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Review

Microplastic levels and sentinel species used to monitor the environmental quality of lagoons: A state of the art in Italy

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ABSTRACT

Lagoons play an important role in providing a variety of ecological services. They provide important habitats for several plant and animal species, also acting as natural filters that regulate water quality. Microplastic (MP) pollution has become a global environmental problem that warrants in-depth studies to understand its impact on socioeconomically and ecologically important areas such as lagoon systems. However, there is a notable lack of data on the occurrence of MPs in Italian lagoon systems, highlighting the need for monitoring and assessment. In this review, peer-reviewed studies from Google Scholar and Scopus databases were examined (n = 10), reflecting the current knowledge on the occurrence of MPs in Italian lagoon systems. A high degree of methodological heterogeneity was recorded, making difficult a meaningful comparison and draw comprehensive conclusions about the occurrence of MPs. Alarmingly, in Italy, only 9 of more than 100 coastal transition ecosystems have been monitored for MP pollution, leaving a significant number unexplored and inadequately studied. In addition, most studies have focused primarily on organism analysis without simultaneously examining the presence of MPs in water and sediments, making it difficult to establish links between MP pollution in abiotic and biotic compartments. To address these gaps, we extended the literature review to research performed worldwide to identify potential organisms suitable for monitoring MPs in lagoons and nearshore transition ecosystems. As observed in many studies, our results highlight the urgent scientific need to standardize methods, procedures, and sampling designs to facilitate comparability and improve the robustness of future research in this area. Overall, this review sheds light on the MP occurrence in Italian lagoon systems, highlights the limitations of existing studies, and emphasizes the urgency of adopting standardized approaches for consistent monitoring and assessment. By addressing these research gaps, we can improve our understanding of MP pollution in lagoons and develop effective strategies to protect these important ecosystems.

1. Introduction

Lagoons are unique coastal ecosystems characterized by shallow brackish water separated from the open sea by sandbars, barrier islands, or spits (Pérez-Ruzafa et al., 2019). Lagoons are semi-enclosed bodies of water typically found along coasts. They are characterized by a combination of freshwater and marine influences, resulting in a unique brackish water environment (Kjerfve, 1994). Water in lagoons can be influenced by tides, freshwater inputs from rivers, and interactions with the adjacent sea (Chacón Abarca et al., 2021). These factors contribute to the high productivity and biodiversity in these ecosystems. Lagoons play an important role in providing a variety of ecological services. They serve as important habitats for various plant and animal species, including migratory birds, fish, and shellfish (Barbier et al., 2011). Lagoons also act as natural filters that regulate water quality by retaining sediments and absorbing pollutants transported by rivers and other sources (Rodrigues-Filho et al., 2023). Vegetation in lagoons helps stabilize sediments, prevent erosion, and maintain water clarity. In addition, lagoons serve as nursery areas for many commercially important fish species (Barbier et al., 2011).

Despite their ecological importance, lagoons are increasingly subject to various anthropogenic pressures. These pressures arise from human activities such as urbanization, agriculture, industrial development, and tourism (Lacoste et al., 2023). Discharges of domestic and industrial

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wastewater, nutrient runoff, and alteration of freshwater flows can negatively impact lagoon ecosystems. These activities can lead to eutrophication, habitat loss, water pollution, and changes in the natural hydrological system (Gjoni and Basset, 2018).

One of the most important anthropogenic pressures on lagoons is chemical pollution, which is predominantly plastic debris (Velez et al., 2020). Plastics are a major component of marine pollution and come from a variety of sources, including land-based activities, coastal tourism, shipping, and fishing (Jambeck et al., 2015; Jiang et al., 2022; Lacoste et al., 2023). Studies have shown that plastic debris can remain in the marine environment for decades, if not centuries (Andrady, 2015). In addition, plastic waste can be transported by rivers and currents, accumulate in lagoons, and pose a significant threat to their ecosystems (Ciglenečki et al., 2020; Paduani, 2020; Velez et al., 2020).

If plastics are the main component of waste entering the lagoons, it is the microplastic (MP) particles that pose the greatest threat. These are tiny plastic particles less than 5 mm in size, classified by size (Perumal and Muthuramalingam, 2022). Microplastics can originate from the degradation of larger plastic items (secondary MPs) or enter the environment directly (primary MPs), such as microbeads used in personal care products or microfibers released during washing (Zhang et al., 2021). Physical weathering of larger plastic items such as bottles or fishing gear, combined with fragmentation by UV radiation and mechanical forces, leads to the formation of MPs (Perumal and Muthuramalingam, 2022). These particles can be transported by rivers and eventually end up in lagoons, where they can remain for long periods of time (Abidli et al., 2017; Garcés-Ordóñez et al., 2022). Due to their unique characteristics and ecological functions, lagoons also act as "sinks" for MP accumulation (Pérez-Ruzafa et al., 2019; Specchiulli et al., 2023). The brackish nature of lagoons, combined with the presence of sediment traps and slower water exchange compared to open coastal areas, can facilitate the storage and accumulation of MPs (Martellini et al., 2018; Scopetani et al., 2021). This accumulation can lead to increased exposure and ingestion by resident organisms, with potential physiological and ecological consequences (Cole et al., 2015; Trestrail et al., 2020). Fisheries and aquaculture, such as shellfish aquaculture, often use plastic gear that can release MPs (e.g., awns) into the aquatic environment (Chen et al., 2021; Wu et al., 2023). In addition, municipal wastewater treatment plants often discharge their treated effluents into lagoon systems, which can serve as significant sources of MP and microfiber pollution from laundry (Gaylarde et al., 2021; Fan et al., 2023). Understanding and mitigating these sources of MP pollution are critical to the sustainable management of lagoon environments and the protection of the aquatic organisms that inhabit them.

MPs have attracted attention not only because of their impact on the environment and their ability to be ingested by a wide range of organisms (Bikker et al., 2020; Koelmans et al., 2022), but also because of their biomagnification through the food chain to humans (Wright et al., 2013; Miller et al., 2020). The risk and adverse effects of MP accumulation on human health have attracted growing research interest, particularly with regard to assessing MP accumulation in economically important organisms (Barboza et al., 2018; Vázquez-Rowe et al., 2021; Vital et al., 2021). Numerous studies have focused on understanding the extent of human exposure to MPs through diet and have shown that, on average, humans can ingest up to 5 g of MPs per week (Senathirajah et al., 2021).

Microplastic pollution in lagoons is a growing problem with significant ecological and environmental implications. Understanding the sources, fate, and impacts of MPs in lagoons is critical to developing effective management strategies to mitigate impacts on these fragile ecosystems. However, there is currently a lack of comprehensive knowledge about MP pollution in this environment. Existing information on pollution levels and analytical methods for assessing MPs in water, sediments, and organisms are dispersed among different sources, making it difficult to integrate data and assess the problem. Therefore, the aim of this study is to review and summarize the progress made in the investigation of MPs in Italian coastal lagoons.

The aim of this review is to define: (1) the state of the art regarding the amount of MPs in abiotic and biotic components of Italian lagoons, focusing on the main sources; (2) the methods used for their determination; (3) types and indicators that could be considered more appropriate for evaluating the presence and amount of MPs to assess lagoon quality; (4) the main gaps and future perspectives of the research.

2. Literature search strategy

This review was based on scientific literature published by international sources and data sources. The Google Scholar (https://scholar.google.com) and Scopus (https://www.scopus.com) search engines were used for the research with the following search parameters (June 1st, 2023): Articles published from 2000, peer-reviewed articles. The keywords used were: "lagoons", "microplastics", "Italy", "Italian", "litter", "coastline", "Mediterranean", "ecological indicators", "sentinel". Keywords were entered into the databases both in conjunction with different combinations and individually, following PRISMA guidelines (preferred reporting elements for systematic reviews and *meta*-analyzes) according to the literature (Page et al., 2021). The selection process was based on an initial reading in which articles were selected based on the inclusion of the appropriate word(s) in the title or abstract. Additionally, references were reviewed to increase the number of articles analyzed. Information on the location of the lagoon and its characteristics (extent, protected areas, human activities) was extracted. The sampling methods used and the ecological matrix in which the analysis was carried out were recorded. Qualitative and quantitative data were extracted, including size ranges, average MPs abundance, units of measure, and polymer types. Potential sources were identified in each scientific publication by analyzing discussion chapters or examining the study area. Information on the extent of lagoons not reported in the studies reviewed was estimated using qGIS (https://www.qgis.org/it/site/).

3. Amounts and sources of microplastic pollution

3.1. Results of literature search

In Google Scholar and Scopus search engines, 55 studies were identified, from which we selected and reviewed 10 papers on MP

Table 1
Reviewed studies with information on the examined lagoons in individual papers, ordered by publication year.

Reference	Digital object identifier (doi)	Lagoon
Vianello et al. (2013)	https://doi.org/10.1016/j.ecss.2013.03.022	Venezia Lagoon
Atwood et al. (2019)	https://doi.org/10.1016/j.marpolbul.2018.11.045	Busa di Scirocco (Po river)
Piarulli et al. (2019)	https://doi.org/10.1016/j.envpol.2019.04.092	Piallassa Baiona, Sacca di Bellocchio, Chioggia Lagoon
Piarulli et al. (2020)	https://doi.org/10.1016/j.marpolbul.2020.110983	Piallassa Baiona, Sacca di Bellocchio, Venezia Lagoon
Renzi et al. (2020)	https://doi.org/10.1016/j.marpolbul.2020.111300	Lesina Lagoon
Sfriso et al. (2021)	https://doi.org/10.3390/w13213032	Sacca di Goro (Po river), Venezia Lagoon
Mistri et al. (2021)	https://doi.org/10.1007/s11270-021-05323-9	Sacca di Goro (Po river), Venezia Lagoon
Mudadu et al. (2022)	https://doi.org/10.4081/ijfs.2022.9973	Calich Lagoon
Specchiulli et al. (2023)	https://doi.org/10.1016/j.scitotenv.2023.164228	Lesina Lagoon
Provenza et al. (2023)	https://doi.org/10.1016/j.etap.2023.104075	Orbetello lagoon; Varano Lagoon

pollution in coastal lagoons (Table 1). The first study on MP pollution in coastal lagoons after 2000 was published by Vianello et al. (2013) on the Venice Lagoon, Italy. Until 2018, the number of publications analyzed on this topic was negligible in Italy, but since 2019 it has been increasing in trend with the rest of the world (Garcés-Ordóñez et al., 2022) (Fig. 1).

Most studies focused on the characteristics and abundance of MPs in individual compartments (biotic or abiotic) (i.e., Vianello et al., 2013; Piarulli et al., 2019, 2020; Renzi et al., 2020; Sfriso et al., 2021; Mistri et al., 2021; Mudadu et al., 2022; Provenza et al., 2023), with limited integration, which affects our understanding of MP dynamics in these lagoons. Only two studies examined two abiotic compartments (water and sediment) (Atwood et al., 2019; Specchiulli et al., 2023). Most coastal lagoons where MPs were studied were in international or national protected areas such as Ramsar sites, nature reserves, sites of wildlife conservation importance, sites of community or regional importance (SIC or SIR), or special protection areas (ZPS) (Table 1).

3.2. Analytical methods

The lack of standardization in the study of MPs in aquatic environments has made it difficult or challenging to compare ecosystems and environmental matrices at local and regional scales (Hermsen et al., 2018; Zarfl, 2019). This is primarily due to differences in filter size and differences in performance measurement (Zhao et al., 2018). In addition, there are other methodological differences, including variability in the dimensions of the MPs studied, as well as variations in density separation and chemical digestion methods for water, sediment, or organism samples, which can vary significantly in different cases (Stock et al., 2022). Finally, there is considerable variation in the tools used to analyze the abundance of MPs, from visual approaches using optical microscopy to more accurate methods such as spectroscopy (i.e., FT-IR, SEM + EDS) as reported by the literature (Fischer and Scholz-Boettcher, 2017; Girão, 2020; Huppertsberg and Knepper, 2020).

Most of studies ($n = 6$) focused the attention on the analysis of MP in aquatic organisms (Piarulli et al., 2019, 2020; Renzi et al., 2020; Sfriso et al., 2021; Mudadu et al., 2022; Provenza et al., 2023). Among them, 2 studies used the crab *Carcinus aestuarii* (Nardo, 1847) (Piarulli et al., 2019, 2020). In one, the crab *Callinectes sapidus* (Rathbun, 1896) was used (Renzi et al., 2020). In 3 studies, the soft tissues of *Mytilus galloprovincialis* (Lamarck, 1819) were used (Piarulli et al., 2020; Mudadu et al., 2022; Provenza et al., 2023). In contrast, algae and kelp were used only in one study (Sfriso et al., 2021). As with the other environmental matrices, in three studies sediment samples were collected at various depths from the surface to a depth of 5 cm (Vianello et al., 2013; Atwood et al., 2019; Mistri et al., 2021). The mass of sediment transported to the laboratory varied, as did the sampling device, which was sometimes not specified. Only two studies analyzed the abundance of MP in the water

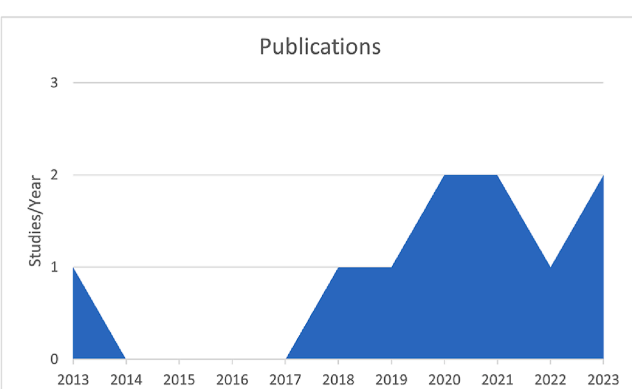

Fig. 1. Number of papers per year (2013–2023) reporting microplastic abundance values in Italian lagoon systems, published in peer-reviewed journals and included in this review.

using different methods (Atwood et al., 2019; Specchiulli et al., 2023). One study used a mini-manta trawl to sample litter directly at the water surface (Atwood et al., 2019), while the other collected 5 L of water in MP-free container (Specchiulli et al., 2023).

A significant proportion (47%) of the studies reviewed in this study used chemical digestion techniques to facilitate detection and quantification of MPs. Seven of these analyzes used potassium hydroxide (KOH) as the digestion agent, and one used a 20% hydrogen peroxide (H_2O_2) solution. A smaller proportion (18%) of studies did not select a digestion method. Three of these studies employed density separation methods using sodium chloride (NaCl) to selectively isolate MPs from the sample matrix based on their buoyancy. In addition, two studies used staining with Nile red to better visualize MPs (Erni-Cassola et al., 2017), while one study used Rose Bengal for identification (Gbogbo et al., 2020). In the enzymatic digestion category, two studies used the CREON digestion method to degrade organic material and isolate MPs (von Friesen et al., 2019). Regarding visualization techniques, the vast majority (82%) of studies used FT-IR spectroscopy, while a smaller proportion (18%) relied only on visual examination.

These results highlight the different methods used by researchers to analyze MP occurrence in lagoons, taking into account specific characteristics such as the presence of seagrasses or algae, as well as the type of sediments or the content of organic matter in the samples, which influence the choice of appropriate sampling methods. While there were differences in laboratory testing methods, they generally followed three main approaches: (1) direct visual inspection, (2) chemical digestion combined with visual inspection, and (3) a combination of chemical digestion and density separation followed by visual inspection (Garcés-Ordóñez et al., 2022). This demonstrates the different approaches used by researchers to analyze MP presence and highlights the importance of the use of standardized methods to improve comparability and understanding of MP pollution in the aquatic environment.

3.3. Abundance of microplastics

A total of 9 lagoons were considered for MP investigation (Table 1; Fig. 2). Since the aim of this review is to provide an overview of the general MP situation in lagoon systems, we have subdivided the results of each lagoon studied for better understanding (Table 2). It is not the aim of this review to compare the presence of MPs in the different compartments, especially since very few studies have been carried out in Italy analyzing both sediments and water.

In this section we present some characteristics of the lagoons studied, define the techniques used and the matrices analyzed, and indicate the abundance of MPs in the different compartments. When available, we describe the form of MP and the main polymers. Finally, where available, we have extracted information from discussions or results and debates on possible sources of MPs.

3.3.1. Venice lagoon

The Venice Lagoon (45°20′12.5″N; 12°16′30.0″E), with an area of 550 km2, is a unique and ecologically valuable coastal ecosystem subject to various environmental pressures (Micheletti et al., 2011). These include urbanization, tourism, port activities, agriculture, and fishing. The presence of urban settlements, including the cities of Venice and Mestre, has led to infrastructure development and changes in the natural hydrological balance of the lagoon. The influx of tourists contributes to the use of boats and navigation in the lagoon's channels, which can lead to disturbance of aquatic habitats and waste pollution. The Venice Lagoon is also home to the Port of Venice, one of the most important ports on the Adriatic. Port activities such as vessel traffic, cargo management, and loading and unloading operations can cause noise pollution, water pollution, and disturb marine habitats (Lee, 2021). Agricultural practices in the hinterland and fishing activities in the lagoon can also have negative impacts on the ecosystem, including the use of fertilizers, pesticides, and the introduction of non-native species

Fig. 2. Map of Italy showing the locations of the examined and reviewed lagoons in our study. Source: adapted from www.worldmapblank.com.

(Çevirgen et al., 2020).

Two studies addressed the analysis of MPs in sediment samples from the Venice Lagoon. The first study, conducted by Vianello et al. (2013), was a pioneering study on MPs in Italy. MPs smaller than 1 mm were separated by density separation (NaCl) and analyzed by Fourier transform infrared micro spectroscopy (μFT- IR). Total abundances ranged from 2175 to 672 MPs per kilogram dry weight (MPs/kg d.w.), with higher concentrations typically observed at landward sites. The most commonly polymers, which accounted for over 82% of the total MPs, were polyethylene (PE) and polypropylene (PP). The predominant size range of the MP (93% of the observed MP) was between 30 and 500 μm. In the second study conducted by Mistri et al. (2021), no density separation was performed. Instead, visual inspection and μFT-IR analysis were performed. The study focused on sampling sites in special protection areas (SAC). MPs ranging in size from 0.5 to 5 mm and averaging 28.4 pieces per kilogram (pieces/kg) were found. The most common polymers found were PE and polystyrene (PS). In both studies, MPs were observed in the form of fragments, fibers, films, and pellets.

Two other studies focused on the analysis of MPs in organisms in the Venice Lagoon studied the crab species *Carcinus aestuarii* (Piarulli et al., 2019, 2020). Digestion with KOH and μFT- IR analysis was performed, yielding an average of 2.2 MPs per individual. Most of the identified polymers belonged to the polyether sulfones group (PES).

Sfriso et al. (2021) assessed the presence of MPs in 15 macroalgal species and one seagrass species from different sites within the Venice lagoon. In this case, digestion with KOH and density separation with NaCl and Na_2EDTA were performed. However, unlike the previous study, no FT-IR analysis was performed; Thus, no information is available on the polymers detected. The MPs were counted and sorted under a stereomicroscope with a Nile red stain after filtering at 0.7 μm. A high percentage (94%) of the macrophyte samples contained MPs ranging in size from 0.16 to 330 pieces per gram fresh weight (pieces/g f.w.). The predominant size range for MPs in these samples was 30–90 μm.

The results of these studies indicate that the Venice Lagoon is contaminated with MPs in a variety of environmental matrices. The sediment samples showed different abundances of MPs influenced by location and proximity to landward areas. The dominance of the polymers PE and PP illustrates the contribution of plastic packaging and synthetic materials to MP pollution. The detection of MPs in organisms, including crustaceans and macrophytes, raises concerns about the potential transfer of MPs through the food web.

3.3.2. *Sacca di Goro (Po River)*

The Sacca di Goro (44°48′00.0″N; 12°21′00.0″E) is a coastal lagoon in Emilia-Romagna Region. It covers an area of about 25 km^2 and is an important resting and nesting place for numerous migratory bird

Table 2
Lagoons under study with their respective organisms and the average abundances or abundance ranges of microplastics (MPs) detected. The polymers are specified as follows (write the complete polymer name after the abbreviation): PES (Polyester), ACN (Acrylonitrile), PA (Polyamide), PP (Polypropylene), PET (Polyethylene terephthalate), NL (Nylon), PVC (Polyvinyl chloride), PU (Polyurethane), PE (Polyethylene), PAN (Polyacrylonitrile), PVA (Polyvinyl alcohol). "n.d." stands for not detected.

Lagoon	Matrix	Microplastics abundance	Unit	Shape	Polymer Types	Reference
	Organism	2.18 ± 1.54	Items/ind.	Fibers	PES, ACN, PA	Piarulli et al. (2019)
Piallassa Baiona	Organism	2.19 ± 1.5	Items/ind.	Fibers	PES	Piarulli et al. (2020)
	Organism	0.04 ± 0.02	Items/ind.	Fibers	PES, ACN, PA	Piarulli et al. (2019)
Sacca di Bellocchio	Organism	0.01–0.03	Items/ind.	Fragments and fibers	PP, PES	Piarulli et al. (2020)
Sacca di Goro	Organism	0.16–330	Items/g	Fibers	n.d.	Sfriso et al. (2021)
(Po river)	Sediment	2250	Items/kg	Fragments, Filaments	PE, PP, PET, NL, PVC, PU	Mistri et al. (2021)
Busa di Scirocco (Po river)	Water	1–6.1	Particles/m^3	n.d.	n.d.	Atwood et al. (2019)
Orbetello Lagoon	Organism	1.00 ± 2.45	items/ind.	n.d.	PET, PE	Provenza et al. (2023)
Chioggia Lagoon	Organism	0.04 ± 0.02	Items/ind.	Fibers	PES, ACN, PA	Piarulli et al. (2019)
	Sediment	1445	Items/kg	Fragments, fibers, films, and pellets	PE, PP, PEP, PES, PAN, PS, PVC, PVA, NL	Vianello et al. (2013)
	Sediment	28.4	Items/kg	Fragments and filaments	PE, PS, and PP	Mistri et al. (2021)
Venezia Lagoon	Organism	2.19 ± 1.5	Items/ind.	Fibers	PES	Piarulli et al. (2020)
	Sediment	24.96–39.91	Items/kg	filament, fragments	PP, PE	Specchiulli et al. (2023)
	Water	0.11	Items/L	filament, fragments	PP, PE	Specchiulli et al. (2023)
Lesina Lagoon	Organism	2.5 ± 1.6	Items/ind.	Fibres, fragments	PE, PET, NL, PES	Renzi et al. (2020)
Calich Lagoon	Organism	1.2–1.45 ± 0.3	Items/g	Fibers, Fragments	n.d.	Mudadu et al. (2022)

species. The lagoon is part of the Po Delta Regional Park, a nature reserve dedicated to the preservation of the area's unique ecosystems. The Sacca di Goro is subject to various anthropogenic influences such as intensive agriculture and fishing (Carafa et al., 2006). In addition, seasonal tourism and recreational activities may contribute to increased anthropogenic pressures at certain times of the year.

Two studies were conducted that focused on sediments and organisms. The first study examined lagoon sediments collected from various sites on the Sacca di Goro (Mistri et al., 2021). No digestion was performed, and MPs were characterized by visual inspection in the field and FT-IR analysis to identify polymers. The study focused on particles ranging in size from 0.5 to 5 mm, and the average result was 2250 pieces/kg of sediment, with many fragments followed by fibers. Analysis of FT-IR showed that PE (polyethylene) and PP (polypropylene) were the main polymers, followed by PS (polystyrene) and TPU (thermoplastic polyurethane), with smaller amounts of PER (polyethylene terephthalate), NL (nylon) and PVC (polyvinyl chloride). The second study, conducted on organisms, used algae and kelp, which contained a total of 16 different species (Sfriso et al., 2021). The range of MPs at the different sampling sites was between 0.16 and 330 pieces/g, with fibers predominating.

Findings suggest that the Po River is an important source of MPs in coastal lagoons. Its contribution to the transport of plastic waste explains the observed differences in plastic concentrations at the sites studied. Interestingly, the predominant plastic form in the sediment samples was fragments, which differs from other studies (majority fibers), possibly due to differences in collection and identification methods (Mistri et al., 2021). The identified polymers, such as PE, PP, PS, and TPU, indicate a mixture of terrestrial and marine sources of plastic pollution. These findings are particularly relevant to the Goro Lagoon, as they highlight the widespread presence of plastics in this particular area and its potential impact on the environment and human health.

3.3.3. *Piallassa Baiona*

Piallassa Baiona (44°30′00.0″N; 12°15′00.0″E) is a coastal lagoon in Emilia-Romagna, about 40 km from the Po Delta. It covers an area of about 8 km^2 and is part of the Po Delta Regional Park. The lagoon includes a variety of habitats, including reed beds, wetlands, and freshwater pools. It serves as an important nesting site for several species of waterfowl and plays an important role in the migratory cycle of many organisms (Volponi, 2000). The Piallassa Baiona is subject to various environmental pressures, including metal pollution, habitat loss, and agricultural activities (Giordani, 2005; Guerra et al., 2014, 2013). The site is a wetland of international importance (RAMSAR Convention, EU Birds Directive, EU Habitats and Species Directives). It receives inputs from six sewers originating from urban, agricultural, and industrial wastewater treatment plants, as well as thermal power plants that contribute to anthropogenic pollution of the area (Fabbri et al., 2003).

One year apart, two studies were published that focused on the same organism, the crab *Carcinus aestuarii* (Piarulli et al., 2020, 2019). Both studies investigated the gastrointestinal tract of the crab and used potassium hydroxide (KOH) digestion and μFT-IR as analytical methods. The results of both studies were quite similar, with an average of 2.18 ± 1.54 pieces per individual in the 2019 study and an average of 2.19 ± 1.50 pieces per individual in the 2020 study. The most abundant MPs observed were fibers, and the predominant polymer types detected in order of abundance were polyethersulfone (PES), acrylonitrile (ACN), and polyamide (PA).

Microplastic pollution in the Piallassa Baiona is influenced by several sources, including fluvial contributions such as the Po River as the main source. Sediments mainly accumulate MPs, with plastic fragments being more abundant compared to fibers. Microfibers are the predominant form, which can lead to longer residence times in organisms. The distribution of MPs in benthic invertebrates varies depending on their location in the sediment.

3.3.4. *Sacca di Bellocchio*

The "Sacca di Bellocchio" (44°37'00.0"N; 12°16'00.0"E) is a coastal lagoon in Emilia-Romagna, located 30 km south of the Po Delta and 10 km north of the lagoon of Piallassa Baiona. It covers an area of about 4 km^2 and is part of the Po Delta Regional Park. This wetland is characterized by a variety of habitats, including reed beds, mud banks and freshwater bodies. The Sacca di Bellocchio is an important refuge for numerous species of waterfowl and marine life. The low human impact on the lagoon is primarily due to seasonal tourism and recreational activities. The Sacca di Bellocchio benefits from several environmental protection designations within the Po Delta Regional Park, as well as local regulations that promote sustainable management of the area, such as the Special Protection Area (ZSC) and the Special Protection Area (ZPS).

Regarding the studies on MPs, two studies were conducted with different organisms. The first study by Piarulli et al. (2019) examined the gastrointestinal tract of the crab *Carcinus aestuarii* using enzymatic digestion followed by FT-IR analysis. An average abundance of 0.04 ± 0.02 pieces per individual was found, with fibers being the predominant form and the most frequently identified polymers being PES, ACN and PA. The second study focused on the mollusk *Mytilus galloprovincialis* (Piarulli et al., 2020), which is commonly used for the determination of MPs by analyzing soft tissue separated from the shell using a simple digestion and FT-IR analysis. A frequency range of 0.01–0.03 pieces per individual was detected, with fragments being the main form, followed by fibers. The most frequently detected polymers were PP and PES.

The low concentration of MPs can be attributed to the limited human activities in the area, consistent with the existing environmental regulations for the Sacca di Bellocchio. However, continuous monitoring of the occurrence of MPs over time is essential to assess potential changes and implement appropriate management measures to maintain the ecological integrity of this important lagoon area.

3.3.5. Busa di Scirocco (Po River)

The Busa di Scirocco (44°56′52.7″N; 12°30′23.1″E) is a coastal lagoon in the Veneto Region of Italy, in the centre of the Po Delta. It covers an area of about 16 km^2. The lagoon is characterized by a variety of habitats, including areas of reeds and mud. As part of the Delta del Po Regional Park, it serves as an important stopover for migratory birds and is protected as a Special Protection Area (ZPS) within the Natural Park. The Busa di Scirocco is exposed to various anthropogenic influences, mainly due to agricultural activities, land reclamation, urbanization, and tourism.

Atwood et al. (2019) focused on the aqueous matrix and was conducted using a "mini-manta trawl". This device was specifically designed to collect MPs in the aquatic environment. It consists of a small, fine-mesh net attached to a frame that is towed through the water. The net is designed to collect particles in a specific size range, typically from a few millimetres to several hundred micrometres (Syakti, 2017). Enzymatic digestion followed by wet cleaning with hydrogen peroxide was performed. Microplastic analysis was performed using FT-IR for the fraction from 5 mm to 300 μm and revealed the presence of MPs at concentrations ranging from 1 to 6.1 particles/m^3. However, no information is available on the form and types of polymers detected, although the analysis was performed using FT-IR.

The study acknowledges the limitations of this analysis and points out that the sampling method only detects MPs floating on the water surface, which may underestimate the total concentration of floating MPs (Kooi et al., 2016). The concentrations of MPs found in the study were an order of magnitude higher than those measured in the open Adriatic Sea (Suaria et al., 2016). Based on the mean MP concentration measured in situ, the average flow velocity of the Po River, and the estimated MP particle count in the Adriatic Sea, it is estimated that the Po River releases about 2.2 to 3.8 tons of MPs per day, which corresponds to 785–1402 tons per year (Liubartseva et al., 2016). The three main polymer types contributing to MP concentrations in beach sediments are PE, styrene-based polymers, and PP, which is consistent with data from other local studies (van der Wal et al., 2015).

3.3.6. Chioggia lagoon

The Chioggia Lagoon (45°13′15.0″N; 12°16′20.8″E) is a coastal lagoon of about 53 km^2 in the Veneto region, more precisely in the southern part of the Venice Lagoon. It is an area characterized by intensive fishing and aquaculture, which can be a potential source of pollution (Berto et al., 2007; De Liguoro et al., 2014). The Chioggia Lagoon is an important coastal ecosystem from both an ecological and socioeconomic point of view. It is designated within the Natura 2000 network (IT3250023 "Lido di Venezia: biotopi litoranei") under the Habitats Directive 92/43/EEC and the Birds Directive 2009/147/ EC as a Special Protection Area (SAC) and a Special Area of Conservation (SPA).

There is only one study on MPs focusing on the gastrointestinal tract of the crab *Carcinus aestuarii* (Piarulli et al., 2019). In the study, both enzymatic digestion and KOH digestion were performed, followed by visual inspection and FT-IR analysis. The microfibers found in the Chioggia Lagoon ranged from 0.03 to 3 mm in length, with an average length of 0.5 ± 0.03 mm, and the most abundant polymer found was PES (99%). The study showed an occurrence of 0.04 ± 0.02 pieces per individual, which is lower compared to other studies with crabs, but in agreement with the values found in the Bellocchio Lagoon.

In this study, one of the first empirical field investigations on the occurrence of MPs in crabs from the Chioggia Lagoon in the northern Adriatic Sea was conducted. The majority of crabs (96% of 180) did not contain MPs in their gastrointestinal tract. However, when MPs were present, they were exclusively in the form of microfibers. This is due to the fact that microfibers tend to become entangled and remain in the digestive tract longer (Watts et al., 2015). The predominant polymer type identified in the microfibers was polyester (PES), which is denser than seawater and likely sinks more quickly into the sediments on which the crabs feed.

3.3.7. Orbetello lagoon

The Orbetello Lagoon (42°28′00.0″N; 11°12′00.0″E) is a coastal lagoon in the Tuscany Region. It extends for about 26 km^2 and is located on the Tyrrhenian coast. The lagoon is characterized by a unique and diverse ecosystem that includes reed beds, ponds, wetlands, and brackish waters. It serves as an important resting and nesting place for numerous migratory bird species and is an important habitat for fish fauna and marine biodiversity. The Orbetello Lagoon is subject to various environmental protection measures and regulations aimed at preserving its ecosystem. These include the Duna Feniglia Nature Reserve, the designation as a Site of Community Importance (SCI) and as a Special Protection Area (SPA) under the European Directives for the conservation of natural habitats and wild species and birds. It is also part of the Protected Area System of the Tuscany Region (SIR). However, the shallow depth of the lagoon and the limited exchange of seawater limit water exchange and reduce the dilution capacity for organic inputs, nutrients (from urban runoff, aquaculture facilities and agricultural effluents) and anthropogenic pollutants (Specchiulli et al., 2008).

A study of MPs in the lagoon was conducted using *Mytilus galloprovincialis* as a bioindicator (Provenza et al., 2023). Mussel gills were subjected to CREON digestion (enzymatic) followed by stereomicroscopic examination; selected particles were measured and chemically analyzed by μFT-IR. An average of 1.00 ± 2.45 MP per individual (range: 0–6 MPs per individual) was found. The predominant MP were filaments of polyethylene terephthalate (PET) with a size of 2640.9 ± 1266.8 μm.

3.3.8. Lesina lagoon

Lesina Lagoon (41°53′00.3″N; 15°25′23.2″E) is a coastal lagoon in the Apulia Region (41.8806° N, 15.4244° E). With an area of about 51 km^2, it is one of the largest coastal lagoons in southern Italy. Lesina Lagoon is separated from the Adriatic Sea by a narrow strip of land, the Tombolo di Lesina, which forms a natural barrier. From an ecological point of view, the lagoon is part of the Gargano National Park, established to preserve and protect the unique ecosystem of this region. Moreover, the lagoon is part of the Natura 2000 network and has been designated as a Site of

Community Importance (SIC) and a Special Protection Area (ZPS) to ensure the conservation of natural habitats and wild species. However, the lagoon is exposed to various anthropogenic influences, including aquaculture, livestock farming, and urban runoff (Breber et al., 2008; Specchiulli et al., 2008).

Two studies were conducted that focused on three different environmental matrices: water, sediment, and organisms (Renzi et al., 2020; Specchiulli et al., 2023). For water samples, digestion was performed with H_2O_2, while sediment samples were separated with NaCl (Specchiulli et al., 2023). In both cases, extracts were filtered on 0.2 μm fiber filter disks and analyzed by μFT-IR. The results showed a concentration of 0.11 pieces per liter in the water samples, while sediment analysis showed a range of 24.96 to 39.91 pieces per kilogram. Filaments and fragments were the most abundant forms, with the polymers PP and PE being the predominant species. One study focused on the crustacean *Callinectes sapidus* and used hepatopancreas, gonads, stomach, and muscle tissues (Renzi et al., 2020). Tissues were digested with CREON, and the Rose Bengal method was used for presorting and subsequent analysis μFT-IR. In this study, an average of 2.5 ± 1.6 parts per individual were identified, with fibers and fragments being the predominant forms, mainly composed of polymers such as PE, PET, NL and PES.

Microplastic pollution in Lesina Lagoon is influenced by different sources and tends to accumulate in certain areas. The presence and distribution of MPs in Lesina Lagoon are associated with anthropogenic influences, with the highest concentrations observed in critical areas such as the city center, channels connected to the sea and freshwater streams. The presence of MPs in Lesina Lagoon is due to the slow degradation of plastic wastes originating from uncontrolled point and non-point sources, including local population, fisheries, and agricultural wastes. Wind and lagoon hydrodynamics can transport MPs to other locations, which explains their presence in smaller quantities away from point sources (Bermúdez et al., 2021). Runoff or flooding during the rainy season can also introduce MPs into Lesina Lagoon, which is becoming more common in the area. The predominant forms of MPs in Lesina Lagoon have been identified as filaments and fragments, suggesting that the majority of MPs in the lagoon are of secondary origin (Wakkaf et al., 2020). Polypropylene (PP) and polyethylene (PE) were among the most detected polymers used mainly as packaging materials, which explains their widespread occurrence in Lesina Lagoon.

3.3.9. Calich lagoon

The Calich Lagoon is located in the Regional Natural Park of Porto Conte, on the northwest coast of Sardinia (40°35′48.1″N; 8°18′12.2″E). The lagoon, about 1 km^2 in size, is connected by a channel to the Gulf of Alghero, where there is a shipyard and a tourist port. The lagoon is under significant pressure from eutrophication caused by industrial activities, urban settlements, agricultural practices, and aquaculture facilities (Bazzoni et al., 2018). It is also designated as a special protection area (ZPS) under the Capo Caccia Protection Plan.

A study of MPs in Calich Lagoon focused on the soft parts of *Mytilus galloprovincialis* using simple digestion methods, followed by filtration through a 5 μm sieve and subsequent visual examination (Mudadu et al., 2022). FT-IR Analysis was not included in this study. The results showed a range of MP concentrations in the soft tissues, which averaged between 1.2 and 1.45 ± 0.3 pieces/g.

4. Sentinel species

Sentinel organisms are critical for the detection and study of MPs in lagoon systems and serve as bioindicators of pollution (Multisanti et al., 2022; Pastorino et al., 2023a). In lagoons, organisms such as algae, seagrasses, crustaceans, and mollusks play an important role in understanding the accumulation and persistence of MP (Garcés-Ordóñez et al., 2022). By integrating exposure data over time, sentinel organisms provide a comprehensive understanding of the chronic and cumulative effects of MP pollution specifically in lagoons (Alimba and Faggio, 2019). They also contribute to trophic transfer studies by revealing the movement of MPs through food chains in lagoons (Mamun et al., 2023). The use of sentinel organisms facilitates standardization and comparability of studies and sites and allows identification of regional and global patterns of MP pollution in lagoons. Ultimately, sentinel organisms are critical for assessing pollution levels, understanding ecological impacts, and developing targeted strategies to reduce pollution in lagoon ecosystems affected by MPs. In this chapter, we discuss the key marine organisms that have been used in the MP monitoring work we have studied and explore the prospects for using sentinel organisms to enhance future research.

4.1. Algae and seagrasses

Algae and seagrasses are important as primary producers in marine ecosystems and are commonly used as indicators. These organisms serve as early indicators of pollution because they come into direct contact with MPs by taking them up from the water column and depositing them on the surface (de Smit et al., 2021; Esiukova et al., 2021). Studies have demonstrated the presence of MPs in the tissues of algae and seagrasses, highlighting their potential as sentinel organisms for monitoring MP pollution (Dahl et al., 2021; Seng et al., 2020). The reviewed study found that 94% of the samples contained MPs, ranging from 0.16 to 330 pieces per gram of fresh weight (Sfriso et al., 2021). On average, MP content was 14 pieces per gram of fresh weight across all species and areas, with little difference between species. In addition, macrophytes with an EPS (extracellular polymeric substance) coating had a significant positive correlation with MP pollution. The EPS coating acted as an adhesive and facilitated the uptake of MPs into the water column (Sfriso et al., 2021). Macrophytes are widespread in lagoon systems and play a critical role in the food chain (Bachelet et al., 2000). Therefore, it is important to consider these factors when using macrophytes as sentinel organisms to assess the presence and impact of MPs in lagoons.

4.2. Crabs

Crabs, such as *Carcinus aestuarii* or *Callinectes sapidus*, are excellent bioindicators due to their ecological characteristics and close association with coastal environments (Piarulli et al., 2019; Waddell et al., 2020). As a benthic organism, it inhabits intertidal zones, estuaries, and lagoons that are vulnerable to MP pollution (Kampouris et al., 2019; Mistri, 2003). Because this crustacean species ingests MPs and accumulates them in its tissues, it provides valuable information about the extent and distribution of MP pollution. Studies have demonstrated the high affinity of crustaceans for MPs, particularly in their digestive tracts. Their foraging behavior and opportunistic feeding habits expose crustaceans to a variety of MP sources, including microspheres, fibers, and fragments (Yi et al., 2021). Their ability to accumulate MPs in their tissues makes them a reliable indicator of MP pollution in their habitat. The crab's position in the food web and its role as prey for larger organisms underscore its importance for MPs research. However, *Carcinus aestuarii* and *Callinectes sapidus* differ in their ecological characteristics and habitat preferences, resulting in different exposure to MPs and the species encountered. *Carcinus aestuarii* is commonly found in lagoons and transitional waters, while *Callinectes sapidus* lives in coastal areas.

4.3. Molluscs

Molluscs, such as *Mytilus galloprovincialis,* are highly valued by the scientific community for the study of MPs in transitional systems. Molluscs have filtration behavior that allows them to efficiently uptake and accumulate MPs from the surrounding water column (Abidli et al., 2017; Expósito et al., 2022; Naji et al., 2018). They are often considered representative species in aquatic ecosystems, which provides a broader insight into the extent of MP pollution. Mollusks are widespread in a variety of marine and estuarine environments, including sensitive systems such as lagoons, where they are common due to their ability to adapt to different conditions (Drummond, 2000). In particular, *M. galloprovincialis* is frequently used in the studies of MPs for several reasons. First, it is widely distributed and easily accessible in coastal areas, making it a suitable species for sampling. In addition, *Mytilus galloprovincialis* is known for its high filtration rate, which increases its exposure and uptake of MPs (Chae and An, 2020). The ubiquity of the species in Italy and its ecological importance in the Mediterranean Sea contribute to its frequent use in MPs research (Tamburini et al., 2020).

4.4. Fish and other species

In addition to mollusks, crustaceans, and macrophytes, fish species such as *Mugil cephalus* and *Sparus aurata* can be used to monitor MPs in Italian lagoon systems (Cheung et al., 2018; Rios-Fuster et al., 2021). Crustaceans such as *Portunus pelagicus* and *Cancer pagurus* can also serve as indicators of MP pollution due to their distribution, economic, and ecological behavior (Kleawkla, 2019). Echinoderms such as *Asterias rubens* (Fang et al., 2018) and echinoderms such as *Paracentrotus lividus* (Hennicke et al., 2021) are other organisms that can be sampled for MP analysis. Marine annelids such as *Nereis diversicolor* and *Littorina littorea* (Buccino comune, common sandpiper) are also of interest in Italian lagoon systems (Doyle et al., 2020, 2019; Missawi et al., 2021, 2020). These organisms could contribute to a comprehensive assessment of MP pollution in Italian lagoons and provide valuable insights into the extent and distribution of MPs in these environments.

The use of organisms that must be euthanized for MP monitoring raises ethical issues and potential environmental impacts. Collecting and killing organisms can affect natural populations and habitats. Therefore, methods that minimize environmental impact are preferable. Of the above organisms, sessile organisms such as macrophytes and bivalves may have less impact on the environment because they can be sampled without significantly affecting their populations. However, when researching MP pollution, it is imperative to use appropriate sampling techniques and consider the potential impact on the organisms.

5. Gaps

Studies of MPs in lagoon systems have several critical gaps and needs that require attention and further investigation. Geographically, available data on MPs are limited to only 9 Italian transitional systems, with a lack of comprehensive studies on other marine littoral systems that are much more numerous (Gardner and Davidson, 2011; Pugnetti et al., 2013). There is also a lack of distinction between different nearshore transitional systems such as lagoons, coastal lakes, and coastal ponds, making a comprehensive understanding of MPs dynamics in these unique environments difficult. In addition, most studies focused on the northern Adriatic region, highlighting the need for more comprehensive studies in other geographic areas and lagoon systems throughout Italy (Fig. 2). Furthermore, the relationship between MPs in lagoons and associated watercourses has not yet been comprehensively analyzed, which calls for further research in this area.

Methodological challenges also contribute to the gaps in MPs research. Methodological differences among studies make it difficult to compare and synthesize results, leading to discrepancies in MP estimates (Garcés-Ordóñez et al., 2022; Ogunola and Palanisami, 2016; Underwood et al., 2017). The lack of proper analysis for polymer identification further limits our understanding of the types and sources of MPs in lagoon systems. Fourier-transform infrared (FTIR) spectroscopy and Raman spectroscopy are often the main analytical methods for the chemical characterization of MP particles (Silva et al., 2022). Analysis is quite quick for MPs larger than 1 mm, but if items are less than 1 mm, the use of micro-FTIR and micro-Raman spectroscopy is highly recommended (Silva et al., 2022). They are, however, time-consuming, and the presence of biogenic material can compromise the analysis. There are other thermo-analytical techniques that allow the identification and mass-based quantification of micro(nano)plastics at low concentrations based on their degradation products (Santos et al., 2023). Pyrolysis gas chromatography-mass spectrometry (Py-GC–MS) is one example (Santos et al., 2023). To overcome these challenges, the adoption of standardized protocols for MP sampling, processing, counting, and reporting is critical to ensure consistency and comparability among studies.

The selection and use of indicator species for assessing MP pollution in lagoon systems must be carefully considered. To comprehensively assess MP pollution, monitoring systems must be established that include the study of water, sediments, and organisms. The actual concentrations in the aquatic environment as well as details on the origins and dynamics of MPs could be obtained from the analysis of water and sediments. However, analysis of water and sediments may not show the effects of the MPs on organisms. On this path, MPs bioavailability cannot be measured correctly. Microplastics concentration in water are also subjected to fast temporal fluctuations raising questions on the true representative value of these analyses. Thus, it is necessary to analyze MPs in both abiotic (i.e., water and sediments) and biotic (i.e., sentinel species) compartments to have a complete characterization of the MPs contamination of an aquatic environment.

Identifying appropriate indicator species that can provide valuable insight into the extent of MP pollution and its impacts is essential for effective monitoring programs (Pastorino et al., 2023a, 2023b). To do this, a variety of biological criteria for the selection of sentinel species need to be considered: a) it is necessary to have a clear taxonomic identification and scientific knowledge on ecology and biology of the species; b) information on habitat and home range of the species is also essential in the selection of sentinel species, as it allows monitoring to be differentiated at different spatial scales; c) the feeding behaviour, feeding mechanism and trophic level of species strongly influences (micro)plastic ingestion/accumulation by aquatic organisms; d) the spatial distribution of the species also need to be considered allowing an appropriate spatial coverage; e) the commercial importance of species which are easily available through fishing activities (potential transfer of microplastics to humans); f) the conservation status should also be taken into account to understand to what extent MPs can affect species conservation. It is also important to assess the ethological, physiological, and toxicological effects of MPs on aquatic species to fully understand the ecological impacts of MP pollution in lagoon ecosystems (Piccardo et al., 2021). Moreover, ethical evaluations regarding the use of organisms as biomonitoring tools are needed to ensure the responsible and sustainable use of these organisms in scientific research.

Finally, the investigation of different environmental matrices in MP studies in lagoon systems presents its own challenges (Bansal et al., 2021; Winkler et al., 2022). There are significant differences among the environmental matrices studied, making it necessary to examine multiple matrices within the same lagoon to gain a comprehensive understanding of MPs distribution and accumulation. However, the different sampling methods used for the same matrices present challenges for data comparability and synthesis, highlighting the need for standardized sampling protocols for all studies.

To address the gaps and needs in MPs research in lagoon systems, interdisciplinary collaboration, standardized methods, and increased research efforts across multiple geographic areas and environmental matrices are needed. These efforts will contribute to a more comprehensive understanding of MP pollution in lagoons and facilitate effective management strategies to mitigate the impacts of MPs on these sensitive ecosystems.

6. Future perspectives

Microplastic pollution in lagoons is a significant ecological and environmental problem that requires focused attention and future research efforts. To address current gaps and needs in this area, several key areas for research and development can be identified (Table 3).

Table 3
Key unresolved challenges and future research directions regarding the issue of microplastic pollution in coastal lagoons as highlighted in the present review.

Key areas for research and development	Issue
Methodological	• Data on microplastics is available for only 9 Italian lagoons • Lack of data for other coastal transitional systems • No distinction made between different coastal transitional systems (lagoons, coastal lakes, coastal ponds) • Studies mainly focused on the Northern Adriatic region • No correlation analyzed between microplastics in lagoons and associated watercourses • Difficulties in comparing amongst MP studies due to methodological differences • Under or overestimation of MP abundances resulting from differences in methodologies • No proper chemical analyses for polymer identification • Need to implement a standard protocol for sampling, processing, counting, and reporting on MPs
Organisms	• Need to establish monitoring schemes integrating waters, sediments, and organisms • Convenience to identify indicator species for MP pollution • Need to assess ethological, physiological, and toxicological effects of MPs on aquatic species • Need for ethical evaluations regarding the use of organisms as biomonitoring tools
Examined Matrix	• Many differences among examined environmental matrices • Need to examine multiple environmental matrices within the same lagoon • Diverse sampling methods for the same matrices

- Standardization of Methods: The development and implementation of standardized protocols for MP sampling, processing, counting, and reporting is critical to improve comparability between studies and to obtain an accurate assessment of MP abundance and distribution.
- Polymer identification techniques: To better understand the types and sources of MPs in lagoons, advances in polymer identification techniques such as Fourier transform infrared spectroscopy (FTIR), Raman spectroscopy or pyrolysis gas chromatography-mass spectrometry (Py-GC–MS) are needed.
- Integration of environmental matrices: studying multiple environmental matrices within the same lagoon, such as water, sediments, and organisms, will provide a more holistic understanding of MP distribution and accumulation.
- Expand geographic coverage: research efforts should be expanded to a wider geographic area, including various coastal transition systems throughout Italy, to gain insight into regional and global patterns of MP pollution in lagoons.
- Long-term monitoring programs: Implementing long-term monitoring programs that include the study of water, sediments, and organisms will provide a comprehensive assessment of MP pollution in lagoon ecosystems over time.
- Interdisciplinary collaboration: Collaboration among scientists, policy makers, and stakeholders from different sectors is essential to address the complex challenges associated with MP pollution in lagoons and to develop innovative and effective strategies (Pastorino et al., 2023b).

By focusing on these perspectives, researchers can improve our understanding of MP pollution in lagoons, develop standardized methods, identify pollution sources, and implement targeted mitigation measures to protect these fragile ecosystems.

7. Conclusions

Microplastic pollution in lagoons is a key environmental problem that requires immediate attention. This review provides an overview of the current state of knowledge on MPs in Italian lagoon systems, highlighting key findings, challenges, and research perspectives. The lack of comprehensive data on MP pollution in lagoons highlights the urgent need for increased research and monitoring efforts.

One of the major challenges in this area is the lack of standardized methods for MP analysis. Different sampling techniques, measurement protocols, and analytical methods have made it difficult to compare studies. Solving this problem is critical to obtain accurate and reliable data on the abundance, distribution, and origin of MPs in lagoons.

In addition, the selection and use of sentinel organisms as bioindicators in MP studies must be carefully considered. Ethical evaluations and minimization of environmental impacts should guide the choice of organisms and sampling techniques. Integrating exposure data over time and assessing the dynamics of trophic transfer can improve our understanding of the ecological impacts of MP pollution in lagoons. The limited geographic coverage of current studies and the lack of distinction between different nearshore transition ecosystems provide opportunities for further investigation. Expanding research efforts across different geographic areas and environmental matrices will provide a comprehensive picture of MP dynamics in lagoon ecosystems and contribute to the development of targeted mitigation strategies.

Interdisciplinary collaborations and long-term monitoring programs are needed to address the gaps and needs identified in this review. By bringing together experts from multiple disciplines and conducting sustained monitoring efforts, we can gain a deeper understanding of MP pollution in lagoons, assess its impacts on ecosystems, and develop effective management strategies. Addressing the challenges and adopting the future perspectives outlined in this report will contribute to a more comprehensive understanding of MP pollution in Italian lagoon systems.

It is critical that scientists, policy makers, and stakeholders work together to implement standardized methodologies, improve polymer identification techniques, expand research efforts, and prioritize long-term monitoring programs. Through these concerted efforts, we can protect and preserve the ecological and socioeconomic importance of lagoon ecosystems and mitigate the threats posed by MP pollution.

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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Further reading

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