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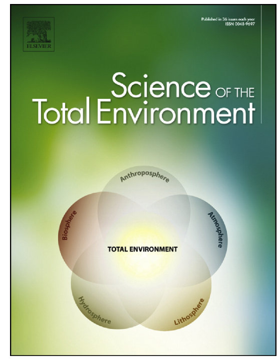

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Trends and characteristics of employing cavitation technology for water and wastewater treatment with a focus on hydrodynamic and ultrasonic cavitation over the past two decades: A Scientometric analysis

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Abstract

Cavitation-based technologies have emerged as a sustainable and effective way to treat natural waters and wastewater, considering their increasing scarcity due to pollution and climate change. For this reason, this work aimed to conduct a scientometric analysis on the topic of cavitation for water and wastewater treatment during the last 20 years, from 2001 to August 2022. We focused on hydrodynamic and ultrasonic cavitation as the prevalent methods of inducing cavitation. Furthermore, an in-depth study on the main trends regarding the number of publications and citations, keywords co-occurrence and evolution, and countries' publication trends was carried out to investigate the future direction of this research topic. The data was gathered from the Web of Science database and analyzed by the Visualization Of Similarities software. This work focused on: i) publication and citation trends, ii) scientific categories, iii) countries' contribution to the topic of cavitation, iv) prominent journals, v) keyword co-occurrence and cluster analysis, and vi) keyword evolution analysis. Results showed a significant increase in publications during the past five years. The scientific categories with the highest number of publications were "environmental sciences" and "environmental engineering," with a combined share of 19.4% of publications.

Keywords evolution analysis showed that limited focus was given to topics related to "energy" and "energy efficiency" in the field of cavitation, but with the rising importance of each process's sustainability, the attention given to these concepts will increase in the future.

Future directions for the topic of cavitation-related water and wastewater treatments will shift towards more environmentally friendly applications of hydrodynamic and ultrasonic cavitation, as well as towards more green and sustainable approaches to address the increasing water pollution problems and shortage. Moreover, it will include other uses besides water treatment, such as manufacturing nanomaterials, food production, and medicine.

Keywords: Cavitation, Research trend, Scientometric analysis, Sustainable treatment, VOS viewer

1. Introduction

The availability of water resources suitable for human use has become increasingly scarce due to (Filipić et al., 2022) a combination of several factors, such as increased water demand for industrial (e.g., textiles, drugs, and plastics production) (Bethi et al., 2021) and agricultural activities (Soto-Verjel et al., 2022) leading to the emission of several classes of chemicals in the environment (e.g., petrochemicals, pharmaceuticals, plant protection products, and fertilizers) (Bokhari et al., 2021; Matheus et al., 2020; Soto-Verjel et al., 2022; Thanekar et al., 2021; Yu et al., 2021). This issue is also further complicated by the predicted increase in urban population, which is estimated to reach up to 6.7 billion by 2050, with the consequent increase in both wastewater produced and freshwater water resources needed (He et al., 2021; United Nations/DESA, 2019). Since other freshwater sources such as desalinization processes or rainfall collection face important technical challenges (Ayaz et al., 2022; He et al., 2021; Oki and Quiocho, 2020), this will create a negative feedback loop that perpetuates the cycle of resource depletion (Di Baldassarre et al., 2018; Greve et al., 2018). Thus, it is fundamental to develop new technologies for managing, treating, and reusing water and wastewater (Fan et al., 2019).

Among the different approaches and technologies considered for this activities, advanced oxidation processes (AOP), such as vacuum ultra-violet photolysis, ultra-violet photocatalysis, photoelectrocatalysis, ozonation, and cavitation (Akintayo et al., 2021; Delgado and Santander, 2017; Issaka et al., 2022; Y. Li et al., 2021; Xie et al., 2019; Ye et al., 2021) are attracting much attention. However, not all AOPs are currently cost-effective at the industrial scale, as they require substantial amounts of chemicals and energy expenditure to operating efficiently (Haździor et al., 2019).

On the contrary, conventional hydrodynamic cavitation (HC) systems do not require the use of additional chemicals and use a significantly lower amount of energy compared to other AOPs, thus showing great potential to be scaled up for industrial use (Sun et al., 2020a).

In particular, hydrodynamic cavitation comprises the emergence of micro- or nano-bubbles, based on the geometrical configuration of the venturi tube used (Gogate, 2002; Nazari et al., 2020), whose growth and eventual collapse release hydroxyl radicals due to a reaction between water and oxygen (Eq. 1).

$$H_2O + 1/2\ O_2 \rightarrow 2OH^{\cdot} \quad \text{Eq. 1}$$

The high local temperature promotes this reaction (i.e., up to 7200K (Montalvo Andia et al., 2021; Temesgen et al., 2017; Yasui et al., 2019)) caused by the shockwaves produced in the bubble collapse, which increases the local pressure up to 10^8 Pascal (Choi et al., 2020, 2019; Montalvo Andia et al., 2021). (Fig.1a).

At the moment, hydrodynamic cavitation is not considered a stand-alone method for water and wastewater treatment purposes due to its low effectiveness in COD removal (i.e., less than 40%), but it has shown several applications as a pre-treatment method due to its easy implementation (Bhat and Gogate, 2021; Dular et al., 2016). Moreover, various methods of inducing hydrodynamic cavitation can be used, including orifice plates, venturi tubes, and rotational generators (reactors) (Repinc et al., 2022), thus allowing it to be combined with other methods based on the situation (Thanekar and Gogate, 2019). Thanks to these characteristics, hydrodynamic cavitation has been shown as a promising and effective process for many environmental applications, and in particular to treat both natural waters and wastewater (Patil et al., 2021) by eliminating many organic substances, such as industrial-grade dye (Zampeta et al., 2021), solvents (Patil et al., 2021; Suryawanshi et al., 2018), pharmaceuticals (Lalwani et al., 2020; Yahong et al., 2019), as well as viruses and microbes (Kosel et al., 2017; Sun et al., 2021).

Furthermore, the formation and collapse of micro- and nano-bubbles can also be obtained by applying other technologies, such as ultrasonic cavitation, optic cavitation, and particle cavitation (Guild et al., 2010)(Benito et al., 2005; Ren et al., 2020).

In particular, ultrasonic cavitation is achieved through pressure gradients caused by ultrasonic waves traversing inside the liquid (Benito et al., 2005; Ren et al., 2020) (Fig.1b). In detail, with frequencies ranging from 16 kHz to 2 MHz, cavities may be created by ultrasound, which causes pressure variations in the medium as a result of the compression and rarefaction of the waves (Gogate and Pandit, 2001). These pressure variations also cause the reaction of water vapor molecules with oxygen to produce hydroxyl radicals (Eq.1). Ultrasonic cavitation has been proven effective in water treatment by several authors, for example, when applied for the degradation of ammonia as well as for turbidity and total suspended solids (TSS) removal (Fetyan and Salem Attia, 2020; Ozturk and Bal, 2015; Tan et al., 2021; Villota et al., 2017).

Optic cavitation is a more intrusive and energy-intensive method concerning hydrodynamic and ultrasonic cavitation, as it uses high-intensity laser pulses, thus making it largely unsuited for environmental applications (Mancuso et al., 2020).

Finally, particle cavitation is generally used for toughness augmentation of materials by altering their matrix and introducing voids that result in increased plastic deformation (Guild et al., 2010).

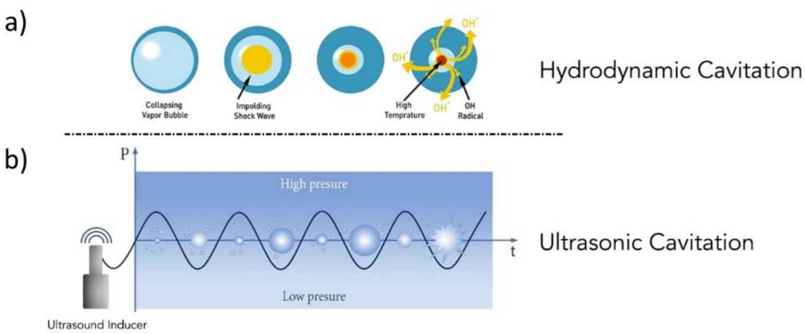

Fig.1. Cavitation steps in hydrodynamic (a) and ultrasonic (b) cavitation.

Even though cavitation has been studied extensively, there is still a distinct lack of knowledge on its uses for water or wastewater treatment. In fact, a preliminary analysis of the Web of Science (WoS) database showed that between 2001 and early 2022, only 166 review papers on this topic were published. Among these works, many reviews were mainly focused on the treatment aspects of cavitation techniques, mostly focusing on the same repetitive material, going through the details of various devices and apparatuses capable of inducing hydrodynamic cavitation in wastewater treatment. In total, 23 reviews were concerned with ultrasonic (ultrasound applications) and 24 with hydrodynamic cavitation.

Moreover, this investigation also showed the lack of scientometric reviews on cavitation processes applied to water-related issues and other environmental applications and on how cavitation technologies can contribute to ameliorating environmental pollution problems.

Additionally, considering the huge number of publications (i.e., 2551 as of August 2022) regarding "cavitation AND (water OR wastewater)" that were added in the last 20 years to the WoS database, it is a virtually impossible task for researchers and scholars to be acquainted with all these publications, let alone find the main trends and points of focus of this research topic.

To address this lack of knowledge, the authors have endeavored to present a general overview of cavitation research trends to assess their idiosyncrasies and potential use in environmental applications, specifically focusing on water and wastewater treatment processes.

In particular, a scientometric analysis from 2001 to 2022 was carried out on this topic by investigating the major aspects of the literature published in the WoS database, including publications number and citations, keywords choice, keyword co-occurrence, authors' networks, countries' contributions, major journals, and keywords evolution. To better visualize the obtained data, SNA (social network analysis) was also used (Macías-Quiroga et al., 2020; Salpeteur et al., 2017). Furthermore, this work includes a critical evaluation of the obtained literature trends from an environmental science and engineering perspective to provide a more comprehensive overview of this topic's past and present trends and to support future research.

2. Methodological approach

2.1 Data collection, screening, and visualization

The bibliometric analysis conducted in this study was carried out by applying the following process: i) selecting and acquiring the most dependable database and software, ii) identifying keywords that are pertinent to the subject matter (i.e., keywords related to cavitation, water, and wastewater treatment) iii) narrowing the search results based on document type, publication date, and scientific categories, iv) exporting the data obtained to other literature-managing tools by using the Web of Science (WoS) exporter for further analysis, v) visual representing the data utilizing social network analysis (SNA), and vi) interpreting the visualized data.

The Web of Science database was selected as it is one of the most powerful and dependable repositories of scientific papers (Merigo et al., 2017; Yang et al., 2013). Additionally, WoS includes dedicated tools (e.g., InCite) to assess bibliographical data in various formats, which facilitates the process of removing irrelevant publications. Furthermore, the Web of Science platform is compatible with various literature analysis tools (Birkle et al., 2020; Newell and Cousins, 2015), such as “InCite” and “Visualization of Similarities” (VOS), that were selected for this work.

In detail, in August 2022, literature data from the Web of Science was compiled and refined. The primary search was carried out using the “advanced search tool,” opting for “cavitation OR ultrasonic irradiation” as keywords to group the various expressions used to describe cavitation since it is the main focus of the current work. Specifically, this search was carried out using the “Topic search” option, where the search is conducted in “title, abstract, author keywords, and keywords plus.”

To limit the selection of publications to the ones related to water and wastewater treatment, additional conditions were used by applying the “All fields” option with the search string “water treatment OR wastewater treatment OR hydrodynamic cavitation OR ultrasonic cavitation.” This second string was added to the first with the END operator. In detail, the “All fields” allows one to search among all the possible fields of entry that might possess the desired keyword. The keywords “hydrodynamic cavitation” and “ultrasonic cavitation” were added to ensure that all works related to these technologies were included since their most relevant applications are usually related to environmental applications (Khan et al., 2019; Vernès et al., 2020).

The search was further refined by period selecting all works from 2001 to August 2022, then only “Articles,” “Review articles,” and “Early Access” were selected by using the “Document Type,” thus excluding “proceeding papers,” “meeting abstracts” and other less relevant categories from the results. Moreover, the final results were refined based only on scientific categories deemed relevant to environmental applications, as reported in Table S1, thus obtaining 2551 articles.

Furthermore, GraphPad Prism (Version 9) and Microsoft Excel (2022) were used to visualize the data and results obtained in this work.

2.2 Scientometric analysis

The scientometric analysis was carried out as a six-tiered process by applying the following steps: i) analyze the language and article distribution, which determines the dominant publication languages and the percentage of each article type (articles, review papers, etc.), ii) study the publication growth trend to explain the changes occurring in the citations and number of publications, iii) investigate the major scientific categories that classify the articles’ main topics to illustrate which are the main fields of study regarding cavitation (e.g., environmental sciences, environmental chemistry, etc.), iv) analyze the contribution of each country to elucidate the geographical distribution of the research effort on cavitation, v) determine which are the journals more prolific in publishing cavitation-related articles, vi) carry out keywords, and cluster analysis to scrutinize the main keywords related to cavitation environmental applications and study how the obtained clusters of keywords are grouped (i.e., cluster stance).

2.3 Keyword co-occurrence analysis and keyword evolution visualization

Keyword co-occurrence analysis, a network mapping method focused on identifying the knowledge components, knowledge structure, and research trends based on the publications' keywords (Radhakrishnan et al., 2017), was carried out by applying the approach reported by (J. Li et al., 2021). Furthermore, all occurrences of keywords that could be considered synonyms were changed to the most common term (e.g., wastewater, waste-water, and wastewater) then only the 100 most used keywords were selected.

Cluster analysis of the results of the keyword co-occurrence search was carried out following the approach reported by de Toledo and co-workers (2019) by means of the Visualization of Similarities (VOS) software. In addition, the VOS viewer program was used to visualize the network, and the "scale" and "size variation" were applied. In detail, each node represents a keyword, and the size of the circle is directly proportional to the number of publications using each keyword, while the thickness of the lines connecting them increases with the number of co-occurrences. The clustering is done by the software with no possibility of modification.

Keyword evolution visualization is a process where the occurrence of the keywords present during the investigated period (i.e., from 2001 to August 2022) is quantified for each year. In detail, the VOS software was used to select the occurring keywords for each year, and the number of occurrences of the 30 overall most present keywords was plotted in a staked bar diagram with the Excel program.

2.4 Social network analysis

Social network analysis (SNA), a technique based on graph theory that analyzes the social networks present in the dataset (Brandes, 2015; Otte and Rousseau, 2002), was applied to visually represented data and the bibliometric network through "Visualization of Similarities" (VOS) software (version 1.6.18) following the approach reported by Wojcik and co-workers (2021). In detail, the nodes in the network include journals, publications, citations, co-occurrences, co-authorships, and countries, which can help characterize these intricate connections.

3. Results and discussion

Cavitation technologies have shown great potential in many water and wastewater treatment applications, but the lack of comprehensive information on past and present trends in this field of research is still a challenge. For this reason, in this work, a scientometric analysis was carried out on the works focused on this topic published in the last 20 years. In particular, publications number and citations, keywords choice, keyword co-occurrence, authors' networks, countries' contributions, major journals, and keywords evolution were investigated, and the results are reported below.

3.1 Language and document type analysis

The main language and document type of the publications regarding a specific topic can give essential information on the scientific community involved and, therefore, on the future trends of the research.

In detail, as illustrated in Fig.2, the results show that the majority of the selected publications are composed of articles (91.67%), followed by review papers (7.08%) and early access (1.24%). The results also showed that, as expected, most of the articles (i.e., 2135) were in English, while the other two most used languages, Chinese and Russian, with 29 and 8 articles, respectively (Yemelyanova et al., 2016; Zhang et al., 2019). The presence of Chinese as the second most used language can be attributed both to a large number of contributing researchers and also to the policies promoted in China that favor the publication of national scientific journals (Wang et al., 2021).

Furthermore, while similar policies are also present in the Russian academic system (Moed et al., 2018), albeit to a lesser degree, to better understand why Russian was the third most present language, the search results were further refined to elucidate the recent trends (i.e., publications in Russian from 2018 to August 2022). Among these publications, the main topics covered were related to “cavitation application in mines” and “oil contaminated sites” (Khrunina and Gevalo, K., 2021; Tikhomirova et al., 2020), related to the fact that the mining sector (e.g., coal, gold, iron, and nickel) is one of Russia’s key economic sectors, with an estimated value of 75 trillion dollars (Mining World, 2019). In particular, several of the most difficult problems related to operating mines, such as waste deposit to the purification of minerals in floatation tanks, can be facilitated using cavitation methods. Furthermore, Russia’s oil and gas sectors comprise 40% of its GDP (Osterreichische National Bank, 2022). Thus, it is logical for this country to invest in research related to cavitation and its environmental applications.

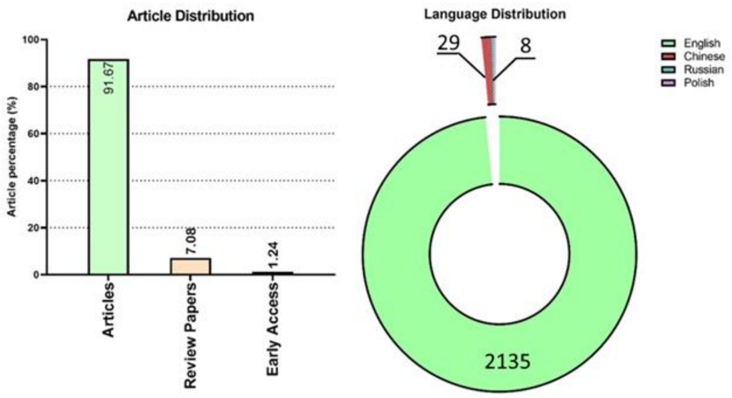

Fig.2. Global and language distribution of articles on cavitation and its application in water and wastewater treatment

3.2 Trend analysis of publications growth

The evolution of the number of articles and citations regarding the topic of cavitation is essential information to understand and clarify the amount of resources dedicated to this field in the past and the prospects for future research.

As shown in Fig.3, the results showed that the number of publications related to cavitation in the field of water and wastewater treatment had been steadily rising during the investigated period, as shown by the increase in the number of publications per year (TP), culminating with the maximum reported for 2021 Together with the similar trend showed by the number of citations (TC), this showed that cavitation-related topics have been receiving a considerable and increasing amount of attention. Conversely, the decrease of studies and citations found for 2022 can be related to several factors, such as that the year 2022 is still on-going, that the indexing of citations requires time to be automatically computed by online repositories, and that the most recently published articles have yet to have the chance to be cited.

Moreover, as highlighted in Fig.3a, the rate of increase in the number of citations was not constant during the investigation period but showed a significant increase after 2017. To investigate this finding, the authors calculated the ratio between the number of articles and review papers (i.e. articles/reviews), showing that in the period 2012-2016, review papers had a smaller share with respect to the period between 2017 and 2021 (with a ratio of 17 and 12, respectively). This difference can be considered an important contributing factor to the increase in citation numbers found after 2017 since reviews are among the most cited publications to report on a topic's state of the art in the introduction section of many papers. To further investigate the reasons for the citation increase found after 2017, the "Analyze Results" WoS analytical tool was used to determine if there was any significant change in the scientific categories related to the publications on "cavitation."

Furthermore, the maximum number of citations was reached in 2021; thus, an investigation of the main topics was carried out. The majority of the most cited articles in 2021 referred to the Chemical engineering category (95 articles), showing research focusing on innovative ways to implement various types of cavitations for wastewater treatment, such as the work by Kim and co-workers (2021) that utilizes hydrodynamic cavitation for bacterial disinfection during microalgal biomass production. Furthermore, other uses of cavitation techniques, not solely focusing on water treatment but also on enhancing the effectiveness of energy recovery processes, were also present, such as using a cavitation reactor to enhance biodiesel fuel production (Samani et al., 2021).

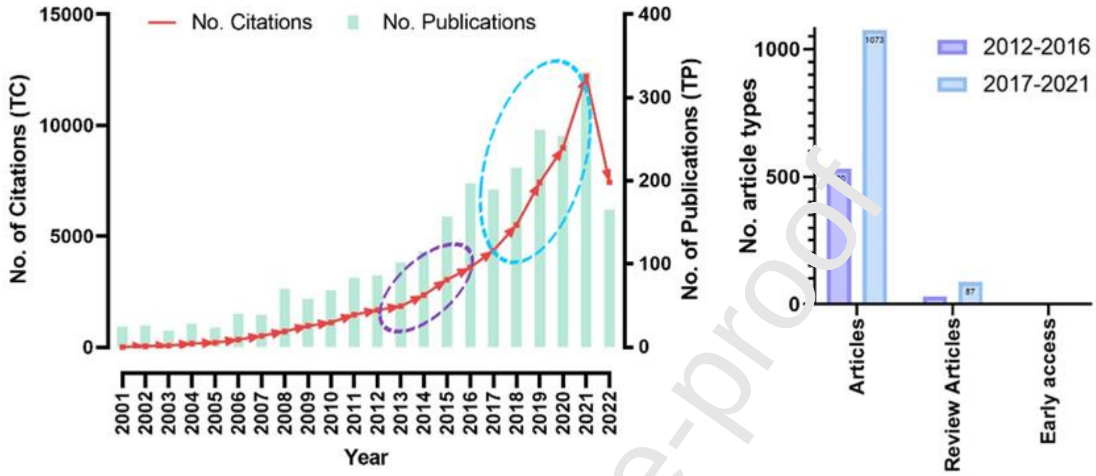

Fig.3. a) Annual number of publications and citations for cavitation. The purple and light blue circles highlight the 2012-2016 and 2017-2021 periods, respectively. b) Comparison of document type between 2012-2016 and 2017-2021.

3.3 Subject categories analysis

Cavitation can be considered a multidisciplinary topic since many of the several technologies used to induce cavitation phenomena, including hydrodynamic and ultrasonic cavitation, have various environmental, physical, chemical, and technical implications. Investigating which are the scientific categories where most of the research is focused and how this can change with time is fundamental to obtaining a clear picture of how the scientific progress on the topic of cavitation is evolving.

In detail, the InCite tool of WoS was used to group the selected publications by their main scientific categories. The results showed that cavitation is a very multidisciplinary topic, with publications spanning up to 25 distinct topics, 11 of which are relevant to our study due to their connection to the environmental application of cavitation processes (Fig.4).

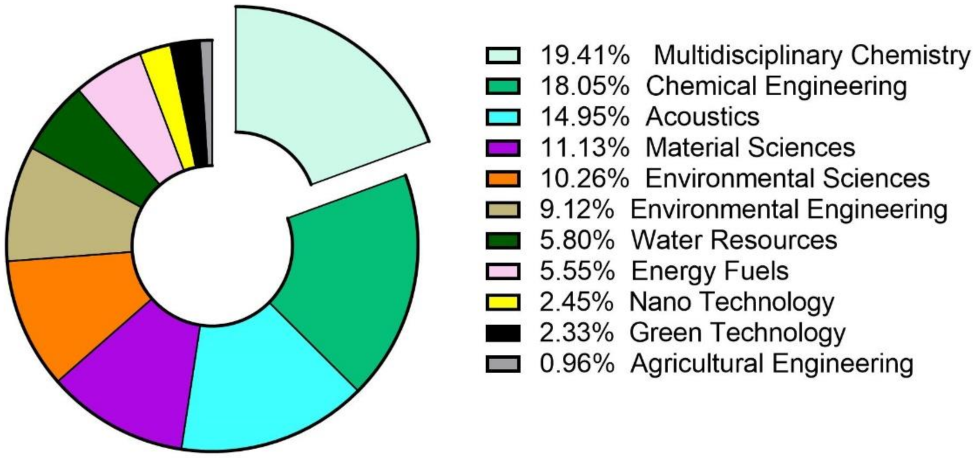

Fig.4. The nine most relevant scientific categories grouping the publications selected in this work

The most prominent categories found in this study were Multidisciplinary Chemistry and Chemical Engineering, with a share of 19.41% and 18.05% of the total publications, respectively. Moreover, a substantial overlap was found between "Environmental Sciences" and "Environmental Engineering"; thanks to their relevance to this article's aim, these two categories were extensively analyzed. To find the most recent trends in those two scientific categories, the publications belonging to these two categories from 2018 to August 2022 were selected. The results showed that the studies belonging to the Environmental Engineering category were mainly concerned with the construction and design aspects (e.g., modeling of the cavitation process and potential enhancement of existing cavitation devices), as is the case with the work of Dutta and co-workers (2021), which strives to offer strategies to enhance venturi tubes for achieving better results in hydrodynamic cavitation.

Additionally, some articles aim to solely model the cavitation phenomena itself, as in the study by Sarvothan and co-workers (2019) on the modeling of vortex-based hydrodynamic cavitation reactors. Furthermore, this category also included publications where other facets of cavitation were considered, such as the work by Das and co-workers (2021) where, in addition to modeling the cavitation process employed, a cost analysis was also carried out. By analyzing the topics studied in this scientific category, it could also be seen that hydrodynamic cavitation was much more studied than acoustic cavitation, and this could be ascribed to the fact that hydrodynamic cavitation is easier to both model and apply to scaled-up systems than acoustic cavitation (Bhat and Gogate, 2021; Dular et al., 2016; Thanekar and Gogate, 2019; Zampeta et al., 2022).

The results of the in-depth analysis of the publications within the Environmental Sciences category showed that most were focused on the application of cavitation for the treatment of various types of wastewater, such as the work reported by Zapata and co-workers (2021) and Doltade and co-workers (2019) which focused on the treatment of textile and petroleum refinery effluent by applying hydrodynamic cavitation, respectively. In addition, several works also reported on novel processes for the treatment of less studied contaminants, such as the work by Honda and co-workers (2021), which employs ultrasonic cavitation to inactivate algae and plankton, and the work by Hao and co-workers (2021) who focused on ultrasonic-assisted cavitation in the process of microalgae oil extraction for hydrogen production.

Among the scientific categories shown in Fig.4., Nano Technology (i.e., nanoscience and nanotechnology) accounted for only 2.45 % of the publications selected in this work. However, its importance showed a significant increase form its first appearance in 2008 (i.e., 3 articles per year) to 2019 (i.e.,12 articles per year and 221 citations), thus making its ranking among the scientific categories related to cavitation increase from 16th place to 9th place. This indicates a promising trend in the growth of this research. Therefore, an in-depth analysis of the works belonging to this scientific category was carried out.

In particular, the most recent articles in 2022 were related to ultrasonic cavitation. The article by Choudhary and co-workers (2022) describes the use of ultrasonic cavitation for the pretreatment of a sucrose hydrothermal carbonization (HTC) precursor solution to control the size of the synthesized carbon nanospheres (CNSs). The combination of cavitation methods and nanotechnology also has a wide variety of other applications, such as in the article by Basov and co-workers (2022) where silver nanoparticles (AgNPs) were obtained by cavitation-diffusion photochemical reduction, and their antibacterial activity on different surfaces was investigated during cycling freezing. The diversity and applicability of the many combinations of nanomaterials and cavitation is the main reason we believe this category will be among the top 6 categories in the years to follow, particularly regarding environmental applications.

The Green Technology category (i.e., green and sustainable technologies) has also shown substantial growth during the investigated period. In detail, this category appeared in 2009 (1 article), but it did not receive significant attention until 2015, after which it experienced an exponential increase in the number of citations from 20 in 2015 to 524 in 2021. The articles in this group are quite multifaceted, for example, on applying cavitation technologies and the energetic efficiency of cavitation processes. For example, Zieliński and co-workers (2019) reported cavitation-based pretreatment for liquid wastes in a small-scale agricultural biogas plant to augment biogas production. This shows the potential of using cavitation in real-scale applications to reduce the environmental impact of energy production from organic waste, thus opening a new market and occupational opportunities in different fields.

Moreover, Albanese and co-workers (2019), focused on how hydrodynamic cavitation can be used to reduce the energy consumption of a process to produce biochar characterized by high porosity and surface area. A similar study was also carried out by Desikan and coworkers (2021), who reported using hydrodynamic cavitation to decrease the energy needed for biomass pre-treatment for bio-ethanol production. Furthermore, in the work of Mancuso and co-workers (2019), low-level hydrodynamic cavitation was used to assist thermos-alkaline pre-treatment for sludge solubility.

These considerations are fundamental for the development of more sustainable cavitation processes. Therefore, we think the importance of the Green Technology category will continue to increase and will play an indispensable role in numerous scholarly publications.

3.4 Country analysis

Since the trends of the research focused on a specific topic can be closely related to the policies and funding programs carried out by different countries and institutions (Schneider et al., 2019), investigating the geographic distribution of the publications related to cavitation is fundamental to obtain a clear understanding of this topic present and future developments.

In detail, Fig.5 shows the 18 most prolific countries based on the number of publications regarding cavitation applied to water and wastewater treatment in the last 20 years. In particular, China and India were the two most productive countries, with 683 (i.e., 26.7%) and 431 (i.e., 16.9%) publications, respectively. The third place belongs to the USA, with 204 articles, followed by Russia, Iran, Japan, South Korea, Italy, England, Malaysia, Poland, France, Germany, Turkey, Canada, Brazil, Spain, and Australia. Based on the results shown in Fig.5, the most prolific countries include nations from various parts of the globe, ranging from well-developed countries (e.g., Japan and the USA) to developing countries (e.g., Iran and India), while also including some European countries such as Germany, Italy, and Spain.

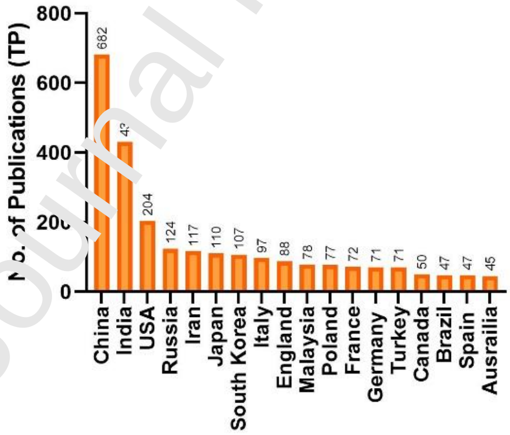

Fig.5. Top 18 most productive countries from 2001 to 2022 in the field of cavitation related to water and wastewater treatment.

Furthermore, an in-depth analysis was carried out on the specific topics researched in each country, and the following criteria were used to compare the results obtained: i) level of development (i.e., developed or developing country); ii) gross domestic product (GDP); iii) inclusion in the European Union; and iv) number of publications. In detail, based on these criteria, the following countries were chosen for further analysis and divided into the following groups: i) China, USA, and Russia; ii) India, Spain, and Iran; and iii) Germany and Italy.

In the first group, it can be seen that in recent years China and the USA have moved on from basic applications of cavitation in water and wastewater treatment to more advanced uses. For example, Hung and co-workers (2021) published a study where hydrodynamic cavitation, along with other techniques, was used to remove polycyclic aromatic hydrocarbons (PAHs) from dredged sediments, while De Alwis and co-workers (2021) investigated the use of hydrodynamic cavitation for the exfoliation of graphene nanosheets. In addition, other advanced applications of cavitation studied in China include improving the functional properties of food proteins and milk pasteurization by hydrodynamic and ultrasonic cavitation (Ren et al., 2020; Sun et al., 2021). Despite the development of those new applications, the results also showed that China is still heavily investing in the use of cavitation methods for wastewater treatment, such as treating tetracycline using HC (B. Wang et al., 2022). The analysis of the publications in Russia for the last 3 years (i.e., ca. 14 articles per year) showed a level of interest in the topic similar to what has been found for the USA (i.e., ca. 17 articles per year), with research topics ranging from more basic research to the more innovative uses of cavitation. For example, Abramov and co-workers (2021). investigated the simultaneous effect of hydrodynamic cavitation and plasma discharge on the bulk treatment of contaminated water, Matafonova and Batoev (2020) exploited dual-frequency ultrasounds (DFUS) for the elimination of pathogens and water disinfection, and Thangavelu and co-workers (2018) studied the use of hydrodynamic cavitation in the delignification of corncob via hydrodynamic cavitation and enzymatic pretreatment. Since the Russian economy is heavily based on the metallurgy and oil industry, several recent publications are focused on such topics, such as the work by Eskin and co-workers (2019) on using ultrasonic cavitation in melt processing, which is a part of the metal casting industry.

The second group of countries (i.e., India, Iran, and Spain) was chosen because of their similar GDP levels (2.62, 1.28, and 1.43 trillion dollars, respectively) and because they are all facing problems related to water scarcity and contamination (Caleb Silver, 2022; Kadkhodamanesh et al., 2021; Xia, 2021). For this reason, the authors wanted to investigate if these have triggered differences or changes in their publications.

In detail, for these three countries, the results showed that many recent articles are concerned with industrial wastewater since environmental regulations are becoming more stringent, restricting the haphazard discharge of chemicals into water reservoirs or other water bodies. For example, in the recent article by Vilarroig and co-workers (2020), an industrial-scale cavitation device was utilized for the pretreatment of animal breeding waste sludges. Moreover, the results also showed a significant difference in the researcher's focus in these countries on the cost of the studied cavitation processes. In fact, most of the articles where also the cost of the investigated process was considered were from Spain and Iran, such as the work from Gallero-Valero and coworkers (2021), who presented an overview on different wastewater treatment costs in the period 1950–2020. Similarly to what has been observed for Spain, a focus on the techno-economic assessment of the proposed cavitation process was found for Iran, as indicated in the publications by Gholami and co-workers (2021a,b) who discussed the costs of using hydrodynamic and ultrasonic cavitation for enhancing biodiesel production. Since in Iran, environmental regulations are quite weak and very rarely applied (Ebadi et al., 2020), in the last three years, only very limited numbers of publications on cavitation refer to such standards. However, since one of the major issues for this country is the lack of operational incinerators, many articles focus on applying cavitation to manage industrial wastewater and landfill leachate (Torkashvand et al., 2021).

The countries considered in the third group (i.e., Germany and Italy) are both parts of the European Union but have significantly different GDPs (1.89 and 3.85 trillion dollars for Italy and Germany, respectively) and different economic situations. These differences could also be seen in the publications produced in these countries. In fact, the research carried out in Italy in the last three years follows the same path as China and the USA, showing great interest in more innovative uses of cavitation, encompassing articles ranging from dye elimination from water (Innocenzi et al., 2020, 2019), water disinfection (Burzio et al., 2020), facilitating seed germination (Ugolini et al., 2021), and antibacterial treatments for longer food conservation (Presentato et al., 2020). In particular, further analysis of the studies published in Italy in the last four years showed they were mainly focused on hydrodynamic cavitation, but the number of works focusing on ultrasonic cavitation has constantly been increasing, showing a promising prospect for the research focused on this topic.

On the contrary, in Germany, most research focused on industrial-scale applications of ultrasonic cavitation for wastewater treatment (Lippert et al., 2020) or the physical processes regulating ultrasonic cavitation and the consequent bubble generation (Izak Ghasemian et al., 2021). This shift in focus can be ascribed to the higher industrialization of Germany, which caused a higher demand for technologies focused on large-scale management of industrial wastes compared to Italy and other European countries. From the results, it can be seen that only a limited number of publications in Germany focused on more innovative uses of cavitation on environmental-agricultural topics (H. J. Wang et al., 2022), but this number is likely to increase in the following years thanks to recent shifts in Germany's policies on environmental management (Baaken, 2022).

In addition to observing the most recent developments in the field of environment-related cavitation technologies, it is also crucial to understand the motives behind the most prolific countries' long-term publication trends. In particular, in Fig.6, we report the results found on the evolution of the annual number of publications on this topic for the eight countries previously discussed in this section.

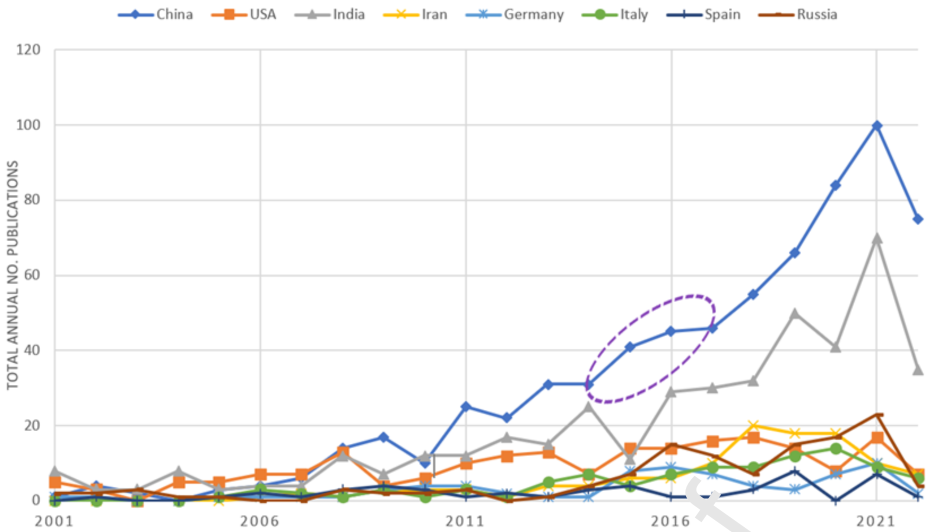

Fig.6. Annual number of publications for the selected 8 countries during the investigated period.

The country with the highest number of publications in 2021 was China (blue line in Fig.6). However, before 2008, the USA (orange line in Fig.6) had a higher scientific production on cavitation processes for water treatment. This trend reversal did not depend on a drop in interest in the topic in the USA, which remained fairly constant during the investigation period but on a sudden increase from the Chinese side. This increase is especially evident after the 2014-2017 period, suggesting the presence of a fundamental shift in China's environmental management policies, particularly regarding water and wastewater treatment. In fact, based on the environmental report by Jianjie and co-workers (2015), in 2015, China declared for the first time a red alert regarding air pollution (Cheng et al., 2015; Chung and Kim, 2015; Liang et al., 2015), and on January 1st of the same year several more stringent environmental protection laws came into effect. In addition, many efforts directed to better conservation and management of environmental resources and to reduce carbon emissions (Tao et al., 2016; Wang et al., 2017; Wu et al., 2015) were carried out after the announcement in 2014 by the Chinese government that China would start decreasing carbon emissions by 2030 (Fang et al., 2019).

As expressed in Fig.6, the second largest increase in the number of publications for the investigated period was found in India (grey line in Fig.6), especially after 2016 -2018. This can be related to the increased interest in policies regarding the environment observed in India over the last few years. The latest report regarding India's environmental budget shows a 20% increase in the allocation concerning the 2020-2021 period, as well as a clear change of policy on emissions with goals such as net zero emission by 2070 and increasing the share of renewable energy production in India by 50% by 2030 (Prachi and Kumar, 2021).

The results reported in Fig.6 show that the number of works published in Iran increased noticeably after 2015 (yellow line in Fig.6) due to the more marked acknowledgment of the grave water shortage problems faced by this country (Ahmadi et al., 2021); and the consequent need of more efficient and affordable water treatment technologies, such as those that can be provided by cavitation. Analyzing the most recent Iranian publications, it emerged that one of Iran's major uses of cavitation (mostly hydrodynamic cavitation) is for the floatation of minerals and their consequent purification since this country's economy is strongly based on the mineral sector (Nazari et al., 2020). As the industrialization of Iran, and therefore the need for more specialized wastewater treatment facilities, is steadily increasing, research is also expected to increase. However, due to the recent economic challenges and sanctions, the development of the research related to cavitation and its uses in water treatment may face several challenges, as also shown by the decreasing number of publications in the last four years.

As for the other countries shown in Fig.6, the difference in the number of articles on cavitation related to water and wastewater treatment was less significant. Nevertheless, thanks to the many results showing the potential of cavitation for industrial-scale applications related and unrelated to the environment, other countries will soon follow the same trend and show more interest in taking advantage of cavitation and its various uses.

Other than investigating the general publication trends of the most prolific countries, it is also fundamental to investigate which are the trends in international collaborations to obtain a clear picture of the direction that the research on cavitation related to water and wastewater treatment will take in the next few years. For this reason, a co-authorship network analysis was carried out among the top 19 countries with more publications on the topic focus of this work, and the results are presented in Fig.7.

In detail, co-authorship networks can be considered social networks made up of scholars who collaborate on a certain subject, thus constituting the nodes of the nodes of network (Savić et al., 2019). The level of connection between nodes (i.e., researchers) is defined as link strength, and it is proportional to the number of shared works. In Fig.7, this can be visualized by the thickness of the lines in the diagram.

The results showed that the strongest collaboration networks had been established between the USA and China, as they are also among the biggest contributors to this topic. Furthermore, close collaboration was also found between Iran and Turkey, as well as between Italy, Spain, and France, owing to the similarities between their socio-economic systems and their environmental regulations.

The country with the most collaboration links in the network was India (31 links), which is higher even than the links established by China (28 links), thus showing that the sole number of publications (682 and 431 for China and India, respectively) should not be the only factor to be considered when assessing the contribution of a country to the international research landscape on a topic. Furthermore, the different policies these two countries applied greatly influenced this difference in the number and importance of international connections. This high number of international collaborations found in India can also be related to increased resources available for research focused on environmental issues, as explained above. These findings highlight the central role that India will continue to play in the field of research related not only to water treatment by cavitation processes but also to the larger landscape of environmental management.

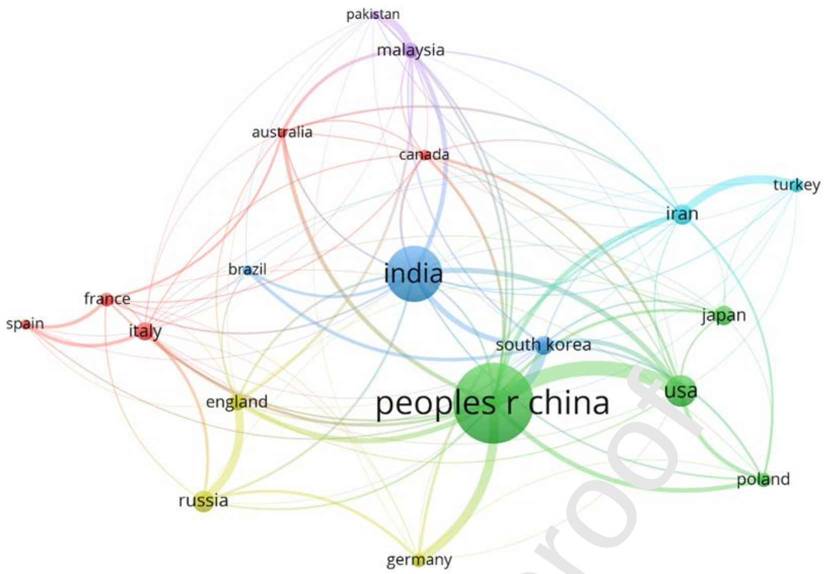

Fig.7. Diagram showing the network of collaborations between the 19 most prolific countries on cavitation based on co-authorship relations. The thickness of the lines connecting each node denotes the number of collaborations, while the radius of the circle indicated the number of publications for each country.

3.5 Journal analysis

Other than the number of publications and citations, and their respective trends, also the analysis of which journals have been chosen to publish the research carried out on cavitation applied to water and wastewater treatment can give fundamental information on the importance given to this topic and the future path of this research effort. Impact factor (IF) is one of the most dependable indexes for measuring the quality of scientific journals, and many researchers use it to select which journal they wish to publish their research (Suiter and Sarli, 2019). Furthermore, a globally applied indicator is also a quartile ranking (QRs), supplied by WoS citation report. Different databases, including Google Scholar, Scopus, and WoS, utilize slightly different methodologies to generate this impact score, but the results have been mostly consistent across these platforms (Gasparyan et al., 2017; Jangid et al., 2014; Sharma et al., 2014).

The results show that the selected publications were published in about 200 journals, but two of these accounted for more than 530 publications. In particular, TableS2 shows the 13 most used journals to publish on cavitation related to water and wastewater treatment based on both IF and QR rankings. Among these journals, the Journal of Ultrasonic Sonochemistry had the highest number of publications related to the topic of interest (i.e., 453 articles), with a focus on hydrodynamic cavitation and ultrasonic cavitation. Interestingly, the number of publications for the second most chosen journal (i.e., Desalination and Water Treatment) is about five times less, with 81 articles. This indicates a quite specific focus on ultrasonic cavitation and hydrodynamic cavitation with respect to other cavitation-induced processes, but the recent discoveries on optical cavitation and particle cavitation application and optimization will make studies on this topic more common in the future (Geng et al., 2021; Luo et al., 2021). The results also showed that the journals traditionally focused on environmental chemistry (i.e., Chemosphere, J. of Hazardous Materials, J. of Water Research, and J. of Cleaner Production) accounted only for a minor part of the articles (i.e., 96), highlighting that the diffusion of this topic within the environmental chemistry community is still limited, but in the future, this trend will likely increase thanks to the recent developments and rising acknowledgment on water scarcity problems across the world (He et al., 2021; van Vliet et al., 2021). Our bibliographic search also showed that 11 out of 12 selected journals belong to the 1st quartile of their respective scientific categories, highlighting that researchers generally chose high-ranking and eminent journals to publish on cavitation.

3.6 Keywords co-occurrence network analysis

Keywords are used to describe the most important aspects and topics of a publication, especially for indexing purposes across the main scientific repositories such as Scopus, WoS, PubMed, and Google Scholar (Falagas et al., 2008). For this reason, we applied keyword co-occurrence analysis (Lozano et al., 2019; Radhakrishnan et al.,2017) to show the most popular study subjects across the topic of cavitation related to water treatment. Among the 8709 keywords that were found, we selected only those that occurred more than five times, thus selecting 793 keywords. As explained in section 2.3, we selected only the 100 most used keywords, while occurrences of keywords that could be considered synonyms were changed to the most common term. The results are shown in Fig.8, where each node represents a keyword, and the thickness of the connecting lines increases with the number of co-occurrences (de Toledo et al., 2019).

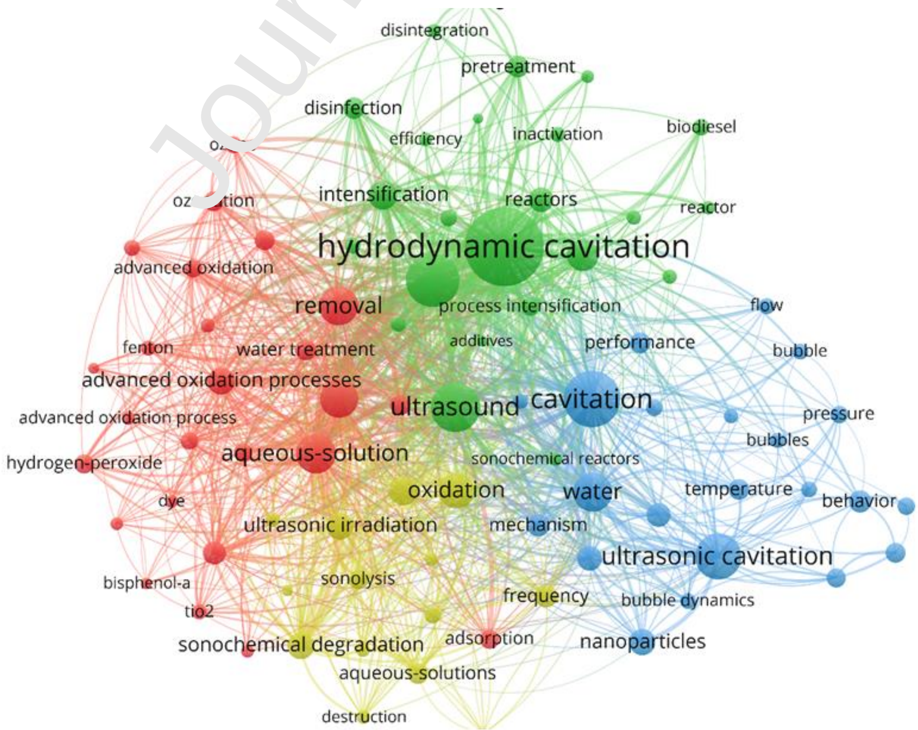

Fig.8. Co-occurrence network of the 100 most used keywords. The thickness of the lines connection each node denotes the number of co-occurrences, while the radius of the circle indicated the number of occurrences for each keyword.

Furthermore, each color represents one of the four clusters used to group the different keywords, as reported in Table1.

Table1: Main keywords for each of the four clusters identified.

Cluster (Color)	Top four keywords in each cluster (Occurrences)
1 (Green)	Hydrodynamic cavitation (784); Degradation (400); Ultrasound (356); Optimization (164)
2 (Blue)	Cavitation (447); Ultrasonic cavitation (310); Water (234); Nanoparticles (122)
3 (Red)	Aqueous solutions (247); Removal (236); Wastewater treatment (226); Advanced oxidation processes (126)
4 (Yellow)	Oxidation (203); Kinetics (139); Sonochemical degradation (125); Ultrasonic irradiation (124)

In detail, cluster 1 (green in Fig.8) contains three major keywords (i.e., “hydrodynamic cavitation,” “ultrasound,” and “degradation”) that show very strong links between each other, showing a close relationship between the type of process used (i.e., hydrodynamic cavitation and ultrasound-induced cavitation) and the aim of those studies (i.e., degradation of contaminants). Furthermore, these keywords are also connected to other words such as “process intensification” and “intensification,” “reactors,” “efficiency,” and “performance.” This also highlights the current focus on using cavitation-related technologies to increase the performance of conventional or innovative water treatment processes.

Moreover, cluster 2 (blue) is shown to contain keywords related to the study of the mechanisms regulating cavitation phenomena, such as “water,” “mechanism,” “temperature,” “bubbles,” “behavior,” “bubbles dynamics,” “pressure,” and “flow.” Fig.8 also shows that a significant part of this research is focused on ultrasonic cavitation due to the fact that the keyword “ultrasonic cavitation” occupies the second biggest node (i.e., it appears in the second largest number of publications) of the cluster and it is strongly connected with the majority of the other nodes in cluster 2. Fig.8 also highlights that the “nanoparticles” keyword has been receiving significant attention, especially in relation to “bubble dynamics,” since the dimension of the produced bubbles has been shown to be a fundamental factor in the efficacy of the treatment process (Movahed and Sarmah, 2021).

Cluster 3 (red) contains most of the keywords related to water and wastewater treatment (e.g., "water treatment," "wastewater treatment," "removal," and "advanced oxidation processes"). By observing how the keywords describing the contaminants whose removal is being studied relate to each other, indications of the main industrial sectors interested in this research topic can be gained. For example, the close relationship between "dye" and "TiO2" keywords shows the central role of the textile and food industries in the topic since they are among the major users of such substances (Ren et al., 2021). In addition, the many links between the red cluster and the "hydrodynamic cavitation" (blue cluster) confirm the vast application of this process for wastewater treatment. Conversely, the keyword "adsorption" is almost unconnected from the other keywords in cluster 3 (red) that describe AOP methods, showing great new opportunities for researching this process as a part of integrated water treatment processes that use it in combination with other AOP methods, such as ozonation or cavitation methods. Some works have recently started to explore the combination of these techniques, such as Mohan and Gokul (2022), who combined ozonation and adsorption for the treatment of landfill leachate.

Fig.8 also shows the scarcity of links connecting the keywords "water/wastewater treatment," "advanced oxidation processes," "hydrodynamic cavitation," "Fenton," and "ozonation" with the words "nano particles," and "bubbles and "cavitation," indicating that only very few studies have been investigating the combination of those different processes. This opens opportunities in the field of study related to wastewater treatment, thanks to the great adaptability of cavitation processes regarding the different technical challenges that will need to be overcome to guarantee better management of the word water supply.

Cluster 4 (yellow) brings together several keywords (e.g., "oxidation," "kinetics," "sonochemical degradation," and "ultrasonic irradiation") describing studies focused on studying aspects related to pollutants' degradation kinetics with cavitation-based processes, and especially ultrasonic cavitation. For example, Wu and co-workers (2007) reported on how the upstream pressures of the orifice plate, the cavitation number, and the solution temperature affect phenols' degradation kinetics.

3.7 Keywords evolution analysis

From the analysis reported in section 3.6, it can be seen that in the last 20 years, the research focused on cavitation-based processes for water and wastewater treatment has evolved into a complex and interconnected network, but to better identify its future trends, a focus on how the use of the selected keywords has changed in time is necessary. In particular, Fig.S1 shows how the 30 most present keywords were used during the investigated period.

The results showed that several keywords considered relevant in 2001 (e.g., "microbial cell disruption using cavitation") are no longer relevant, while others have gained more importance, such as "hydrodynamic cavitation" and "cavitation."

In particular, the keyword "cavitation" has been gaining much interest since it is more general and can incorporate many research aspects, from investigating the cavitation phenomena to modeling aspects and environmental applications. Furthermore, thanks to innovations and discoveries in the last few years, especially after 2016, the use of "hydrodynamic cavitation" has significantly increased. This shows how, after investigating the more general aspects of cavitation, more diverse and specific processes emerged in this field and how this was reflected in the choice of keywords over the years. Moreover, "hydrodynamic cavitation" was the most used keyword in 2021, as well as a fundamental node in the co-occurrence network discussed in section 3.6. Thus it is expected that this topic will be the focus of an increasing number of publications in the following years.

Fig.S1 shows how the competition between ultrasonic and hydrodynamic cavitation evolved over the years, with 800 and 300 total occurrences, respectively. In detail, the use of "ultrasound," "ultrasonic cavitation," and "hydrodynamic cavitation" was relatively constant until 2012 and then had a marked increase in 2014 (Fig.S2), thanks to the discoveries on the multiple possible applications of these processes, such as for water treatment (Agarwal et al., 2011; Pilli et al., 2011; Saharan et al., 2011), microbial inactivation, and food processing (Gogate, 2011; Maddikeri et al., 2012; Rajasekhar et al., 2012). However, the increase in "hydrodynamic cavitation" was much more significant, thanks to the discovery that HC could be more easily used as a pretreatment method integrated into other processes (Agarwal et al., 2011; Doltade et al., 2019; Pilli et al., 2011; Saharan et al., 2011; Zapata et al., 2021) than ultrasonic cavitation. The application of ultrasonic cavitation showed a more contained increase due to the several technological, energetic, and cost limitations discovered for its application (Asgharzadehahmadi et al., 2016), but thanks to the discoveries made on how to limit the effects of these problems (Fedorov et al., 2022) the focus on this topic will increase, especially in countries where there are already some advanced applications (e.g., Germany).

The results also show that while researchers are pursuing cavitation methods, their water and wastewater treatment applications are not on the same level as those focused on the more generic aspects of cavitation. In fact, the keywords "water treatment" and "wastewater treatment" have significantly fewer occurrences (i.e., between 250 and 300) than the three main keywords (i.e., "cavitation," "ultrasonic cavitation," and "hydrodynamic cavitation"). Nevertheless, their utilization has been increasing from 2018 and 2017, respectively (Fig.S2), showing that the interest in this topic will likely increase in the future.

The keyword analysis results also show the use of cavitation processes during the past two decades for water and wastewater treatment as a stand-alone method is limited (Dular et al., 2016; Tao et al., 2016), and such industrial-scale uses of these technologies are not pervasive. In fact, they are mostly combined with other keywords indicating other processes, such as membrane filtration and chemical oxidation (Gujar et al., 2021; Titchou et al., 2021). Consequently, future research will use processes combining cavitation and other technologies.

The results reported in Fig.S2 also highlight the evolution of the keywords "nanotechnology" and "nanobubbles," which appeared in 2008 and 2011, respectively. Both of these keywords were used to a limited extent until 2013 when their importance increased significantly thanks to the focus on nanoscale materials and processes caused by the several innovations in the field of nanoscience that characterized that period (Parak et al., 2015; Roco et al., 2018). In particular, Fig.S2 shows that the use of "nanoparticles" increased much faster than the use of "nanobubbles," indicating that the research has been focused for the most part on the use of cavitation processes for the synthesis of nanomaterials (Afreen et al., 2019; Choudhary et al., 2022; De Alwis et al., 2021; Sun et al., 2020b; Wright and Mitchell, 2020). While the trend shown in Fig.S2 indicates that the use of nano-sized bubbles in cavitation processes is still in its infancy, the occurrence of "nanobubbles" started to significantly increase in 2017 corresponding to the shift from studying surface nanobubbles (that cannot be utilized for water treatment and other environmental applications) to bulk nanobubbles (Bu and Alheshibri, 2021; Nirmalkar et al., 2018; Yasui et al., 2018). Nevertheless, the topic of nanobubbles concerning water treatment has not been extensively investigated, but very promising results have been reported by several authors (Fan et al., 2019; Movahed and Sarmah, 2021; Nazari et al., 2020; Temesgen et al., 2017) indicate its potential use for water treatment, especially with hydrodynamic cavitation. In addition, several other applications of nano-sized cavitation have also been reported for other fields, such as the study by Xuan and Nastac (2017) on materials manufactured by also using ultrasonic-induced nanobubbles.

The results reported in Fig.S1 and Fig.S2 show that only a limited focus was given to "energy" and "energy efficiency" in the cavitation field. However, with the rising importance of each process's sustainability, researchers are expected to give more importance to these concepts in their studies.

In this section, the authors gave an overview of the trends regarding the most important keywords used in the field of cavitation-based water treatment processes, but the trends of the rest of the keywords reported in Fig.S1 can be seen in Fig.S3.

4. Concluding remarks and future directions

In the present work, a scientometric analysis of the bibliography (i.e., 2551 publications) related to the application of cavitation processes for environmental applications, especially water and wastewater treatment, was carried out, and a critical evaluation of the present and future trends of this field of research were provided. Considering the last 20 years, the number of publications and citations showed an incremental trend, proving the increasing significance of these applications of cavitation related to environmental and water management. The increasing number of citations was attributed to the multidisciplinary nature of the topic and to the many applications found in many fields, both directly and indirectly related to the environment.

The languages used in most articles, after English, were Chinese and Russian, demonstrating the effects these countries' policies had on the development of the research on this topic, as well as the focus on studies related to their mayor economic sectors, such as oil extraction and mining.

The most prominent scientific category for the topic of water treatment-related cavitation processes was "Multidisciplinary Chemistry" with 19.4% of the overall publications, but "Environmental Sciences" and "Environmental Engineering" accounted for a combined 19.3 %, showing a positive trend toward the use of cavitation for environmental applications.

Country analysis revealed that three groups based on GDP similarity, state of development, and publication behavior could be identified among the most prolific countries. The publication behavior indicated that developed countries have the tendency to pursue more innovative uses of cavitation, while developing countries are more interested in implementing less complex applications in their major industrial sectors, in addressing their water shortage problems, or they are not in the situation to pursue more innovative applications due to economic limitations. As representatives, China, the USA, Russia; Iran, Spain, India; Germany, and Italy were chosen to be investigated.

Journal analysis highlighted that most studies were published in the "Ultrasonic Sonochemistry" journal, followed by "Desalination and Water Treatment." Furthermore, while the journals traditionally focused on environmental chemistry accounted only for a minor part of the articles, this trend will likely increase thanks to the recent developments and rising acknowledgment of water scarcity problems worldwide. Most of the selected journals belong to the 1st quartile of their respective scientific categories, showing that researchers generally chose high-ranking and eminent journals to publish on the topic of cavitation.

Keywords co-occurrences and cluster analysis showed that four clusters could be identified, referring to improving the performance of cavitation-related technologies, the mechanisms regulating cavitation phenomena, the uses of cavitation specific for water and wastewater treatment, and studying aspects related to pollutants' degradation kinetics.

Keywords evolution analysis showed that the use of both "hydrodynamic cavitation" and "ultrasonic cavitation" has seen a significant increase, but ultrasonic cavitation was less studied due to its technological, energy, and cost limitations, but thanks to new advancements on this topic the focus on this process will increase, especially in countries where there are already some advanced applications (e.g., Germany).

The occurrence of keywords related to nanoscience and water treatment showed significantly in the last five years, showing the increased interest in applying cavitation-based processes in these fields. These trends will likely continue to grow in the future thanks to new discoveries on the topic of nanobubbles and on the coupling of cavitation with other AOP. While only a limited focus was given to topics related to "energy" and "energy efficiency" in the field of cavitation during the investigated period, with the rising importance of each process's sustainability, the attention given to these concepts will increase in the future.

The publications analyzed in this work showed that there had been significant developments in bringing attention to the industrial uses of hydrodynamic cavitation for water and wastewater treatment, especially in coupling this process with other processes such as AOP, electro-Fenton, and photochemical reactions.

In the case of ultrasonic cavitation, the studies found for this work highlighted that industrial-scale applications are generally more energy demanding, thus presenting many challenges for future researchers to obtain more sustainable processes involving this technology. Furthermore, the combination of hydrodynamic and ultrasonic cavitation as a single process will offer many opportunities for future research

Based on the results of the reported scientometric analysis, we showed that the future directions for the topic of cavitation-related water and wastewater treatments would probably shift towards more environmentally friendly applications of hydrodynamic and ultrasonic cavitation, as well as towards more green and sustainable approaches, especially considering the potential of this technology to address the increasing demands of water pollution and shortage. Moreover, the research on cavitation will also increase regarding its uses for purposes other than water treatment, such as manufacturing nanomaterials, food production, and medicine.

Acknowledgments

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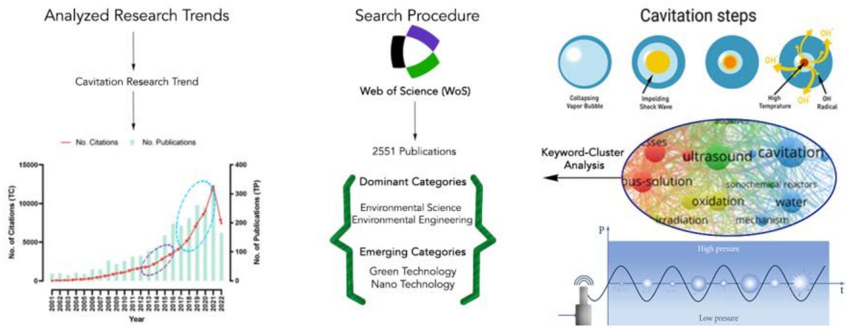
Declaration of interests

☒The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

☐The authors declare the following financial interests/personal relationships which may be considered as potential competing interests:

Graphical abstract



Highlights

- Keyword analysis revealed "water/wastewater treatment" as the focus of cavitation.
- Cluster analysis disclosed a great potential for cavitation in sustainable methods.
- Environmental science and engineering were the dominant categories for cavitation.
- Cavitation is of interest to both developed and developing countries.
- Environmental science and engineering were dominant categories for cavitation topic.