., Kontos, A.G, Dunlop, P.S.M., Hamilton, J.W.J., Byrne, J.A., O'Shea, K., Entezari, M.H., Dionysiou, D.D.	USA, Ireland, Greece, UK, Iran	(2012) Applied Catalysis B: Environmental	1891
Decontamination of wastewaters containing synthetic organic dyes by electrochemical methods: A general review [98]	Martínez-Huitle, C.A., Brillas, E.	Italy, Spain	(2009) Applied Catalysis B: Environmental	1368
Diverse and abundant antibiotic resistance genes in Chinese swine farms [99].	Zhu, Y.G., Johnson, T.A., Su, J.Q., Qiao, M., Guo, G.-X., Stedtfeld, R.D., Hashsham, S.A., Tiedje, J.M.	China, USA	(2013) Proceedings of the National Academy of Sciences of the United States of America	825
Antibiotic resistance genes as emerging contaminants: Studies in northern Colorado [100].	Pruden, A., Pei, R., Storteboom, H., Carlson, K.H.	USA	(2006) Environmental Science and Technology	780
A review on emerging contaminants in wastewaters and the environment: Current knowledge, understudied areas and recommendations for future monitoring [7].	Petrie, B., Barden, R., Kasprzyk-Hordern, B.	UK	(2015) Water Research	717
The occurrence of pharmaceuticals, personal care products, endocrine disruptors and illicit drugs in surface water in South Wales, UK [101].	Kasprzyk-Hordern, B., Dinsdale, R.M., Guwy, A.J.	UK	(2008) Water Research	662
Emerging organic contaminants in groundwater: A review of sources, fate and occurrence [8].	Lapworth, D.J., Baran, N., Stuart, M.E., Ward, R.S.	UK, France	(2012) Environmental Pollution	637
Role of membranes and activated carbon in the removal of endocrine disruptors and pharmaceuticals [102].	Snyder, S.A., Adham, S., Redding, A.M., Cannon, F.S., DeCarolis, J., Oppenheimer, J., Wert, E.C., Yoon, Y.	USA, South Korea	(2007) Desalination	632
Degradation and removal methods of antibiotics from aqueous matrices - A review [103]	Homem, V., Santos, L.	Portugal	(2011) Journal of Environmental Management	625
A review of the effects of emerging contaminants in wastewater and options for their removal [9].	Bolong, N., Ismail, A.F., Salim, M.R., Matsuura, T.	Malaysia, Canada	(2009) Desalination	540
A national reconnaissance for pharmaceuticals and other organic wastewater contaminants in the United States - II) Untreated drinking water sources [104].	Focazio, M.J., Kolpin, D.W., Barnes, K.K., Furlong, E.T., Meyer, M.T., Zaugg, S.D., Barber, L.B., Thurman, M.E.	USA	(2008) Science of the Total Environment	519

(carbamazepine and gabapentin) were the most common. The occurrence of such compounds was associated with the discharge of inefficiently treated wastewater.

The most cited papers regarding the removal of EC from water were based on the application of electrochemical technologies, oxidation, membranes and activated carbon. Martínes-Huitle and Brillas published in 2009 a review of great impact related to the use of electrocoagulation and electrocatalysis in the treatment of effluents containing dyes [98]. This paper focused on aspects such as the influence of electrode material and operational conditions (pH, temperature, chemical species and use of UV irradiation) in the reaction efficiency. Bolong and co-workers highlighted the adverse effects of EC to aquatic fauna and humans, and pointed out activated carbon and membrane filtration as the most significant technologies to remove EC removal, over other technology options such chlorination, ozonation and activated sludge treatment [9]. Snyder and co-workers also underlined the potential of activated carbon adsorption processes and membrane filtration as promising technologies capable of greatly remove the concentrations of EC [102]. Homem and Santos after reviewing state-of-knowledge regarding degradation and removal of antibiotics concluded that the combination of several treatment processes is the best strategy to treat effluents containing this type of EC. According to the paper, from a practical point of view, the coupling of an AOP with either a biological treatment or a membrane technology or an adsorption process is the best option [103].

4. Future perspectives

Since the human civilization has rapidly increased over the last century (7.7 billion people by November 2019, according to Department of Economic and Social Affairs/Population Division, United Nations [39], the demand of suppliers, the consumption of energy, waste generation, among other, are also increasing dramatically, leading to environmental global concerns. Nevertheless, population is also becoming aware of the responsibility we have as a humanity with the environment. One of current concerns are the called EC. Physicochemical-based processes have been widely used to deal with EC; however, these processes are costly. Recently, genetically engineered bacteria have been used as alternative and eco-friendly approach to face with EC, as reviewed by Ref. [105].

Usually, the treatment options to remove contaminants are focused on the pollutants that are specified in the existing regulations. However, the occurrence of new “unregulated” contaminants requires more advanced treatments. In this context, it is necessary to evaluate the effectiveness of different treatment alternatives considering the implementation costs incurred [106]. One possible research line could be focused in the assessment of the marginal efficiency of different treatment options versus marginal cost required for its development. The comparison between treatment options to remove emerging unregulated contaminants must consider the use of marginal analysis techniques.

As the need to control the presence of emerging pollutants becomes aware, it is necessary to assess the impact of these pollutants on the health of the population. The occurrence of emerging contaminants generates new challenges to environmental regulation due to it could be necessary modify the structure of the methodologies for estimating environmental infractions [106]. The growing emergence of emerging pollutants requires the refinement of environmental damage assessment mechanisms and the consequent relevant compensation.

Finally, new, further and stronger global policies and regulation are needed to achieve and keep a healthy environmental entire world.

From a technical point of view, there are many challenges that must be faced to have a more efficient management of EC. Given the increasing generation of wastewater and the accumulation in the environment of EC, several routes have been proposed:

Firstly, it is necessary to design and develop new strategic measuring techniques that facilitate the detection and monitoring of a wide spectrum of contaminants in the environment in real-time. This allows monitoring the release of EC from different industrial sectors and taking timely corrective actions. Monitoring can diminish the negative impact due to the presence of EC and identify the sources of contamination. Electrochemical biosensors are profiled as novel and useful tools to easily detect contaminants of different kind such as toxic heavy elements [107] and other analytes of interest such as endocrine disruptors [108] or metabolites from different EC. It is necessary to continue developing this type of tools with capacity to detect trace pollutants to favor taking early actions to control of the pollution.

Also, it is pertinent to develop more efficient water treatment methods that reduce the generation of wastes, sludge or the emission of volatile material. It is worth highlighting the advances that so far have been made in the handling of polluted water streams. The combination of different physicochemical methods or the coupling of biological and physicochemical treatments is projected as promising alternative. Some works have shown that applying two or more different AOPs simultaneously leads to the generation of a synergistic effect that is manifested by an increased generation of reactive oxygen species, which in turn translates into more efficient consumption of the used reagents, the development of higher degradation rates, shorter process times and complete mineralization of the contaminants [67,109]. It is necessary to continue developing new hybrid systems and optimizing the operating conditions that maximize their performance.

The valorization of agricultural wastes and plastic materials in the preparation of adsorbent or catalytic materials to be used in water treatments is a very important alternative [110,111]. These processes offer new alternatives to dispose of these wastes that in many cases are difficult to handle.

5. Conclusions

According to the results of this work, over the past twenty years there has been a rather fast evolution in scientific research devoted to the environmental occurrence of emerging pollutants. This is result of an increasing attention that social, political and legislative authorities are paying to the environment, which has led to the development of environmental monitoring and protection programs and the emergence of more severe regulations aimed to promote a more reasonable use of natural resources.

A total of 4968 papers related to emerging contaminants were published in scientific journals indexed to Scopus database in the period 2000–2019. The leading countries in research in this field were United States, Spain and China, of which Spain occupied the first place in terms of productivity stratified as the ratio of number of publications or number of citations to GDP. During the last decades, the global scientific output related to EC was focused in the areas of *Environmental science*, *Chemistry* and *Chemical Engineering* with a contribution of 41, 18 and 9% of the indexed documents, respectively. According to the number of published works, adsorption and advanced oxidation correspond to the most studied technologies to treat EC.

Declaration of competing interest

None declared.

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