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Review

Microalgal-based industry *vs.* microplastic pollution: Current knowledge and future perspectives

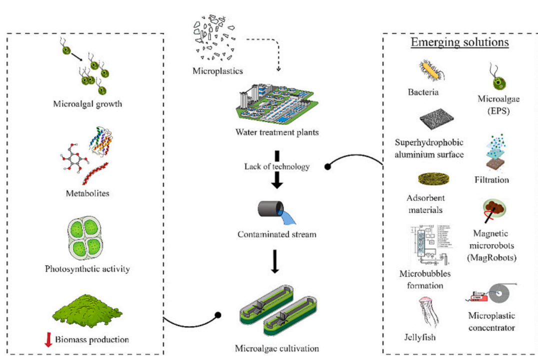
Ivana Mendonça, Marisa Faria, Filipa Rodrigues, Nereida Cordeiro *

LB3 - Faculty of Science and Engineering, University of Madeira, Portugal
CIIMAR – Interdisciplinary Centre of Marine and Environmental Research, University of Porto, Portugal

HIGHLIGHTS

- MPs in water directly impact microalgal biomass production and its quality.
- Water free of microplastics is vital for the microalgae industry's success.
- Strict guidelines and MPs controls are key for post-treatment water quality.
- Biodegradable materials provide sustainable solutions to MPs pollution.

GRAPHICAL ABSTRACT



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ABSTRACT

Microalgae can play a crucial role in the environment due to their efficient capture of CO_2 and their potential as a solution for a carbon-negative economy. Water quality is critical for the success and profitability of microalgal-based industries, and understanding their response to emergent pollutants, such as microplastics (MPs), is essential. Despite the published studies investigating the impact of MPs on microalgae, knowledge in this area remains limited. Most studies have mainly focused on microalgal growth, metabolite analysis, and photosynthetic activity, with significant discrepancies in what is known about the impact on biomass yield. Recent studies show that the yield of biomass production depends on the levels of water contamination by MPs, making it necessary to reduce the contamination levels in the water. However, present technologies for extracting and purifying water from MPs are limited, and further research and technological advancements are required. One promising solution is the use of bio-based polymer materials, such as bacterial cellulose, which offer biodegradability, cost-effectiveness, and environmentally friendly detoxifying properties. This review summarises the current knowledge on MPs pollution and its impact on the viability and proliferation of microalgae-based industries, highlights the need for further research, and discusses the potential of bio-solutions for MPs removal in microalgae-based industries.

* Corresponding author.
E-mail address: ncordeiro@staff.uma.pt (N. Cordeiro).

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1. Introduction

The intersection of the expanding microalgal-based industry and the escalating issue of microplastic (MPs) pollution presents a critical meeting of environmental science, industrial innovation, and sustainable practices. Microalgae, a diverse group of microscopic photosynthetic organisms, has garnered significant attention for its potential applications in biotechnology, biofuel production and aquaculture (Camacho et al., 2019; Kandasamy et al., 2022; Morais Junior et al., 2020; Zhuang et al., 2022). However, alongside the growth of the microalgal-based industry, the unintended consequences of human activity have become increasingly evident – the proliferation of MPs in ecosystems.

MPs pose severe risks to marine life, ecosystems, and human health in terrestrial and aquatic environments worldwide. New research findings have revealed that microalgae, the cornerstone of aquatic food webs and primary producers, are not immune to the pernicious influence of MPs (Mendonça et al., 2023; Prata et al., 2018). With far-reaching ecological implications, these microparticles can interact with microalgae in such behaviour that alters their growth, physiology, and nutritional quality (Xu et al., 2023; Zheng et al., 2021), affecting the economic viability of the microalgae-based industries and their by-products.

The dynamic realm of microalgal research, coupled with emerging technologies and innovative solutions, aims to tackle the challenges posed by MPs pollution, emphasising the significant role of microalgae in carbon sequestration and a sustainable bioeconomy. This review aims to deepen insights into the interplay between MPs and microalgae, offering a comprehensive overview of their mutual impact, especially concerning the viability and sustainability of microalgae-based industries and their by-products. Furthermore, it sheds light on potential remedial measures using bio-based materials, like bacterial cellulose, in mitigating MPs pollution within these industries.

In the meticulous execution of this review, a set of specific, carefully chosen criteria guided the selection process for studies included in the comprehensive analysis. The selected studies had a direct connection to the microalgal-based industries, exploring the impact of MPs on microalgae and examining technologies for MPs removal. The criteria placed a premium on the publications' relevance to these subjects, employing specific search terms like 'microalgae and industry,' 'microalgae and microplastic,' and 'microplastic and removal.' Furthermore, priority was given to the inclusion of peer-reviewed original research articles and reviews. This approach ensures a precise alignment with the overarching objectives of the review, which delves into the intricate interplay within the microalgal-based industries and sheds light on the multifaceted challenges of MPs pollution and innovative solutions for their removal.

2. Microalgal industry

Microalgae comprise a diverse array of photosynthetic microorganisms that grow in various environments, including fresh-, sea- and

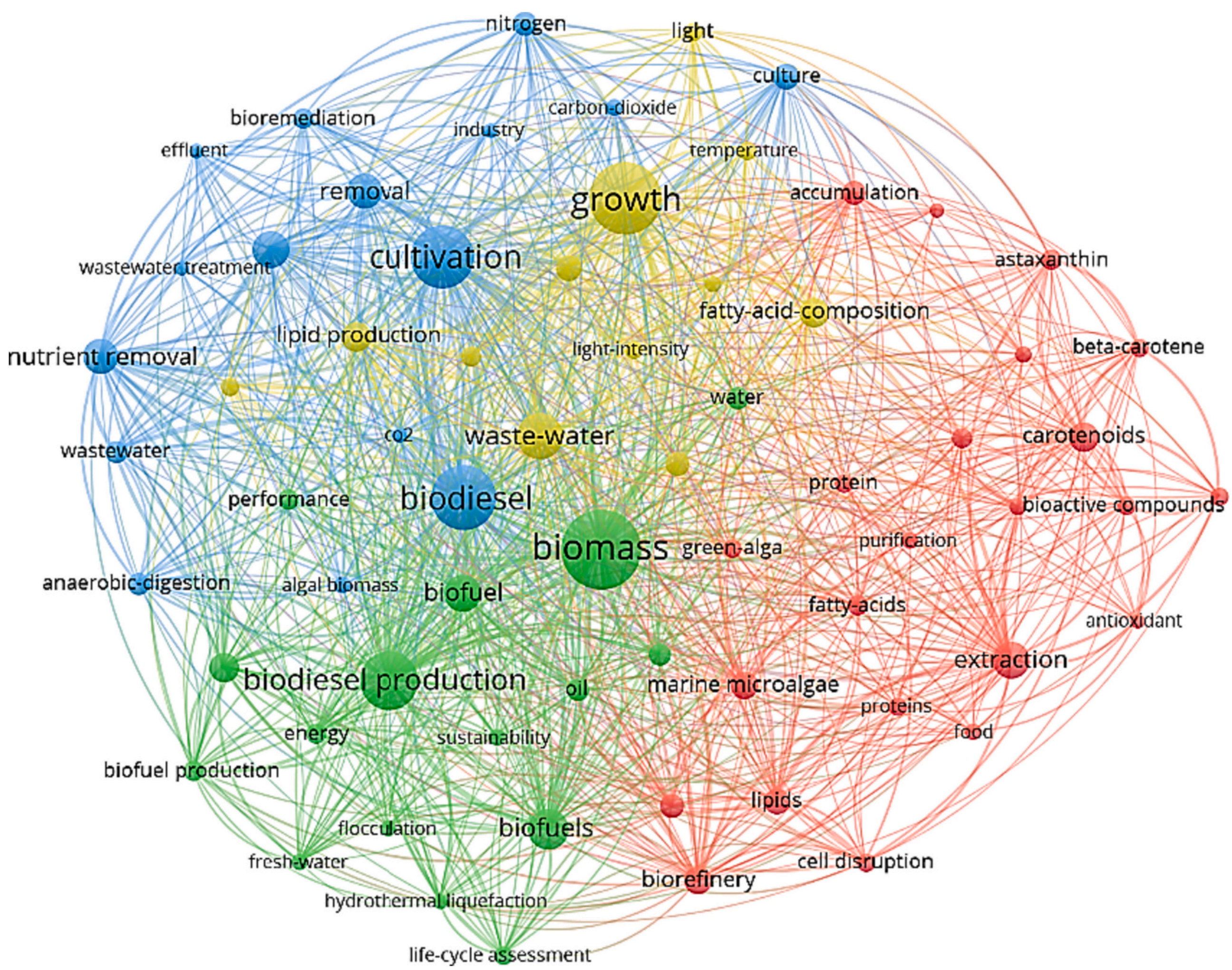

Fig. 1. Main concepts and concepts network, obtained from VOSviewer software ("VOSviewer," 2023), identifying hotspots in bibliometric research of "*microalgae AND industry*" in the web of science database ("Clarivate. Web of Science," 2023).

brackish waters, soils, rocks, and trees (Borowitzka, 2018; Buono et al., 2014). Various bioactive compounds can be found in them, making them useful in several commercial applications. Production of microalgae on an industrial scale kicked off in Japan in the early 1960s when *Chlorella* (Fig. 1, *extraction* and *growth* clusters in red and yellow, respectively) was introduced as a food additive (Araújo et al., 2021; Buono et al., 2014). Between 1960 and 1990, there was a limited amount of development. However, the energy crisis at the start of the 21st century influenced the development of microalgae favourably toward the concept of a possible source of biofuels (de la Jara et al., 2016). With the

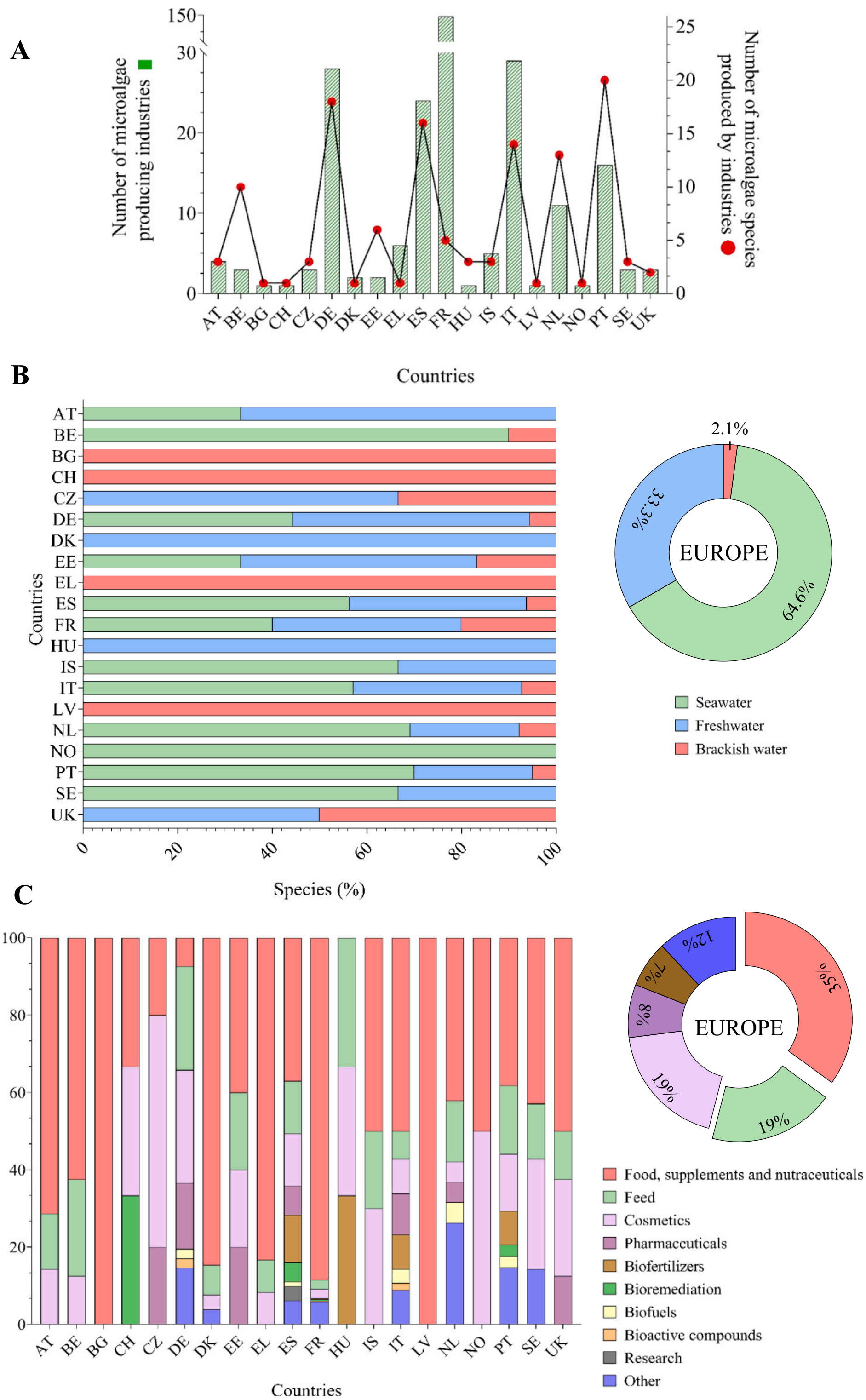

Fig. 2. Microalgae production in Europe: (A) Number of industries producing microalgae biomass *vs.* number of species exploited in Europe; Relative abundance of: (B) the different microalgae aquatic system species in Europe; (C) the different applications of biomass by industries in Europe. AT - Austria; BE - Belgium; BG - Bulgaria; CH - Switzerland; CZ - Czech Republic; DE - Germany; DK - Denmark; EE - Estonia; EL - Greece; ES - Spain; FR - France; HU - Hungary; IS - Iceland; IT - Italy; LV - Latvia; NL - Netherlands; NO - Norway; PT - Portugal; SE - Sweden; UK - United Kingdom. Based on EMODnet and Joint Research Centre databases ("Microalgae | EMODnet Human Activities," 2023; "The bioeconomy in different countries | Knowledge for policy," 2023).

high price of crude oil at the time, it was crucial to discover a sustainable and economically viable fuel alternative (Fig. 1, *biomass* cluster in green) as soon as possible (Li et al., 2020). This crisis made major energy firms interested in microalgae biotechnology invest considerably in pursuing that goal. Despite all efforts, the yield from the current production systems significantly lagged behind the anticipated values from laboratory tests, making sufficient bioenergy production from microalgae still unattainable. Nonetheless, this led to a breakthrough in technology and production capacity, which currently enables an increase in commercial microalgae use (Garrido-Cardenas et al., 2018). Nowadays, microalgae present with a wide range of emerging products (Fig. 1, *cultivation* cluster in blue), including agriculture-related products (biofertilisers, biostimulants and biopesticides), wastewater treatment, bioplastics, among others (Fernández et al., 2021; Rumin et al., 2020).

While the commercial potential of microalgae is evident, certain limitations and avenues for further investigation are noteworthy. The challenges in scaling-up production to meet laboratory-based expectations need a more in-depth exploration of optimisation strategies. Additionally, a critical assessment of the ecological and environmental impacts of large-scale microalgae cultivation is vital, as it can have unforeseen consequences on local ecosystems and biodiversity. Finally, considering the vast array of applications, there is a need for thorough investigations into the safety and regulatory facets of products derived from microalgae. These studies are essential to guarantee the safety of consumers and the responsible management of environmental resources.

To obtain an extensive comprehension of the bibliometric landscape within the domain of "*microalgae AND industry*", this investigation thoroughly explored collaboration and co-citation networks. Fig. S1 serves as a valuable resource, providing multifaceted insights into this research domain. In the realm of collaborative research, particularly within country and institution collaboration networks (Fig. S1A and B), notable trends were uncovered. Specifically, the People's Republic of China emerged as a prominent leader in fostering collaborative research in this field, with crucial contributions originating from renowned institutions such as the Chinese Academy of Sciences.

Simultaneously, the investigation extended into the co-citation networks encompassing journals, authors, and articles (as depicted in Fig. S1C, D, and E). These networks unveiled critical sources that have significantly influenced the discourse surrounding "*microalgae AND industry*". Bioresource Technology emerged as the foremost journal in this subject, underlining its profound impact in the field. The author most frequently cited in the scholarly literature is M. A. Borowitza, attesting to their significant contributions. The publication by Chisty (2007) has garnered remarkable citation frequency, solidifying its status as the most cited reference in this dynamic research landscape.

According to the latest data from EMODnet, there are currently 400 microalgae-producing industries in Europe (Fig. 2A) distributed across 20 countries (Microalgae|EMODnet Human Activities, 2023). France, Italy, Germany, and Spain have the highest number of microalgae industries (each with >20). France stands out as the epicentre of this production, contributing to 50 % of Europe's total output. It's also worth highlighting that a significant portion of Europe's microalgae production is situated away from coastal regions, predominantly taking place in the interior regions of the continent.

However, beneath this promising growth, several limitations and areas for further exploration warrant attention. Firstly, the geographical distribution of these industries, including a significant presence away from coastal regions and in the continent's interior, raises questions about the environmental impact of inland microalgae cultivation. Detailed environmental assessments, including water use, land management, and waste disposal, are necessary to understand and mitigate potential ecological consequences. Moreover, it is essential to consider the regulatory framework and standards governing microalgae production in Europe. Critical assessments of current regulations, followed by necessary adjustments, could help maintain industry growth while safeguarding environmental and consumer interests.

Only a small portion of the naturally occurring microalgae species (Fig. 2A) is used for commercial purposes due to environmental, economic, and regulatory issues (Vigani et al., 2015). Along with *Arthrospira maximum* (Spirulina), microalgae *Chlorella* spp., *Nannochloropsis* spp., and *Haematococcus pluvialis* are the most extensively exploited and over the last 20 years, have reportedly been among those employed the most, in biotechnology applications globally (Araújo et al., 2021; Fernandes and Cordeiro, 2021). Other microalgae from the *Tetraselmis*, *Isochrysis*, *Porphyridium*, and *Scenedesmus* genus, are also among the most cultivated microalgae in Europe (Araújo et al., 2021). Portugal, Germany, and Spain are the top three European countries in terms of exploiting the greatest variety of microalgae species (Fig. 2A). European-wise, marine microalgae account for 65 % of industrial production (Fig. 2B), while inland countries tend to focus more on exploiting more fresh- and brackish water microalgae.

Utilising only a small fraction of naturally occurring microalgae species for commercial purposes restricts the industry's potential and poses challenges related to biodiversity preservation. Therefore, research should focus on understanding the regulatory, economic, and environmental factors hindering lesser-known microalgae species' use, and evaluating the untapped potential of underutilised species could contribute to increased biodiversity in the microalgae industry. Furthermore, evaluating the environmental footprint of inland microalgae cultivation is crucial to ensure ecological sustainability and address any unforeseen environmental consequences.

Microalgae contain diverse bioactive compounds that make them useful in a wide range of commercial applications. >54 % of European microalgae industries primarily dedicate their biomass to feed and food markets, including human food, food supplements, and nutraceuticals. Cosmetics, pharmaceuticals, and fertilisers also rank as top sectors (Fig. 2C). Although microalgae production in Europe is primarily allocated to these purposes, emerging markets, such as bioremediation in Switzerland, and investment in bioactive compounds in countries like Germany and Italy, indicate many additional potential future applications for microalgae.

Given the wide range of applications for microalgae, further research is needed to explore innovative and sustainable technologies for large-scale cultivation. This could help address production limitations, optimise resource use, and reduce the environmental footprint associated with microalgae industries. Further, the emphasis on certain sectors, such as feed and food markets, may overshadow the sustainability, environmental impact, and regulatory requirements of other applications like cosmetics, pharmaceuticals, and fertilisers. Therefore, comprehensive research should delve into the sustainability and regulatory demands of various sectors. This could guide industry practices and ensure responsible growth by accounting for the diverse impacts and requirements of each sector.

While microalgae biotechnology holds great promise, producing high-quality microalgal biomass poses significant challenges. Microalgae require specific environmental conditions to grow, including appropriate light intensity, temperature, nutrient availability, and water quality. Ensuring these conditions can be challenging, especially when scaling up from laboratory to industrial production. Moreover, a reduction in biomass and/or by-product production can significantly influence the final costs of marketable goods. Thus, it's crucial to meet these requirements to produce an economically desirable end-product. Efforts are being made to identify resilient microalgae strains with higher growth and biomass rates, improved nutrient uptake, and enhanced by-product production. By addressing these challenges, the microalgae industry has the potential to offer sustainable solutions for a wide range of applications, both in currently explored domains and new areas yet to be tapped commercially.

Meeting specific environmental conditions for microalgae growth, especially when transitioning from laboratory to industrial scales, remains a significant challenge. Variability in biomass and by-product production can affect cost-effectiveness. Therefore, research should focus on consistent, cost-effective, and large-scale production strategies. Identifying robust microalgae strains with enhanced growth rates, improved nutrient utilisation, and increased by-product production is essential to overcome these challenges and produce economically desirable end-products.

3. Microalgae *vs.* microplastics

Given the pivotal role microalgae play in both the ecosystem and microalgae-centric industries, it becomes essential to comprehend how these organisms react to various emerging contaminants. With MPs emerging as a significant global concern, the unknown potential effects of this pollutant on microalgae warrant further investigation. Therefore, in-depth research is required to unravel the intricate mechanisms by which microalgae are affected by different types, sizes, and concentrations of MPs. Understanding these interactions is pivotal to gauging the full extent of the ecological and environmental repercussions.

The National Oceanic and Atmospheric Administration defined MPs as plastic particles of all shapes and sizes, smaller than five millimetres (5 mm) in length (NOAA, 2020). These particles are persistent and pervasive contaminants. They can originate either from the fragmentation of larger polymers into smaller pieces due to environmental factors or be intentionally produced for commercial applications (Fig. 3) (Andrady, 2011; Browne et al., 2011). MPs have been documented in practically every ecosystem, including urban networks (Dey et al., 2021), marine (from the equator to the polar regions), and freshwater (Bergmann et al., 2015; Novotna et al., 2019) environments, as well as drinking, fresh and wastewater (Koelmans et al., 2019).

Among the vast array of MPs identified in these aquatic environments, some of the most commonly found include polystyrene (PS), polyethylene terephthalate (PET), polyvinyl chloride (PVC), polypropylene (PP), and polyethylene (PE) (Fig. 4) (Erni-Cassola et al., 2019; Rima, 2019; Wan et al., 2019).

Several studies have been conducted on how MPs affect microalgae (Table S1). However, the information available is still somewhat limited, as none of the studies have been done at an industrial scale. Conducting research at an industrial scale is crucial to assess whether the observed effects of MPs on microalgae in controlled settings hold true in real-world scenarios. Investigating the feasibility of implementing findings from lab-scale studies in industrial microalgae production is necessary.

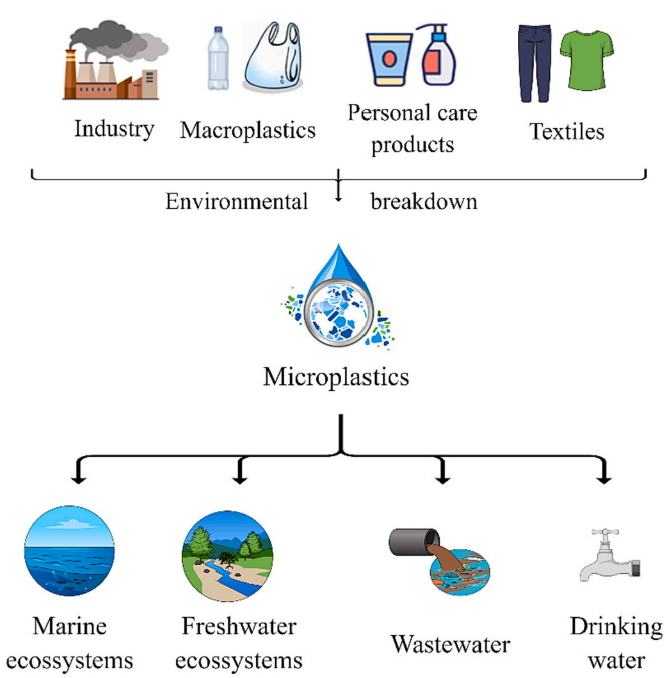

Fig. 3. Schematic representation of microplastics' origin/sources and destination.

The types of MPs commonly utilised in research of this kind are primarily found in aquatic settings, with PS accounting for 45 % and PE for 18 % of the total, predominately in fragment form (Fig. 5). The effects on microalgae, from freshwater to seawater (primarily during the exponential growth phase), have been examined using MPs ranging from spherical, to microbeads to fragments, with concentrations spanning from 0.001 to 5000 mg/L and diameters reaching up to 1000 μm (Fig. 5 and Table S1). Some of these studies have already indicated that MPs might adversely affect these primary producers. The impact on microalgae growth, specifically on microalgae density, is one of the most frequently assessed endpoints in such research (Fig. 6). Several studies have reported that these particles induce growth inhibition in several microalgal species (Casado et al., 2013; Hazeem et al., 2020; Li et al., 2020; Lin et al., 2020; Mao et al., 2018). The most widely recognised and discussed theory to explain this finding is that MPs particles may contribute to this reduction in growth by encouraging shading effects, obstructing algal pores, inhibiting gas exchanges, and negatively affecting photosynthesis and development (Bhattacharya et al., 2010). However, a few studies have reported a stimulating effect of MPs on the growth of certain microalgae species. Specifically, they noted an increase in microalgae density, as observed by Canniff and Hoang (2018), Cunha et al. (2019), Wu et al. (2021a), and Yokota et al. (2017). In contrast, some research, such as those by Sun et al. (2021b), Tunali et al. (2020), and Zhu et al. (2020), found that MPs might not have any significant impact on the growth processes of certain microalgae species. The observed variations in responses can be attributed to factors such as the type, size, concentration, and duration of exposure to the MPs. Moreover, given that microalgae have distinct cellular characteristics, elements like cell walls might influence MPs penetration or adsorption. Consequently, the responses can vary significantly depending on the specific species of microalgae in question (Chae et al., 2019; Fu et al., 2019). The diverse responses observed in different microalgal species to MP exposure underscore the need for a deeper understanding of species-specific reactions. Therefore, investigating the factors that contribute to these variations, including cellular characteristics like cell walls and metabolic pathways, is crucial. Research should aim to elucidate the underlying mechanisms that drive species-specific responses to MPs. In addition to their impact on microalgal growth, researchers have found that MPs may also impact microalgal photosynthesis (Fig. 6), as evidenced by the decreases in chlorophyll content and photosynthetic efficiency observed in response to the contaminant exposure (Tunali et al., 2020; Xiao et al., 2020; Zhang et al., 2017). MPs may hinder photosynthesis by a reduction in the expression of genes involved in the photosynthetic process (Lagarde et al., 2016), altering the electron donor sites, the photosynthesis centres, and the electron transport chains, which can also result in electron build-up and generation of reactive oxygen species that contribute to oxidative stress (Bhattacharya et al., 2010; Mao et al., 2018). Moreover, the presence of MPs could lead to alterations in the morphology of microalgal cells. Mao et al. (2018) and Seoane et al. (2019) reported that cells exposed to MPs may modify their energy metabolism to adapt to the stress conditions. Nonetheless, plenty of these effects appear to be transitory, with microalgae going through a susceptible phase before recovering as a consequence of adaptive processes (Cunha et al., 2020a; Yokota et al., 2017). Investigating the long-term consequences of MPs exposure and the mechanisms by which microalgae recover from initial stress is essential. Research on this subject could shed light on microalgae populations' resilience and capacity to adapt to prolonged MPs exposure.

As previously stated, in the numerous studies on this matter, microalgal growth is one of the most frequently explored parameters (*c. a.* 33 %), followed by the analysis of the metabolites and photosynthetic activity (Fig. 6). However, there are still significant gaps in the current

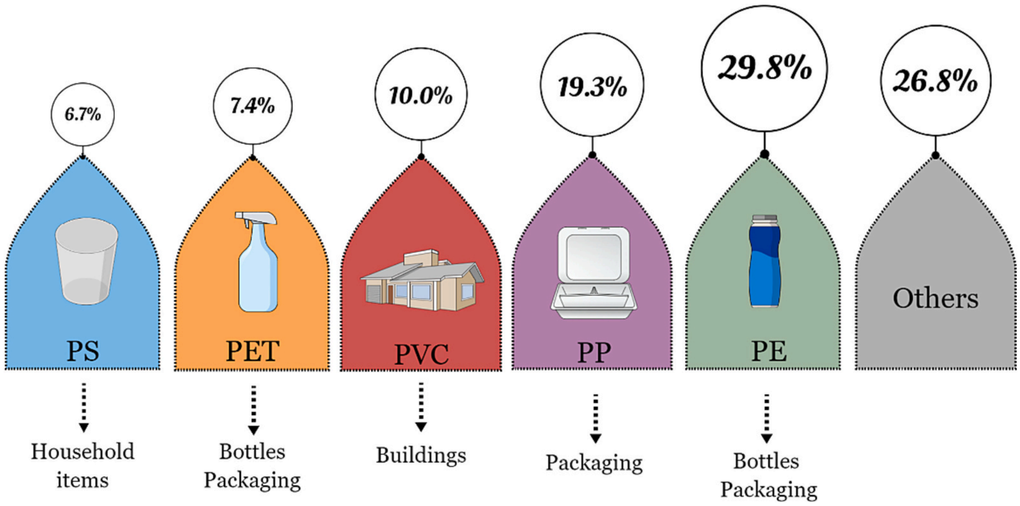

Fig. 4. Different types of microplastics and their principal uses worldwide. Based *on:* Setting the Facts Straight on Plastics | World Economic Forum, n.d.

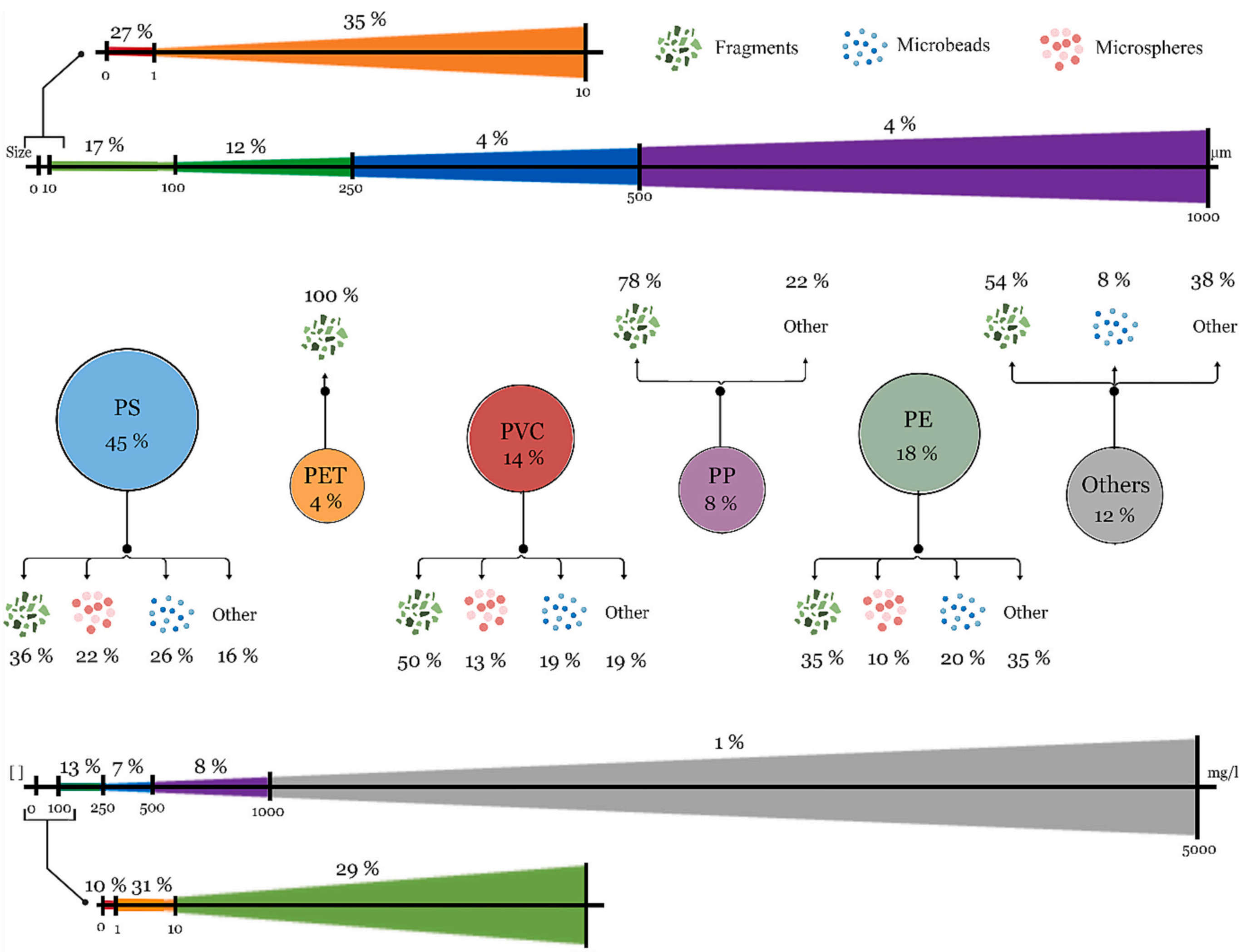

Fig. 5. Percentage breakdown of microalgae bioassay experiments with MPs exposure, including the types of microplastics, shapes used, sizes examined, and concentrations studied (based on Table S1).

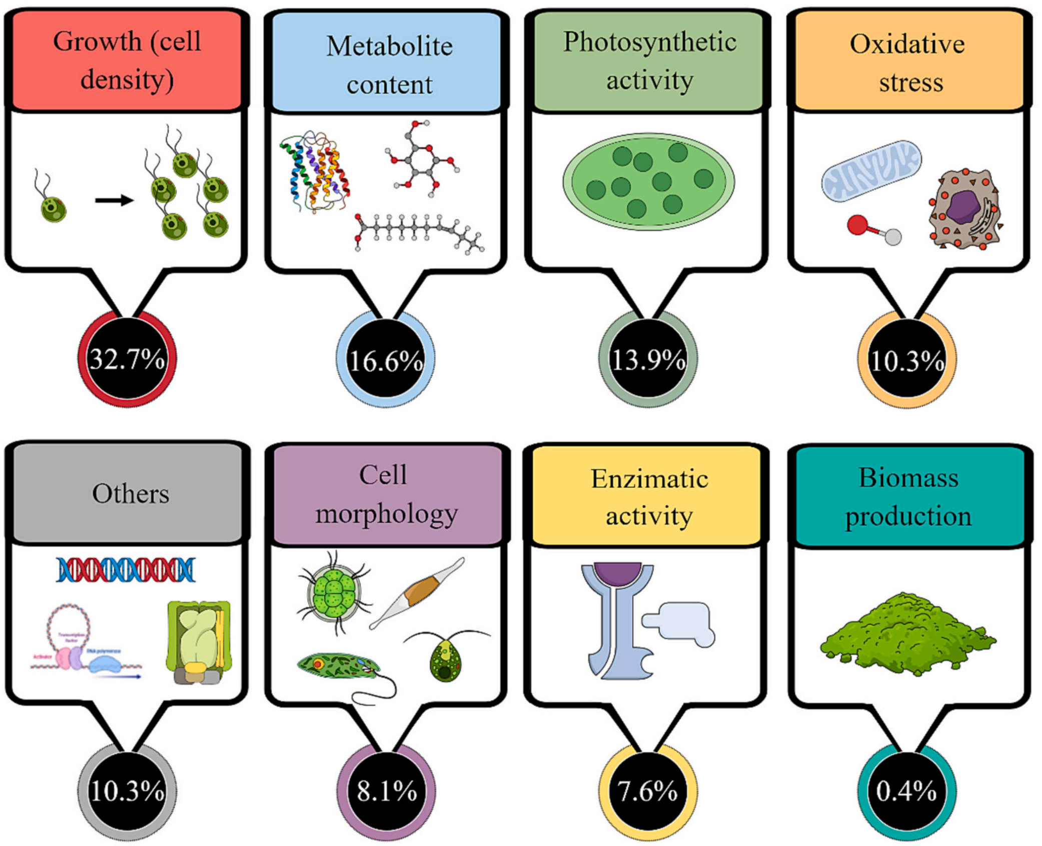

Fig. 6. Relative abundance of parameters studied in research investigating the impact of MPs on microalgae (based on Table S1).

understanding regarding biomass production. Among the existing studies, only two published works have investigated the influence of MPs on biomass yield (Cunha et al., 2020a; Mendonça et al., 2023). These studies revealed that some microalgae species experienced considerable reductions in biomass production, with decreases of up to 50 %. These reductions in biomass yield were primarily attributed to a decrease in single-cell weight, and in some cases, the production of smaller-sized cells. In light of this, it is crucial to determine and understand how this type of contaminant affects microalgae that are economically relevant to the industry. While these studies have highlighted reductions in biomass production, a comprehensive assessment of the economic impact of these reductions is lacking. Therefore, research should not only focus on understanding the biological aspects but also assess the economic consequences of reduced biomass yield in microalgae-based industries. Evaluating the cost-effectiveness of potential mitigation strategies is necessary for informed decision-making. Moreover, bridging the gap between research and industry practices is often challenging. So, promoting collaborative efforts between academia, industry, and regulatory bodies could facilitate the translation of research findings into practical solutions for mitigating the negative impacts of MPs on biomass production. This collaborative approach could also help ensure the sustainability of microalgae-based industries.

Considering that in microalgae-based industries, water quality is an essential criterion and essential element when it comes to biomass production, it is important to find effective methods of mitigating the negative impacts brought on by the presence of MPs.

4. Microplastic removal

Among several other sources, the contribution of wastewater effluents to MPs pollution in aquatic environments has recently gotten a significant amount of attention (Carr et al., 2016; Sun et al., 2019). Within the wide range of microalgae-based industries, each has its distinctive manufacturing procedures and methods, which may involve water from various sources. Potential sources of water for microalgae cultivation include wastewater treatment plants (WWTPs), drinking water treatment plants (DWTPs), well as fresh and seawater environments (Fig. 3). Given that water quality is one of the most vital parameters in microalgae production, it is imperative to ensure that the water used is free of contaminants that could have serious negative repercussions on the quality of the end products (Cunha et al., 2020a; Mendonça et al., 2023).

As discussed earlier, MPs represent a growing worldwide concern; therefore, removing this contaminant from water sources for microalgal production is of utmost importance (Fig. 7).

A bibliometric analysis was conducted to pinpoint the primary research hotspots in the realm of MPs removal. The network visualisation depicted in Fig. 8 reveals three correlated clusters. The prominent *blue cluster* addresses MPs contamination in aquatic ecosystems. The *red cluster* illustrates the current status of MPs pollution, while the *green cluster* predominantly concentrates on water treatment plants' contamination by MPs, covering both wastewater and drinking water treatment facilities.

Fig. S2 comprehensively depicts collaboration and co-citation networks in the context of "*microplastic AND removal*", contributing to a deeper understanding of the bibliometric scenery in this specific domain. These networks, as illustrated in Fig. S2A and B, delve into the collaborative dynamics among countries and institutions, revealing notable patterns in research cooperation. Notably, the analysis highlights the resurgence of the People's Republic of China as a central hub for collaborative research, closely engaging esteemed institutions such as the Chinese Academy of Sciences. Furthermore, Fig. S2C, D, and E offer a profound insight into the co-citation networks of journals,

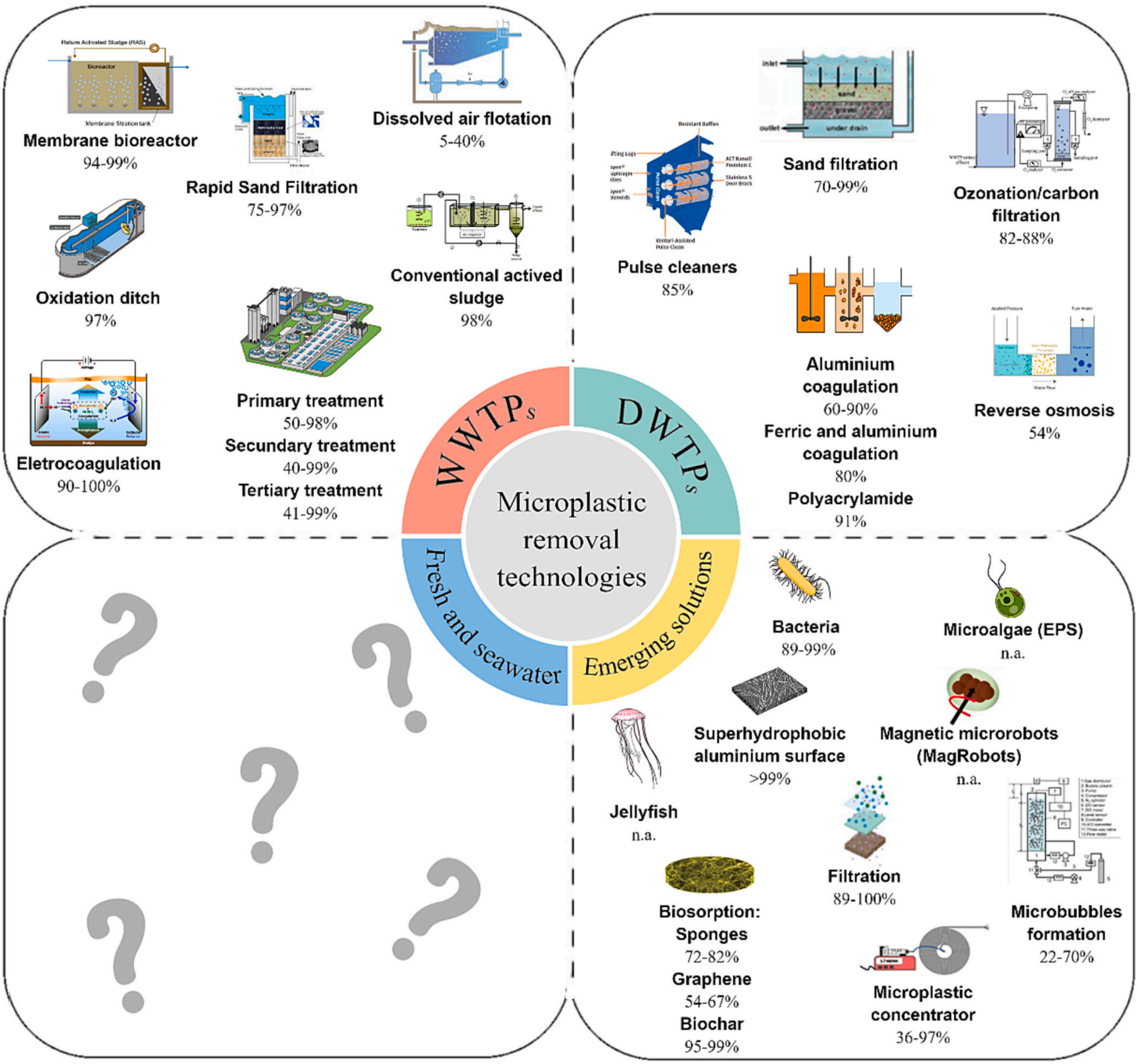

Fig. 7. Technologies for MPs removal and their efficiency (%) across various aquatic environments, which may serve as water sources for microalgae-based industries. Environments covered include wastewater treatment plants (WWTPs), drinking water treatment plants (DWTPs), and fresh and seawater habitats. Additionally, emerging solutions are also highlighted. n.a.: not available. Based on: Petroody et al., 2020; Dris et al., 2015; Hongprasith et al., 2020; Michielssen et al., 2016; Murphy et al., 2016; Tagg et al., 2020; Alvim et al., 2021; Edo et al., 2020; Lee and Kim, 2018; Zhang and Chen, 2020; Ziajahromi et al., 2021; Blair et al., 2019; Mintenig et al., 2019; Ziajahromi et al., 2017; Bayo et al., 2020; Lv et al., 2019; Lares et al., 2018; Hidayaturrahman and Lee, 2019; Bilgin et al., 2020; Talvitie et al., 2017; Perren et al., 2018; Novotna et al., 2019; Xue et al., 2021; Prokopova et al., 2021; Ma et al., 2019; Pivokonsky et al., 2018; Dalmau-Soler et al., 2021; Wang et al., 2020; Sarkar et al., 2021; Risch and Adlhart, 2021; Sun et al., 2020; Sun et al., 2021a; Wang et al., 2021b; Yuan et al., 2020; Liang et al., 2019; Yogarathinam et al., 2022; Kuoppamäki et al., 2021; Wang et al., 2022; Chen et al., 2022; Rius-Ayra and Llorca-Isern, 2021; Zhou et al., 2021; Cunha et al., 2019; Cunha et al., 2020b; Faria et al., 2022; Liu et al., 2021b; Lengar et al., 2021.

authors, and articles. Critical sources that have significantly shaped the discourse on "*microplastic AND removal*" are unveiled within these networks. Among the journals, Science of Total Environment stands out as a key journal in this field, underscoring its substantial influence. Additionally, the most cited author, J. Talvitie, is recognised for their pivotal contributions to the scholarly literature on this subject. Likewise, the article by Murphy et al. (2016) has garnered remarkable citation frequency, affirming its status as a central reference within this dynamic research landscape.

These networks provide invaluable insights into this research's collaborative and influential dimensions, enhancing the exploration of the dynamic and evolving research landscape within this specific domain.

Treatment processes in facilities like WWTPs and DWTPs play a pivotal role in mitigating MPs pollution in aquatic ecosystems. Yet, the efficacy of MPs removal can differ significantly depending on the treatment method and the specific type of plant, as illustrated in Fig. 7. Identifying the factors contributing to these variations and optimising treatment processes is crucial for enhancing MPs removal and reducing environmental contamination.

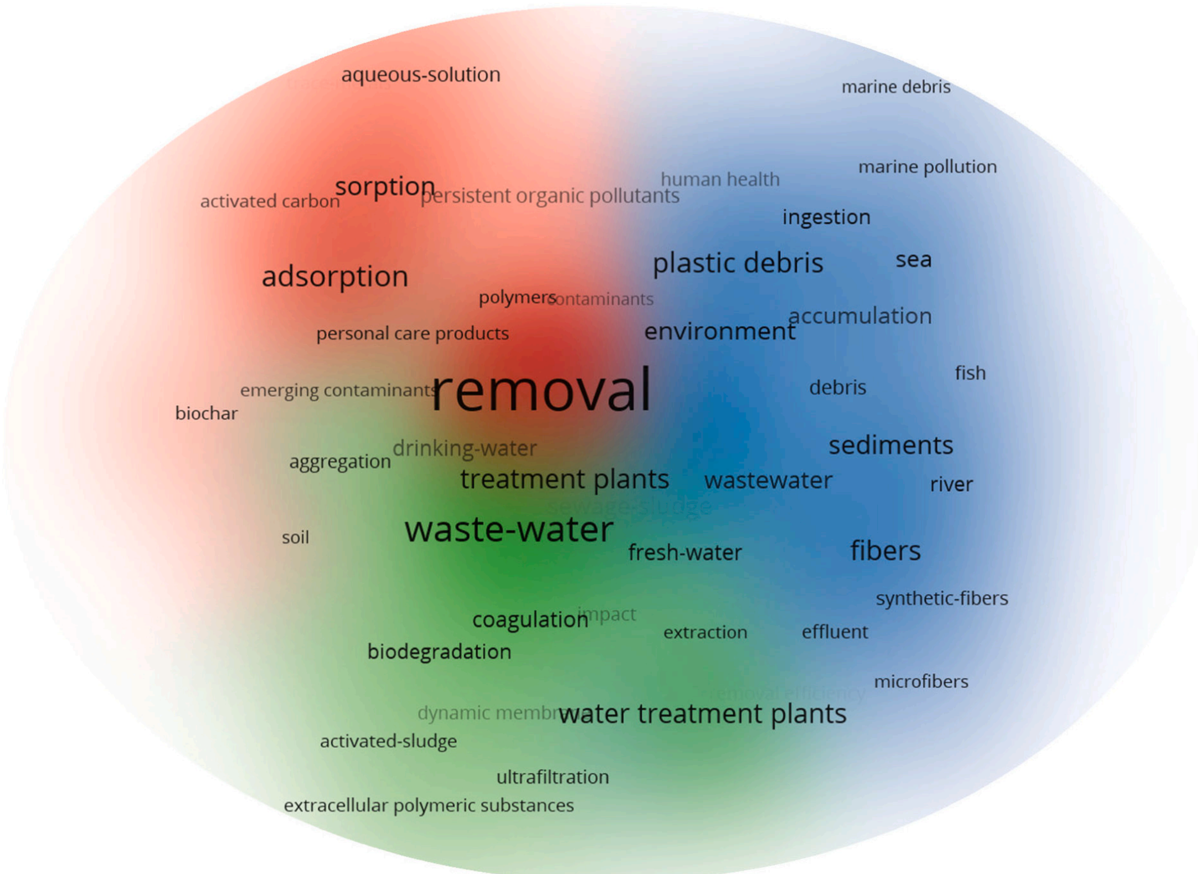

Fig. 8. Main concepts and concept network analysis obtained from VOSviewer software ("VOSviewer," 2023), identifying hotspots in bibliometric research of "*microplastic AND removal*" in the Web of Science database (Clarivate. Web of Science, 2023).

WWTPs primarily focus on primary and secondary treatments to eliminate MPs. Primary treatment aims to remove suspended solids, mainly by sedimentation and cause them to settle at the bottom of the storage tank as sludge (Talvitie et al., 2017; Wu et al., 2021b), while secondary treatment involves biochemical action treatment of the sewage (Michielssen et al., 2016). As most secondary effluents typically satisfy the prescribed legal discharge standards, tertiary treatment becomes optional (Sun et al., 2019).

Each step of the WWTP process aims to clean the water flow, but the efficiency of MPs removal varies based on the incoming wastewater's characteristics and influent periods (Cao et al., 2020; Zou et al., 2021). Various methods, including conventional activated sludge, oxidation ditch, rapid sand filtration, and dissolved air flotation, show diverse success rates (Bayo et al., 2020; Bilgin et al., 2020; Hidayaturrahman and Lee, 2019; Lares et al., 2018; Lv et al., 2019; Talvitie et al., 2017). Additionally, the emerging electrocoagulation process offers a higher removal efficiency (Perren et al., 2018). Among these, membrane-related technologies, especially membrane bioreactors (MBRs), demonstrate the highest efficiency, with up to 99 % removal (Bayo et al., 2020; Lv et al., 2019; Michielssen et al., 2016; Poerio et al., 2019). However, the use of polymeric membranes can contribute to MPs pollution, emphasising the urgency for sustainable alternatives.

Despite the diverse treatment processes, MPs smaller than 100 μm often persist in wastewater and pose challenges in removal (Azizi et al., 2022; Jiang et al., 2020; Sharma et al., 2021). The extent to which wastewater effluent contributes to the total MPs release remains uncertain, yet its potential environmental dispersion is concerning. As such, it's critical for WWTPs to innovate and refine their technologies, especially in removing smaller MPs. Therefore, research should focus on innovative technologies and methods specifically designed to address the removal of smaller MPs, which are of particular concern due to their potential environmental dispersion. These particles can contaminate both fresh and seawater ecosystems and impact industries dependent on clean water sources, including those centred around microalgae cultivation. Since this impact is not fully explored, research should extend to investigate the specific implications of MPs contamination in water sources for industries like microalgae cultivation. Assessing the economic and ecological consequences and developing tailored solutions is essential for industry sustainability.

To ensure the safety of drinking water, it has become increasingly significant to examine the MPs' whereabouts of **DWTP**. Coagulation-flocculation-sedimentation (CFS) processes are commonly used (Xue et al., 2021), with removal rates of up to 90 % using aluminium or ferric and aluminium sulphate as coagulants (Novotna et al., 2019; Prokopova et al., 2021; Xue et al., 2021). With Fe-based coagulants, removal efficiency could be slightly improved by adding polymeric flocculant polyacrylamide (Ma et al., 2019). When associated with other procedures, sand filtration could also be used to enhance the removal of MPs. However, this technology's biggest downside is that it tends to break down the MPs into smaller particles, making them even more challenging to remove, adding to MPs pollution (Phillips et al., 2016). Other methods (Fig. 7), including reverse osmosis, ozonation/carbon filtering, and pulse cleansers, demonstrate varying degrees of efficacy (Dalmau-Soler et al., 2021; Prokopova et al., 2021; Sarkar et al., 2021; Wang et al., 2020). Unfortunately, these methods are inefficient or are neither biodegradable nor ecologically friendly. Therefore, there should be a focus on developing and optimising biodegradable and sustainable methods for MPs removal in DWTPs. Moreover, the environmental impact of alternative treatment methods, including their by-products, should be thoroughly assessed to ensure sustainable and safe drinking water production.

MPs have been found in water supplies, pipe scales, and distribution systems, necessitating further improvements in the removal efficiency and stability of pipe scales (Chu et al., 2022; Eerkes-Medrano et al., 2019; Koelmans et al., 2019; Mintenig et al., 2019). Thus, additional research should address pipe scales' stability and removal efficiency, especially in the context of combating MPs pollution within water distribution systems. Additionally, investigating novel materials and techniques to enhance scale performance could contribute to the reduction of MPs in drinking water.

MPs are also present in sea and freshwater environments, where they impact aquatic life (Kühn and van Franeker, 2020; Li et al., 2018). Research on their elimination from natural ecosystems is still in the early stages, with no standardised procedures currently available. Thus, there is a critical need for advancing research in the removal of MPs from natural ecosystems. Standardised protocols for assessing and mitigating MPs in freshwater and marine environments should be developed to address this emerging environmental challenge.

In summary, while WWTPs and DWTPs employ a variety of methods to address MPs in water, the efficiency levels differ significantly. There's a pressing need for ongoing research and technological advancement, especially in the elimination of smaller particles, to ensure the protection of both human health and the environment.

5. Emerging solutions to MPs removal

In recent years, the issue of MPs pollution has surged to the forefront of environmental concerns, prompting a significant surge in research efforts focused on MPs removal. This escalating attention is evident in the growing number of scientific publications dedicated to this topic. Fig. 9 vividly illustrates this trend by showcasing the number of articles published between 2014 and 2023, as recorded in the Web of Science database. Notably, the topic has drawn researchers from various countries and disciplines, emphasising the global nature of both the problem and the response to it. The subsequent years witnessed remarkable leaps, as shown in Fig. 9. As of 2023, there are already an astonishing 323 articles dedicated to MPs removal, underscoring the unwavering commitment to addressing this critical issue.

As the world moves forward, the combined insights from these studies will be crucial in shaping global policies and practical solutions to combat MPs pollution.

Lately, natural bio-based polymer materials derived from renewable resources have sparked interest due to their biodegradable, cost-effective, environmentally friendly, and efficient detoxifying properties with little environmental impact (Vázquez-Núñez et al., 2020). However, while bio-based polymer materials and innovative methods offer promising avenues for MPs removal, there are challenges in scaling-up these approaches to address the vast quantities of MPs in contaminated waters. Therefore, there should be a focus on the scalability of these methods and the development of cost-effective large-scale solutions. This should include assessing the environmental impact of producing and implementing these innovative materials and technologies on a broader scale.

In the quest to combat MPs pollution in contaminated waters, various innovative methods have emerged. Biosorption (Fig. 7), employs adsorbent materials and has proven to be a viable option (Table 1). Sponges, with their intricate 3D porous structures, have shown promise in removing water contaminants, as well as 3D-reduced graphene oxide adsorbents (Risch and Adlhart, 2021; Sun et al., 2020, 2021a; Wang et al., 2021b; Yuan et al., 2020). Due to its numerous advantages, including cost-effectiveness and wide surface area, biochar can be enhanced with magnetic nanoparticles, reaching removal efficiencies of up to 99 % (Liang et al., 2019). It's important to note that several factors, such as pH, temperature, and adsorbent type, can influence MPs removal efficiencies (Wang et al., 2021a). Adsorption stands out as a desirable bioremediation solution due to its high MPs removal efficiencies, energy efficiency, and recyclability. However, a potential concern is the release of MPs back into the environment during the separation process from the adsorbent after use. In-depth environmental impact assessments are essential to fully understand the consequences of implementing these methods. This includes evaluating the long-term effects on ecosystems and the fate of released MPs, emphasising the need for sustainable solutions.

Filtration, solar-driven methods (microbubbles), and microfluidic technology (MPs concentrator) offer other effective approaches for MPs removal (Chen et al., 2022; Kuoppamäki et al., 2021; Wang et al., 2022; Yogarathinam et al., 2022). Moreover, innovative solutions such as superwettable materials and adhesive microrobots, inspired by the adhesive properties of mussels, have also been developed to enhance the efficient extraction of MPs (Rius-Ayra and Llorca-Isern, 2021; Zhou et al., 2021). While innovative solutions like these show promise, their long-term sustainability and environmental compatibility require in-depth evaluation. Future research should include a comprehensive assessment of the sustainability of these innovative solutions, considering factors like material sourcing, energy requirements, and potential secondary environmental impacts.

Jellyfish mucus has been explored as a unique bioflocculant material capable of sequestering PS-MPs in aquatic environments (Lengar et al.,

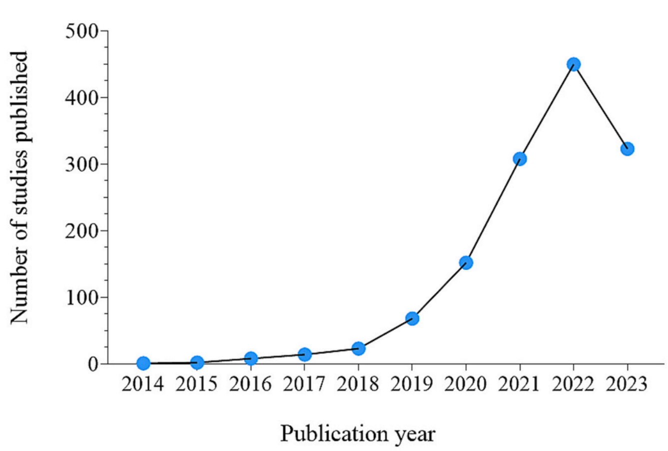

Fig. 9. Number of scientific articles obtained from VOSviewer software (VOSviewer, 2023), identifying hotspots in bibliometric research of "*micro-plastic AND removal*" in the Web of Science database (Clarivate. Web of Science, 2023).

Table 1
Emerging technologies for MPs removal and efficiency (%).

Removal technologies	Removal efficiency (%)	References
Biosorption:		
Sponges	72–82	Risch and Adlhart, 2021; Sun et al., 2021a,b; Wang et al., 2021b
Graphene	54–67	Yuan et al., 2020
Biochar	95–99	Liang et al., 2019
Filtration	89–100	Kuoppamäki et al., 2021; Yogarathinam et al., 2022
Electrocoagulation	22–70	Perren et al., 2018
Microbubble formations	36–97	Wang et al., 2022
MPs concentrator	>99	Chen et al., 2022
Superhydrophobic aluminium surface	*n.a.*	Rius-Ayra and Llorca-Isern, 2021
Magnetic microrobots	*n.a.*	Zhou et al., 2021
Jellyfish	*n.a.*	Lengar et al., 2021
Microalgae	*n.a.*	Cunha et al., 2019; Cunha et al., 2020a,b
Bacteria	89-99	Faria et al., 2022; Mendonça et al., 2022

n.a.: not available.

2021) (Fig. 7; Table 1). Recent research has also identified certain microalgae, such as *Tetraselmis* sp., *Gloeocapsa* sp., *Cyanothece* sp., *Microcystis panniformis*, and *Scenedesmus* sp., that produce exopolymer substances (EPS), are suitable for aggregating MPs and forming hetero-aggregates, thus potentially serving in phytoremediation processes (Cunha et al., 2019; Cunha et al., 2020a). Nonetheless, while jellyfish mucus and microalgae-based bioflocculants show promise in sequestering MPs, there are practical challenges in harvesting these materials in sufficient quantities for large-scale application. Hence, upcoming research should focus on developing efficient and sustainable methods for harvesting and producing these bioflocculants in quantities suitable for practical environmental remediation. Moreover, the effectiveness of bioflocculant can vary depending on the species, environmental conditions, and the types of MPs present. So, additional studies should aim to identify the optimal conditions and species for bioflocculant production. Standardisation of bioflocculant properties and applications could enhance their reliability in MPs removal processes.

Microbial biopolymers have also shown high removal efficiencies, up to 99 % (Liu et al., 2021b; Faria et al., 2022; Mendonça et al., 2022). Bacterial cellulose (BC) stands out for its remarkable versatility and wide range of applications across various industries (Azeredo et al., 2019; Liu et al., 2020; Swingler et al., 2021). Its distinctive structural features, biocompatibility, and biodegradability make it an auspicious choice for the removal of MPs and a range of other environmental applications (Faria et al., 2022; Mendonça et al., 2022). However, while BC and microbial biopolymers show high removal efficiencies for MPs, forming and maintaining biofilms for practical applications can be operationally challenging. The stability and robustness of biofilms in dynamic aquatic environments are areas of concern. Thus, methods to enhance the stability and longevity of biofilms and understanding the factors influencing biofilm detachment and regrowth are crucial for real-world applications. Furthermore, the environmental impact of large-scale production and disposal of microbial biopolymers, also needs further examination. Questions regarding biodegradability, waste management, and potential unintended ecological consequences should be addressed. This includes assessing their long-term biodegradability in natural environments and exploring sustainable production processes.

In summary, various innovative methods, from biosorption and filtration to bioflocculants and microbial biopolymers, hold promise for effectively removing MPs from aquatic environments, addressing a critical environmental concern.

6. Research perspectives and recommendations

Microalgae-based industries hold substantial potential within the bio-based sector, offering a wide array of promising applications in various commercial domains. However, the successful cultivation of microalgal biomass relies heavily on maintaining precise environmental conditions to ensure optimal quality. Recent data highlight a growing concern that threatens the viability of microalgal-based industries – the presence of MPs in the waters (Mendonça et al., 2023; Cunha et al., 2020a).

The pervasiveness of MPs in various water sources highlights the need for effective regulation to improve water quality. Water quality emerges as a paramount factor influencing the outcomes of microalgal-based industries, directly impacting biomass production and final product quality. Detection and monitoring of MPs are essential for understanding the scale of the problem and assessing the effectiveness of mitigation measures. Unfortunately, there is currently no universal method for detecting MPs in water, making it difficult to compare results across studies and monitor trends over time. Advanced detection methods must become essential to identify and quantify the presence of MPs in diverse environments, from oceans to water supply systems. Only through these sophisticated methods can we truly understand the extent of the MPs pollution problem. Recently, detailed studies have unveiled the alarming scope of this phenomenon, underscoring the urgent need for actions to mitigate the harmful impacts of MPs on our ecosystems and human health (Blair et al., 2019; Chu et al., 2022; Dey et al., 2021).

As such, innovation becomes imperative. Regulatory agencies should establish standardised guidelines for acceptable MPs concentrations in different types of water bodies, such as drinking water, wastewater, and natural aquatic environments. This will ensure that water treatment facilities can comply with the established standards, protecting public health and the environment. Additionally, policymakers should consider implementing stricter regulations governing industrial waste disposal, particularly in regions where microalgal cultures are prevalent. Exploring alternative water sources, such as treated wastewater devoid of MPs, represents another avenue to explore. Encouraging collaborative research and development efforts from academia, industry, and government agencies can foster the creation of novel technologies and strategies to effectively remove MPs from water sources. Additionally, increasing public awareness of MPs pollution and promoting responsible consumption and waste management practices can help reduce the input of MPs into the environment. Governments should also take a proactive approach to addressing MPs pollution by implementing stringent regulations for industries that contribute to the problem. These may include imposing restrictions on the production and use of single-use plastics, encouraging the development of biodegradable alternatives, and promoting recycling and circular economy initiatives.

Newly published work has spotlighted BC as a promising solution to this pressing challenge. BC presents itself as a biodegradable and environmentally friendly material with exceptional capabilities in eliminating MPs from water sources. Its high adsorption capacity and cost-effectiveness make it a compelling choice for water treatment. Furthermore, BC aligns with the vision of a circular and sustainable alternative, extending its appeal.

In conclusion, addressing the MPs pollution problem requires a concerted effort from all stakeholders. Establishing effective methods for MPs concentrations in water, developing standardised detection methods, and fostering innovation in water treatment technologies are essential steps toward improving water quality and safeguarding public and environmental health. Through collaborative efforts, the global challenge can be surmounted, ensuring a sustainable future for generations to come. By prioritising regulatory measures and the development of effective mitigation strategies, the continued growth and sustainability of microalgal-based industries can be ensured while protecting water quality for future generations.

CRediT authorship contribution statement

Ivana Mendonça: Conceptualization, Writing – original draft, Writing – review & editing. **Marisa Faria:** Writing – review & editing. **Filipa Rodrigues:** Writing – review & editing. **Nereida Cordeiro:** Supervision, Project administration, Conceptualization, Writing – review & editing.

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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Appendix A. Supplementary data

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