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S-curve and landscape maps for the analysis of trends on industrial textile wastewater treatment

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A R T I C L E I N F O

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A B S T R A C T

The textile industry is one of the most important and economically significant industries in the world. China is the largest textile producer, for countries such as India, Pakistan, Bangladesh and Malaysia this sector is of crucial importance and it is also a growing sector in Latin America. This industry is responsible for 10 % of annual global carbon emissions and 20 % of global wastewater. This figure is worrying as this wastewater is highly recalcitrant, which has led to research into different treatment methods that are efficient and can provide a sustainable solution to this problem. The aim of this literature review was to identify the existing methods for the treatment of dry scrubber wastewater (TWWT) and the effects of this wastewater and its composition, focusing on biological, chemical and physicochemical processes from the point of view of advantages and disadvantages. It was analyzed which are the most important scientific areas of TWWT and which countries are the most important in this field, as well as the primary pollutants and TWWT processes. Finally, this analysis provides a context for current trends in TWWT research. In general, coagulation methods have been found to be fast but present difficulties due to the use of toxic coagulants; advanced oxidation processes (AOPs) are positioned as very effective methods that can disinfect and decontaminate these effluents. Currently, biological systems coupled with AOPs are a growing trend. Microalgae and cyanobacteria processes coupled with AOPs have attracted great interest due to the possibility of obtaining high added value products through the biorefining of biomass.

Abbreviations

TWW	Textile wastewater
TWWT	Textile wastewater treatment
CC	Coagulation
EC	Electro-coagulation
AOP	Advanced oxidation process
AOP/UV	Advanced oxidation process with UV radiation
EAOP	Advanced electrochemical oxidation processes
UV	Ultraviolet radiation
PL	Photolysis
PC	Photocatalysis
PEC	Photoelectrocatalysis
EO	Electrooxidation
FT	Fenton
PFT	Photo-Fenton
EFT	Electro-Fenton
PEFT	Photoelectro-Fenton
RhB	Rhodamine B
CR	Congo red
MB	Methylene blue
RBBR	Remazol brilliant blue R
MG	Malachite green
MO	Methyl orange
MF	Microfiltration
UF	Ultrafiltration
NF	Nanofiltration
RO	Reverse osmosis

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FO	Forward osmosis
MOF	Metal organic framework
MBBR	Moving bed biofilm reactor
MBR	Membrane bioreactor
AD	Adsorption
AC	Activated carbon
AS	Activated sludge
PcR	Phycoremediation
MCR	Mycoremediation
AnDMBR	Anaerobic dynamic membrane bioreactor
CW	Constructed wetland
MFC	Microbial fuel cell
TDS	Total dissolved solids
COD	Chemical oxygen demand
BOD	Biological oxygen demand

List of bibliometric indicators

SP	Scientific productivity
SR	Scientific relevance
TP	Total publications
NAY	Active years of publication
TCP	Total citations
SD	Scientific domain
CNP	Cumulative number of publications
TMR	Technological maturity readiness
ERL	Expected remaining life
PPA	Potential publications

1. Introduction

The World Bank estimates that 17 % to 20 % of the world's wastewater comes from the textile industry (The World Bank 2019; Seneviratne, 2008). This wastewater comes mainly from the "wet processes" of textile production, which include the phases of (i) singeing, (ii) ungluing, (iii) drying, (iv) bleaching, (v) mercerizing and (vi) dyeing (the phase that consumes the most water). The composition of these waters depends on many factors, such as the type of fabric, the type of process and the chemicals used. (Patel and Vashi, 2015).

Textile wastewater (TWW) is a mixture of various compounds, including microfibers, microplastics and dyes, salts such as sodium, chlorides and sulfates, alkalis that contribute to a high pH, biodegradable and non-biodegradable, nitrogenous organic compounds, recalcitrant, aromatic, heterocyclic, oils and fats, hydrocarbons, heavy metals, surfactants, anionic and volatile compounds. These waters are characterized by their intense color (a dye concentration that varies between 25-2500 mg/L, with 1 mg/L being hazardous in natural wastewater) (Javed et al., 2022), limiting the absorption of light by microorganisms, severely affecting aquatic ecosystems and posing a risk to human health (Serejo et al., 2019).

The group of treatments that are responsible for TWWs is often referred to as textile wastewater treatment (TWWT). Solvents, oils, plastics, metal residues, suspended solids, and various disinfection by-products that are often difficult to identify and almost impossible to eliminate without more advanced technology than the existing ones. In general, the basic principles of TWWT are based on (i) the separation of solids versus liquid., (ii) oxidation of organic and oxygen-requiring materials, (iii) neutralization, (iv) removal of toxic substances, and (v) waste disposal and the methods commonly used for such purposes are physical, chemical and biological or may constitute a combination of several methods (Patel and Vashi, 2015).

Since 1970, TWWT research contributions have steadily increased every year. Since the last five years, research has tripled, an event correlated with the 2016 implementation of the United Nations Sustainable Development Goals (SDGs) for 2030, particularly SDG6, related to safe drinking water and sanitation for all (Ellis). The first two stages of TWWT, i.e., primary and secondary, were established and standardized by water experts over the years, especially since the late 20th century; however, the scientific community has struggled to advance the third stage or tertiary process due to the difficulty in removing dyes and in an attempt to reuse wastewater, especially in parts of the world where water is scarce (Jahan et al., 2022).

Among the countries with the most significant TWW production are China and India, the leading players in the world textile and clothing trade. (Lu). Both countries are an example of TWWT policy development, as together with the implementation of state regulations, scientific research on TWW has been gradually increasing since the end of the last century (Chen et al., 2021), the company is environmental regulations and the pollution of natural effluents, and water shortages for domestic and industrial activities have been considered.

Therefore, a bibliometric analysis was performed to identify the major countries and their respective contributions and the main TWWTs. Bibliometric analysis is beneficial for understanding research and development in various research fields. (Ren et al., 2018; Zhao et al., 2018; Rajeswari et al., 2022). This article aims to briefly address the main scientific areas of TWWT, which are the leading countries that have addressed research in the area, as well as an overview of the main TWWTs. The primary pollutants are identified, as well as the trends in TWWT research. Since about 80 % of the publications on TWWTs were published from 2000 onwards, the study focused on the last ten years (2012 - 2022) to evaluate the most current treatments and their future research trends.

2. Materials and methods

2.1. Search and selection of articles

In order to compare and evaluate the main wastewater treatments for the textile industry, a search for publications was carried out in Elsevier's Scopus database since comparative studies have shown that the use of Scopus over other similar databases is more efficient since it allows a more excellent treatment of scientific information. (Garrido-Cardenas et al., 2020). In the initial stage, authors identified related keywords after reviewing the most cited publications on TWWT and thereby determined the search equation in Fig. 1, which resulted in 5517 publications. Articles related to microfibers and microplastics present in TWWT were excluded.

The study was limited to the last ten years (2012-2022). During this period, researchers begin to focus more on several aspects of research on all types of textile waste and the impact of textile waste on the environment. (Kasavan et al., 2021). The search was applied only once (2022/12/1) to avoid bias that could occur due to the continuous updating of the database. In addition, the search was focused on research publications excluding all other documents, such as review articles and proceedings, meeting abstracts, early access, editorial material, data document, and letters, as the search was oriented to original and unpublished production of publications referring to TWWT. These filters resulted in a database of 2645 scientific and technological research articles.

2.2. Bibliometric analysis

The statistical-descriptive analysis of the results (Fig. 2) was performed using four software: 1) VOSviewer for the co-authorship and co-occurrence maps (van Eck and Waltman, 2010); 2) Microsoft Excel 2022 for the graphical analysis and calculation of scientific productivity and relevance indicators (Eq. 1 and 2); 3) Orbit Intellixir using the Landscape of concepts tool to generate a map of main treatments in which the main groups of colorants within the analyzed studies were identified (Scientific Data Analysis Solution - Orbit Intellixir - Questel 2023); and 4) Loglet Lab for S-curve analysis (Loglet Lab 4: Growth of a Sunflower 2023).

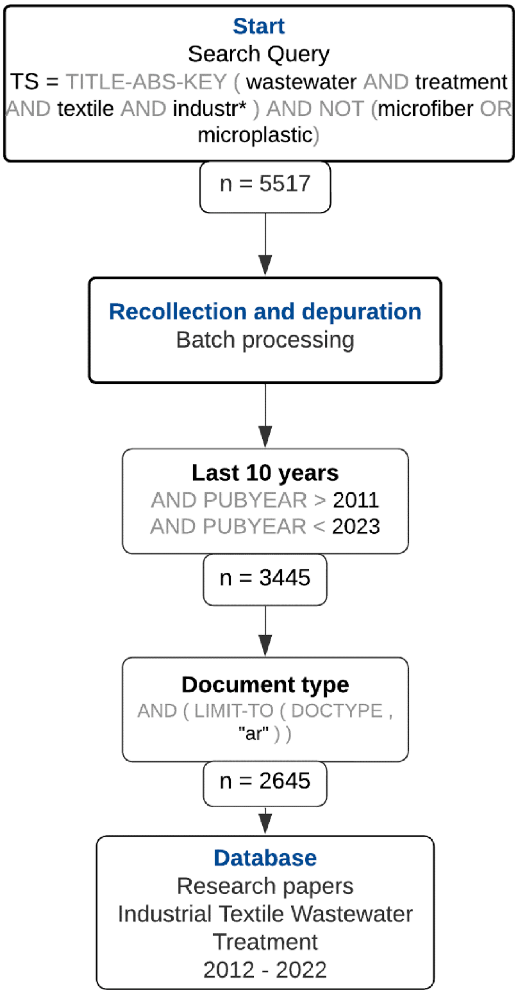

Fig. 1. Seach protocol. Source: Authors

$$SP = \frac{TP}{NAY} \quad (1)$$

$$SR = \frac{TCP}{TP} \quad (2)$$

Where TP total publications, NAY number of active years of publication, TCP total citations, SP scientific productivity, and SR scientific relevance.

The S curve was based on previous research that has used this method to assess the maturity of a specific technology or product (Meng et al., 2021; Mao et al., 2021; Saidulu et al., 2021; Ding and Zeng, 2022). The evolution of technologies and products follows four stages: emergence, growth, maturity, and saturation. (Angel-Ospina and Machuca-Martínez, 2022). There are several models to construct it, but for the present study, we used Gompertz model, a special case of the logistic model, which mathematically describes a growth process with an asymmetric form in lieu of the symmetry ascribed by the logistic function:

$$y = Ke^{-e^{-r(t-t_m)}} \quad (3)$$

Where *y* represents the dependent variable of the S curve as the number of publications accumulated annually, and *t* represents the time in years as the independent variable of the model. *K, r*, and *tm* are parameters of the model that define the saturation value of the system in the number of publications, the speed or growth rate, and the meantime, respectively. Finally, to analyze the performance of the S curves, the indicators proposed by (Yoon et al., 2018) allow a forecast of the number of potential documents and the time remaining before the analyzed technology enters its saturation stage. Table 1 shows the S-curve forecast indicators used in the study.

3. Results and discussion

3.1. Contributions by country

Along with textile solid waste research, TWW research has become one of the most attractive and needed research fields in the last decade (Kasavan et al., 2021), probably due to the growing concern in the production and disposal of wastewater from this industrial sector since it

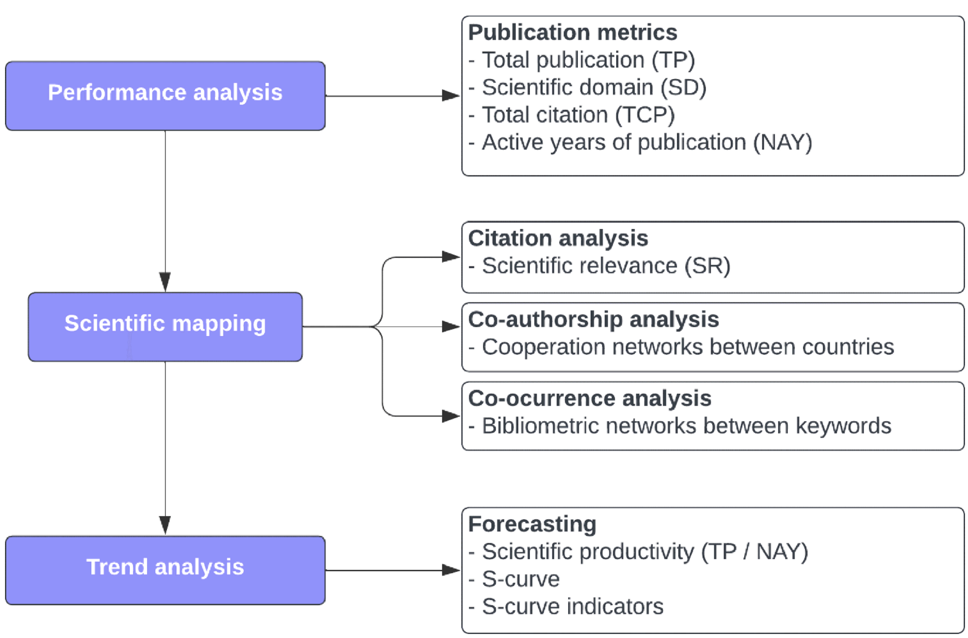

Fig. 2. analysis of results. Source: Authors

Table 1
Forecasting indicators for curve S.

Indicator	Name	Units	Equation
TMR	Percentage technological maturity readiness	%	$TMR = \frac{K_{current}}{K} * 100$ (4)
ERL	Expected remaining life	Time	$ERL = t_k - t_{current}$ (5)
PPA	Potential publications	No. Documents	$PPA = K - K_{current}$ (6)

Fuente: Authors

is the second most polluting on the planet, only surpassed by oil and gas, not only affecting the disposal of solid and liquid waste, but they also produce the equivalent greenhouse gas emissions of all international flights and shipping combined annually.

In this study, the search led to 2634 scientific research publications. Fig. 3 shows that the growth of publications on industrial TWWT was steady until 2014; however, from 2022 onwards, TP experienced an acceleration to the present and comprises about 90 % of the total analyzed publications. The annual TP indicator per country also shows an exponential growth in the number of global publications (black line with dots), with India and China publishing the most research articles per year since 2012 (n=543 and n=419 respectively), followed by Brazil (n=197), Turkey (n=196), Iran (n=168) and Pakistan (n=132). Research articles from these countries were identified by extracting information from the authors' correspondence addresses.

Looking at the scientific output of China and India, it is very likely that the boom in TWWT research is mainly due to the impact of the textile industry on the countries' water quality (as these countries are the first textile producers in the world) and the high-water stress to which their inhabitants are exposed. According to the World Bank, India has 18 % of the world's population but only 4 % of its water resources, making it one of the most water-stressed countries in the world (The World Bank). In China too, 80 to 90 % of groundwater is unsuitable for drinking water, and half of the aquifers are too polluted for industry and agriculture (Storey).

Brazil (the third largest country in scientific production) has the fourth largest textile and garment industry in the world (Brazilian Textile and Apparel Industry Association (Abit)). This country does not have water stress, but it has problems with water supply far from the areas where most of the country's population lives (along the Atlantic coast), with large urban centers that have grown exponentially in the twentieth century but have not had adequate planning for wastewater infrastructure (Mirumachi et al., 2021).

Table 2 shows the ten countries with the highest scientific production in terms of TP, TCP, SR, and SP indicators. India ranks first in TP and SP, second in TCP, but eighth in SR, implying (according to Eq. 2) a lower impact of their research. India is a country that has introduced policies

Table 2
Top 10 countries by scientific contribution in TWW.

Country	TP (Total publication)	TCP (Total citation)	SR (Scientific Relevance)	SP (Scientific productivity)
India	385	8557	22,23	38,50
China	337	9788	29,04	33,70
Brazil	152	3317	21,82	15,20
Turkey	147	2929	19,93	14,70
Iran	127	2950	23,23	12,70
Pakistan	97	2497	25,74	9,70
United States	86	3227	37,52	8,60
Malaysia	80	1958	24,48	8,00
South Korea	77	2064	26,81	7,70
Spain	70	2920	41,71	7,00

Source: Authors

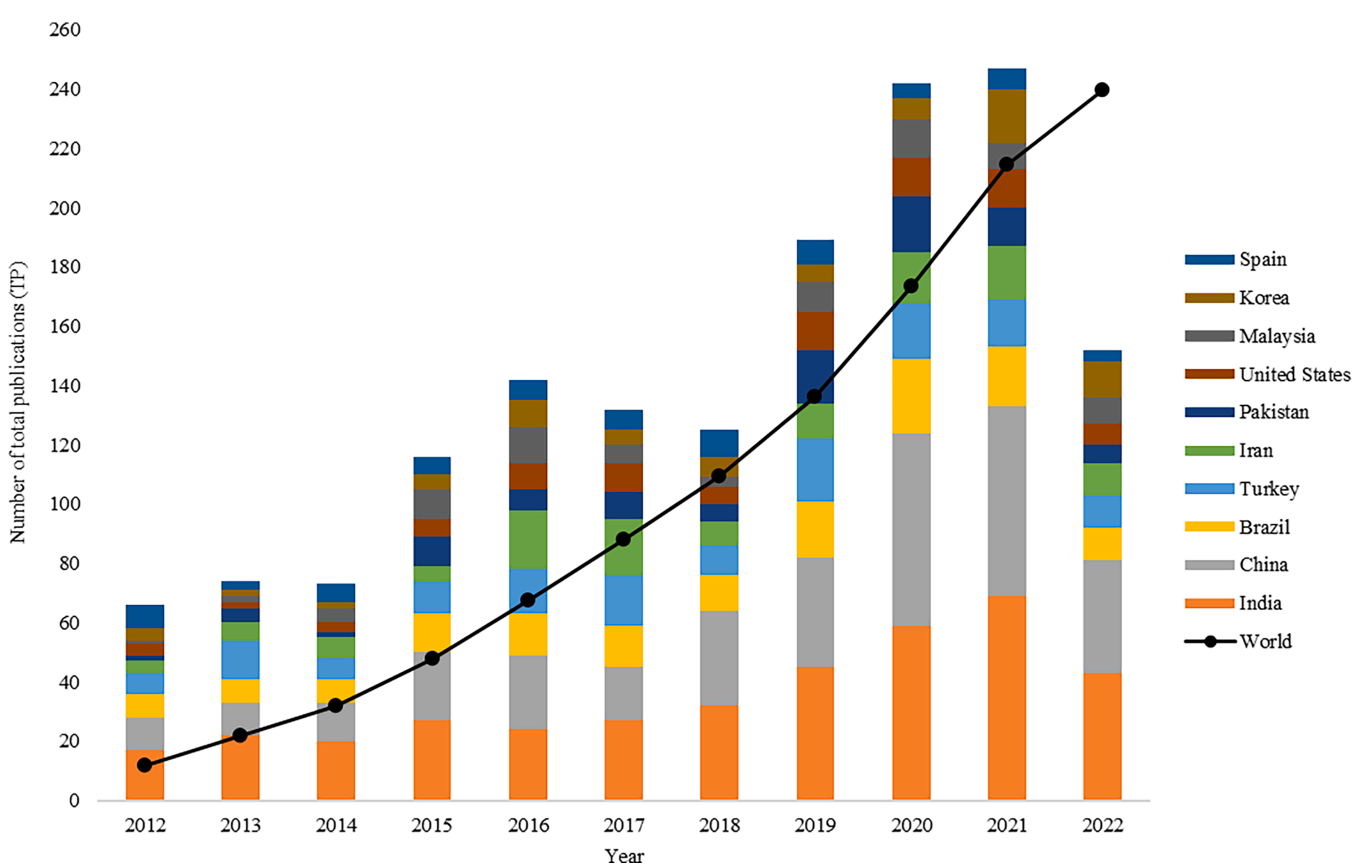

Fig. 3. Annual TP per country. Source: Authors

to transform the water sector since 1980 and has been implementing laws that address water management, planning, and pollution problems since the 1990s (Wahi, 2022). In addition, due to the country's water scarcity problems, the Twelfth Five-Year Plan (2012-17) has focused attention on aquifer mapping, watershed development, NGO participation and efficiency in irrigation capacity development, and environmental compliance related to water through the Right to Information Act (Sonia Luthra and The National Bureau of Asian Research). Their research focused mainly on biological and adsorption TWWT, as evidenced by their research on natural adsorbents (Ingle et al., 2022) and bioremediation (Patel et al., 2022).

China is the second largest country in TP and SP, the first in TCP, and the third in SR, behind Spain and the United States. In recent years, the literature on wastewater in China has experienced exponential growth, especially after the "Twelfth Five-Year Plan" (2011 - 2015), where water pollution from industrial activities was one of the main targets. Subsequent plans (Thirteenth and Fourteenth Five-Year Plans) have also focused on developing innovations in wastewater treatment (Mao et al., 2021; People's Government of China 2015; People's Government of China 2021). Unlike India, China has focused its research mainly on physical (Lan et al., 2022) and chemical processes (Liu et al., 2022; Zhang et al., 2021). Fig. 4 illustrates the relationship between SR and SP. While India and China have the highest scores for SP, it is clear that the importance of their research is comparatively lower than that of other countries such as the United States, Malaysia, South Korea and Spain, which have higher SR. It is noteworthy that the combined contributions of the major countries of South Asia (Pakistan and India), Southeast Asia (Malaysia), East Asia (China and South Korea) and the Middle East (Iran) account for up to 40 % of the global research articles in the field of TWWT.

The academic collaboration between the top 30 countries in terms of TCP was analyzed in Fig. 5. Each rectangle represents a country, and the size of the rectangle represents the total number of citations in all published articles (∑TCP per published article). The lines connecting these rectangles represent the scientific collaboration between authors according to their direction of correspondence, and the thickness of the line reflects the number of joint publications between countries (Van Eck and Waltman, 2021)

Five clusters are observed. Green cluster has China as its leading country, which plays a central role in the whole co-authorship map, as it has cooperative relations with the 30 countries analyzed, and its size indicates a high result for TCP. The major countries with which it has academic relations are the United States, India, and Pakistan. However, an earlier bibliometric analysis of trends in the TWWT shows that even when India and China have well-developed collaborative networks, a significant proportion of their publications are confined to a single country, meaning that most of their research outputs are exclusively authored by researchers or institutions within the same country (Halepoto et al., 2022)

The blue cluster is dominated by India, whose primary relationships are with South Korea, the United States, and the United Kingdom. The third cluster is yellow, with Brazil and the United States as the major countries with solid cooperative relationships. Fourth cluster is red, with Iran and Turkey as core countries that maintain relations with each other, the United States, Algeria, China, and Canada. It is essential to mention that more than 50 % of scientific production of industrial TWW is concentrated in Asia, especially in China, India, Turkey, Iran, and Pakistan, which is related to the fact that these countries are the leading fibers producers in the world.

3.2. Keyword analysis

The primary purpose of keywords in scholarly articles is that indexing systems enable search engines, academic databases, and library catalogs to identify the most relevant hits for a search query. Researchers conducting systematic reviews on a topic also use keywords to provide an overview and synthesis of various research findings. Therefore, identifying and integrating relevant keywords into a search strategy is critical to conducting a full systematic review (Horvat et al., 2014).

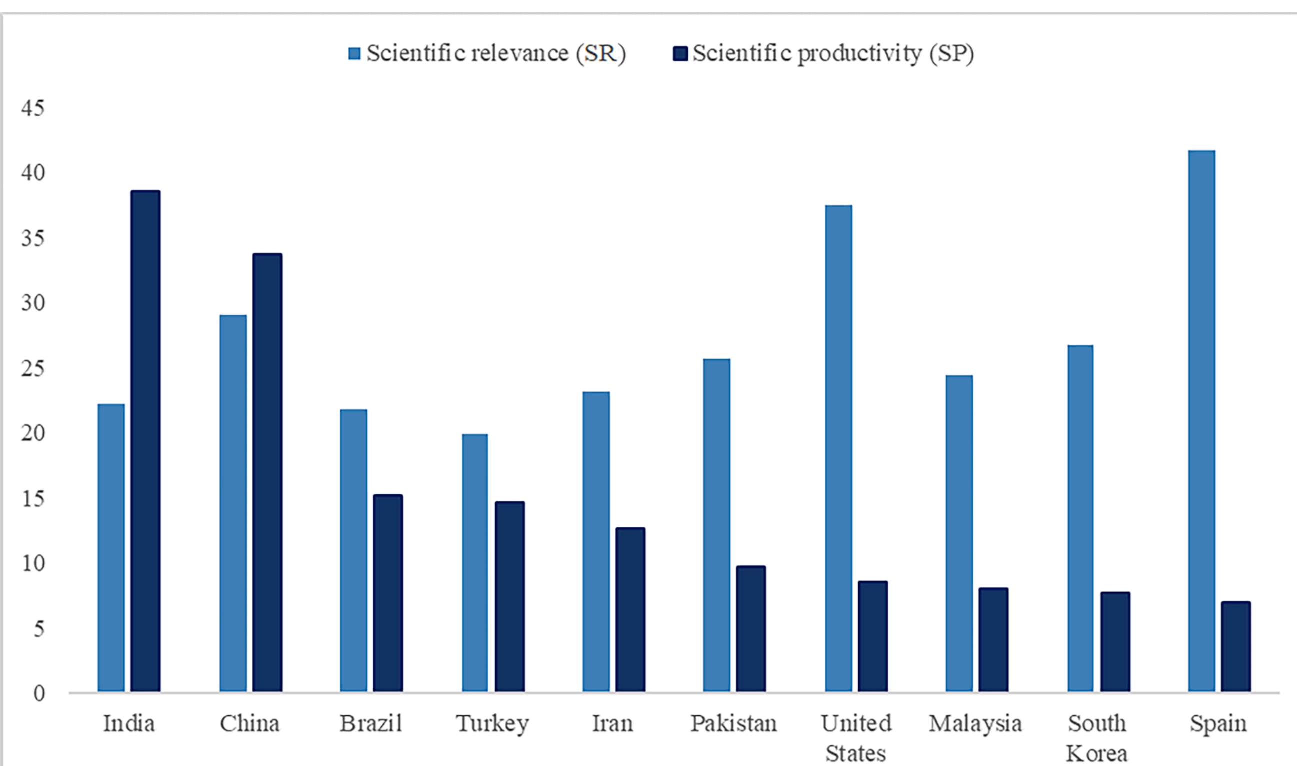

Fig. 4. Relation between SR and SP per country. **Source:** Authors

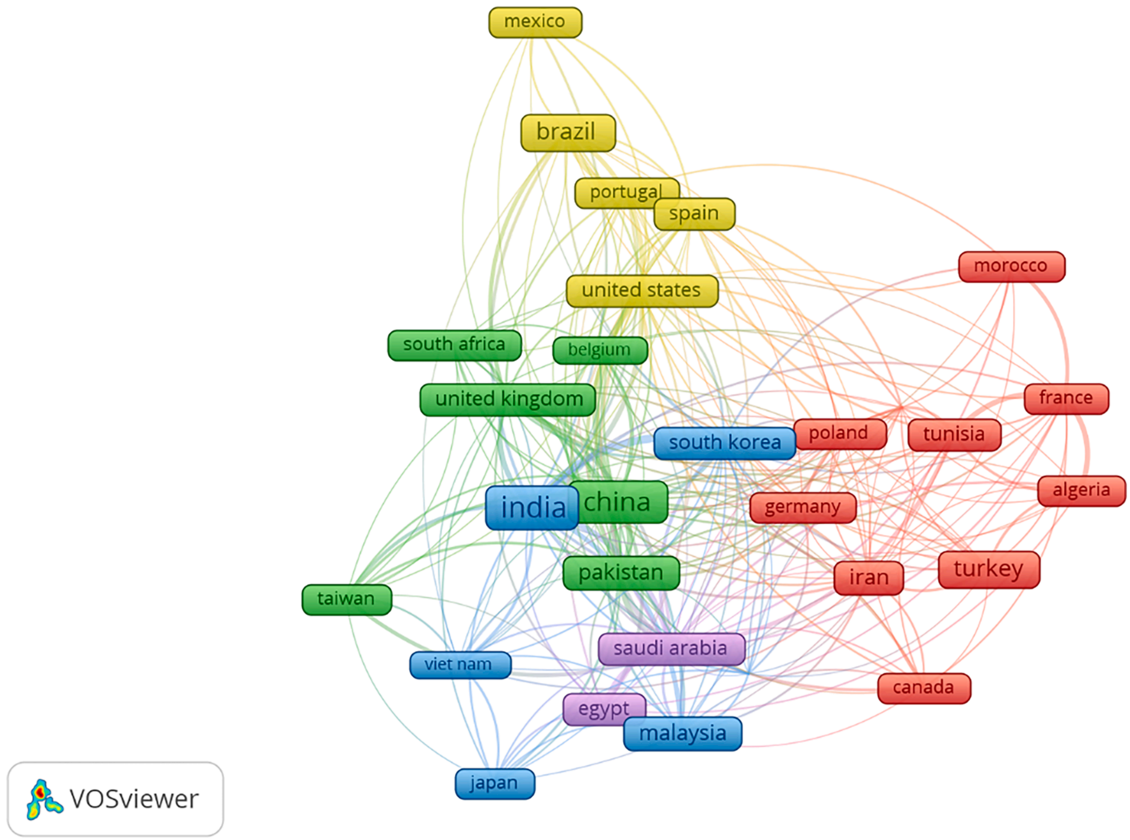

Fig. 5. Most important countries and their cooperation networks. **Source:** Authors, created with VOSviewer.

Fig. 6 shows a co-occurrence keyword map commonly used by authors in their publications divided into six colors/clusters and typically associated with different TWWTs. Three main groups can be identified clearly: (1) chemical, which includes UV, FT, O_3 and CC-based treatments; (2) physical, which includes mainly adsorption and filtration-based treatments; and (3) biological, which includes bacteria, fungus, and algae treatments. Each of these depends entirely on the composition and pollutants of the effluent, which vary from type of industry, country, the intensity of textile use, the application of different chemicals and dyes, the type of fabric, and seasonal sewing trends, among others. (Behera et al., 2021).

To identify a relationship between the keywords in Fig. 6 and the evolution of scientific knowledge production per research area, the SD indicator in Fig. 7 allows observing a temporal coverage for TPs classified in six main SDs. This analysis makes it possible to observe trends in research concepts. The bars show the temporal coverage for global TP and the lines of TP by SD and show that the field of environmental sciences has grown the fastest. This area includes disciplines such as ecology, environmental chemistry, environmental engineering, waste management and disposal, and water science and technology and accounts for 63.71 % of total TP. Keywords associated with this area are found throughout the keyword map in Fig. 6, such as “wastewater treatment”, “biodegradation”, “biological water treatment”, “COD removal”, “total organic carbon” and others. The next SD in the TP indicator are chemical engineering, chemistry and materials science, which are respectively associated with keywords in yellow, green, purple, dark blue and light blue clusters (which fall under chemical and physical methods). Finally, SD Biochemistry and Biosciences are associated with keywords from the red cluster, which fall under biological treatments.

Following the TP for each SD, the next sections explain the clusters in the chemical, physical and biological groups shown in Fig. 6, taking into account the characteristics of each SD, such as equipment configuration, reactors, degradation rates, materials for catalysts, bacterial strains and others. Finally, to illustrate the relationship between the keywords, the SDs and the countries from Section 3.1, Fig. 8 shows an analysis of the co-occurrence of keywords with the main treatments per country to evaluate the most studied TWWTs. The selected countries were India and China as representatives from Asia, Brazil from South America, the United States from North America and Spain from Western Europe. The most important articles (highest TCP indicator) from each country and treatment are discussed to highlight the situation of each country and its contribution to TWWT research.

3.3.1. Chemical treatments

In this group, a chemical substance is added to change the nature of the contaminants and accelerate the water matrix’s disinfection and the contaminant’s separation, which is transformed into another species that other physical, chemical, or biological species methods can easily remove. This is the treatment group with the highest number of publications (TP=943). In Fig. 6, the chemical treatments are found in purple (CC/EC), yellow and green clusters (AOPs without and with UV) and belong to chemical engineering, chemistry and material science SD in Fig. 7.

Purple cluster: coagulation and electrocoagulation. This cluster has a TP=268 and includes coagulation (CC) and electrocoagulation (EC). CC is a mature technology widely used in the industry due to its high efficiency and low cost, as the use of organic and inorganic coagulants helps to separate dissolved and suspended solids, especially surfactants and high molecular weight dyes, for subsequent removal; however, there are two problematic aspects: 1) the adaptability and coagulation removal mechanisms of many dyes are not yet known due to the wide variety of dyes used in industry (Wei et al., 2022) and 2) the use of inorganic coagulants generally produces toxic sludge (Dotto et al., 2019). EC is an electrochemical method that uses a direct current source to cause in situ

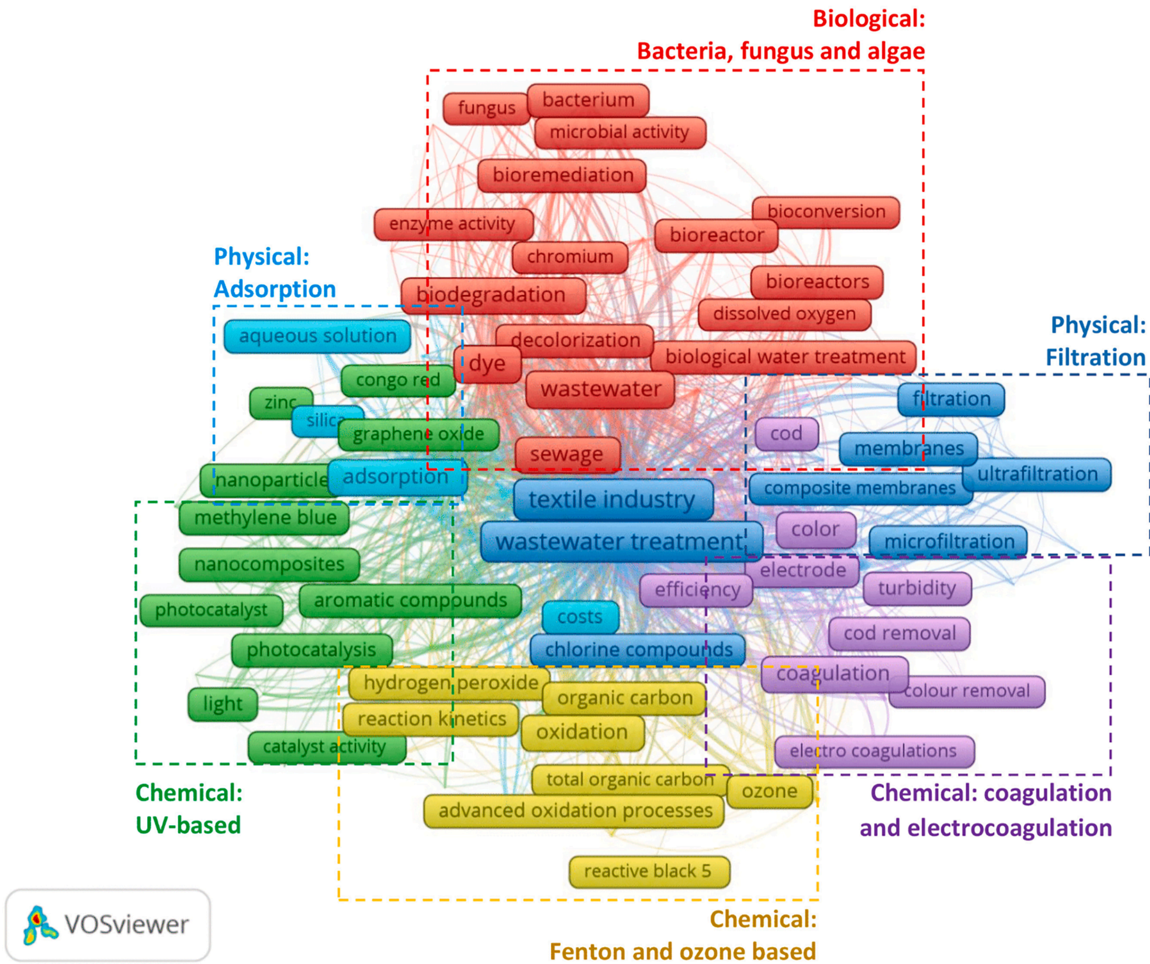

Fig. 6. Co-occurrence keyword map by clusters. **Source:** Authors, created with VOSviewer

dissolution of a suitable anodic material (usually Fe or Al metals) in wastewater; subsequently, at a suitable pH, the metal ions can form a wide range of coagulated species and metal hydroxides that destabilize colloidal particles and adsorb dissolved contaminants (Tibebe et al., 2022). EC was developed to overcome the disadvantages of conventional CC technologies in water and wastewater treatment by providing a simple, reliable, and cost-effective method without additional chemicals and, thus, without secondary contamination. It also reduces the generation of sludge, a common problem at CC. However, this method is generally more expensive than CC alone due to the use of electricity and metal electrodes (that could suffer from electrode passivation).

These methods are widely used in studies from India (Fig. 8a) and Brazil (Fig. 8c). For example, in a study by Nippatla and Philip (Nippatla and Philip, 2019) in India (TCP=56), EC flotation with Al-based electrodes and pulsed plasma treatment technologies was tested to treat a synthetic wastewater containing CR and MB dyes. With EC flotation alone, they were able to significantly reduce the dye concentrations. However, to tackle the problems of electrode passivation and sludge formation caused by EC flotation, they combined it with pulsed plasma treatment. This hybrid approach achieved 100 % degradation of MB and 100 % mineralization of both pollutants without generating waste or using additional chemicals.

Finally, in Brazil, the article by Dotto et al (Dotto et al., 2019) had the highest TCP value (TCP=255). This study compared the effectiveness of CC with different coagulants in the treatment of real wastewater from an industrial laundry containing the reactive dyes Red-HE7B and Orange 84. Instead of synthetic coagulants, the study focused on natural alternatives due to their cost-effectiveness and environmental friendliness in dye removal. The coagulants tested included two organic coagulants derived from the seeds of Moringa oleifera Lam and one inorganic coagulant ($Al_2(SO_4)_3$), one of the most commonly used inorganic coagulants in the industry. Organic coagulants, especially Moringa, showed superior performance, achieving 82.2 % removal for apparent colour, 83.05 % for COD, 78.4 % for Red-HE7B and 89.7 % for Orange 84.

In general, research has shown the effectiveness of other natural coagulants based on mucilage, and various seeds such as nirmali, starch, and chitosan, (Dotto et al., 2019; Freitas et al., 2015; Prabhakaran et al., 2020), with one of their main limitations being that their effect is stronger at low turbidity levels (between 50 and 500 NTU) compared with inorganic coagulants (Alazaiza et al., 2022).Combination of CC with electrochemical and Fenton methods in real wastewater are also being tested to reduce generation of toxic compounds and sludge, with good results in COD removal (about 80 %) (Torres et al., 2019; GilPavas et al., 2017).

The research trends in both technologies (CC and EC) focus on the synthesis of efficient, long-lasting coagulants based on natural or waste materials and durable electrodes made of non-toxic materials impregnated with nanoparticles. These research areas fall into the areas of chemistry and materials science SD from Fig. 7. In both cases, these technologies have been combined with AOPs or other physico-chemical or biological methods to improve performance, and in the case of EC, renewable sources such as solar energy have been utilized to generate electricity. Finally, in developing countries where financial resources may be limited, cost-effective water treatment methods such as CC and EC may attract more attention because 1) they are more economical

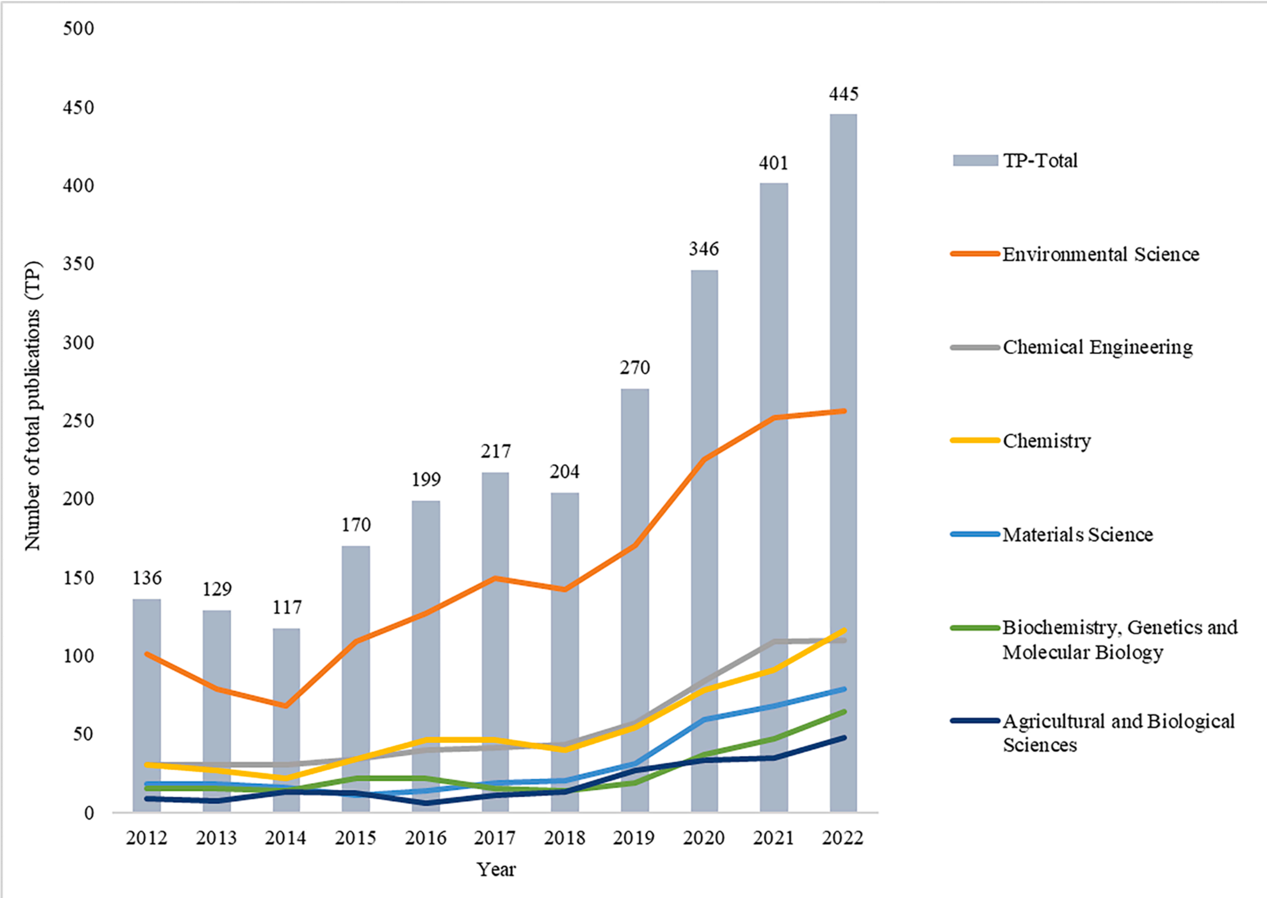

Fig. 7. TP for main SD. **Source:** Authors created with Orbit Intellixir

compared to other chemical methods such as AOPs and 2) they can demonstrate effective results in meeting the regulatory standards of these countries, as regulations are often less stringent, especially with regard to emerging pollutants.

Yellow cluster: AOPs without UV radiation. This cluster (TP =110) includes AOPs without UV radiation, which belongs to chemical engineering, chemistry, and material sciences SD. AOPs are based on the in-situ generation of highly reactive chemical radicals (generally represented by the hydroxyl radical, •OH) that react with contaminants and reduce them to harmless or less harmful chemicals when introduced directly into the contaminated source. The formation of these radicals is caused by the decomposition of strong oxidants, which include hydrogen peroxide (H_2O_2), persulfate ($S_2O_8^{2-}$), permanganate (MnO^{4-}), and ozone (O_3) (Zhou et al., 2019). Some AOPs that belong to this group are O_3-based processes (heterogeneous and homogeneous catalytic ozonation, O_3/H_2O_2 or another homogeneous oxidant), FT, EAOPs (advanced electrochemical oxidation processes such as EO or EFT), hydrodynamic cavitation, ultrasound, and others, all in the absence of UV light (Paździor et al., 2019).

O_3 methods are popular in research from China (Fig. 8a) and FT and FT-based can be seen in India (Fig. 8b), Brazil (Fig. 8c), the United States (Fig. 8d) and Spain (Fig. 8e). Other AOPs without UV radiation, such as EAOPs have fewer studies or are being investigated in other countries, such as Morocco and France (Hien et al., 2022; Zazou et al., 2019). Finally, other oxidants different from O_3 are being investigated as well, such as carbonate and bicarbonate, which accelerate the degradation of H_2O_2 and generate several reactive species, such as peroxymonocarbonate, superoxide, singlet oxygen, and carbonate radicals (Zhao et al., 2018; Yang et al., 2012). Nevertheless, when compared with O_3, they lack sufficient TP to be visible in Figs. 6 and 8.

O_3 processes can be classified as AOPs if the indirect reaction of decomposition of O_3 into radical species, typically radical •OH, is favored, which occurs at basic pH (pH > 8) (Paździor et al., 2019), with the addition of oxidants such as H_2O_2, or in the presence of catalysts that support the decomposition. (Rizvi et al., 2022; Khataee et al., 2020). Relevant O_3 studies in real wastewater usually compare O_3 performance with UV-based AOPs (such as PC and PFT) or combine it with other processes (such as ultrasound, hydrodynamic cavitation, biological, among others) to overcome by-products generation. Even when O_3 can be combined with catalysts to diminish by-products generation, authors in this article found that these types of methods are still in an emerging stage, so most of the studies are related to O_3 alone, probably due to limitations regarding catalyst recovering and mass transfer issues in heterogeneous systems. In general, the effectivity of O_3 depends on the selectivity of O_3, the pH of the solution, the O_3 dosage, the mass transfer between bubbles and the bulk of the liquid, and the presence of •OH radical-sabotaging compounds such as bicarbonates and carbonates.

In a study in China by Yin (Yin et al., 2019) (TCP=62), for example, O_3 is used as a secondary treatment (after flocculation, sedimentation and two sand filtration systems) for the treatment and reuse of real TWW. The study shows that O_3 alone can thoroughly eliminate colour in real wastewater samples, but the removal rate of colour is proportional to the O3 dosage, which can be an economic challenge, especially in developing countries.

In South America, FT has gained prominence in Brazilian research due to the importance of the textile industry to the country and the effectiveness of this process in colour removal. A study by Silva et al (Silva et al., 2020) with the highest TCP indicator (TCP=31) compared four AOP/EAOP processes in a real TWW and obtained a colour removal

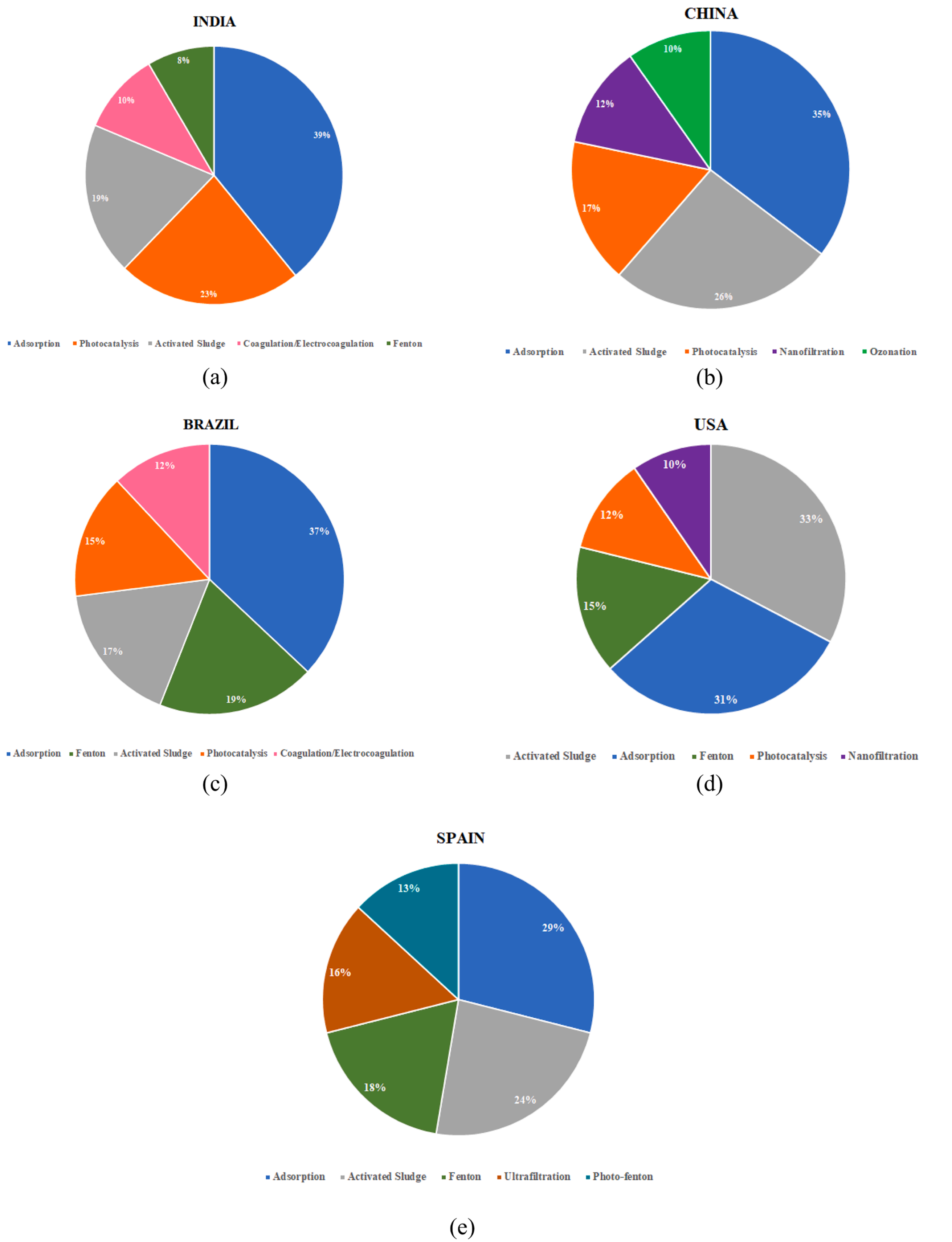

Fig. 8. Co-occurrence analysis for main treatments per country: (a) India, (b) China, (c) Brazil, (d) the United States/USA and (e) Spain. Source: Authors **created with Orbit Intellixir**

efficiency varying as follows after a running time of 45 minutes: PEFT with UVA (85-100 %) > PFT with UVA (80-98 %) > EFT (76-94 %) > FT (68-95 %), with FT alone being the more cost-effective process. However, a major limitation within FT is the formation of sludge, the persistence of iron residues and the recurring need for pH regulation. The need to maintain an acidic environment for optimal FT reaction efficacy requires continuous pH control, which adds complexity to operations. Regeneration of the iron catalyst is also a problem due to iron precipitation and the generation of large amounts of iron hydroxide sludge which must be properly disposed of at high cost.

Other advances include treatments such as plasma electrolytic oxidation, synthesis of zero-valent metal catalysts, and processes such as peroxy-coagulation (in situ production of ferrous ions and H_2O_2 to promote the FT effect), which suggest the design of systems with simultaneous reagent production and oxidation (Tichonovas et al., 2013; Khatri et al., 2018). For all these treatments, mechanisms of reaction and degradation of contaminants are still proposed.

Green cluster: AOPs with UV radiation. These methods are comprised in chemical engineering SD from Fig. 7. The combination of AOP/UV has gained popularity, especially in the last two decades, as these treatments offer the dual benefit of treatment and disinfection and the combination with UV radiation can enhance the effect of commonly used oxidants, such as H_2O_2 and chlorine (direct degradation by photolysis), O_3 (E.g., O_3/UV or photocatalytic ozonation), PFT and PEC (Kumar and Pandit, 2013; Orimolade and Arotiba, 2020). Depending on the physical state of the catalyst, these processes can be divided into homogeneous (when the reaction occurs in a single phase) and heterogeneous (when the reaction occurs in two or more phases) (Anisuzzaman et al., 2022).

Fig. 8 shows that keyword "photocatalysis" appears in main research concepts for India, China, Brazil, and the United States, while Spain has more occurrences for "photo-Fenton" concept. Dye photodegradation is considered the most promising technology within AOPs for TWWT because it is environmentally friendly, cost-effective, and does not involve secondary contaminants. Studies have mainly centered their efforts in the photocatalysts synthesis and characterization to improve generation of •OH radicals. PC has been tested on cationic (such as thiazine, basic red, RhB, MB), anionic (brilliant blue), and azo dyes (CR), mostly under controlled conditions with doped water, but with some approaches and good results in industrial wastewater (Mohammed et al., 2020; Grčić et al., 2014; Nikravesh et al., 2020; Wen et al., 2020).

The most frequently cited study in the field of PC, for example, comes from India (Adeleke et al., 2018) (TCP=240). In this study, a nanocomposite photocatalyst of ZnO/$NiFe_2O_4$ was successfully synthesized by a solid-state method involving the calcination of green-synthesized ZnO nanorods and prismatic $NiFe_2O_4$ nanorods at high temperature (850 °C). The novel aspect of this report lies in the combination of green-synthesized ZnO with NiFe2O4 in a solid-state reaction, which is typically a simpler synthesis method. In chemical engineering SD, next study corresponds to Brazil (Cardoso et al., 2016) (TCP=179), which compared three UV-based AOPs with O_3 (PL, PC, and PEC) in a sample of real wastewater. The best results were obtained for the combination of O_3 and PEC, with a color removal up to 90 % and a reaction time of 15 minutes. It is essential to mention that the presence of carbonates and bicarbonates reduces the effectiveness of the treatment, as they act as radical scavengers for •OH.

As far as PFT is concerned, Spain has made significant contributions. The article by Cabrera-Reina et al (Cabrera-Reina et al., 2019) has a TCP=21 and represents one of the first approaches in the study of the selection of photoreactors for the treatment of industrial wastewater with solar PFT. The novelty of the article is the comparison made by the authors between conventional tubular reactors and pond reactors, which are simpler and cheaper than the formers by at least two orders of magnitude (according to the authors' results).

In recent years, research on AOP/UV has focused on homogeneous configurations, achieving high yields at the lowest possible operating costs, coupling different types of AOP/UV processes, or combining them with other AOPs in the absence of light. The use of photocatalytic membranes is also an exciting contribution (Wang et al., 2020). As for materials, research has focused on synthesizing efficient nanoparticles under visible light and environmentally friendly catalyst synthesis methods (materials derived from waste or synthesized by microorganisms) (Noman et al., 2020).

3.3.2. Physical treatments

This group has a TP=682 and includes the removal of substances by forces such as electrical attraction, gravity, particle size, van der Waal forces or physical barriers (Mani et al., 2018). In Fig. 6, they are divided into dark blue (filtration) and light blue (adsorption) clusters. Research is mainly carried out in the fields of materials science and chemical engineering SD in Fig. 7. These methods do not change the chemical structure of the substances in the water; they merely trap and separate them from the aqueous matrix. In addition, ion exchange sorption is also a physical treatment method in which a specific type of ion is attracted and then exchanged between a solid resin and an aqueous solution (Acelas et al., 2015); however, its use in TWWT does not seem to be as relevant, as it does not appear in the concept map in Fig. 6.

Dark blue cluster: filtration. In the dark blue cluster in Fig. 6 are treatments related to membrane filtration. These include MF, UF, NF, and RO. The advantage of the membrane filtration is its fast processing with low requirements and the possibility of reusing the membrane and the permeate obtained; however, the high cost, clogging, and membrane replacement affect its applicability (Mani et al., 2018). The most important properties of membranes include rejection ratio, hydrophobicity, thermal stability, and mechanical properties, with fouling being one of the most limiting factors for membrane use.

In Fig. 8, China, the United States, and Spain have the highest percentage in keywords occurrences related to filtration. Table 3 shows some important articles regarding each filtration type. In general, China has some of the most important works in this cluster. For example, Jin et al. (Lin et al., 2015; Lin et al., 2016) studied the flow behavior and effectiveness of NF membranes in treating common textile contaminants (direct red 23 and 80, reactive blue 2, and Congo red) in synthetic wastewater. In their first study, the authors found that the large-scale applicability of these membranes was severely limited due to two main factors: 1) concentration polarization (which is affected by membrane permeability, separation factor, membrane thickness, and interfacial mass transfer coefficient) and 2) the formation of a dye layer (cake) that drastically degrades membrane flux. In their second study, in response to the limitations found in NF membranes, they investigated hermetic UF membranes, which could be an alternative to NF due to their better desalting and dye recovery performance.

In recent years, research with membranes for dye removal has focused on UF and NF, mainly searching for new membrane materials that improve their properties using carbon additives (such as graphene or multi-walled nanotubes) and biomacromolecules (Hubadillah et al., 2020). Some of the most common materials used to make these membranes are polymeric (semiautomatic polyamide, polyethersulfone, polyacrylonitrile, polyvinylidene difluoride) or ceramic (Al_2O_3, SiC, TiO_2). On the other hand, despite the low retention rate of MF and, in some cases of UF, studies on chemical modification of membranes, combination with nanocatalysts, and coupling of different types of membranes continue to be investigated to improve membrane performance.

Dark blue cluster: Adsorption (AD). In this process, ions, or molecules in one phase (either gaseous or liquid) tend to accumulate and concentrate on the surface of another (usually solid) phase by usually Van der Walls forces. The main advantages include low operating costs, relatively high

Table 3
Types of membranes.

Types of membranes	Molecular weight limit (MWCO) (kDa)	Pore size (μm)	Rejected species	Contribution	Year	TCP	Country	Ref
MF	> 100	0.1–10	Suspended solids, bacteria, colloids, fats.	A pilot plant with a moving bed biofilm reactor coupled with membrane bioreactor (MBBR-MBR) for real industry TWW. COD removal reached 93 %, color removal achieved 85 % and 99 % of TSS were removed.	2021	7	Spain	(Yang et al., 2021)
UF	1–500	0.01–0.1	Suspended solids, bacteria, viruses, colloidal silica, polypeptides, proteins, antibiotics, dyes.	Composite membrane composed of bacterial nanocellulose embedded with mesoporous polydopamine and decorated with palladium nanoparticles	2020	31	USA	(Gholami Derami et al., 2020)
NF	0.2–10	0.001–0.01	Multivalent ions, organic matters, dyes, sugars, antibiotics	Zirconium-based MOFs (UiO-66) were prepared and constructed universal, high-performance, and flexible NF membrane for various dyes and antibiotics separation.	2022	131	China	(Fang et al., 2020)
RO/FO	< 200	< 0.001	Monovalent ions, sodium ions, micropollutants.	Hybrid membrane distillation + FO that recovers dye while producing clean water.	2020	55	China	(Li et al., 2020)

Source: Authors

efficiency, simple design, low toxicity, and, most importantly, the fact that it is a regenerative process. In Fig. 8, AD is a fundamental process in TWWT for each country. However, it also has disadvantages such as low selectivity (Saravanan et al., 2021), loss of adsorbent effectiveness over time, and an inconvenience in its final disposal when its useful life has expired.

Examples of adsorbents are activated carbon (AC), silicon polymers, and metallic adsorbents capable of adsorbing various dyes. AC is the most widely used adsorbent due to its structure, high porosity, and ease of extraction (it can be obtained from coal, petroleum coke, or biomass). The effectiveness of AC depends mainly on the type of material used for its production and the conditions of the activation process (either chemical or physical). When the raw material used for AC synthesis comes from biomass, AC is referred to as biochar. Some articles show biochar derived from red mud and lignin waste in China (TCP=171) (Cho et al., 2019), agribusiness waste in India (TCP=102) (Vigneshwaran et al., 2021) and cocoa shells in Brazil (TCP=140) (Ribas et al., 2014). Biochar can also be modified, as in the case of its combination with metallic nanoparticles and nanocomposites in the United States (TCP=46) (Zhang et al., 2019) and Spain (TCP=18) (Sharma et al., 2020).

Finally, in line with various environmentally friendly practices based on nature, natural adsorbents known for centuries have been rescued, and their effectiveness in TWW has been studied. These include eggshells, sugarcane bagasse, chicken feathers, almond skins, and seeds of various plants (Mani et al., 2018). Some attractive natural adsorbents from plants such as Mexican argemone seed were applied to RhB and achieved 80 % removal of the dye with only 0.06 g/100 ml of adsorbent for 2 hours. (Khamparia and Jaspal, 2016); Other mineral adsorbents (kaolin, bentonite, clay, vermiculite, among others) were combined with hydrogels and obtained a yield of 95 % in removing heavy metal ions and dyes (at low initial concentrations), suggesting a potential for tertiary treatment of industrial TWW. These materials are less expensive, easy to produce, and can be recycled many times (Wang et al., 2022).

3.3.3. Biological treatments

Red cluster: Biological. Red cluster in Fig. 6 and SD related to biochemistry and biological sciences as SD in Fig. 7 comprises biological treatments for dyes that can be divided into bacteria, MCR, and PcR. These methods use organisms and microorganisms to process biodegradable fraction of TWW into flocculent, adsorbable, oxidizable materials and gasses that can be easily removed. Microorganisms interact with pollutants either through biosorption, bio-flocculation, or enzymes (organic molecules with protein or RNA character) that react with the pollutants to produce simpler molecules that are readily biodegradable by other microorganisms (Buthelezi et al., 2012; Darwesh et al., 2019; Karaca et al., 2022). These methods are relatively cost-effective, have high activity and flexibility depending on the microorganism and type of dye, and can reduce some heavy metals, such as chromium, to relatively less toxic forms. They are also natural, reduce the presence of pathogens and fats, and, at the same time, can generate renewable energy. Finally, they can treat water with high organic load and reduce their BOD by up to 90 %.

Combining these treatments with a physicochemical method offers a better result in terms of effectiveness and economy, making them environmentally friendly, cost-effective, and attractive for combination with other treatments (Jamee and Siddique, 2019). However, among their many disadvantages are that 1) they're slow are less effective when dyes are large in structure; 2) it's required more research to make them more stable; 3) certain pollutants (heavy metals and many emerging contaminants) are not removed; 4) considerable odors and sludge are generated, and, 5) there are considerable gaps in the understanding of the microbial environment and degradation mechanism for some of the treatments (Saravanan et al., 2021).

In Fig. 8a-8e, all selected countries have a common involvement in biological treatment through the concept of 'activated sludge', which is understood as a complex mixture of microorganisms including bacteria, fungi, protozoa and in some cases metazoans (such as rotifers and nematodes) that can form flocs or floc-like structures that help in the removal of organic matter and pollutants from wastewater through processes such as biosorption and biodegradation. Although AS is the most commonly used treatment, it is not the only one in this group. PhR (involving plants and algae) and MCR (using fungi) are important methods that are currently at an early stage of research in the field of wastewater treatment. The following sections look at the contributions of different countries to these three primary subgroups..

Bacteria. The use of bacteria is a well-known and mature method in TWWT. Unlike other microorganisms such as fungi or microalgae, which mainly show biosorption of toxic compounds and dyes, bacteria can degrade them by growing in a short time and interacting directly with them through oxidative-reducing enzymes such as azoreductase and laccase-peroxidase, which catalyze the mineralization and effective degradation of many dyes (Paz et al., 2017; Waghmode et al., 2019). Phyla such as Bacteroidetes, Acidobacteria, Actinobacteria, Proteobacteria, and Firmicutes have been isolated and characterized and show good efficiency in dye degradation (Tara et al., 2019; Song et al., 2021; Chaudhari et al., 2017; Gomaa et al., 2022; Srivastava et al., 2022).

The oxygen demand determines whether the treatment is aerobic (including AS, CW and biofilm) or anaerobic (fixed film reactors, anaerobic reactors with baffles, anaerobic updraft reactors, and others). Some examples of aerobic and facultative bacteria used in the removal of various reactive (Remazol black b), direct (R-Blue 13), azo (CR), and acid (A-Orange 12) dyes are *E. Coli, Pseudomonas sp, Bacillus subtilis, Aeromonas hydrophila*, and *Xanthomonas campestris* (Paadzior and Bilinska, 2022), while examples of anaerobic bacteria include *Actinomyces, Bifidobacterium, Clostridium, Propionibacterium*, and *Peptostreptococcus* genera (Kumar et al., 2022).

Fig. 8d shows that the United States is the largest contributor of all concepts in AS for TWWT. Due to the complicated nature of microbial mixtures in an AS reactor and in the systems, a seminal study by Han et al. (TCP=24) (Han et al., 2021) is of paramount importance. The authors meticulously investigate the diversity and underlying factors that influence microbial communities in domestic wastewater treatment systems that incorporate industrial wastewater into biological treatment. The results indicate a significant 72.5 % inhibition of metabolic functions in the AS from the TWW-fed system. Of note, metabolic pathways were affected, including pentose phosphate metabolism, purine metabolism and glycerophospholipid metabolism, contributing to a significantly lower richness and diversity in the culture compared to that fed with municipal wastewater.

Given the heightened toxicity of TWW, other authors such as Kishor et al (TCP=32) (Kishor et al., 2021) and Zeng et al (TCP=17) (Zeng et al., 2021) also have underscore concerns regarding the attenuation of microbial activity and metabolism in biological industrial wastewater treatment, particularly those pertaining to TWWT, and the necessity in the isolation of new strains of bacteria from the AS that can withstand the aggressive conditions of the TWW.

Algae and microalgae (PcR). PcR comprises methods for TWWT by both macro and microalgae. Among these, research in microalgae has increased greatly in recent years because they can effectively biosorb and degrade azo dyes, due to the production of the enzyme azoreductase, which cleaves azo bonds by reductive cleavage. The resulting degradation products, mainly aromatic amines, are degraded in the presence of oxygen (Kapoor et al., 2021). The most commonly used types of algae include blue-green algae (cyanobacteria), green algae, and diatoms (brown algae) (Sehar et al., 2022). In general, decolorization by algae is based on three mechanisms: 1) use of chromophores (molecules that absorb light and transfer energy for use in photosynthesis) to produce algal biomass; 2) conversion of colored molecules to uncolored molecules; and 3) adsorption of chromophores onto algal biomass (producing natural pigments) (El-Kassas and Mohamed, 2014). The effectiveness of decolorization depends on the type of dye, its various substituent groups, and the physicochemical properties of the wastewater, such as pH, temperature, salinity, and the presence of other organic contaminants (Solís et al., 2012).

Some azo dyes have been observed to have high toxicity to aquatic life and bacteria-based methods (Han et al., 2021), but do not significantly reduce microalgae. Unlike bacteria and fungi, which rely on external sources for growth, microalgae obtain energy from sunlight and carbon from the air, and some remove atmospheric nitrogen (Solís et al., 2012), making them economically attractive for the biological treatment of wastewater.

The most used microalgal species include *Scenedesmus sp., Chlorella sp., Synedra sp.*, and *Achnanthidium sp.*, which have been used at different temperatures in TWWT with real and doped wastewater for dye removal, with room temperature usually being the optimum for the process (25-30 °C), as enzyme inactivation occurs at higher temperatures. According to Fig. 8a, India also has an important participation in biological methods through AS concept, however, their efforts can be found in microalgae research as well. One major contribution is from 2022 with a TCP=6 (Arutselvan et al., 2022), where authors use freshwater microalgal strains, including *Chlorella vulgaris, Scenedesmus dimorphus, Coelastrella sp.,* and *Chlorococcum sp.*, isolated from a betel field, for treating TWW and tannery real samples. Additionally, the *Chlorella vulgaris* and *Scenedesmus dimorphus* consortium produced substantial lipid content, making it a promising candidate for biodiesel production.

Bioenergy/biodiesel production from microalgae has several advantages, including (1) low water consumption (per unit weight of biomass and unit energy) compared to other crops and no fertilizer consumption (Bhatnagar et al., 2011); (2) avoidance of competition with agriculture; (3) purification of wastewater (Arutselvan et al., 2022); 4) consumption of CO_2 in flue gas through photosynthesis; (5) achieving commercial potential by optimizing growing conditions to increase lipid content in microalgal biomass (Nagaraj et al., 2022; Wu et al., 2017; Behl et al., 2020); (6) produce valuable by-products such as fatty acids, pigments, stable biochemical isotopes, (Wu et al., 2017; Moldovan et al., 2022), animal feed, and fertilizers; (7) produce biofuels (ethanol or methane); and (8) produce hydrogen (H_2) that green microalgae can produce under anoxic conditions (Shen, 2014).

In countries where the economy relies more on agricultural use, biofuel production and biorefinery operations, and where regulations for wastewater treatment are less stringent, microalgae represent a significant advantage. After the remediation process, microalgae can be used as a valuable source of biofuel, fertilizer and nutrient-rich food, offering remarkable economic benefits. However, the use of microalgae in TWWT also presents challenges, particularly in terms of their inability to thrive in concentrated wastewater and their relatively low biomass productivity. The presence of high levels of suspended solids in concentrated wastewater reduces light transmission and mass transfer, while increased nutrient concentrations can hinder or suppress the growth of microalgae (Gao et al., 2021). Consequently, the effective use of microalgae in TWWTs requires the dilution of concentrated wastewater with clean water to promote optimal microalgae growth.

Fungi (MCR). MCR represent a promising group of TWWT for biosorption and biological degradation of toxic substances in wastewater because it has great potential for enzymatic reactions such as manganese peroxidases, lignin peroxidases, and laccases capable of degrading recalcitrant pollutants, dyes, lignocellulosic compounds, and organic pollutants such as aromatic hydrocarbons, chlorophenols, and polychlorinated biphenyls (Deveci et al., 2016). Species of the genus *Aspergillus* and *Lichtheimia sp.,* have been effectively used to degrade direct, reactive, and azo dyes with yields as high as 98-99 %; however, these studies were conducted on a laboratory scale using simulated water (Moldovan et al., 2022; Abd El-Rahim et al., 2017). Research indicates that the trend is to isolate new strains from plant roots or industrial wastewater (Chatterjee et al., 2020; Al-Tohamy et al., 2020).

In general, most commonly reactors for TWWT for MCR include stirred tanks, packed beds, bubble columns, and air lifters, with stirred tanks being the most commonly used, where the culture medium is mechanically stirred, ensuring a fluid mixture and good oxygenation (Hanafiah et al., 2022). However, the main limitations of mycoremediation include the stress caused by stirring and the high energy consumption due to the aeration system and high stirring speeds (Lanfranconi et al., 2022). To address these operational drawbacks, trends have been developed to immobilize the species in the medium.

In Brazil, for example, there is a relevant study with TCP=56 from 2019 (Almeida and Corso, 2019), in which the authors carried out biosorption and biodegradation tests with the dyes A-Blue 161 and Procion Red MX-5B in simple and binary synthetic solutions. In the biosorption, the dyes were effectively removed by the fungi Aspergillus niger, Aspergillus terreus and Rhizopus oligosporus, while the biodegradation treatment was evaluated with the fungus Aspergillus terreus. In the biodegradation tests, toxicity analysis with Lactuca sativa seeds and Artemia salina nauplii indicated the presence of highly toxic metabolites in the reaction medium at the end of the treatment, so the authors suggest that biosorption could be a more suitable alternative for these pollutants, as it is a method capable of removing pollutants from the medium, with the advantage of preventing the formation of highly toxic by-products.

As with the methods using bacteria and microalgae, one of the main advantages of using fungi-based methods for wastewater treatment, and in particular for wastewater treatment plants, is the cost-effectiveness and accessibility of this approach. Fungi can thrive in a variety of environmental conditions and can be used to effectively degrade pollutants in wastewater without the need for sophisticated infrastructure or high operating costs. In general, biological treatment is often more affordable than certain conventional treatment methods, such as chemical treatment, making it particularly attractive for regions with limited financial resources. In addition, fungi have the ability to adapt to a wide range of pollutants and can help improve water quality by addressing environmental and health concerns in a cost-effective way.

3.3.4. *Pollutant type*

Using the Orbit Intellixir Concept Landscape tool, a map of the principal treatments was created. Then the main dye groups within the analyzed studies were identified: Azo (e.g., CR, Tartrazine), Direct (such as D-Blue), Reactive (such as R-Red), and Basic (such as MB). Orbit algorithm generates an interactive map of the analyzed documents, explores concepts, and refines their categorization according to a search equation. Command "TI:AB" in Fig. 9 was added to each keyword to ensure that it was found in the title and abstract of the articles.

Fig. 9 shows 6 clusters with similarities to Fig. 6 being (1) CC/EC; (2) AD; (3) FT/PFT; (4) PC; (5) membrane filtration and bioreactors; and (6) biological treatment by bacteria (e.g., AS). As this map resembles the outlines of geographic maps, clusters (1), (4), and (5) have the highest number of documents, followed by clusters (2), (3), and (6), respectively. Articles analyzing azo dyes are the most numerous and are mainly distributed among biological, membrane, and CC/EC treatments. Azo dyes are the most common group used in the textile industry and consist of various aromatic organic compounds with one or more azo bonds (-N=N-) in their chemical structure, which allows them to absorb the visible light spectrum. The azo group may be substituted by a phenyl or naphthyl group, which in turn may be substituted by one or more groups such as chloride (-Cl), amino (-NH_2), hydroxyl (-OH), carboxyl (-COOH), nitro (-NO_2), and methyl (-CH_3), resulting in a wide variety of azo dyes (Sehar et al., 2022). Finally, direct dyes are concentrated in membranes, PC, and CC/EC; reactive dyes between membranes and CC/EC; and basic dyes in AD, PC, and CC/EC.

To identify the most important pollutants, Fig. 10 shows the top 10 most frequently investigated dyes based on a coincidence analysis. MB (a cationic thiazine dye) is by far the most common in research with a share of 26 %, followed by CR (12 %) and R-Red (12 %). MB is an important dye in research due to its effectiveness as a model dye for the investigation of treatment processes. It falls into the category of basic/cationic dyes, i.e. it has a positive charge, just like A-Red, MG and RhB. This is of crucial importance, especially in the selection of materials for adsorption processes in TWWTs (Gajera et al., 2022). Azo dyes are also represented by CR and MO dyes.

Fig. 10 also illustrates the prevalence of reactive dyes, including R-red (such as Nos. 120, 198, and 141), R-blue (such as Nos. 19, 21, and 4), R-black (such as Nos. 5 and 8), and R-yellow (such as Nos. 176, 15, and 145). These dyes are known for their ability to form covalent bonds with cellulosic fibers through nucleophilic substitution or nucleophilic addition, resulting in dyed fibers with exceptional wash fastness properties. Reactive dyes contain a reactive group (halogen or activated vinyl compound) that bonds directly with the hydroxyl or amino groups of the fibers. This helps to ensure that the color does not change during dyeing and makes them more effective than basic or acidic dyes, for example. Nevertheless, their complicated structure contributes to increased toxicity, even at concentrations lower than those used in typical commercial dyeing processes (Barathi et al., 2022).

Finally, Table 4 summarizes the top 10 most relevant and recent TWWTs found with the bibliometric analysis and literature review. Treatments were selected based on novelty, year of publication, country, and TC. Priority was given to studies with real samples of TWWs.

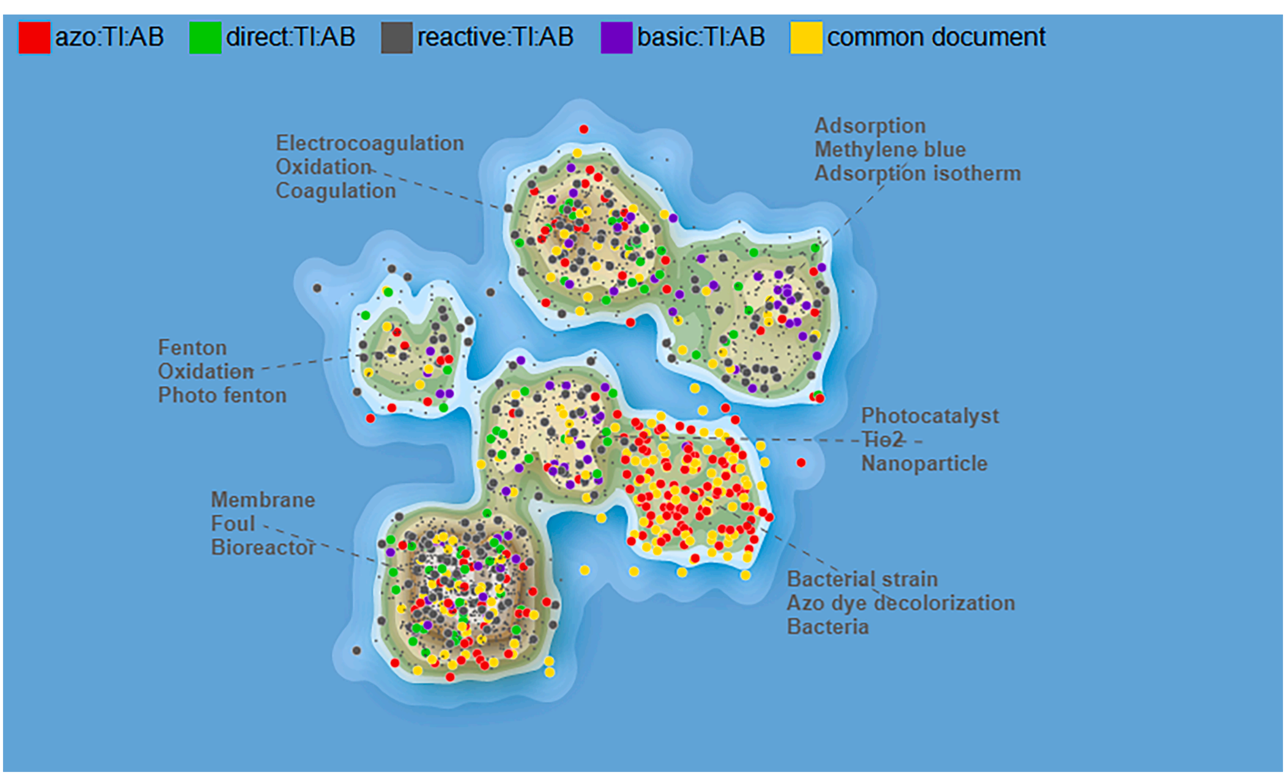

Fig. 9. Landscape of concepts for major dye types. **Source:** Authors, created with Orbit Intellixir.

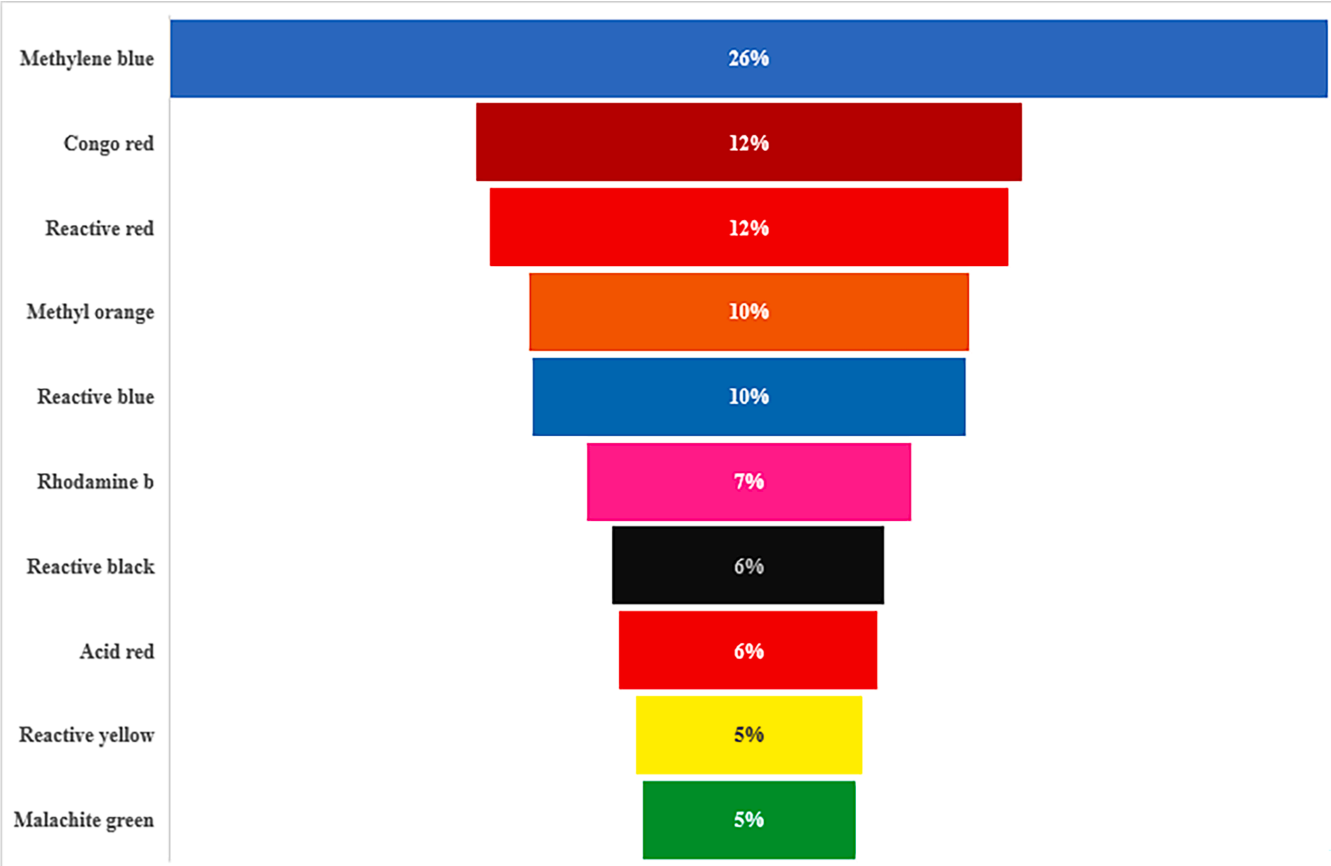

Fig. 10. Top 10 dyes identified in research on TWWTs. **Source:** Authors, created with Orbit Intellixir.

3.4. *Trend analysis*

3.4.1. *S-curve and forecast indicators*

To evaluate the trends in scientific productivity of the chemical, physical, and biological treatment groups and their subgroups, S-curve analysis was applied to CNP during 2012-2022 (Fig. 11a-c), respectively. The predictive indicators were calculated in Table 5 and the statistics of the fit were analyzed in terms of standardized residuals, R^2 and p-value. The fit was performed using the Monte Carlo method and the objective function was the sum of squares. Based on the Gompertz model, maturity is reached at TMR = 37 %. At the time of this study (t = 2022), the scientific maturity levels (TMR in Table 5) for each treatment group were 42 % (chemical), 37 % (physical), and 48 % (biological), respectively, indicating which the chemical and biological treatments are at an early stage of maturity, while the physical treatments are just beginning to do so. All models showed high accuracy with an R^2 of more than 90 % and a p-value > 0.00001 (Table 5). However, while the residuals of the chemical and biological treatments (Fig. 11a and c) show a cloud with no pattern, Fig. 11b (physical treatments) shows a clear V-pattern, indicating that the data are not well fitted by the Gompertz model.

Table 5 shows that all the treatments have similar values for ERL and PPA before reaching saturation. Biological treatments are the most developed, so they have fewer potential documents before reaching saturation (PPA). Fig. 11 also shows S-curve analysis was applied to subgroups of treatments inside main group, which will be further explained in next paragraphs.

In Fig. 11a, chemical treatments with higher CNP were UV-based, CC/EC, FT, and O_3. Table 5 shows an ERL = 28 years and a PPA = 1216 remaining publications. Fig. 11a also shows that AOPs, especially AOP/UV processes, are the most developed because they offer the possibility of completely mineralizing soluble and insoluble dyes through a radical mechanism triggered by the interaction among photons, radicals, and pollutants, either in the presence or absence of a catalyst. Previous bibliometric analysis of industrial wastewater trends shows that AOPs and AOP/UV have gained great attention since 2008 in TWWT, with technologies such as PC and especially solar PC as promising processes that are hoped to be realized at a commercial scale to treat dyes in wastewater (Mao et al., 2021; Zheng et al., 2015; Macías-Quiroga et al., 2021).

UV processes can also remove color through a photodegradation mechanism in which UV radiation can break chemical bonds. AOPs do not produce sludge, a disadvantage in both CC and FT, where the sludge is contaminated with toxic aluminum and iron-based compounds in CC/EC and FT, respectively. However, UV-based methods such as PC or PFT are generally more expensive for industrial application than CC, FT or biological processes (Ortega-Méndez et al., 2017), which may pose a challenge for AOP/UV methods for TWWT. Furthermore, a 2021 bibliometric analysis by Raji & Ahmad showed that TWWTs are currently and will continue to be the most focused industrial wastewaters that can be efficiently treated by applying FT-based AOPs (Raji and Mirbagheri, 2021).

According to what has been analyzed so far, UV-based AOPs have the following advantages:

- They can be used in synthetic aqueous solutions containing selected organic compounds as model contaminants with good performance or in real water samples with a low concentration of contaminants. In some studies, it has been found that an initial value COD ≤ 700 can serve as a starting point, provided that the water has a TDS/COD ratio that is not very high and a low concentration of other compounds, such as fats (Tanveer et al., 2022; Rao, 2012).

Table 4
Top 10 TWWTs and primary pollutants identified.

Treatment		Pollutant	Type of water	Description	Country	Year	TCP	Ref
Chemical	PC/AD	MB	Synthetic	Integrated adsorption and photocatalysis process using a TiO_2 biochar composite catalyst prepared from a macroalgae culture from an industrial wastewater stream	Pakistan	2020	93	(Fazal et al., 2020)
	PC	D-Red 89, R-Red 223, D-Red 2, A-Red 13, R-Red 142, defoamers, salts and aromatic amines	Real	Photocatalysis in real textile and tannery wastewater using biosynthesized magnesium oxide nanoparticles. The nanoparticles were synthesized utilizing the metabolites secreted by *Aspergillus niger* strain F1.	Egypt and China	2021	73	(Fouda et al., 2021)
	EC/EFT/ PEC/EO	MB, azo dyes, nitrogen, phosphorous, potassium, etc.	Real	Different electrochemical methods were applied. EC/EFT sequential system was found to be the best configuration with 97 % COD removal	Morocco and France	2020	43	(Afanga et al., 2020)
	O_3/H_2O_2	R-Black 5	Synthetic	Application of electroperoxone, a method that combines ozonation with electrolysis and produces H_2O_2 in situ using the excess O_2 generated during the ozonation process.	India	2022	10	(Koulini et al., 2022)
Physical	NF	R-Blue 19	Synthetic	NF through a polyethersulfone membrane with MoS_2 catalyst and multi-walled oxidized carbon nanotubes.	China, Iran, Turkey, and Rusia	2022	91	(Arefi-Oskoui et al., 2022)
	AD	MB y MO	Synthetic	Synthesis and validation of a natural-based adsorbent from pullulan hydrogel (polysaccharide produced by fermentation of the fungus *Aureobasidium Pullulans*) embedded in a polydopamine/montmorillonite structure.	China	2021	74	(Qi et al., 2021)
Biological	O_3/ AnDMBR	RBBR	Synthetic	O_3 pretreatment, followed by a lab-scale biological membrane reactor with a dynamic membrane fabricated by a 3D printer. The seed for the bacterial consortium came from the sludge of a municipal wastewater treatment plant	China and Australia	2020	52	(Berkessa et al., 2020)
	Bacteria	R-Black 5, R-Red 120, R-Blue 19, AS-GR, AzB	Synthetic	Use of a unique and recently isolated yeast strain, *Sterigmatomyces halophiles* SSA-1575, from the gut system of a wood-eating termite. 100 % removal was achieved in 24 hours	China and Egypt	2020	49	(Al-Tohamy et al., 2020)
	CW/MFC	N/A	Real	Combination of microbial fuel cell and augmented constructed wetland pilot scale with electrodes and an electrogenic bacterial consortium of *Fimbristylis ferruginea* and Elymus repens, both native species, collected from a textile dye contaminated site near the plant. This process increased the cell's power generation.	India	2021	36	(Patel et al., 2021)
	MC	MB, sales, fosfatos	Synthetic	Simultaneous use of the microalgae species *Chlorella vulgaris* for bioremediation and biodiesel (fatty acid methyl ester) production	Pakistan and Turkey	2021	35	(Fazal et al., 2021)

Source: authors

- Better efficiency with a suspended form of catalyst (Cui et al., 2022) by increasing the ratio of free radical generation.
- Combination with adsorbents improves products' removal of toxic oxidation (Rizzi et al., 2022).
- Better efficiency under artificial UV radiation (UVC) compared to sunlight (mostly UVA and UVB).
- Work best at sufficiently high dissolved oxygen concentrations, which implies mass transfer limitations between phases.
- Have reasonable operating costs (Tanveer et al., 2022)
- Sludge formation is reduced or eliminated (Feuzer-Matos et al., 2022).

O_3-based treatments are in last place with respect to its CNP. In contrast to UV treatments, O_3 is a mature technology which currently has a reputation in the field of industrial wastewater. Its main drawbacks are the generation of toxic by-products, limitations in mass transfer and high selectivity of O_3 molecules. Studies such as that of (Bilińska et al., 2016) have analyzed synthetic water with the dye R-Black 5 and found that O_3 processes (O_3 and O_3/H_2O_2) provide more less expensive than the combination of O_3 with UV-based processes. However, the authors point out that this research focused only on the oxidation of aqueous dye solutions without considering the conditions of industrial TWWs, which may lead to biased results.

Physical treatment group is the second in Fig. 11b with the highest CNP. Table 5 shows an ERL = 28 years and a PPA = 1385 remaining publications. AD and membrane filtration are the most researched processes by the academic community. A previous bibliometric analysis of industrial wastewater research revealed that one of the most cited articles is from China and deals with the use of sorbents and biosorbents for the treatment of polluted, dye- containing wastewater, suggesting a continuing interest in the development of increasingly efficient bio-adsorbents (Zheng et al., 2015). Currently, AD is a set of mature and cost-effective technologies that are widely used in industry because they solve (at least temporarily) the disadvantage of a pollutant (such as dyes) that is difficult to biodegrade and very stable; however, their main problem is the disposal of the adsorbent (it must be burned, regenerated, or replaced) (Crini and Lichtfouse, 2019). Trends in research are focused on developing stable, natural-based, easily regenerated adsorbents with large surface areas to increase the adsorption yield.

In membrane filtration, NF is one of the most researched filtration methods. However, the main drawback is that the capital cost of membrane treatments is too high for small and medium enterprises (Crini and Lichtfouse, 2019), as not only the capital cost a constraint but also the operating cost; it's also common for membranes to clog quickly (fouling at high concentrations), which limits the initial concentration of wastewater as well as the operating flow rate. One of the main

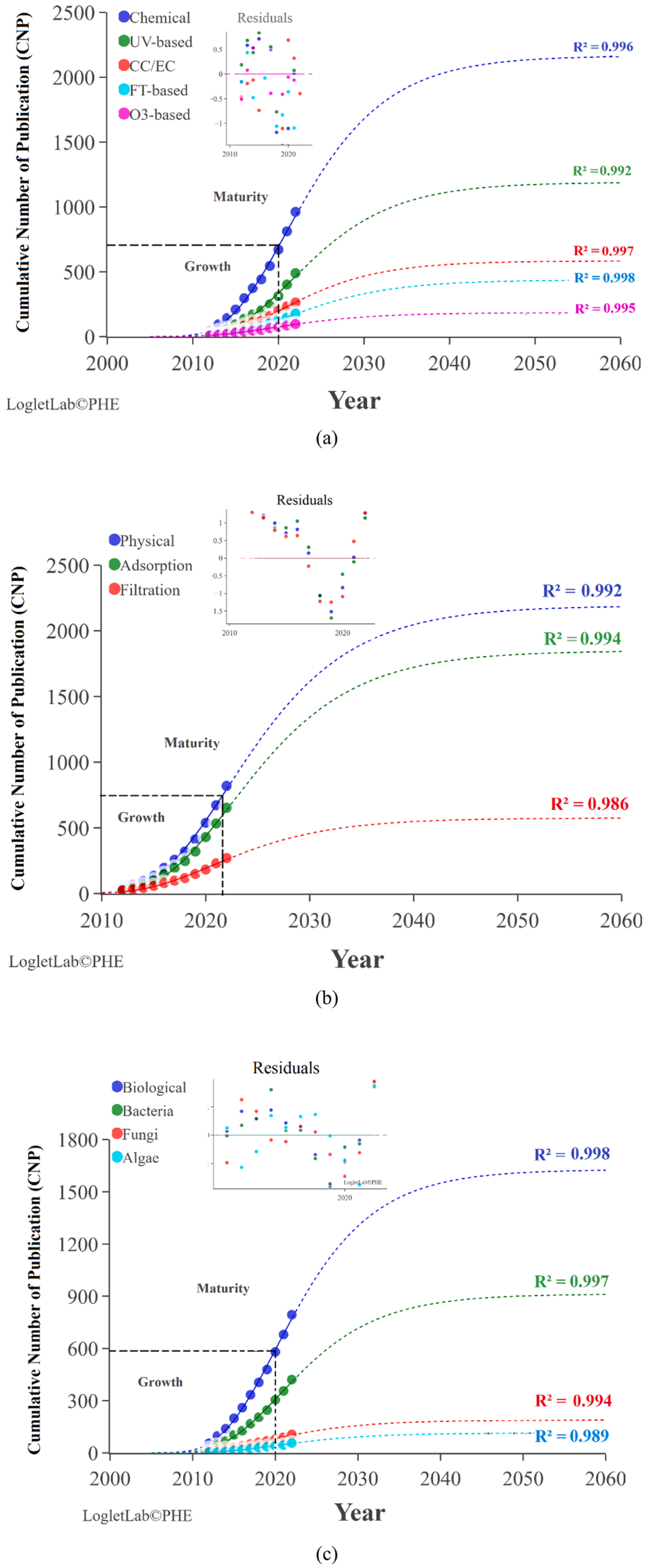

Fig. 11. S-curve and residuals for chemical (a); physical (b); biological (c). **Source:** Authors, created with Loglet Lab 4.

Table 5
S-Curve and forecasting indicators.

Type of treatment	Forecast indicators TMR (%)	ERL (years)	PPA (No. documents)	Statistics R^2	p-value
Chemical	42	28	1216	0.996	<0.00001
Physical	37	28	1385	0.992	<0.00001
Biological	48	27	850	0.998	<0.00001

Source: authors

advantages is that by recovering the concentrated dye and a colorless permeate, the reuse of the concentrate in the manufacturing process (Han et al., 2016; Yu et al., 2019) or the combination with other, primarily biological, processes (Hossain et al., 2016) to treat the permeate can be considered.

Fig. 11c shows biological treatments and Table 5 shows an ERL = 27 years and a PPA = 850, which means they are expected to reach their saturation stage more quickly. Because dyes are very stable compounds that retain their color and structural integrity to sunlight, bacteria, water, or soil, biological treatments have one major disadvantage compared to chemical treatments –the biodegradability of the dyes. These methods have been rapidly developed for wastewater treatment over the last decade as they are more economical and environmentally friendly than chemical and physical processes. Previous trend analyses shows that the most important methods include MBR, biofilm, AS and biosorption (as in the case of MCR and PcR) (Mao et al., 2021).

Even when one of their main disadvantages is the low biodegradability of TWW, this factor is compensated by microorganisms that become accustomed to the toxic textile waste and naturally develop new strains resistant to it, which then convert the toxic chemicals into less harmful forms (Mao et al., 2021; Ito et al., 2016). In these systems, the biodegradation mechanism of recalcitrant dyes is based on the attack of enzymes such as laccase, lignin peroxidase, NADH-DCIP reductase, tyrosinase, hexane oxidase and aminopyrine N-desmethylase, which can degrade some azo dyes almost completely under certain environmental conditions (Paz et al., 2017).

Finally, the treatment of microalgae is the least developed in terms of accumulated scientific productivity, although it is one of the most recent and promising biotechnological research areas in TWWT. Up to this study date, there are already some bibliometric analyses that allow to analyse the trends in microalgae research (Melo et al., 2022). The advantages of using microalgae include that they do not require a carbon source, can degrade azo dyes (probably by enzymatic and biosorptive action, although further research is needed), can generate bioenergy, and can produce degradation by-products (such as aromatic amines) that are less phytotoxic compared to conventional bacterial degradation (Yaseen and Scholz, 2019).

4. Future prospects

As shown in this study, various technologies have been used to treat textile wastewater; however, no specific treatment system can be universally applied to all types of textile wastewater (Holkar et al., 2016). Physicochemical characterization of these wastewaters is one of the most important components in the selection of one or another technology. Recent advances in this field show that pretreatments before the main treatment processes and the integration of different types of treatments (AOPs-biological-chemical) are strategies that could improve the quality of removal and the possibility of valorization of the effluents and other components generated during the treatment process (Shabir et al., 2022). This study shows that physical treatments, especially membranes, have been extensively studied, with efficiencies of up to 85 % in dye removal, but scale-up and operating costs have limited their implementation (Holkar et al., 2016). Conventional biological processes and coagulation-flocculation have their limitations in treating such wastewaters. Although these studies are essential for the treatment of textile wastewater, they often fail to remove the minimum pollutant load required by discharge regulations due to the various reactive pollutants. Color and COD removal technologies have been extensively studied, in some cases achieving 90 % and 75 % removal, respectively (Ramos et al., 2021); likewise, photocatalytic processes using UV/H2O2 have been studied, showing removal of over 80 % for color, 55 % for COD and 48 % for TOC (Urbina-Suarez et al., 2022). The results reported when using these technologies as the only treatment and the disadvantages and costs of their implementation have led research in this area to focus in recent years on the combination of two or more treatment methods to remove the color and the pollutant load; this type of process has been termed hybrid wastewater treatment (Fig. 12) (Solayman et al., 2023).

This technology is still in its infancy, but it has been shown to have the advantage of being more stable, efficient and sustainable (Tee et al., 2016), and allows significant savings in the removal of energy and pollutants (Patel et al., 2020). Nanofiltration processes in combination with reverse osmosis removed up to 98 % of pollutants expressed as COD, dissolved solids, dyes and heavy metals (Zango et al., 2020), Similarly, the integration of an electrocatalytic system with an anaerobic biological system showed a 93 % increase in dye removal compared to 44 % for the anaerobic system and 29 % for the electrocatalytic system alone (Ezugbe and Rathilal, 2020). This study provides a methodological way to evaluate different AOPs for wastewater treatment that effectively remove organic contaminants from water. However, several of these methods tend to be more expensive and require more reagents and energy sources, which limits their industrial applicability. Combining AOPs with biological treatment can be an ideal approach to reduce operating costs and increase the profitability of the treatment process. The technological maturity of this biotechnological strategy is necessary to generate useful data that allows us to know the aspects and conditions that influence the process and to make techno-economic comparisons with other technologies. It is therefore necessary to evaluate different AOPs that produce an effluent that can be integrated into a biotechnological process mediated by bacteria, microalgae or cyanobacteria and that allows the reuse of the treated effluent and thus the valorization of the biomass and the metabolites it produces such as lipids, proteins, exopolysaccharides, pigments and others. Finally, it must be ensured that the new technology is cost competitive by including all costs in the economic strategy. Once the technology is mature, life cycle analyses must therefore be carried out to enable the sustainability of the process in terms of a circular economy.

Limitation of the study

This article uses Scopus' TI-ABS-KEY command in its search equation and limits its results to a specific type of document (research article) so that the keywords only appear in the title, abstract and keywords of that type of document. All articles that did not fulfil these conditions were excluded from the analysis. All the indicators calculated in this article also depend fundamentally on the search equation and the date on which the search was performed. It is therefore possible that these results may vary if the search is performed again. The authors only

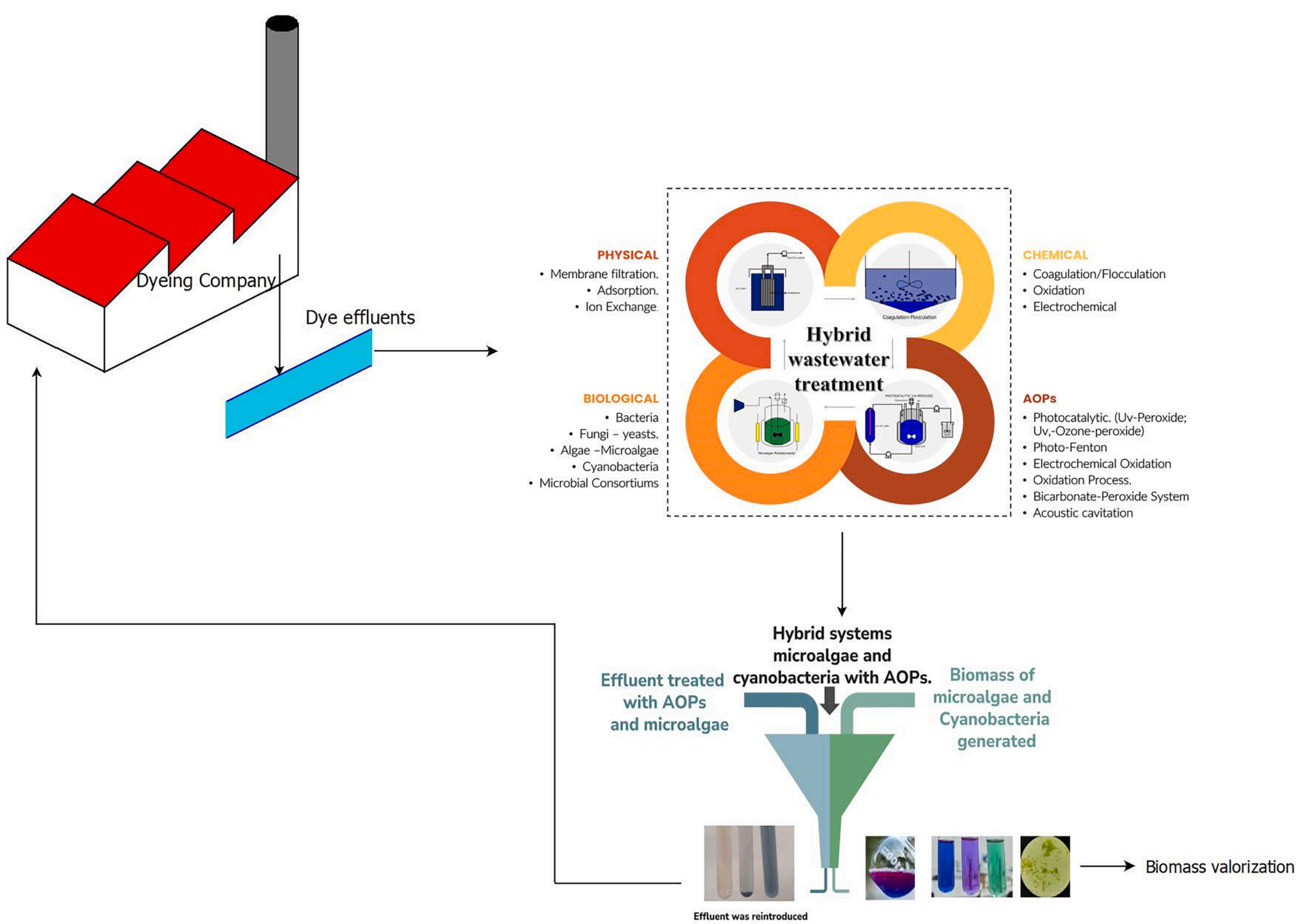

Fig. 12. Hybrid treatment methods for dyeing wastewater and utilization of wastewater and microbial biomass. **Source:** Authors

conducted the search in the Scopus database, so there is the possibility of conducting a study covering a larger number of databases in the future. Similarly, this study focuses on the last 10 years of research (2012-2022), as we wanted to give more importance to recent advances and hotspots in the field rather than a historical development of TWWT research. Finally, it was not the authors' intention to deepen the statistical analysis of the S-curve, but to show in a simple way the maturity level of the selected groups and subgroups of technologies. In the future, it is important to test the statistical significance of these adjustments with more in-depth analyses of normality, independence of residuals and homoscedasticity.

5. Conclusions

This article provides a comprehensive overview of TWWT through a bibliometric analysis of scientific research publications between 2012 and 2022. This field has experienced a significant increase in research activity, with publications multiplying by over 300 % from 2012 (n=136) to 2022 (n=445).

The main objective of this article was to explore the TWWTs and examine their relationship by analyzing the co-occurrence of keywords, examining the number of papers (TP) per country, assessing international collaboration, examining scientific domains (SD), and analyzing relevance (SR) and productivity (SP). In terms of TP, the TWWT has attracted great attention worldwide, especially in Asian countries, which contributed 40 % of the world's research articles. Within this region, India and China have emerged as leaders in TP and SP indicators and play a central role in international cooperation networks. In the Americas, the United States and Brazil have made significant contributions to TP and SP, while Spain stands out in Western Europe, probably due to its emphasis on the reuse of industrial wastewater.

Despite the dominance of India and China in TP and SP, it is interesting to observe that other countries such as the United States and Spain perform better in terms of SR, which raises relevant questions about the content, quality, relevance and visibility of research conducted in Asia.

To assess the relationship between the bibliometric indicators for the main countries and the most researched treatments, a map of keyword coincidence was used. The analysis of representative countries — India, China, the United States, Brazil and Spain— - shows a trend towards chemical treatments, particularly AOP/UV methods, including PC and PFT, which are effective but pose financial and operational challenges. A promising prospect is the combination of these methods with emerging biological treatments, which offer a pragmatic approach to reducing toxicity and improving the biodegradability of wastewater. In addition, the integration of adsorption processes using biochar or natural adsorbents offers an opportunity to develop more environmentally friendly technologies for industrial wastewater treatment.

In the investigation of pollutants, the focus has been on four primary dye groups — azo, direct, reactive and basic dyes. While MB and CR have been central to the study of synthetic effluents in the laboratory, the increasing importance of studies on reactive dyes, which are widely used in the textile industry, underlines the need for further studies in real water samples to adapt them to operational conditions.

In terms of trends, the S-curve analysis shows that chemical and biological TWWTs dominate due to their high efficiency. However, further research on AOPs is essential to improve their cost-benefit ratio. Chemical and physical treatments take longer to reach saturation compared to biological treatments, indicating a significant area for R&D. For biological treatments, while bacteria-based approaches are being extensively researched and developed, microalgae are emerging as a promising area of research due to their ability to virtually eliminate colorants in wastewater and their potential for the production of bioenergy and valuable compounds.

CRediT authorship contribution statement

Néstor A. Urbina-Suarez: Conceptualization, Methodology, Validation, Formal analysis, Investigation, Writing – original draft, Writing – review & editing. **Astrid C. Angel-Ospina:** Formal analysis, Investigation. **German L. Lopez-Barrera:** Methodology, Validation. **Andrés F. Barajas-Solano:** Methodology, Validation. **Fiderman Machuca-Martínez:** Conceptualization, Writing – review & editing, Supervision, Funding acquisition.

Declaration of competing interest

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.

Data Availability

Data will be made available on request.

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