Marine Pollution Bulletin 208 (2024) 117075

Contents lists available at ScienceDirect

Marine Pollution Bulletin

journal homepage: www.elsevier.com/locate/marpolbul

Review

Marine plastic pollution: A systematic review of management strategies through a macroscope approach

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ARTICLE INFO

Keywords:
Systemic assessment
Marine plastic pollution
Sustainability

ABSTRACT

Alternatives to address the ocean plastic crisis have been a hot topic in scientific literature, although a systemic approach to assess their effectiveness and identify bottlenecks is still lacking. To contribute to discussions on this topic, this study aims to conduct a literature review on current scientific information regarding management strategies for marine plastic pollution. The PRISMA method was used to select the most relevant articles from the Scopus® database, resulting in a sample of 176 articles after applying exclusion criteria for full-text evaluation. Unlike other literature review studies, Odum's Macroscope is used here to develop a model that provides a systemic view of the plastic crisis on a large scale, encompassing various compartments and their interactions. Specifically, eight compartments are identified: industry, consumers, waste collection & management, freshwater systems, fisheries, aquaculture and shipping, marine ecosystems, marine plastic collection and recycling, and life cycle. Each piece of literature reviewed is categorized into one of these compartments and discussed accordingly. The highlights of the results indicate that: (i) waste collection & management and freshwater systems, which are primary pathways for plastic litter reaching the ocean, have been relatively under-investigated compared to other compartments. (ii) Most studies originate from developed countries, raising doubts about the effectiveness of management proposals in underdeveloped countries. (ii) Existing strategies for collecting and recycling marine litter are unlikely to be implemented at a large scale due to operational obstacles, thus offering insufficient mitigation for the plastic crisis. (iv) The development of new biomaterials has proven mostly ineffective and harmful. (v) Alternatives management for microplastic pollution are still in their infancy, resulting in scarce information across all compartments. (vi) No studies focus on the origin of the plastic issue, which lies in the petrochemical industry. From a general perspective, the literature indicates that there is no one-size-fits-all management strategy to the plastic crisis, and the available options are often scattered and disconnected, making a systemic approach essential for studying such a transboundary issue. While efforts exist, stakeholders must act to effectively address the problem, or at least make meaningful progress. The marine plastic crisis operates systemically, analogous to the climate crisis, both stemming from human dependence on fossil fuels. Similar to achieving carbon neutrality, designing a globally sustainable economy should prioritize achieving plastic neutrality as a core component.

1. Introduction

Among the several threats posed to marine ecosystems, pollution caused by human activities stands out as a growing, systemic problem, with difficult solutions. The release of effluents from human activities has caused damage to biodiversity, as well as food security (United Nations, 2021). Much pollution reaches coastal environments from diffuse sources, such as surface water runoff, which further complicates

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https://doi.org/10.1016/j.marpolbul.2024.117075
Received 14 August 2024; Received in revised form 27 September 2024; Accepted 27 September 2024
Available online 2 October 2024

control and monitoring efforts. Moreover, the interaction between pollutants can worsen environmental impacts. For example, plastic waste can carry toxic pollutants over long distances (Rafa et al., 2024), causing both the plastic issue itself allied with toxic components diffusion. Furthermore, the consequences of pollution are exacerbated in a scenario of climate change, with the systemic dimension of these impacts still poorly understood (Ford et al., 2022). Among the several human threats to the oceans, plastic pollution deserves attention due to the exponential increase of plastics produced and released to the natural environment reaching aquatic ecosystems (Borrelle et al., 2020), as well as the lack of more precise information regarding the impacts that plastic pollution can cause from a systemic perspective (Tuuri and Leterme, 2023).

Plastics represent 80 % of solid waste pollution found in the oceans. It is estimated that 19 to 23 Mt., or 11 %, of plastic waste generated globally entered aquatic ecosystems in 2016 (Borrelle et al., 2020; United Nations, 2021). Currently, plastic waste can be found in all marine environments and its presence is increasing even in remote areas, such as uninhabited islands. A recent study identified rocks containing plastic debris in their formation on Trindade Island, located more than a thousand kilometers off the Brazilian coast (Santos et al., 2022). The impacts of plastic on oceans are extensive. The most well-known include the mortality of fish and seabirds due to accidental ingestion of macro and mesoplastics, the introduction of invasive exotic species that use floating debris as vectors, and the bioaccumulation of microplastics along food chains (Loganathan and Kizhakedathil, 2023; Tuuri and Leterme, 2023). According to Tuuri and Leterme (2023), the chronic and synergistic effects of these impacts are still poorly understood by the scientific community, especially at the ecosystem level.

On the other hand, that is no expectations of a reduction in plastic production. The petrochemical industry announced over $204 billion U. S. investment, leading to a projected acceleration in virgin plastic production (Borrelle et al., 2020). Under a business-as-usual scenario, 90 Mt./year of plastic waste could reach the world's aquatic ecosystems by 2030 (Borrelle et al., 2020). This catastrophic scenario has moved the scientific community to a global task force on plastic pollution problem (Kwon, 2023).

Management strategies for preventing plastics from reaching the coastal ecosystems or removing them from the ocean are vast and have been a hot topic in the scientific literature (Winterstetter et al., 2021). Three main strategies are claimed to be the umbrella of solutions: circular economy, policies, and innovative plastic materials (Kwon, 2023). Nevertheless, a systemic approach for assessing the effectiveness of such strategies and identifying bottlenecks is lacking. Given the current and growing problem related to plastics in the ocean, the business-as-usual scenario for plastic production and consumption patterns, combined with the lack of scientific studies that consider a systemic approach to better understand and discuss causes and solutions for this problem, this study aims to review the currently available scientific literature and discuss on the management strategies proposed for the problem of plastic pollution in the marine environment. Discussions are based on a systemic perspective to identify where and what kind of efforts worldwide researchers are undertaking to address the plastic pollution issues, identifying areas that require future efforts to better diagnose the problem and support effective public policies.

2. Methods

2.1. Odum's macroscope approach

Unlike other literature review studies, Odum's macroscope (Odum, 1996) is considered here to support a systemically rooted understanding of plastic pollution in the ocean. The macroscope approach is a framework for assessing complex systems in a comprehensive way. By identifying the main components of a system, the sources and flows of energy and materials, and the ways they interact with each other, one can recognize cause-and-effect circuits and interdependences. It also elucidates how man-made systems relate to the natural systems. Moreover, it could provide a scientific model to formulate strategies for managing societal development under ecosystem constraints (Giannetti et al., 2020).

In the present study, the energy diagram of Fig. 1 was elaborated from a collaborative approach of experts for identifying the pathways of plastic litter towards the ocean. The diagram elucidates the pathways of plastic from production to consumption, discard, and finally, the natural ecosystem. The pathway starts with the extraction of natural resources (petroleum) that are refined within the petrochemical industry, resulting in many products, among which are the many types of plastics. Then, plastics are used by every manufacturer industry, either as a component of the product or packaging. During this process, part of the plastic is discarded as waste. The product is then delivered to the consumers, generating plastic waste. Part of that waste is collected by the waste collection and management system and recycled or immobilized at landfills. On the other hand, part of that waste is mismanaged and leaks into the natural environment, ending at the freshwater systems. Most of the plastic that enters the coastal environment comes from continental sources, mainly carried by rivers that flow to the ocean. That comprehends macro-plastics and microplastics. A fraction of the marine plastics comes from the industries inserted in the marine ecosystems, such as aquaculture, fisheries, and shipping. Plastics accumulate in the marine environment, generating a floating stock. Part of that plastic negatively interacts with the marine biodiversity and landscape, causing a loss of environmental services. Another part that is degraded into microplastics accumulates at the ocean floor. A small fraction is washed back to the shoreline, carried out by the marine currents. Only the macro-plastics can be removed from the ocean, and it occurs by active collection. Part of that plastic can be recycled, and the remaining ends in landfills.

Fig. 1 is fundamentally important as a model representing plastic pollution in the ocean and the important drivers that affect the issue positively or negatively. Without understanding and visualizing the interrelations among different human production systems, it is difficult to assess plastic pollution appropriately. Specifically, Fig. 1 supports the structure of discussions in this study, as explained in the next section.

2.2. Search and screening

The systematic review procedure was adapted from the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) statement (Page et al., 2021). For the author, the PRISMA statement is a guide for conducting and reporting systematic reviews, based on a flow diagram of steps for searching and screening studies and a checklist addressing how to properly report the review. In this study, the PRISMA method was adapted to comprise the macroscope view approach. This is particularly relevant since this study investigates how scientific publications relate the plastic litter pathways towards the ocean.

The search procedure was conducted at the Scopus database (scopus.com) from August to October 2023. Scopus was selected because of its broader coverage in terms of Journals Indexed. The search terms used were ocean OR marine AND litter; AND plastic; AND solution OR policy OR management, covering Title, Abstract, and Keywords (Fig. 2). The search terms were selected based on the most recent publications and aimed to represent the wider picture of this research topic. It is important to highlight that all types of plastics were covered in this assessment, regardless of size and chemical composition.

The first screening used document type criteria, selecting the documents categorized as “original article” and “review”. Manuscripts written in non-English language and/or not available for full-document download were also excluded. The second screening was based on abstract content analysis, in which articles that proposed or assessed a technological, management, policy, or any other type of strategy for the problem of plastic litter pollution were selected. As a result, 176 documents were considered for this literature review, as shown in Fig. 2.

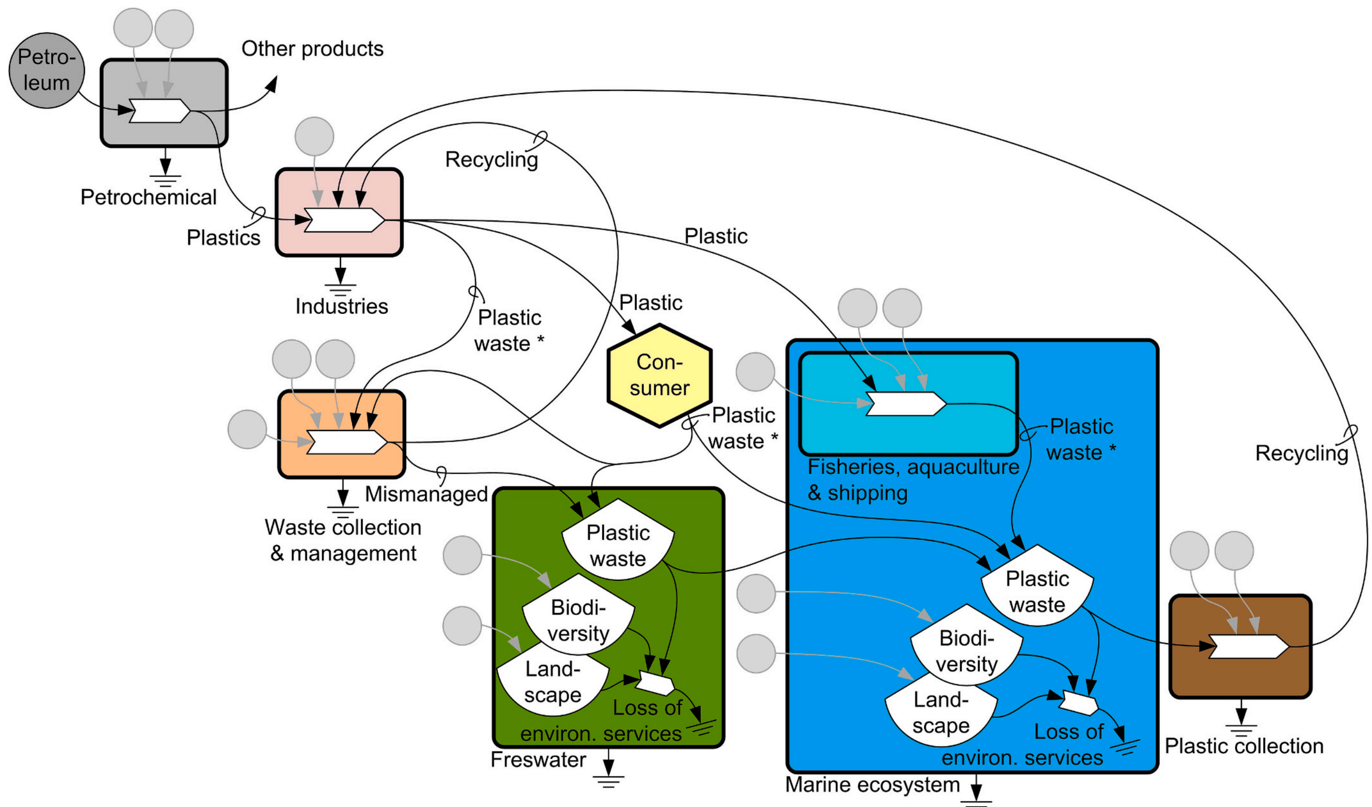

Fig. 1. Energy diagram representing plastic production, its usage, and how it circulates during its life cycle from a systemic perspective. Plastic waste* flows (on a national or regional scale) may be composed by imported and/or exported plastic.

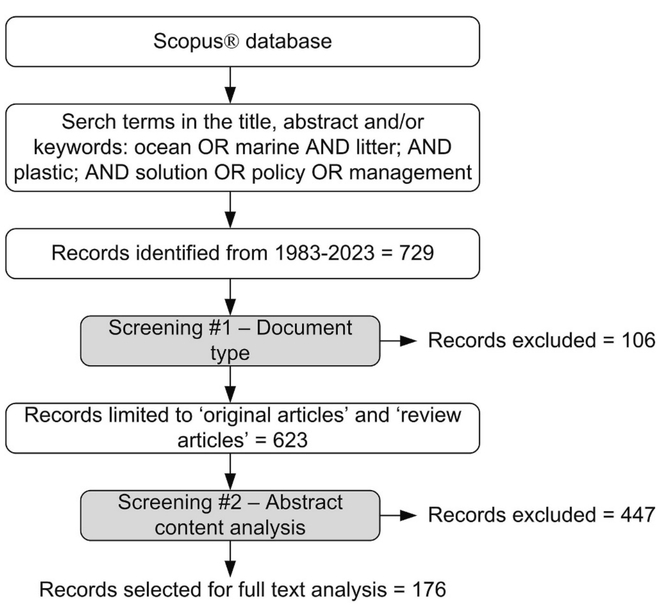

Fig. 2. Procedure used for selecting the scientific articles considered in this literature review.

Table SM-A of the Supplementary material provides detailed information about all documents supporting this study.

2.3. Full text analysis and categorization

The analysis of the selected documents was carried out to collect information regarding the bibliometric aspects, such as journal, country of origin, and year of publication, and content aspects, such as whether is a preventive or a mitigative solution. Preventive solutions are assumed to be those measures that prevent plastic from entering the ocean, such as reducing plastic leakage. On the other hand, mitigative solutions are assumed to monitor or remove the plastic litter from the marine environment (Table SM-A of the Supplementary Material). For a better understanding and to support the development of this literature review, the total sample of articles was grouped into the following eight categories based on the model shown by Fig. 1:

1. Life cycle of plastic;
2. Industries;
3. Consumers;
4. Waste collection and management;
5. Freshwater systems;
6. Fisheries, aquaculture, and shipping;
7. Marine ecosystems;
8. Plastic removed from the ocean.

It is important to highlight that some articles presented more than one management strategy, or that some strategies apply to multiple categories. In these specific cases, the articles were registered under all relevant categories. For each category, the main aspects of the proposed management strategies were summarized. The review also identified synergies between the propositions, their applicability in the short or long term, and scalability, i.e., whether the proposed management strategy can be applicable at a local, regional, or global level. Additionally, it was noted which system components are underrepresented or even neglected in the current scientific literature.

3. Results and discussions

3.1. Bibliometric status

The search procedure identified 729 documents, with the first article published in 1983. After applying the first exclusion criterion (Screening #1 – document type), 623 remained, representing original and review articles. The second exclusion criterion (Screening #2 – abstract content analysis) further refined the sample to 176 articles. As shown in Fig. 3, about 99 % of these 176 articles were published in the last 10 years (2013–2023), and 86 % were published in the last 3 years (2020–2023). This result suggests that the scientific community has only recently acknowledged the problem of plastic pollution and that management strategies are likely still under development. On the other hand, the rapid increase in interest in this topic can be considered a positive aspect. Most of the articles were produced by more developed nations: Italy (118), United Kingdom (97), United States (72), Germany (56), Spain (51), and Australia (50), exception of India (44) and Brazil (42) that are recognized as developing countries. China ranks 21st in terms of the number of publications, a position uncommon in many scientific fields. The main journals are Marine Pollution Bulletin (176), Science of the Total Environment (50) and Environmental Pollution (38).

Fig. 4 shows that the 176 articles presented an overall balance between preventive and mitigation solutions applicable mostly at a global scale (44 %); there is a slight tendency towards mitigation, with 57 % of publications focusing on this aspect. The analysis of strategies to address plastic pollution revealed a balance between short-term and long-term solutions, with 48 % and 52 % respectively. Considering the type of management strategy, geographical coverage, and implementation timeframe, one can say that they are overall balanced. Therefore, none of these aspects urgently calls for more studies, when the balance among publications is an important criterion.

Another important aspect deserving attention is the system studies have focused on (Fig. 5). Most of the articles relate to marine ecosystems (27 %), such as plastic litter monitoring, and to the full life cycle of plastic (25 %), such as policies to promote a circular economy. On the other hand, only 2 % of the articles present strategies to the waste collection and management systems, 3 % to consumers, and 5 % to the freshwater systems. This indicates that these systems are still underrepresented in the scientific literature, highlighting the need for future studies to diagnose and propose alternatives for them under a systemic perspective.

3.2. Status on the alternative strategies proposed

The strategies identified within the reviewed studies are presented

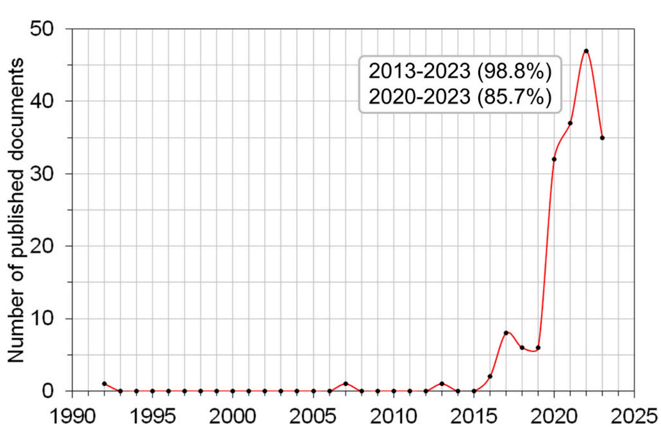

Fig. 3. Number of articles published approaching solutions for marine plastic pollution over time.

and discussed in a structure supported by Fig. 1, which includes eight categories as individually presented in the following sections.

3.2.1. Life cycle of plastic

Management strategies for the full life cycle of plastics account for 25 % of the investigated literature, predominantly focusing on strategies to reduce litter generation and implement a circular economy. Most articles assessed the effectiveness of current international and local policy frameworks in reducing litter pollution. Among these, single-use plastic bans were identified as an increasingly popular policy strategy, with potential for significant long-term results, although short-term outcomes have not yet been identified (Abbott and Sumaila, 2019; Adam et al., 2020; Amenábar Cristi et al., 2020; Clayton et al., 2021; Kiessling et al., 2023; Knoblauch et al., 2018; Wagner, 2020, 2017). Issues associated with this strategy include a lack of clear definitions regarding the types and compositions of plastics (Steensgaard et al., 2017). Single-use plastic bag bans appear to be effective, with positive impacts observed in the short term (Hocherman et al., 2023; Maruf, 2019). The approach to plastic bans varies among the countries studied, with developing nations adopting more restrictive laws than developed countries, likely due to the more visible harm caused by pollution in these regions (Adam et al., 2020; Hermawan and Astuti, 2021; Knoblauch et al., 2018).

Legislation conflicts among different levels of government were identified as a barrier to the successful implementation of plastic bans, as they create uncertainty and lead to non-compliance (Wagner, 2017). In the USA, for example, local government actions have given rise to state-level resistance (Wagner, 2017). A global level of coordination via international regulations on marine debris could be strategic. The Stockholm and Basel Conventions and the Montreal Protocol, for example, are international instruments identified to offer the best opportunity to reduce the impacts of plastic waste globally; however, they were found to be insufficient to manage the entire lifecycle of plastic (Raubenheimer and McIlgorm, 2018, 2017), demonstrating the importance of a multi-level action on regulations. Additionally, most authors identified public engagement as crucial. Campaign investments resulted in larger reductions in environmental waste compared to investments in policies (Willis et al., 2018). Bottom-up initiatives have led to more successful stakeholder arrangements than top-down policies (Amenábar Cristi et al., 2020).

Economically oriented policies, such as Extended Producer Responsibility (EPR) schemes, are proposed as a strategy to finance waste management and encourage companies to invest in circular product designs (Abbott and Sumaila, 2019; Baxter et al., 2022; Diggle and Walker, 2022; Mazhandu et al., 2020; Raubenheimer and Urho, 2020; Vanapalli et al., 2023). The principle behind this strategy is that plastic waste is a negative externality generated by companies operating on a linear production model. Therefore, they should be financially and operationally responsible for dealing with the end-of-life of their products. To become effective, the development of global design standards for products, consumer engagement in waste separation and collection, and well-developed reverse logistics in production chains are necessary (Abbott and Sumaila, 2019; Baxter et al., 2022; Diggle and Walker, 2022; Mazhandu et al., 2020; Raubenheimer and Urho, 2020; Vanapalli et al., 2023). Surprisingly, no real-life cases of EPR implementation were discussed in the evaluated literature, even though there have been examples of EPR initiatives. A recent example comes from Brazil legislation. In 2023, the government approved the Decree N° 11.413 that establishes the Reverse Logistics Recycling Credit Certificate, the Packaging Structuring and Recycling Certificate and the Future Mass Credit Certificate. Although the implementation is in its early steps, this decree allows a EPR logic to be adopted by demanding that companies reinsert in their production systems the same amount of solid waste that is generated by them, in a mass balance approach. The inappropriate disposal of waste, including plastics, must be reduced, minimizing the impact of micro and nanoplastics, at least in relation to the release of

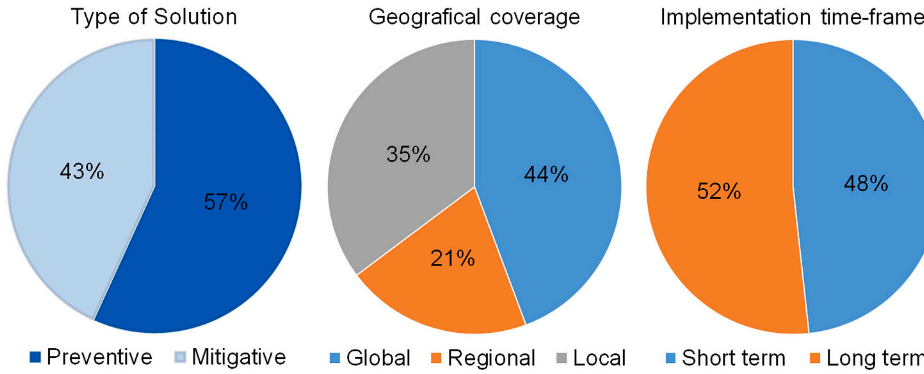

Fig. 4. Published articles on solutions for marine plastic pollution categorized on type of solution, geographical coverage, and implementation time-frame.

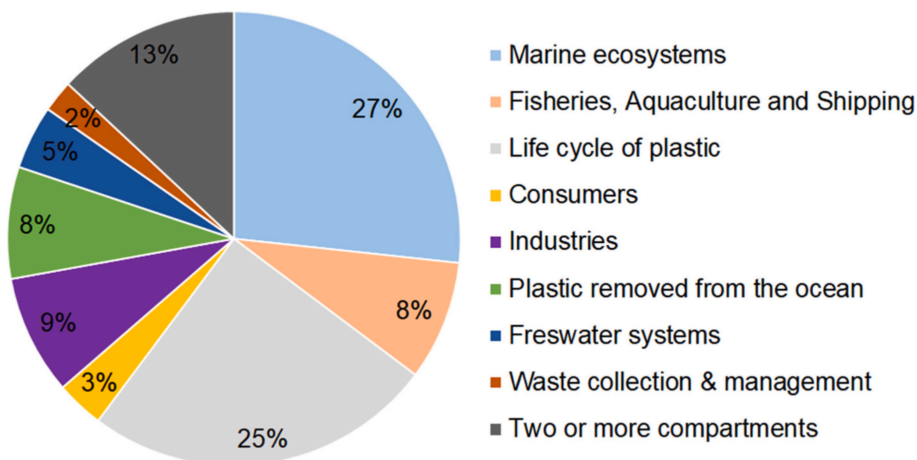

Fig. 5. Published articles on the solutions for plastic pollution categorized according to the system that the solution focuses on. Life cycle of plastic relate to solutions applicable from the production of plastic to its discharge. Two or more compartments mean solutions applicable to more than one of the categories.

waste into the environment in its natural state.

Large-scale effective management alternatives remain elusive, although the idea that the best response is to ensure that plastic does not convert litter has become a consensus (Black et al., 2020). Alternatives that comprise microplastics are an enormous gap in this review (Dang et al., 2021; Sharma et al., 2021). Cunha et al. (2023) propose that the economy should incentivize innovation, as dealing with microplastics is approximately 11 times more expensive than dealing with macroplastics. Additionally, based on the magnitude of hazards caused by plastic, more ambitious solutions and targets should be investigated. For example, Steensgaard et al. (2017) proposed that plastics should have the same high level of monitoring and reporting requirements as hazardous waste, involving stricter requirements for labeling, record-keeping, monitoring, and control over the whole lifecycle. Even though alternative strategies for the life cycle of plastic have been highly investigated in the literature, efforts seem unlikely to have a transformative effect on the problem.

3.2.2. Industries

Innovative materials that could reduce plastic pollution were the most investigated alternatives related directly to the plastic industry sub-system. Biodegradable polymers have been widely used by the industry, and their efficacy and side effects are the most discussed topics. Overall, authors agree that there is not enough evidence to support that biodegradable polymers are, in fact, degraded under natural conditions (Catarci Carteny and Blust, 2021; Ganesh Kumar et al., 2020; Genovesi et al., 2023; Manfra et al., 2021; Oliveira et al., 2020; Raddadi and Fava, 2019; Viera et al., 2020). Experimental evidence on two different biodegradable polymers, polylactic acid (PLA) and polyhydroxyalkanoates (PHA), suggests that biodegradable plastic behaves similarly to traditional plastic in the marine environment, even after six months (Catarci Carteny and Blust, 2021). These materials have a higher potential for marine litter formation, as they create a false sense of security that inappropriate waste disposal is mitigated by their presumed lower environmental persistence (Boone et al., 2023). Furthermore, there are significant knowledge gaps regarding the effects of these materials on marine organisms (Manfra et al., 2021). Viera et al. (2020) emphasized that regulatory measures for these materials must be discussed, particularly concerning adequate labeling.

Another frequent research topic is the assessment of the environmental impacts of traditional plastic production compared to alternative materials, such as bio-based plastic, biodegradable plastic, paper, or glass, predominantly assessed by Life Cycle Assessment (LCA) (Gao and Wan, 2022; Saling et al., n.d.; Stefanini et al., n.d.; Zanghelini et al., 2020). These studies conclude that traditional plastic performs better for most indicators, especially for global warming potential (GWP). However, current LCA methods do not account for marine pollution impacts, as they erroneously assume that all plastic waste generated during production is adequately disposed of in landfills. Methodologies for accounting for plastic leakage, including both macro and microplastics, as well as their environmental and human health impacts, are urgently needed. Recent studies considering micro and nanoplastics effects on biota as additional impact factors in LCA suggests that the potential impacts of the traditional polymers could be much higher than what is currently accounted for, mainly because there are several categories yet to be modeled for micro and nanoplastics (Corella-Puertas et al., 2023).

Therefore, the existing scientific evidence suggesting that traditional and biodegradable plastics are less harmful for people and the environment should be considered cautiously due to the uncertainties and lack of appropriate LCA methods for quantification.

3.2.3. Consumers

Consumers are asserted to play a pivotal role in addressing alternatives for the plastic pollution (Cai et al., 2022). However, the literature review conducted reveals a limited understanding of the extent to which consumers drive marine plastic pollution and solutions, necessitating strategies to promote responsible consumption behaviors. To illustrate some figures, Amadei et al. (2022) modeled the plastic footprint of EU citizens and the likelihood of this plastic entering marine environments. EU citizens have a plastic footprint ranging from 84 to 129 kg per capita per year, with approximately 1 % potentially ending up in the ocean. A significant portion of this plastic consists of single-use packaging materials.

Cai et al. (2022) advocate that governments should create opportunities for consumers to make more informed decisions, such as by reporting trends in plastic waste loads. Besides, communicating to consumers the correct disposal methods through appropriate labeling is recommended for reinstating their responsibility (Bhagwat et al., 2020). Education as a tool for behavior change has also been investigated, both in academic settings and through citizen science approaches like beach clean-ups (Bettencourt et al., 2023; Nguyen et al., 2022), concluding that knowledge, awareness, perceptions, and behavioral intentions were boosted by the interventions made. Product design, exemplified by beach trash cans, can encourage interaction and influence littering behavior (Portman and Behar, 2020).

Consumer perspectives on policies and plastic bans have also been studied. Grilli et al. (2022) found that people generally support policy implementation, including short-term efforts to remove litter from coastal habitats and long-term measures like bans on single-use non-recyclable plastics and local deposit return schemes. However, this support is particularly strong among younger respondents with a preference for immediate action. Additionally, Martinho et al. (2017) studied the effect of the tax payment mechanism on plastic bag consumption, finding a 74 % reduction in plastic bag consumption with a simultaneous 61 % increase in reusable plastic bags after the tax was implemented. They concluded that the tax efficiently promoted the reduction of plastic consumption but highlighted the role of hypermarkets and supermarkets in providing alternatives by distributing reusable plastic bags (Martinho et al., 2017).

Overall, results indicate that consumers could contribute to reducing plastic consumption and discharge when they are properly oriented towards that, and conditions are favorable. Therefore, management strategies for this compartment must be linked with strategies for Life cycle and Waste collection & Management systems.

3.2.4. Waste collection and management

Alternatives for waste collection and management system were the focus of 3 % of the reviewed articles, which was unexpected considering that mismanaged waste is a significant source of plastic pollution. Technologies addressing land-based sources of marine plastic litter are considered the most cost-effective and should be prioritized as the primary solution (Liu et al., 2013; Winterstetter et al., 2021). However, as emphasized by the authors, there are numerous knowledge gaps in this area, including the lack of quantification of plastic leakage, which impedes understanding the scope of the problem and potential propositions. Alencar et al. (2022) recommend that urban cleaning companies and solid waste management agencies invest in unifying and making data available across all municipalities. Chitaka and von Blottnitz (2021) identified that leakage rates vary among different products, with food packaging being highly prone to leakage, suggesting the need for product-specific guidelines to be developed.

Another investigated aspect is the necessity to enhance the value of plastic waste for reintroduction into the mainstream economy, in line with the principles of a circular economy (Prabawati et al., 2023). This requires efficient waste collection and separation processes. The use of NIR spectroscopy technology for classifying and sorting landfill and marine litter plastics has been proposed to enhance separation efficiency and improve material quality (Chen et al., 2021). Additionally, the externalities of plastic waste collection - such as the benefits of conserving primary resources and the costs avoided by preventing leakage - should be factored into the valuation of plastics (Velis et al., 2022). Finally, the same authors emphasized that the informal sector is recognized as a crucial stakeholder in improving waste management practices, particularly in developing countries. Improving the circular economy model in plastic waste management by financially supporting informal waste services (promoting waste banks, for example) could positively impact the environment and the people (Alencar et al., 2022; Chen et al., 2021; Chitaka and von Blottnitz, 2021; Liu et al., 2013; Prabawati et al., 2023, 2023; Velis et al., 2022; Winterstetter et al., 2021).

The development and assessment of alternatives for plastic waste collection and management systems are promising to have a transformative impact in the short term, especially in developing regions. Nevertheless, more studies are needed to support that statement.

3.2.5. Freshwater systems

Freshwater systems receive plastic litter through dumping, runoff, and residual water from treatment plants, later delivering this plastic litter to the ocean. Methods for monitoring and cleaning freshwater systems have been the main topics in the literature for this system compartment. Results indicate that over 80 % of the total annual plastic discharges towards the ocean come from rivers, according to local-level modeling performed in Indonesia (Veiga et al., 2023). On the other hand, that estimative is not a consensus. Freshwater systems can perform as a sink for plastics, since many factors can influence the flow and sinking of plastics in this system, such as river morphology and size, wind speeds, or agricultural drainage systems (Ita-Nagy et al., 2022). The same authors emphasize that this miscalculation can result in an overestimation of the plastic released and negligence of the impacts of plastic in freshwater ecosystems. Therefore, hydrometeorology and hydrological infrastructure, combined with cultural aspects in handling practices and waste generation, are critical features to consider when studying alternatives for plastics management, including the potential pathways from production until its end in the ocean (Lauer and Nowlin, 2022; Veiga et al., 2023).

Some authors highlighted that a significant level reduction of plastic debris in the ocean could be only achieved by the combination of plastic collection at rivers with clean-up devices and implementation of river barriers (Axelsson and van Sebille, 2017; Hohn et al., 2020; Lauer and Nowlin, 2022). For instance, in a study on the legislation on aquatic environmental protection at the United Kingdom, Davey (2021) advocated that a legal improvement compromising a duty on statutory bodies to clear litter from aquatic environments like rivers, canals, and lakes should be discussed. However, although cleanup practices are urgent, technologies are still insufficient. Winterstetter et al. (2021) summarized the current clean-up technologies for freshwater systems and concluded that none has achieved sufficient scale to tackle the problem. These results are supported by Schmaltz et al. (2020), which stated that the current capacity and widespread implementation of cleanup technologies are limited compared to the vast extent of the plastic pollution problem.

Microplastic pollution through residual domestic effluent has been pointed out, although quantitative information about microplastic released is scarce. Legislation on microplastic pollution is in its infancy (Narloch et al., 2022). Cleanup techniques assessed demonstrate that they are insufficient, and in many cases, they can allocate the problem from water to the generated sludge (Barcelo and Pico, 2020). Advanced wastewater treatment plants indicated a retention capacity of over 99 %, after secondary treatment (Talvitie et al., 2017). Nevertheless, the authors concluded that a considerable source of microplastics remains in the aquatic environment because of the large volumes of effluent discharged constantly.

Results highlight the need for an integrated approach, considering freshwater and coastal ecosystems when identifying and/or proposing alternatives for managing plastic pollution. Both ecosystems face similar challenges regarding the environmental damage caused by pollution and the difficulties in removing the plastic litter, once it is in the environment. Moreover, a significant amount of plastic litter reaches the ocean through freshwater systems. Only 13 articles assessed in this review discussed about management alternatives that comprised freshwater systems, indicating that this system has been under-represented. It is important to acknowledge that marine plastic pollution must be tackled not only in coastal areas.

3.2.6. Fisheries, aquaculture, and shipping

The scientific literature acknowledges fisheries and aquaculture industries as sources of plastic pollution due to the degradation or disposal of plastic instruments such as gears, fishnets, longlines, and aggregation devices. The most frequently discussed strategy is the replacement of traditional materials with bio-based or biodegradable plastics (Arantzamendi et al., 2023; De Domenico et al., 2023; Skirtun et al., 2022; Zudaire et al., 2023). However, as previously discussed, this approach is controversial because biodegradable plastics do not fully decompose in natural environments, and the environmental impacts of contamination by these materials are not fully understood. Other solutions discussed in the literature include improved management practices, inclusive stakeholder participation, gear retrieval efforts, and enhanced legal frameworks (Andriolo and Gonçalves, 2023; De Domenico et al., 2023; Finska et al., 2022; García et al., 2021; Gilman et al., 2022; Sinopoli et al., 2020; Stolte et al., 2022). Monitoring actions to identify abandoned, lost, or discarded fishing gear is recommended, utilizing techniques such as sonar, drone-based surveillance, and satellite remote sensing (Andriolo and Gonçalves, 2023; Stolte et al., 2022; Tian et al., 2022).

The shipping industry contributes to ocean pollution through illegal littering, container loss, and other materials. Recovering these materials once they reach the ocean is challenging and, therefore, not a viable solution (Jo, 2020). Instead, better management practices, appropriate legislation, and monitoring are proposed as strategies to prevent these issues. Hwang (2020) advocates for the ratification and implementation of the 2012 Cape Town Agreement, adopted by the International Maritime Organization (IMO), to prevent marine plastic pollution from abandoned fishing nets and equipment. Serra-Gonçalves et al. (2023) assessed the effectiveness of the International Convention for the Prevention of Pollution from Ships (MARPOL) in reducing marine debris incidence in Australia. Their findings suggest that MARPOL has the potential to partially reduce beach debris from ocean-based sources in the short term; however, they argue that this legislation is inadequate for addressing the problem in the long term.

Existing management alternatives for fisheries, aquaculture and shipping are promising and have been investigated by 13 articles since 2020, being the 4th most investigated system in this review. Nevertheless, the magnitude of contribution from that system to the problem is not clear; therefore, the real impact of these alternatives cannot be accounted for. Another important point is the role of traditional/small scale fisheries, since fishermen usually are victims of plastic pollution rather than agents. Therefore, it would be important to propose alternatives that consider inequalities among actors to promote environmental justice.

3.2.7. Marine ecosystems

Almost one-third of the assessed articles focused on strategies for plastic litter already deposited in marine ecosystems, with all proposing mitigation actions. The identified strategies for marine ecosystems can be categorized into monitoring techniques, methods for collecting plastic litter, and approaches for degrading plastic litter. Degradation techniques primarily involve the application of microorganisms, often genetically modified, for biodegrading plastics (Ganesh Kumar et al., 2020; Oliveira et al., 2020). However, this technology requires extensive research and regulation, as data on biodegradation rates and negative extents remain limited. Available evidence suggests that microbial adaptation to conventional plastics in terrestrial and aquatic environments occurs slowly (Raddadi and Fava, 2019). Therefore, plastic degradation cannot be considered a viable alternative at this moment.

Monitoring is a critical step in addressing the plastic pollution problem as it provides accurate insights into the quantity and characteristics of plastics entering the ocean, facilitating more effective management strategies. Various technologies for monitoring were identified in the literature. Drones, satellite imagery, sensors, AI modeling, and other techniques are widely discussed for diagnosing floating litter (Andriolo et al., 2021; Brabo et al., 2022; Duncan et al., 2020; Grøsvik et al., 2023; Kremezi et al., 2022; Merlino et al., 2021; Migliaccio et al., 2022; Molina Jack et al., 2019; Park et al., 2021; Sannigrahi et al., 2022; Taddia et al., 2021). Citizen science projects have proven effective for monitoring beach litter and engaging the public in beach clean-ups (Davies et al., 2022; Ershova et al., 2021; Merlino et al., 2021; Nelms et al., 2022; Winton et al., 2023). Nature-based solutions, such as protecting dune vegetation to trap plastic litter carried by runoff water, and using seabirds for biological monitoring, were also identified (Acampora et al., 2016; Avery-Gomm et al., 2018; Battisti et al., 2023; Ben-Haddad et al., 2023; Gallitelli et al., 2021; Mancuso et al., 2023; Navarrete-Fernández et al., 2022), showing that some strategies could be simple and low-cost.

Collecting plastic from marine environments poses significant challenges, requiring substantial efforts and resources to retrieve litter from open waters and bring it ashore. Current strategies primarily address macro litter. The 'fish for litter' approach encourages fishermen to remove plastic accumulating in fishnets and gear from the ocean, often through payments for environmental services projects (Balcells et al., 2023; Forleo and Romagnoli, 2023; Mannaart and Bentley, 2022; Ruiz et al., 2020). This strategy supports fishing communities affected by marine pollution and natural resource depletion, while also engaging local stakeholders in tackling the issue (Balcells et al., 2023; Forleo and Romagnoli, 2023; Mannaart and Bentley, 2022; Ruiz et al., 2020). However, its scalability for large-scale plastic removal remains uncertain. Other strategies involve skimmers, floating garbage bins, dredgers, and similar equipment (Brouwer et al., 2023; Leone et al., 2023; Parker-Jurd et al., 2022; Schmaltz et al., 2020; Schneider et al., 2018). Despite their use, these technologies may have lower efficiency and can inadvertently cause mortality among marine organisms (Parker-Jurd et al., 2022).

In the literature review conducted, a subject that has been low investigated within this system is the role of coastal management as a strategy to marine plastic pollution. The only research on this topic was from Baroth et al. (2022) which investigated how marine protected areas (MPAs) can influence the quantity and quality of marine litter in India. They found that MPA had the lowest litter density but the highest proportion of plastic litter, mainly single-use plastic bottles (Baroth et al., 2022). More studies are needed to corroborate this result.

Overall, the literature indicates that the existing strategies for monitoring plastic pollution are relevant, well developed, and should be implemented worldwide. Once implemented, a global database could support better investigations on collecting and management strategies. On the other hand, collecting and degrading technologies are in their infancy and should be further investigated.

3.2.8. Plastic removed from the ocean

Once plastic is successfully collected, the next challenge lies in determining its destination (Schneider et al., 2018). Reintroducing marine plastic into the production chain is advocated to enhance plastic circularity, prompting investigations into the feasibility of reusing or recycling marine plastic.

Recycling is typically feasible when the original material quality is maintained. Stapleton et al. (2023) studied the physical, mechanical, and chemical changes in four types of plastics - polyethylene terephthalate (PET), polypropylene (PP), polycarbonate (PC), and polylactic acid (PLA) - after simulated environmental degradation. They concluded that only PC shows good potential for upcycling, while PET and PP could still be recycled into lower-value products like construction materials. Using the life cycle assessment method, Cañado et al. (2022) found that reusing polyamide fishing nets as feedstock for 3D printing is feasible and more environmentally friendly than using virgin materials. Caniato et al. (2021) developed a foam from microplastics but noted that low efficiency in raw material collection could make commercial production unfeasible. Additionally, laboratory-scale investigations into processing marine litter for energy recovery via pyrolysis were conducted (Faussone et al., 2021; Liu et al., 2022; Pietrelli et al., 2017; Veksha et al., 2022). However, the methods of material collection in these studies - manual collection, scuba diving, or kiln boats - resulted in low efficiency, negatively impacting economic viability.

While marine plastic recycling may be feasible from a technological perspective, its economic viability as a management alternative remains uncertain due to the challenges in scaling up plastic collection processes.

4. Challenges in implementing strategies to reduce plastic in the oceans

The management alternatives identified and discussed by the scientific community will only prove effective after assessing their potential implementation over sufficient time and scale to address the problem. Marine plastic pollution is a transboundary issue, and therefore, a globally coordinated effort is necessary. To accomplish this global mission, two questions seem fundamental: (1) Is there a global governance system capable of implementing the proposed alternatives? (2) Are the proposed technologies adequate for large-scale incorporation into production systems?

Governance can be broadly defined as the management of practices by both public and private authorities, including international institutions, state laws, nongovernmental standards, corporate codes of conduct, and societal norms of right and wrong (Dauvergne, 2018). Global governance of marine plastic pollution has been recognized as particularly challenging due to the globalization of the plastic industry and its resistance to change from the business-as-usual status quo, in addition to the durability and dispersal nature of plastic polymers (Dauvergne, 2018). Another significant obstacle is the unequal roles that countries play in terms of responsibility and the damage they suffer. For instance, in 2024, a Belgian citizen generated 16 times more plastic waste than a Bangladeshi citizen (POD, 2024). Conversely, a 2023 report on the costs of plastic pollution revealed that 93 % of recorded deaths directly associated with plastic production occur in low and middle-income countries (WWF, 2023a). These inequalities - or unfairness - are also reflected in the characteristics of scientific publications, as previously discussed in Sections 3.1 and 3.2. An interesting approach to addressing the plastic problem would be to consider plastic pollution within the framework of sustainable development commitments, such as the SDGs or other socio-environmental agendas, emphasizing the need to identify development opportunities that promote environmental justice (Stoett et al., 2024). As a practical roadmap, Ferraro and Failler (2020) highlighted four areas for institutional action: harmonization of international laws, coherence across national policies, coordination of international organizations, and science-policy interaction.

The absence of a coherent global regulatory framework limits the ability to effectively mitigate marine pollution, as local and regional efforts are often uncoordinated and underfunded (Gottlieb, 2021). In the recent years, there has been a significant push to establish a binding global treaty on plastic pollution. In 2022, the United Nations Environment Assembly (UNEA) adopted a resolution to develop an internationally legally binding instrument that addresses the entire lifecycle of plastics, including their production, design, and disposal (Kibria et al., 2023; UNEP, 2023). This effort aims to fill governance gaps and establish an integrated approach that aligns various local and regional actions under a more coherent framework. The International Negotiating Committee (INC) sessions began in 2022, with the goal of concluding a treaty by 2024, representing an effort to coordinate global actions and strengthen international governance (UNEP, 2023). However, for this international cooperation to be effective, it is crucial for countries to develop national and regional capacities to implement internationally agreed-upon policies. Implementation depends not only on political commitments but also on financial and technical support, which are often insufficient in developing countries. This requires a robust financing mechanism and a monitoring structure that ensures transparency and accountability from all involved parties.

In this context, the concept of 'country archetypes,' as proposed by the Plastic Overshoot Day Report (POD, 2024), deserves attention as an approach to operationalize actions. This report proposes that each country has its own plastic overshoot day, which marks the point when its plastic waste generation exceeds its waste management capacity, leading to environmental pollution. This day is determined by four parameters: (1) the amount of plastic waste produced by the population; (2) how effectively plastic waste is managed; (3) how much plastic waste the country exports; and (4) how much plastic waste the country imports. These parameters are used to establish categories, or 'archetypes' of countries, so that relevant and meaningful solutions for nations with similar characteristics can be identified, discussed, and proposed. Specifically, the POD (2024) report has outlined six archetypes (Table 1): moderate polluters, overloaders, low-waste producing polluters, toxic waste producers, transactors, and the self-sustained, represented by the Russian Federation, Australia, Ghana, Qatar, the Netherlands, and Colombia, respectively.

Some management alternatives previously discussed in this study are also recommended by the POD report for different archetypes of countries. For example, becoming circular, represented by the recycling arrows in the macroscope (Fig. 1) and recommended by Prabawati et al. (2023) as a general strategy to reintroduce plastic into the mainstream economy, is also proposed for Overloaders, Toxic Waste Producers, Transactors, and Self-sustained countries. These nations have moderate to high levels of plastic waste generation, and while they generally have efficient plastic waste management (except for Toxic Waste Producers), some issues persist, preventing them from becoming more effective in addressing the plastic problem. For example, in the case of Overloaders - a category that includes all G7 members - an effective plastic waste management system is associated with a high level of plastic waste exports. This export can overload the waste management systems of receiving countries, masking the real problem. The circular economy approach could help reduce exports and the associated overloading. A similar issue exists for Transactors, represented by wealthy European countries like the Netherlands, which have efficient plastic waste management but are also involved in high levels of plastic waste import and export with neighboring countries. In this case, although there is no overload for the receiving countries, the circular economy is recommended to reduce pollution and transport-related costs. The circular economy could also enhance waste management in self-sustaining countries such as Brazil, China, and Mexico, where plastic waste generation per capita is not as high as in more developed countries, but inefficient waste management systems result in a higher percentage of plastic waste mismanagement. In these countries, applying circular economy principles should involve integrating existing informal waste services (Alencar et al., 2022; Chen et al., 2021; Chitaka and von Blottnitz, 2021; Liu et al., 2013; Prabawati et al., 2023; Velis et al., 2022; Winterstetter et al., 2021). This approach could positively impact both the environment and the population by creating new jobs.

Another recommendation proposed by the POD (2024) report is the implementation of Extended Producer Responsibility (EPR), a key

Table 1
Countries archetypes and its proposed strategies according to the POD (2024).

Archetype	Characteristics	Reference country	Proposed strategies
Moderate polluters	Medium plastic waste generation level; half of theme exports some of their waste; management not effective with damage both domestically and abroad	Russian Federation	Develop local waste management infrastructure; reduce plastic consumption; invest in waste management policies including Extended Producer Responsibility
Overloaders	High plastic waste generators; waste generally well managed; significant export; import < export; overloading of the waste management systems of other countries; mismanagement issues in countries that receive the waste	Australia	Reduce plastic production and use; become circular
The low-waste-producing polluters	Low waste production levels; poor waste management practices.	Ghana	Develop local waste management infrastructure; Invest in waste management policies including Extended Producer Responsibility,
The toxic waste producers	High plastic waste generators; waste is mismanaged at high levels; some of these countries export their waste to places that do not have proper waste management infrastructure.	Qatar	Reduce plastic production and use; Develop local waste management infrastructure; become circular.
The transactors	High rates of plastic waste production; waste tends to be well-managed; high import and export with imported waste = exported waste	The Netherlands	Reduce plastic production and use; become circular
The self-sustainers	Moderate plastic waste generators; able to some extent manage their waste internally; improvements are needed	Colombia	Reduce plastic production and use; develop local waste management infrastructure; become circular.

strategy to finance waste management and encourage companies to invest in circular product designs (Abbott and Sumaila, 2019; Baxter et al., 2022; Diggle and Walker, 2022; Mazhandu et al., 2020; Raubenheimer and Urho, 2020; Vanapalli et al., 2023). EPR could be a crucial factor for countries classified under the 'low waste-producing polluters' archetype. These nations, primarily the poorest in Africa and Asia, generate low levels of plastic waste but suffer from extremely high rates of plastic waste mismanagement due to the lack of basic infrastructure. Thus, EPR would provide both economic and technological support to develop waste management infrastructure in these countries.

Companies should adopt a proactive and collaborative stance, engaging in meaningful practices that include tracking and reporting their plastic footprint, eliminating unnecessary plastic (especially single-use plastics), shifting from virgin to recycled plastic, creating opportunities for innovative products and practices, and avoiding greenwashing. A global initiative led by the Worldwide Fund for Nature (WWF, 2023b), which created a hub for some of the largest global companies, aims to support this transition. However, their 2023 project report concludes that the results achieved by the companies after four years of the project are far from transformative. For instance, in 2022, four out of nine companies increased their virgin plastic consumption, and efforts to reuse and recycle remain slow and limited in scale. Although companies have made improvements in accounting for and reporting plastic data, a much more ambitious change is needed to achieve a broader impact.

An effective and innovative approach to mitigating marine plastic pollution requires a combination of robust governance and technological innovation, that until that moment has shown insufficient to address the problem. International cooperation plays a critical role in creating a harmonized regulatory framework, while technological innovations offer practical solutions to address challenges on the ground. By integrating these elements, we can move towards a more sustainable and resilient future for our oceans. Technological innovation should not be limited to the development of new materials and degradation technologies. Integrating these technologies with public policies and governance initiatives will be essential to ensure their effectiveness and long-term sustainability. For example, Brazil has been implementing initiatives to promote collaboration between universities, governments, and the private sector to develop integrated strategies that address not only mitigation but also the prevention of plastic pollution (Iwanicki and Zamboni, 2020). Therefore, although advances were made at global and local levels in the recent years, a more ambitious and transformative global pact is necessary.

5. A macroscope view to better understand the problem and support future studies

This systematic review of scientific literature, by using Odum's macroscope approach, has revealed the complexity and multifaceted nature of marine plastic pollution crisis. Despite significant efforts by the scientific community over the past decade to understand and address marine plastic pollution, the literature review reveals that no single, simple strategy can adequately address the magnitude of this threat. Promising alternatives include advancements in monitoring technologies, which could enhance the development of more effective management strategies. Policies such as single-use plastic bans and Extended Producer Responsibility (EPR) also show potential by guiding society towards more responsible production and consumption pathways. However, as Kwon (2023) emphasizes, there is no indication that these efforts alone will suffice to tackle the problem. According to Borrelle et al. (2020), estimates suggest that addressing plastic pollution would require an 85 % reduction in plastic waste generation, proper management of ≥99 % of plastic waste, or the recovery of 85 % of annual global plastic waste. Achieving these targets appears challenging in the short to medium term.

The lack of a systemic perspective has hindered the efficiency of scientific efforts. For instance, some proposed strategies can potentially cause more harm than benefit or are impractical to scale up, such as ocean litter collection or plastic degradation using genetically modified bacteria. Additionally, crucial aspects like waste management and freshwater cleaning have been neglected in the current literature. It is recognized that mismanaged waste enters the ocean through freshwater ecosystems, with plastic waste more likely to enter aquatic environments the closer it is generated and mismanaged (Borrelle et al., 2020). Therefore, strategies to improve waste management and cleaning freshwater systems could significantly reduce plastic entering the ocean.

The macroscope approach applied in this study to better understand the causes and consequences of plastic pollution reveals that one critical compartment has been overlooked by all evaluated scientific publications: the pre-manufacture of plastics. The petrochemical industry provides the raw materials and energy that sustain the entire plastic production chain. However, no management alternatives have been assessed or proposed for this stage, indicating that scientific efforts have not yet addressed the root causes of the plastic problem. Similar to the current climate crisis, the plastic pollution crisis stems from an economic system reliant on fossil resources. Both issues are global, transboundary in impact, and carry socio-environmental implications. It is imperative to elevate discussions on plastic pollution to the same global level as climate change, with the establishment of global regulations, targets, and considerations for environmental justice. Like carbon emissions, plastic production and consumption are higher in wealthier countries, yet the consequences disproportionately affect poorer countries (Black et al., 2020; Kalina, 2020). Furthermore, as identified in this study, most research on strategies originates from developed countries, posing challenges for application in developing countries due to differences in culture, economy, and climate.

A potential limitation of this study is related to the number (sample of 176) of scientific articles considered in the literature review. However, it is recognized that this sample is representative of existing scientific publications on the topic. In future efforts, alongside expanding and updating the sample, it is suggested that the plastic crisis be comprehensively evaluated similar to the food, water, and energy (FEW) nexus, addressing both the problems and solutions. Consider a simple conceptual exercise to illustrate this suggestion: Plastic pollution contributes to the depletion of freshwater resources, with a significant portion originating from food and beverage packaging. Excessive packaging is driven by long-distance transportation, a consequence of linear global production chains primarily driven by economic interests. Within these traditional systems of production and consumption, strategies for plastic pollution can also incur significant environmental costs. Furthermore, bio-based plastics utilize environmental resources that could otherwise be allocated to food and clean energy production. Thus, the existing nexus of plastics with the FEW elements is evident and could be leveraged to better understand the plastic crisis and propose effective management alternatives.

As a final message, the literature review underscores that no single strategy comprehensively addresses the highly complex issue of ocean plastics. Due to the transboundary nature of the plastic crisis, adopting a systemic perspective is crucial to better comprehend its origins, impacts, and develop effective actions. As a result of a round table with experts in plastics (Ulgiati and Agostinho, 2022), including representatives from academia and industry, experts highlighted that we have many opportunities to prevent plastics from being discharged in the first place, either by industry or policy innovation. It is time for a global coordinated action plan.

6. Conclusion

Using Odum's Macroscope, the systematic review conducted in this study revealed that while many high-quality papers have been published on the topic of ocean plastics, the strategies evaluated and/or proposed remain insufficient to solve the problem. An analogy can be drawn to a puzzle in which the pieces do not fit together perfectly. Most of the studies considered were carried out in an uncoordinated and fragmented manner, resulting in underrepresented topics, inconsistencies in some of the strategies — with outcomes pointing in opposite directions — and an absence of a systemic approach to integrate the various aspects of the issue. This likely reflects a broader lack of systemic thinking in addressing the problem, which has led to limited impact and hindered effective decision-making. Future research should adopt a systemic approach, such as Odum's Macroscope, to develop strategies that foster synergies between the various dimensions of plastics in the ocean, allowing for scalable and long-term solutions.

Supplementary data to this article can be found online at https://doi.org/10.1016/j.marpolbul.2024.117075.

CRediT authorship contribution statement

T. Fonseca: Writing – original draft, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **F. Agostinho:** Writing – review & editing, Visualization, Validation, Methodology, Conceptualization. **J.M.S.J. Pavão:** Writing – review & editing, Resources, Project administration, Funding acquisition. **F. Sulis:** Writing – review & editing, Visualization, Validation, Conceptualization. **M.M.C. Maceno:** Writing – review & editing, Visualization, Validation, Conceptualization. **C.M.V.B. Almeida:** Writing – review & editing, Visualization, Validation, Methodology, Conceptualization. **B.F. Giannetti:** Writing – review & editing, Visualization, Validation, Supervision, Methodology, Conceptualization.

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.

Acknowledgements

The authors are grateful for the financial support received from Vice-Reitoria de Pós Graduaçao da Universidade Paulista (UNIP), the University Centre Cesmac and from CNPq Brazil (405449/2022-4), Project 'Plastic oceans: Monitoring the plastic production chain. Integrating disposal and recycling strategies to tackle pollution', coordinated by Dr. Jessé Marques da Silva Júnior Pavão. T.F., F.S. and F.A. are also grateful for the financial support provided by CNPq Brazil (305593/2023-4; 384630/2023-5; 305593/2023-4).

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