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Review

A systematic review on microplastic pollution in water, sediments, and organisms from 50 coastal lagoons across the globe☆

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ABSTRACT

Coastal lagoons are transitional environments between continental and marine aquatic systems. Globally, coastal lagoons are of great ecological and socioeconomic importance as providers of valuable ecosystem services. However, these fragile environments are subject to several human pressures, including pollution by microplastics (MPs). The aim of this review was to identify and summarize advances in MP pollution research in coastal lagoons across the world. We consider peer−reviewed publications on this topic published in English and Spanish between 2000 and April 21, 2022, available in Scopus and Google Scholar. We found 57 publications with data on MP abundances and their characteristics in 50 coastal lagoons from around the world, 58% of which have some environmental protection status. The number of publications on this type of pollution in lagoons has increased significantly since 2019. Methodological differences amongst studies of MPs in coastal lagoons were nevertheless a limiting factor for wide−ranging comparisons. Most studies (77%) were conducted in single environmental compartments, and integration was limited, hampering current understanding of MP dynamics in such lagoons. MPs were more abundant in lagoons with highly populated shores and watersheds, which support intensive human activities. On the contrary, lagoons in natural protected areas had lower abundances of MPs, mostly in sediments and organisms. Fiber/filament and fragment shapes, and polyethylene, polyester, and polypropylene polymers were predominant. MPs had accumulated in certain areas of coastal lagoons, or had been exported to the sea, depending on the influence of seasonal weather, hydrodynamics, anthropogenic pressures, and typology of MPs. It is advised that future research on MP pollution in coastal lagoons should focus on methodological aspects, assessment/monitoring of pollution itself, MP dynamics and impacts, and prevention measures as part of a sound environmental management.

1. . Introduction

Coastal lagoons are transitional environments between continental terrestrial and marine aquatic systems that occupy approximately 13% of the world's coastlines (Pérez-Ruzafa et al., 2019). These shallow (usually, <3 m water depth) marine or brackish water bodies have different sizes (usually, from ~1 to 10,000 km^2) and shapes (usually, irregular triangular or delta with its long axis oriented parallel to the shoreline), which may be totally or partially enclosed and separated from the sea by a barrier island, spit, reef, or sand bank (Larson, 2012; Kennish, 2016; Pérez-Ruzafa et al., 2019). The water in coastal lagoons is usually quiet and its residence time can vary from a few days to more than a year, and is influenced by the number of water inlets, tidal and river flows, rainfall, wind−induced circulation, wave−driven currents, and evaporation, among other factors (Larson, 2012; Mahapatro et al., 2013; Kennish, 2016; Pérez-Ruzafa et al., 2019). According to the

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characteristics of the exchange flow between the lagoons and the open sea, they are classified into choked lagoons, leaky lagoons, and restricted lagoons (Larson, 2012; Mahapatro et al., 2013) (for details of the coastal lagoon typologies see Supplementary Fig. S1).

Solar energy often reaches all levels (surface−bottom) of the shallow lagoonal systems and due to wave and current action, the water bodies are usually well mixed. These dynamics favor the recycling of nutrients and high productivity, ranging from 50 to 7000 g C m^{-2} yr^{-1} (Kennish, 2016; Pérez-Ruzafa et al., 2019). Coastal lagoons often host a great biodiversity, including different habitats such as seagrasses, coral reefs, beaches, and mangroves (de Wit, 2011). These habitats support the life of different species of microorganisms, plants, and resident and migratory animals that find in these areas the necessary resources for their feeding, reproduction, and growth (Esteves et al., 2008; Pérez-Ruzafa et al., 2019). Lagoons also function as regulators of floods, water quality and climate, prevent erosion, provide job opportunities, food, and raw materials, and they are areas of recreational, cultural, educational, economic, and research interest (Newton et al., 2018). For all these ecosystem services, coastal lagoons are considered of great importance for the conservation of biodiversity and for the well−being of coastal human populations (Anthony et al., 2009; Kennish and Paerl, 2010; Newton et al., 2018; Pérez-Ruzafa et al., 2019). According to the Ramsar Sites Information Service (2022), there is a record of 409 coastal brackish/saline lagoons worldwide. These are found mainly in Europe (45.7%), Africa (15.6%), North America (15.4%), Latin America and the Caribbean (11.5%), Asia (6.4%) and Oceania (5.4%) (Ramsar Sites Information Service 2022).

Like most coastal ecosystems, lagoons are exposed to anthropogenic pressures such as the development of industrial, touristic, and fishing activities, changes in land use, urban expansion and placement of infrastructures, and pollution (Pérez-Ruzafa et al., 2019; Wakkaf et al., 2020a; Vélez et al., 2020; Ramsar Sites Information Service 2022). Urban expansion and pollution are serious problems for coastal lagoons because the pollutant loads and their concentrations in water, sediments, and organisms often reach harmful levels caused by the dumping of waste from industrial and domestic activities, affecting biodiversity, ecological balance, and the quality of ecosystem services (Martínez-Megías and Rico, 2022; Espinosa et al., 2021; Garcés-Ordóñez et al., 2022). This is due to the accumulation of pollutants that reach the lagoons because of limited exchange of water, causing eutrophication, anoxia, and risks of toxicity and mortality of organisms (Rocha et al., 2016; Paduani, 2020; Espinosa et al., 2021; Li et al., 2022; Martínez-Megías and Rico, 2022).

One of the pollutants that is threatening the environmental quality and biodiversity of coastal lagoons is marine litter, defined as all manufactured or processed solid waste from industrial and domestic activities reaching coastal marine environments via different pathways, which is currently considered a major global environmental problem leading to long−lasting impacts (UNEP, 2009; Löhr et al., 2017). Plastics are the most abundant waste category in marine and coastal environments (Iñiguez et al., 2016). This could be explained by: (1) the high production of plastic products (i.e. 380 Mt in 2015), (2) the accumulated effects of one generation of plastic dumping (6300 Mt from 1950 to 2015), (3) the very low rate of plastic recycling globally, (4) the high leakage into the natural environment, and (5) the slow degradation rates of many plastic polymers (Bollmann et al., 2010; World Economic Forum, 2016; Weinstein et al., 2016; Iñiguez et al., 2016; Geyer et al., 2017).

Plastic waste can reach coastal lagoons by direct dumping or transported by winds, rivers, and other water ways from inland sources (Lebreton et al., 2017; Chico-Ortiz et al., 2020; Paduani, 2020). A subcategory of plastics in the environment are microplastics (MPs), defined as plastic particles with sizes <5 mm–1 μm, which are considered an omnipresent pollutant that is not regulated in most countries (GESAMP, 2019; Anagnosti et al., 2021). MPs are classified as primary when they are manufactured on purpose for a specific use (e.g., powders for injection molding and pellets as raw material for other products) or secondary when they result from the breakage of larger plastic objects, either during use or after disposal, due to physical, chemical, and biological factors (Weinstein et al., 2016; Boucher and Friot, 2017; GESAMP, 2019). Both types of MPs are subject to similar processes once in the lagoonal or marine environment and will tend to degrade and break down into progressively smaller fragments due to UV exposure and mechanical abrasion (Weinstein et al., 2016; GESAMP, 2019).

The investigation of physical, chemical, and biological dynamics of MPs in the environment is an active field of research, which suffers from the inherent complexity of the topic and the lack of standardized methods for their assessment and impacts once in the natural environment (Hidalgo-Ruz et al., 2012; Wang et al., 2016; Yu et al., 2020; Xi et al., 2022). MPs are accumulating in aquatic environments, such as coastal lagoons, where they interact with organisms (e.g., by ingestion or colonization) posing a risk to biodiversity and the livelihoods of human communities exposed to these pollutants (Lusher et al., 2017; Antão-Barboza et al., 2018; Vázquez-Rowe et al., 2021; Vital et al., 2021). MP ingestion by organisms can cause the obstruction of the digestive tract, the accumulation of toxic chemicals, increased morbidity, reduced fertility rate, and deaths (Cole et al., 2015; GESAMP, 2015; Lusher et al., 2017; Antão-Barboza et al., 2018; Alimba and Faiggio, 2019; Trestrail et al., 2020; Huang et al., 2021; Xiang et al., 2022).

Coastal lagoons have an important role in conserving biodiversity and providing ecosystem services (especially food) on which vulnerable human communities depend (Newton et al., 2018). Also, they are highly susceptible to the accumulation of pollutants such as MPs, toxic organic, and inorganic substances that can interact with each other (Huang et al., 2021; Xiang et al., 2022). This pollution would be affecting different species of ecological and commercial importance (Vázquez-Rowe et al., 2021). For this reason, it is essential to improve knowledge about this problem in coastal lagoons in order to design and develop effective prevention and mitigation strategies helping to their conservation in the best possible conditions (Akdogan and Guven, 2019; Vélez et al., 2020; Paduani, 2020). This will contribute to progress towards achieving the targets of conservation and sustainable use of coastal marine environments of the Sustainable Development Goals –SDGs (United Nations, 2015).

Despite the ecological and economic importance of many coastal lagoons, no summary is available on the current state of knowledge about MP pollution in this sensitive environment. Information about pollution levels and methodologies for the analysis of MPs in the water, sediments, and organisms is dispersed over many different sources, hampering integration of data and the evaluation of this problem. Here we provide a first overview with the aim of identifying and summarizing advances in MP research in coastal lagoons across the world. We aim at answering the following questions: (1) which are the most used methodologies for sampling MPs in water, sediments, and organisms from coastal lagoons and for subsequent analysis? (2) What is the situation of coastal lagoons in terms of abundance and most common shapes, colors, and polymers of MPs in water, sediments, and organisms? (3) Which are the main sources and sinks of MPs in coastal lagoons? (4) What are the dynamics of MP pollution in coastal lagoons? (5) Are the pollution levels and sources of MPs different than in other environments? (6) What are the key issues and future research questions for MPs in coastal lagoons that the researchers identify in their articles? Building on this information we also aim at helping to raise awareness about the harm on the good environmental status of coastal lagoons posed by MP pollution.

2. Methodology

This paper builds on a systematic review of the available scientific literature on MP pollution state in coastal lagoons globally (accessed April 21, 2022), following the guideline of preferred reporting items for systematic reviews and meta−analyses (PRISMA) statement (Page et al.,

2021) on this kind of assessments. Such an exercise has eased summarizing scientific advances but also identifying information gaps that would require attention by the scientific community, environmental managers, and policy makers (Page et al., 2021).

The search of the scientific literature was first carried out in Scopus using the keywords: lagoon AND microplastic OR litter OR debris, within article title, abstract and keywords. Subsequently, a second advanced search was carried out in Google Scholar, using the keyword combinations ("lagoon" "microplastic"), ("lagoon" "microplastics"), ("lagoon" "litter") and ("lagoon" "debris") within article titles. The types of publications considered for this review were peer-reviewed research papers, books, and book chapters published in English and Spanish in the period between 2000 and April 21, 2022 (Table S1). The selection process of the scientific literature found in Scopus and Google Scholar was based on a first review of the title and abstract, and those that explicitly indicated the topic of pollution by MPs in coastal lagoon were selected for a second review. Additionally, we checked all relevant references cited in the documents obtained from the topic−based search, and other studies on MP pollution were sought as a conceptual basis and references of pollution in other environments to compare with coastal lagoons.

Following the selection of the specific studies, detailed information was then extracted from each selected document, including the complete citation, lagoon/s assessed and its/their characteristics (location, extension, protected area status and human activities possible sources of MPs). Likewise, for water and sediments, field sampling and laboratory analytical methods, size range, mean abundances of MPs and units of measurement, and shapes, colors and polymer types were recorded from each study. For organisms, the information was similar with indication in each case of the number of individuals and analyzed species, and the prevalence. Also, information was extracted on organic and inorganic contaminants and microorganisms associated with MPs in coastal lagoons.

In most of the reviewed studies, the data were faithfully extracted from the main text and tables or from the supplementary material. In other studies, MP abundance data in water, sediments, and organisms were obtained from the figures as an approximate value. Probable sources of MPs in the reviewed studies were identified in the sections of study area and discussion (or results and discussion section), where the authors mentioned and related this pollution to human activities in the broader study area. Key issues and future research on MP pollution were identified in the introduction, discussion, and conclusion sections of the reviewed studies. We have considered as "key issues" the aspects that would help advance knowledge of MP pollution in coastal lagoons and in the conservation of lagoons in the face of this environmental problem. These were addressed as a research problem, justification, and recommendations for future implementation. Information on the extension of the lagoon that was not reported in the reviewed studies was estimated using the "polygons" tool of Google Earth Pro. The information on protection status was consulted in other sources of information available on the web or from the Ramsar Sites Information Service (2022).

All extracted data were tabulated in an Excel file to facilitate analysis. Publication trends (years, journals), geographic distribution, and analyzed environmental matrices were determined. The most studied taxonomic groups and MP pollution patterns were identified according to the characteristics of the coastal lagoons (protected and unprotected). The main shapes, colors, and polymers of the MPs in the studied matrices were identified. We determined the frequency of MP sources that were mentioned in the 57 reviewed studies. Finally, for each study we collated the key issues and future research lines on MP pollution, which we summarized into broader thematic categories.

3. State of knowledge on microplastic pollution in coastal lagoons

3.1. Literature review outcomes

In the Scopus search engine, 269 studies were identified. In the selection process, with the first review, 229 studies were discarded for not studying MPs in coastal lagoons, and not reporting information on the state of pollution by MPs or pollutants associated with these particles. This resulted in 40 studies found in Scopus qualifying for the review. In the Google Scholar search engine, 62 studies were identified, of which we selected and reviewed 17 studies on MP pollution in coastal lagoons, which had not been found in the initial Scopus search results. In total, 57 studies were used for this review (Table S2).

The first study found on MP pollution in coastal lagoons after the year 2000 was published by Vianello et al. (2013) on the Venice Lagoon, Italy. Whereas until 2018 the number of screened publications on the topic was quite low, it ramped up in 2019, 2020, and 2021, with 9, 15, and 22 screened publications, respectively (Fig. 1). In 2022 (until April 21st) seven publications were found. Most studies (77%) investigated the characteristics and abundance of MPs in single compartments (water, sediment, or organisms), and integration was limited, hampering our understanding of MP dynamics in these lagoons (Table 1 and Table S2). Two of these reviewed studies also reported heavy metals and organic pollutants associated with MPs (Fred-Ahmadu et al., 2022a, b). Meanwhile, three studies investigated the microbial community on MPs and their antibiotic resistance genes (Pinnell and Turner, 2020; Sun et al., 2021; Shi et al. 2022). In the supplementary material the journals with publications on MP pollution in coastal lagoons are detailed (Table S2).

The reviewed studies had information on MP pollution in 50 coastal lagoons from 20 countries (Fig. 2 and Table S3). These lagoons were found mainly in Europe (32%), Asia (20%), Latin America and the Caribbean (18%), Africa (12%), North America (10%), and Oceania (8%). Coastal lagoons with the largest number of studies on MP pollution were Bizerte (Tunisia; n = 5), Venice (Italy; n = 4), Ciénaga Grande de Santa Marta (Colombia; n = 3), Lagos (Nigeria; n = 3), Laguna Madre (USA; n = 3), Mar Menor (Spain; n = 3), and Ria Formosa (Portugal; n = 3). Most of the coastal lagoons (58%) with studies on MPs were in protected areas under international or national status, such as Ramsar sites, biosphere reserves, areas of importance for wildlife conservation or natural reserves/parks (Fig. 2 and Table S3).

3.2. Microplastics sampling and analytical methods

The need for standardized methodologies in studies of MPs in aquatic environments has been discussed rather extensively. The lack of standardization has prevented or posed serious difficulties to comparisons amongst ecosystems and environmental matrices at local, regional, and global scales (Weiss et al., 2021). This has been mostly related to mesh size, measurement units and MP isolation methods (Hidalgo-Ruz et al.,

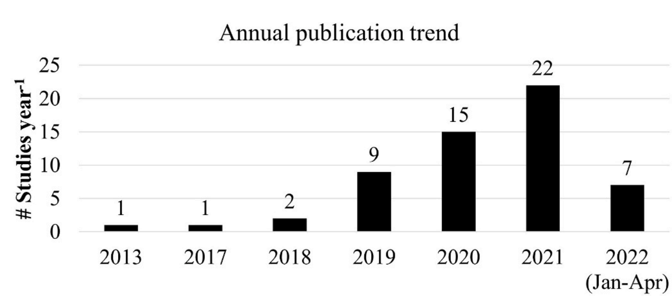

Fig. 1. Number of papers per year (2013–2021 and January–April 21, 2022) on microplastics in coastal lagoons published in peer reviewed journals included in this review following screening and filtering (for the full records see Table S2).

Table 1
Environmental matrices addressed in papers on microplastics in coastal lagoons published in peer–reviewed journals included in this review following screening and filtering. The total number of studies for each environmental compartment of the coastal lagoon is highlighted in the gray envelope.

Analyzed compartments for microplastics			No. Studies
Water			10
Water	Sediments		4
Water		Organisms	5
Water	Sediments	Organisms	2
	Sediments		15
	Sediments	Organisms	2
		Organisms	19
21	**23**	**28**	**57**
Total studies			

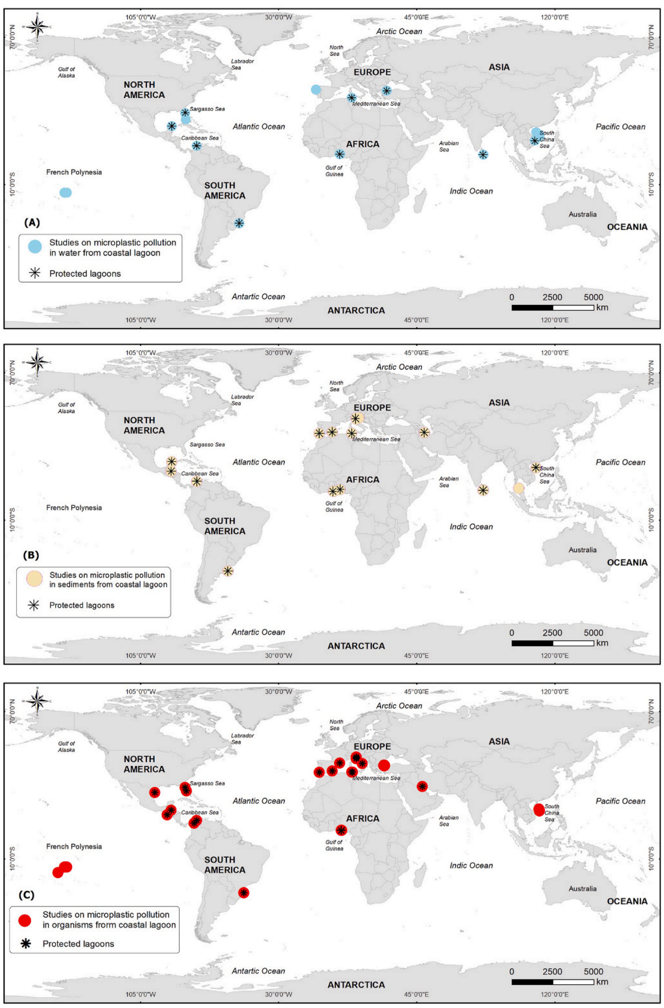

Fig. 2. Microplastic pollution studies on (A) water (n = 21), (B) sediments (n = 23), and (C) organisms (n = 28) from coastal lagoons worldwide.

2012; Wang and Wang, 2018; Stock et al., 2019; Cutroneo et al., 2020; Yang et al., 2021). Further methodological differences that were applied to coastal lagoons involve the size ranges of the analyzed MPs and the density separation and chemical digestion techniques for samples of water, sediment, or organisms.

In 21 reviewed studies, MP sampling was carried out in lagoon water (Table S2 and Table S4). For this, six types of devices have been used, encompassing plankton nets (8 studies), glass bottles (6 studies), water pumps (3 studies), plastic gallons/bottles (2 studies), metal buckets (1 study) and integrating sample pole of PVC (1 study), with in situ or in lab volume reduction over mesh sizes from 0.45 μm to 5.0 mm (Table 2 and Table S4). This last device was typically used in the joint study of plankton and MPs (Badylak et al., 2021). In the lab, 48% of the studies on MPs in lagoon water were carried out by visual inspection of the samples using optical equipment (Table 3). Many (48%) of the reviewed studies also applied chemical digestion with H_2O_2 (5 studies), KOH (3 studies), HCl + Fe (II) (Quesadas-Rojas et al., 2021), Fe (II) (Silva and de Sousa, 2021) or Lipase + H_2O_2 (Strady et al. 2020) to remove organic matter for better visualization of MPs (Tables 3 and 4). This chemical digestion was usually necessary for samples collected in eutrophic lagoons. Four studies that applied chemical digestion included separation by density (eg, NaI or NaCl) (Silva and de Sousa, 2021; Strady et al. 2020; Wakkaf et al., 2020a, b).

In 23 reviewed studies, MP analysis was carried out in lagoon sediments (Table S2 and Table S4). In these studies, sampling was done with steel spatula/trowel/spoon (13 studies), corers (5 studies) or grabs (5 studies) with sediment penetration depths from 0 to 30 cm (Table 2 and Table S4). Spatula/trowel/spoon were commonly used in surface sediments and lagoon shoreline beaches (e.g., Saldanha Vogelmann et al. 2019; Bayo et al., 2019, 2020; Fred-Ahmadu et al., 2022a, b). These were also used to collect sediment samples obtained from the bottom of the lagoon with a grab (e.g., Garcés-Ordóñez et al., 2022). Corers were used to analyze the profiles of MP pollution in lagoon sediments (Chico-Ortiz et al., 2020) and mangrove areas (Pradit et al., 2022), and to collect samples in seagrass beds (Cozzolino et al., 2020). In the lab, the MP insolation in 39% of the reviewed studies was carried out as an initial screening (Table 3). These usually corresponded to sediments from sandy beaches (e.g., Saldanha Vogelmann et al. 2019; Bayo et al., 2019, 2020; Fred-Ahmadu et al., 2022a, b). Also, 79% of the studies on MPs in sediments employed density separation using solutions of NaCl (14 studies), $ZnCl_2$ (Díaz-Jaramillo et al., 2021), HCO_2K (Olarinmoyec et al., 2020), $CaCl_2$ (Quesadas-Rojas et al., 2021), or a combination of NaCl and $ZnCl_2$ (Ghayebzadeh et al., 2021) (Table 3, Table 4 and Table S4). This has allowed segregating of MPs with densities lower than the respective saline solution. In 39% of the reviewed studies, density separation was combined with chemical digestion using 10% KOH, 30% H_2O_2, 10% NaClO or Fe (II) (Table 3, Table 4 and Table S4).

Regarding organisms, 28 reviewed studies analyzed MPs in tissues, organs, digestive systems, or whole organisms. Among the organs analyzed were the stomach, intestines, hepatopancreas, gonads, gills, seagrass leaves, and algal fronds. Also, bird feces (Gbogbo et al., 2020) and coral skeletons (Ding et al., 2019) have been analyzed for MPs. Organisms were caught with the support of fishermen (e.g., Acar and Ateş, 2018; Dantas et al., 2019; Renzi et al., 2020; Garcés-Ordóñez et al., 2020), collected on site by the researchers (e.g., Waite et al., 2018; Ding

Table 2
Different types of devices or methods used for microplastic sampling in water, sediments, and organisms from coastal lagoons in the reviewed studies.

Matrix	Sampling devices or methods	No. Studies	Analyzed size of MPs (mm)
Water (n = 21)	Net	8	0.04–5.0
	Glass bottles	6	<5
	Pump	3	0.05–5.0
	Plastic gallons/bottles	2	<5
	Metal bucket	1	0.30–5.0
	Integrating sample pole (PVC)	1	0.03–0.19
Sediments (n = 23)	Spatula/trowel/spoon	13	<5
	Core	5	0.0002–5.0
	Grabs	5	<5
Organisms (n = 28)	Purchase from fishermen, local market, or hatcheries	5	<5
	Caught with the support of fishermen	8	
	Direct collection by researchers	11	
	Combination of two sample acquisition methods	4	

Table 3
Laboratory processes used in the reviewed studies for the analysis of microplastics in water, sediments, and organisms from coastal lagoons.

Lab process	Water % (n = 21)	Sediments % (n = 23)	Organisms % (n = 28)
Direct observation	48	0	11
With initial screening	0	39	0
Without initial screening	0	61	0
With density separation	19	79	36
Without density separation	81	22	64
With chemical digestion	48	39	79
Without chemical digestion	52	61	21
With staining	14	17	14
Without staining	85	83	86
With hot needle test	0	0	14
Without hot needle test	0	0	86
Visual inspection	100	100	100
With FTIR	71	61	61
Without FTIR	29	39	39

Table 4
Studies and reagents used in the chemical digestion and density separation of microplastics in water, sediments, and organisms of the coastal lagoons under consideration.

Lab process	Reagents	Water (No. Studies)	Sediments (No. Studies)	Organisms (No. Studies)
Chemical digestion	KOH (10%, 20%, 1−1.8M)	3	0	13
	30% KOH: NaClO	0	1	1
	H_2O_2 (15%, 30%)	5	7	2
	10M NaOH	0	0	2
	20% HNO_3	0	0	1
	37% HCl	0	0	1
	HCl + Fe (II)	0	0	0
	Fe (II)	1	1	0
	Creon digestion	0	0	1
	Lipase + H_2O_2	1	0	0
	Enzymes	0	0	1
Density separation	NaCl	2	14	8
	HCO_2K	0	1	0
	$CaCl_2$	0	1	0
	$ZnCl_2$	0	1	0
	NaCl + $ZnCl_2$	0	1	0
	NaI	2	0	1
	10% glycerin	0	0	1

et al., 2019; Illif et al. 2020; Sfriso et al., 2021; Coc et al., 2021), purchased at a local market, to fishermen or to a hatchery (e.g., Calderon et al., 2019; Garnier et al., 2019; Lin et al., 2021; Gardon et al., 2021; Garcés-Ordóñez et al., 2022), or combining two of these organism acquisition methods (Table 2; e.g., Abidli et al., 2019; Garnier et al., 2019; Gbogbo et al., 2020; Vital et al., 2021). The use of chemical digestion methods with KOH, H_2O_2, NaOH or HNO_3 was very common (79% of 28 reviewed studies) (Tables 3 and 4). Enzymatic digestion was also used to analyze MPs in the digestive tract of crabs, being more expensive and with a higher risk of contamination in the laboratory process than KOH digestion (Piarulli et al. 2020). However, these methods have impeded the study of the natural (organic) food from the gut contents (e.g., fish), which can provide very important information about the color, sizes, and types of natural food items (Ory et al., 2017; Fernández-Ojeda et al., 2021). In some cases, density separation and filtering were carried out to reduce the volume before visual inspection using optical microscopy equipment, which was applied to all studies (Table 3).

For the isolation of MPs from non−plastic particles, criteria such as the absence of visible cellular or organic structures were considered, usually in studies where no chemical digestion was performed (Hidalgo-Ruz et al., 2012; Garcés-Ordóñez et al., 2022). As a confirmatory step, a hot needle for melt testing was brought close to potential MP particles (Table 3; Illif et al. 2020; Garcés-Ordóñez et al., 2020, 2022; Mazariegos-Ortíz et al., 2021). Also in seven studies, staining with Rose Bengal (Gbogbo et al., 2020; Renzi et al., 2020) or Nile Red (Chico-Ortiz et al., 2020; Prata et al., 2020; Sevwandi Dharmadasa et al. 2021; Coc et al., 2021; Sfriso et al., 2021) was applied to improve the identification of MPs by visual inspection, reducing confusion with organic materials, and avoid the overestimation or underestimation of MP abundances (Erni-Cassola et al., 2017; Gbogbo et al., 2020; Prata et al., 2020).

Nile Red is a lipophilic stain usually dissolved in acetone or methanol, used to stain MPs for fluorescence identification (Erni-Cassola et al., 2017). However, the usefulness of Nile Red may be limited by primarily staining natural materials such as algae and chitin (Maes et al., 2017; Erni-Cassola et al., 2017) or not successfully applied to polyvinylchloride, polyamide, and polyester (Shim et al., 2016). Rose Bengal exclusively stains the cytoplasm of living or dead cells. This stain has been widely used in studies of benthos and has a high potential to identify non−plastic materials among isolated samples (Gbogbo et al., 2020). The Nile Red and Rose Bengal stains were used especially in studies where polymer identification analyses were limited or restricted (considering intrinsic limitations) and in studies to improve analytical techniques. During visual inspection, physical characteristics such as shape and color of MPs were recorded, too. Nile Red staining affects the color of MPs and may have a risk of overestimating the size of strongly fluorescent polymers (Erni-Cassola et al., 2017). Furthermore, Rose Bengal staining makes it difficult to identify red MPs (Gbogbo et al., 2020).

Finally, Fourier transform infrared (FTIR), or Raman spectroscopy have been applied in most studies to identify polymer composition, thus reducing uncertainties associated to visual inspection (Wang and Wang, 2018; Table 3). Usually, not all MPs found in the samples were analyzed by FTIR or Raman. In some studies on MPs in water and sediments, the authors analyzed between 15% and 50% of the MPs selected at random (Sevwandi Dharmadasa et al. 2021; Garces-Ordóñez et al., 2022); and in organisms, up to 100% can be analyzed, depending on the number of MPs found (Calderon et al., 2019; Gardon et al., 2021). However, there are also studies where no specific techniques for polymer identification were applied (Table 3) (e.g., Abidli et al., 2017; Rodríguez-Sierra et al., 2020; Chico-Ortiz et al., 2020; Cozzolino et al., 2020; Quesadas-Rojas et al., 2021; Mazariegos-Ortíz et al., 2021). This is usually due to the high costs and limited access to the analytical equipment that would be required.

In summary, the methodologies to study MPs in lagoons were being adjusted to the conditions of each study area, for example, the presence of seagrasses, corals or mangroves and sediment types, which will determine the most appropriate sampling devices. Although there were differences in laboratory testing procedures, they follow three general patterns, (1) direct visual inspection, (2) chemical digestion and visual inspection, and (3) a combination of chemical digestion−density separation and visual inspection. Variations in the size of analyzed MPs in the different studies was a severe limitation for abundance comparisons. However, it is important to advance in the quantification of smaller MPs (<200 μm), which seem to present a greater abundance and to be responsible for a large part of the pollution by these MPs in coastal environments (Badylak et al., 2021). Again, in certain regions of the world this is limited by the non-availability of the adequate technical equipment.

3.3. Abundances of microplastics in water, sediments, and organisms

According to the review, the mean abundances of MPs in water ranged from 0 to 24,000,000 items m^{-3} (Fig. 3A). No MPs were found in the surface waters of Bundala, Embilikala and Malala lagoons located in a protected area in Sri Lanka (Sevwandi Dharmadasa et al. 2021; Table S4). Another lagoon that stands out for the low abundance of MPs in surface waters was Acaraí (0.03–0.05 items m^{-3}), located in a protected natural area in Brazil (Lorenzi et al., 2020, 2021). The studied MPs in this lagoon ranged in size from 0.5 to 5 mm. The highest abundance of MPs was recorded in Barnes Sound and other smaller lagoons to the north of Florida Bay (8–24 million items m^{-3}) in the United States, which are also within protected areas (Table S4). In these lagoons, the studied MPs ranged in size from 0.03 to 0.19 mm, similar as the sizes of the studied microplankton, and their high abundance was associated with the effects of storms that occurred before sampling (Badylak et al., 2021). Lagoons with high MP pollution in water were Lagos in Nigeria (208,000 items m^{-3}, 0.01–1 mm in sizes; Olarinmoyec et al., 2020) and Sakumo in Ghana (90,000 items m^{-3}, <5 mm in sizes; Gbogbo et al., 2020). On the other hand, Silva and de Sousa (2021) reported 0.21 g of MPs m^{-3} in the Patos lagoon in Brazil. Since it was the only study with this type of measurement units (g m^{-3}), its representation in terms of MP pollution with respect to other coastal lagoons was difficult to compare and understand (Table S4).

Mean abundances of MPs in lagoon sediments varied between 0.24 and 7960 items kg^{-1} (Fig. 3B). The lowest abundances were found in sediments from the protected lagoons of Ciénaga Grande de Santa Marta in Colombia (0.24 items kg^{-1}; Garcés-Ordóñez et al., 2022) and Ria Formosa in Portugal (34 items kg^{-1}; Cozzolino et al., 2020), whereas the highest abundances of MPs in sediments from Bizerte Lagoon in Tunisia, which is subject to significant anthropogenic pressures (Abidli et al., 2017; Table S4). Other lagoons with high abundance of MPs in sediments were Sacca di Goro in Italy (2250 items kg^{-1}; Mistri et al., 2021) and Sakumo in Ghana (1850 items kg^{-1}; Gbogbo et al., 2020; Table S4).

MP pollution in coastal lagoons has exposed aquatic organisms to interactions with these particles. This review showed noticeable advances in quantifying the prevalence and abundance of MPs, and in characterizing them in a variety of groups, such as jellyfish (1 species), polychaetes (1 species), echinoderms (1 species), seagrasses (2 species), crustaceans (5 species), mollusks (13 species), algae (18 species), corals (22 species), and fishes (96 species), some of which were of commercial importance (Fig. 4, Table S5 and Table S6). The habitats of these organisms were commonly polluted by MPs, and the abundance of ingested particles was slightly higher in those inhabiting lagoons without any protection status (Fig. 3C).

In fishes, prevalence of MP ingestion has been reported in up to 100% of the examined individuals, with mean abundances from 1 to 65 MPs ind.$^{-1}$, depending on the study (Fig. 4 and Table S6). MP ingestion in fishes was higher in the unprotected lagoons compared to the protected ones. DuBois et al. (2021) examined the guts of 75 individuals of the fish *Lagodon rhomboides* from Laguna Madre in United States, and no MPs were found. The lowest prevalence (7%) and mean abundance of MP ingestion were reported in fish species from coastal lagoons in the Cispata conservation areas in Colombia (Garcés-Ordóñez et al., 2020), whereas the highest MP ingestion corresponded to fish species (*Liza aurata* and *Sarpa salpa*) from the Bizerte and Ghar El Melh lagoons in Tunisia (Abidli et al., 2021). For 27 fish species from North Reef and Yongle Atoll in Xisha Islands in China, abundances between 0 and 2.3 MP g^{-1} were reported (Ding et al., 2019). The gastrointestinal tract of the fish was where most MPs have been found (Fig. 4E and F). The body conditions of the fish can be affected by the MP ingestion, environmental stress, and nutritional and biological conditions, as reported by Danta et al. (2019) for the fish *Genidens genidens* from Santo Antônio dos Anjos and Imaruí Lagoons in Brazil. In that same study, the skeletons of 22 species of corals were examined for MPs, recording abundances on the skeleton surface from 1 to 37 MPs ind.$^{-1}$ and up to 0.99 MP g^{-1}; and inside the coral skeleton from 0 to 7 MPs ind.$^{-1}$ and up to 0.32 MP g^{-1} (Ding et al., 2019).

In the case of mollusks, MP ingestion has been reported in 11 coastal lagoons, with abundances up to 16.7 MPs ind.$^{-1}$ and a high prevalence in most studies (Fig. 4). The species with the highest ingestion of MPs per individual was *Crassostrea virginica* from Mosquito Lagoon in United States (Waite et al., 2018). MP abundances from 1 to 46 MP g^{-1} was also reported (Fig. 4), being higher for pearl oyster species from Manihi in French Polynesia (Gardon et al., 2021). In crustaceans, MPs were found in the muscles, gonads, gills, and gastrointestinal tracts (Fig. 4E and F), in the latter the highest abundances were reported. The crab species *Callinectes sapidus* from Lesina Lagoon in Italy had a high MP abundance (2.5 MPs ind.$^{-1}$) in the stomach and was also reported from the gonads (Renzi et al., 2020). MP presence was also recorded on seagrass leaves and algae fronds from Ria Formosa Lagoon in Portugal, with a mean abundance of 0.17 ± 0.15 MP cm^{-2} (Cozzolino et al., 2020). In the echinoderm *Holothuria floridana* (sea cucumber) from Placencia Lagoon in Belize, an abundance of 8.4 MPs ind.$^{-1}$ and 0.6 MP g^{-1} gut content was reported (Coc et al., 2021). In fecal material of shorebirds collected in Sakumo Lagoon, Ghana, 0.35 MP g^{-1} was reported (Gbogbo et al., 2020).

3.4. Characteristics of microplastics in coastal lagoon

Overall, the composition of the different MP characteristics (shapes, colors, and polymers) was very similar in the three studied compartments (water, sediment, and organisms; Fig. 5). The predominant shapes of MPs in water, sediments, and organisms from coastal lagoons were fibers/filaments and fragments, but other categories such as films, foams, and pellets were also recorded (Fig. 5A). In terms of colors, the

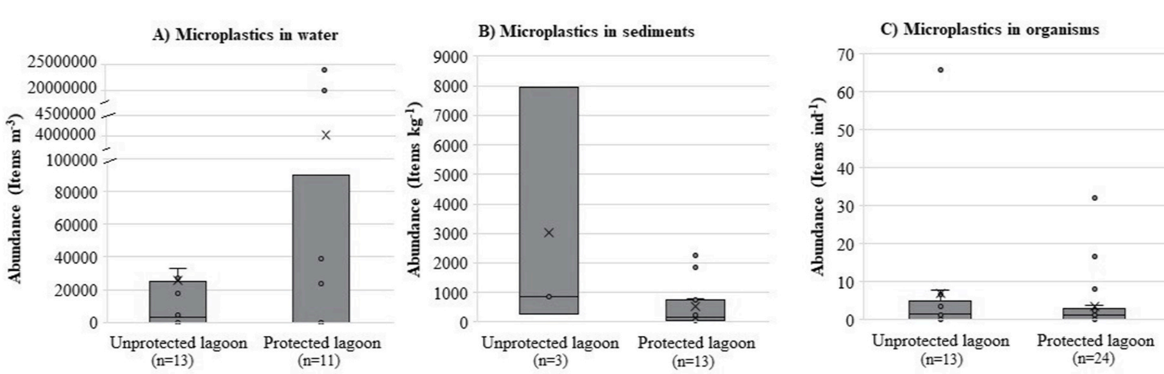

Fig. 3. Abundance of microplastics in (A) water, (B) sediments, and (C) organisms in coastal lagoons according to scientific reviewed studies on a global scale. Only reports of microplastics per mL, L and m^3 of water (values converted to items m^{-3}), per g or kg of sediment (values converted to items kg^{-1}), and per individual of the taxonomic groups analyzed in the respective studies (items ind.$^{-1}$).

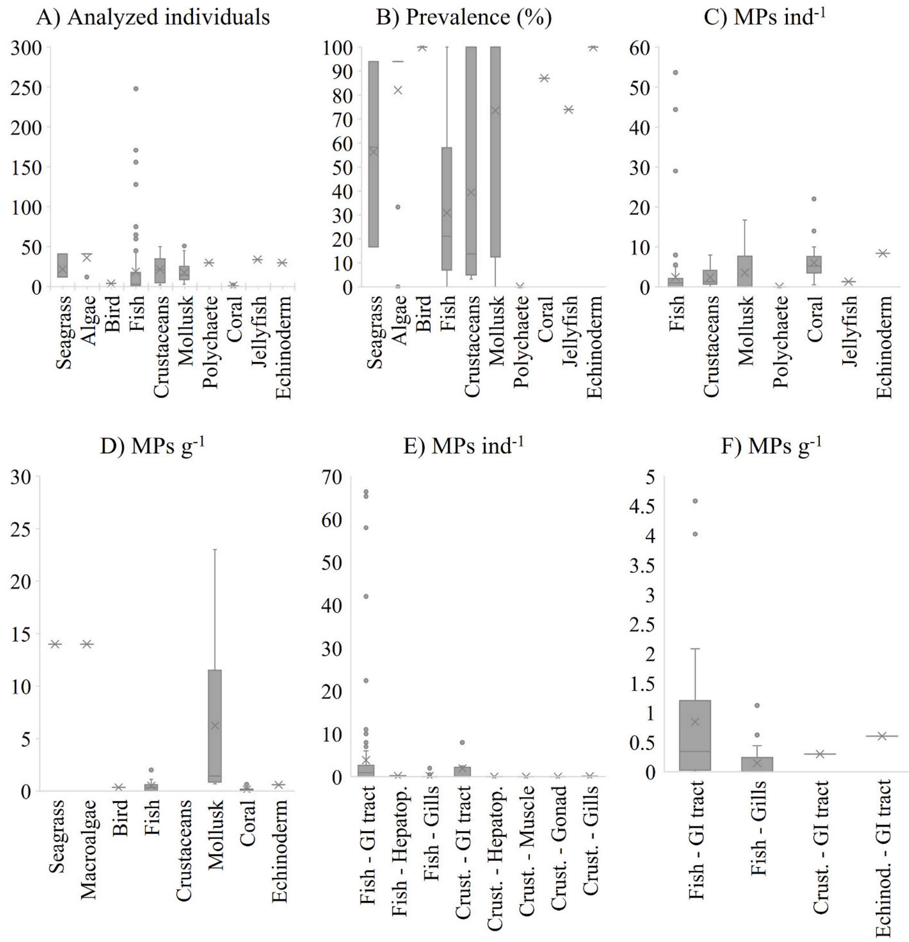

Fig. 4. Microplastics (MPs) in taxonomic groups from coastal lagoons as reported in the reviewed studies. A: number of analyzed individuals. B: Prevalence of MPs reported in percentage. C: Abundance reported in MPs per individual. D: Mass in MPs per grams of organism. E: Abundance reported in MPs per individual according to organs/system. F: Mass in MPs per grams of organism according to organs/system. The groups that are not detailed in figures E and F were analyzed the whole organism (jellyfish, polychaete), soft tissue (mollusks), leaves (seagrass), fronds (macroalgae) and skeletons (corals). GI: Gastrointestinal tract. Hepatop: Hepatopancreas. Crust.: Crustaceans.

most common MPs in lagoon waters, sediments, and organisms were blue and colorless/transparent, followed by white, black, red, green, yellow, and brown (Fig. 5B). Colorless/transparent and white colors were often associated to particle discoloration due to environmental factors (Fan et al., 2019). Colored MPs can come from household solid waste and from boat paint too (Aliabad et al., 2019; Li et al., 2020). Visual predatory fishes preferably ingest MPs with colors and sizes resembling those of their natural food (Ory et al., 2017, 2018; Xiong et al., 2019).

Regarding polymer composition, polyethylene (PE), polyester (PES) and polypropylene (PP) were the predominant ones (Fig. 5C). Other reported polymers include polystyrene (PS), polyethylene terephthalate (PET), nylon (NL), rayon (RY), polyamide (PA), polyurethane (PUR), high−density polyethylene (HDPE) and low−density polyethylene (LDPE), to cite some (Table S4 and Table S6). PE and PP are two of the most produced polymers globally (Geyer et al., 2017; PlasticEurope, 2019), which are commonly used in single use and short−lived products such as plastic bags, containers, and packaging. Inadequate waste management causes these polymers to be present in great abundance in coastal lagoons and other natural environments (Costa et al., 2017).

3.5. Main sources and sinks of microplastics

The probable sources of MPs in coastal lagoons most frequently identified in study area and discussion section of the reviewed studies were population centers, fishing, aquaculture, tourism and recreation, ports, agriculture, and watercourse discharges, among others (Fig. 6). These most likely sources of MPs were recognized by the authors of the reviewed studies considering their presence and intensity in the different studied coastal lagoons. Near some protected coastal lagoons there are urban centers, or they receive water from rivers that contribute to pollution by MPs.

MP shapes have been used to tie them to primary sources (e.g., pellets, granules, and microbeads) or secondary sources (e.g., fibers, fragments, films, and foams) (Wang et al., 2019; Delvalle et al., 2020; Garcés-Ordóñez et al., 2021; Quesada-Rojas et al. 2021; Cozzolino et al., 2021). Fibers were commonly associated to wastewater discharges and fishing gear such as nets and ropes (Browne et al., 2011; Edo et al., 2020; Wright et al., 2021; Bayo et al., 2021). Fragments have generally resulted from any kind of hard plastic items that break during use or due to environmental conditions (Wang et al., 2019; Faruk et al., 2021). Films are often produced by the breakage of plastic bags and plastic greenhouses (Wang et al., 2019; Garcés-Ordóñez et al., 2019; Bayo et al., 2019), whereas foams usually derived from the breaking of expanded polystyrene items, such as food packaging, iceboxes, or buoys, among others (Wang et al., 2019). Finally, pellets and microbeads usually come from cosmetics, personal care and household products and enter the environment mainly through domestic and industrial wastewater (Boucher and Friot, 2017; Wang et al., 2019).

The accumulation of MPs has resulted from domestic and industrial activities taking place in the watersheds of lagoons, from where they are subsequently transported by water courses and runoff to the lagoon, which often acts as a sink due to limited water exchange and shallow depths (Toumi et al., 2019; Vianello et al., 2013; Paduani, 2020; Wakkaf et al., 2020a; Mudadu et al., 2022). Rivers are the main pathways of plastic litter from inland sources into the marine environment (Lebreton et al., 2017; Mai et al., 2020; Weiss et al., 2021). Sediments in water courses flowing into the Bizerte Lagoon have an average abundance of

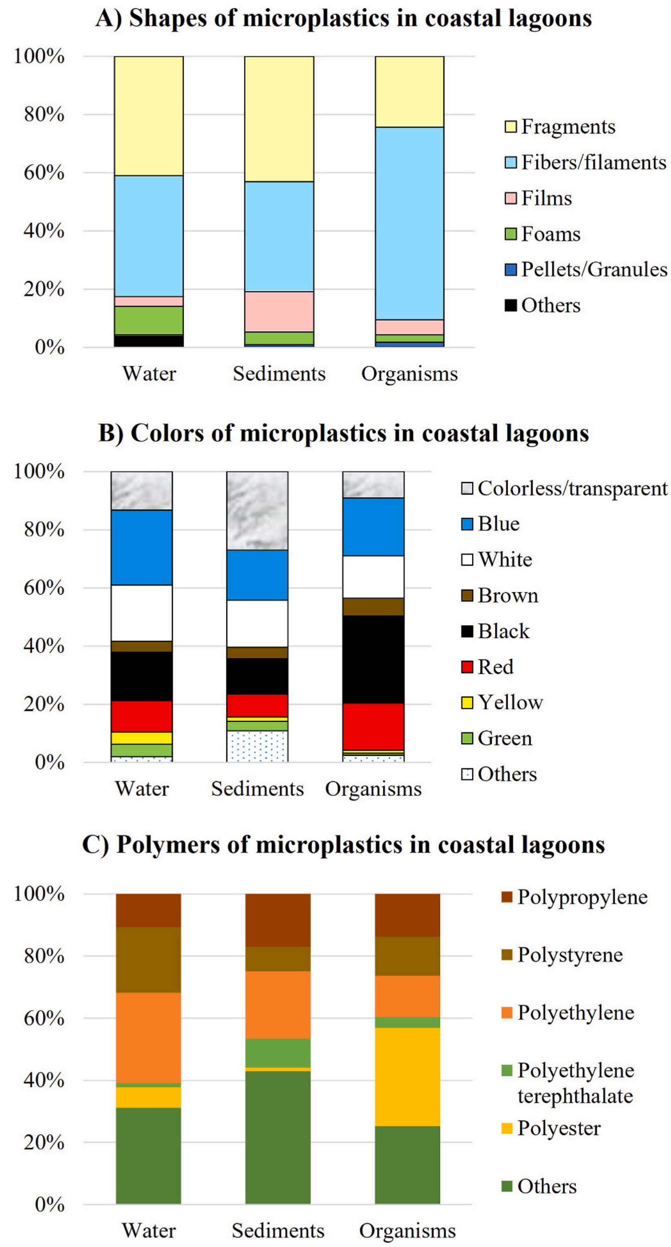

Fig. 5. Characteristics of microplastics in coastal lagoons, according to data available in the reviewed studies.

MPs from 2340 ± 227 to 6920 ± 396 items kg^{-1} dry weight (Toumi et al., 2019). In the Ciénaga Grande de Santa Marta, Colombia, it has been reported that MP abundances in surface waters increase close to the river mouths (Garcés-Ordóñez et al., 2022). In the protected Mar Menor Lagoon in Spain, MP pollution largely comes from runoff from agricultural areas where MP−rich sewage sludge from wastewater treatment plants is used as fertilizer (Bayo et al., 2019, 2020).

52% of all plastic pollution emitted by rivers accumulates in areas near their mouths while the remaining percentage is distributed into other coastal and marine environments (Harris et al., 2021). Coastal lagoons are often located near the lower courses and mouths of large rivers, commonly accompanied by extensive areas of mangroves (e.g., Ciénaga Grande de Santa Marta and Cispata; Garcés-Ordóñez et al., 2020, 2022) and seagrasses (e.g., Ria Formosa; Cozzolino et al., 2020; Sfriso et al., 2021). Commonly, coastal lagoons are also located along wave−dominated coasts with sandy beaches, mangroves, seagrasses, and corals. It is estimated that 11.6% of the plastic pollution discharged by rivers reach these types of coasts (Harris et al., 2021).

Mangroves along the shores of coastal lagoons occur in tropical areas. Mangrove trees have tangled roots that trap plastic litter carried by water courses (Luo et al., 2021; Deng et al., 2021). Likewise, seagrasses and macroalgae in coastal lagoons trap MPs, which subsequently accumulate in the sediments (Cozzolino et al., 2020; Sfriso et al., 2021). Coral reefs retain MPs at their surface or within their skeleton (Ding et al., 2019). On sandy beaches, MPs come from tourist activities or are transported by waves and littoral currents from other sources and locations (Bayo et al., 2019, 2020). All these habitats in the coastal lagoons act as refuge, feeding, and reproduction areas for many aquatic species of environmental and commercial importance, which are often ingesting MPs (Abidli et al., 2019; Mazariegos-Ortíz et al., 2021; Coc et al., 2021; Garcés-Ordóñez et al., 2022).

The reviewed studies eventually reported human settlements located along the lagoon banks (Chico-Ortiz et al., 2020; Olarinmoyec et al., 2020; Abidli et al., 2019, 2021). These urban areas are subject to expansion following population growth and settlement, subsequently generating sewage and solid waste that in many cases is poorly managed and dumped into the lagoons (Acar and Ateş, 2018; Garcés-Ordóñez et al., 2019, 2022; Li et al., 2020; Wang et al., 2020; Wakkaf et al., 2020a; Cozzolino et al., 2021). This is well illustrated by several examples of MP pollution. For instance, higher loads in Kpeshie Lagoon in Ghana occur near the city of Accra (Chico-Ortiz et al., 2020). Likewise, higher MP pollution was found close to the megacity of Lagos in the lagoon of the same name in Nigeria, which is the largest one in West Africa (Olarinmoyec et al., 2020). In the Bizerte Lagoon, Tunisia, the highest MP abundances were commonly observed in areas with dense human population and high maritime and industrial activity (Abidli et al., 2017; Wakkaf et al., 2020a). Other authors have found a positive relationship between MP abundances and closeness to sources (Browne et al., 2011; Quesada-Rojas et al. 2021; Garcés-Ordóñez et al., 2022).

Aquaculture, fishing, and port activities were also MP sources to some coastal lagoons, as shown by Bayo et al. (2019) and Cozzolino et al. (2020) after analyzing sediments from Mar Menor and Ria Formosa lagoons, in Spain and Portugal, respectively. The relationship between MP abundances in sediments or water and the intensity of aquaculture and fishing activities were also pointed out for other lagoons, such as Küçükçekmece Lagoon in Türkiye (Faruk et al., 2021), Santo Antônio dos Anjos and Imaruí Lagoons in Brazil (Dantas et al., 2019; Monteiro et al., 2022) and Bizerte Lagoon in Tunisia (Abidli et al., 2021), and some lagoons with mangroves like Ria Lagartos in Mexico (Quesada-Rojas et al. 2021), Ciénaga Grande de Santa Marta and Cispata lagoons in Colombia (Garcés-Ordóñez et al., 2019, 2020; 2022), and Songkhla Lagoon in Thailand (Pradit et al., 2022). MPs were also examined in lagoons with seagrasses such as Sacca di Goro in Italy where clam farming was carried out (Sfriso et al., 2021). Storms were identified as a release agent for MPs in Barnes Sound and other smaller lagoons to the north of Florida Bay in the United States, which increased their abundances in waters (Badylak et al., 2021).

3.6. Dynamics of microplastics in coastal lagoons

3.6.1. Seasonal and spatial fluctuations

MPs can be accumulated in certain areas of coastal lagoons or be exported out of them, depending on seasonal weather changes, hydrodynamics, anthropogenic influence, and MP characteristics. Faruk et al. (2021) reported higher abundances of MPs in autumn (48.03 items L^{-1}) and lower ones in summer (8.82 items L^{-1}) in Küçükçekmece Lagoon, Türkiye, with fragments predominating in autumn (41.8%) and winter (41.4%), and fibers in spring (49.7%) and summer (44.9%). The same authors did not identify a seasonal pattern for primary MPs as they would be entering the lagoon continuously through wastewater discharge. Secondary MPs had a greater abundance in autumn, which is suggested to be associated with the dynamics of macro/mesoplastic breakup due to greater exposure to solar radiation during summer

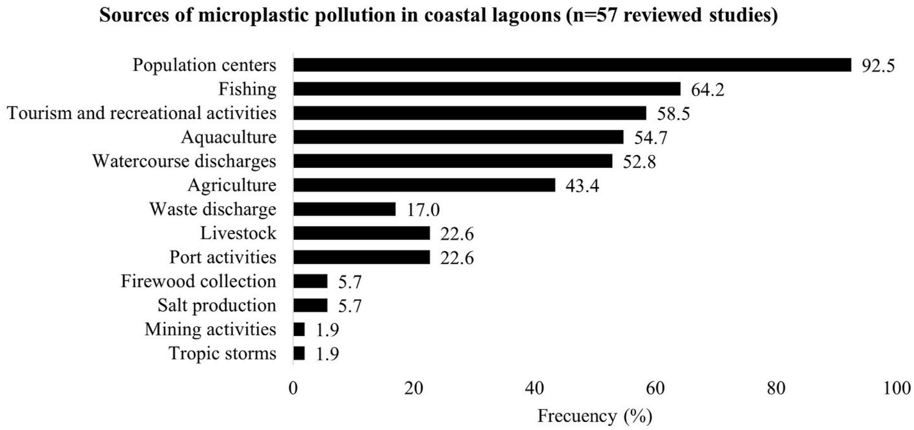

Fig. 6. Frequency of the sources of microplastic pollution in coastal lagoons worldwide identified in the reviewed studies. For most coastal lagoons there are multiple coeval sources.

(Faruk et al., 2021). In Ciénaga Grande de Santa Marta, Colombia, Garcés-Ordóñez et al. (2022) reported slightly higher MP abundance in surface water during the rainy season (0–0.30 items L^{-1}) compared to the dry season (0–0.22 items L^{-1}), and also showed a preferential accumulation of these particles in water and sediments near population centers and river mouths opening into the lagoon. Quesadas-Rojas et al. (2021) also found in the Rio Lagarto Lagoon, Mexico, higher MP abundances in sediments during the rainy season (68 ± 100 items kg^{-1}) than in the drier winter season (42 ± 53 items kg^{-1}), with maximum abundances near sites where human activities are more intense. On the contrary, in Xincun Lagoon, China, Wei et al. (2022) found greater MP abundance in water and sediments in the dry season (72.6 items L^{-1} and 240.6 items kg^{-1}, respectively), compared to the rainy season (60.9 items L^{-1} and 197.1 items kg^{-1}). This could be a consequence of MPs accumulation during the dry season, which are later resuspended and exported out of the lagoon at the occasion of typhoons and rains causing enhanced seaward flow (Wei et al., 2022).

In the Acaraí Lagoon, Brazil, Lorenzi et al. (2020), (2021) recorded higher MP abundances in the water during winter (2.45 items 100 m^{-3}; 0.056 items m^{-3}) than in the other season of the year, which is attributed to a reduction in stormwater runoff and an increase in the dynamics of coastal currents that flush seawater into the lagoon, transporting MPs from the urbanized area located in the lower and outer part of the lagoon. Lorenzi et al. (2020, 2021) also reported that increases in river flow associated to summer rainfall episodes and wind direction favor the export of MPs from the lagoon towards the sea, thus reducing the pollution load from the lagoon itself.

3.6.2. Flotation vs. accumulation in sediments

Once in the lagoon water, MPs can stay afloat or sink to the bottom, where they accumulate depending on relative densities (Qian et al., 2021; Xi et al., 2022). Temperature and salinity−driven changes of density in coastal lagoon waters may lead to different behaviors of MP particles that are close to the floatability threshold (Wakkaf et al., 2020a). Several mechanisms can also lead low specific density MPs to ultimately sink and accumulate in bottom sediments. These ballasting mechanisms include biofouling and colonization by organisms, mineral adsorption, and ingestion by organisms and subsequent deposition within feces, amongst others (Piarulli et al., 2020; Qian et al., 2021; Xi et al., 2022). MPs in sediments within shallow lagoons can be easily resuspended and returned to the water column by the effect of bioturbation and other both natural and human−driven sediment disturbing processes such as wind and precipitation events, or boat traffic and bottom−touching fishing, eventually favored by the buoyancy of plastic particles themselves (Qian et al., 2021). Also, MPs can be transported by currents to beaches and mangroves along the lagoon's shorelines.

In Mar Menor Lagoon, Spain, Bayo et al. (2019) described how the light floating microfibers in the water are transported towards the shore where they are retained in coarser grained sediments (>2 mm) favored by the low energy of the waves in the lagoon compared to those in the adjacent Mediterranean Sea. Fragments were more abundant in intertidal (35.8 items kg^{-1} dry sediment) than in backshore samples (12.9 items kg^{-1} dry sediment; Bayo et al., 2019). In Lagos Lagoon, Nigeria, Olarinmoyec et al. (2020) found that fine−grained sediments tended to have higher amounts of MPs compared to sandier sediments, with accumulation of 125–500 μm fragments attributed to in situ fragmentation; while in the water, fibers with sizes of about 1000 μm were more abundant. In Rio Lagarto Lagoon, Mexico, Quesadas-Rojas et al. (2021) found a significant negative correlation between MPs (fibers, fragments and total) and mud contents in the wet season.

In Mar Chiquita Lagoon, Argentina, Díaz-Jaramillo et al. (2021) reported a higher MP abundance in surface sediments of the upper intertidal zone (~900 items kg^{-1}) compared to the lower intertidal zone (~124 items kg^{-1}). Also, they found larger numbers of MPs in the topmost sediments (0–10 cm = 875–1184 items kg^{-1}), which decreased in deeper levels. This same distribution was noted by Chico-Ortiz et al. (2020) in sediment cores collected in Kpeshie and Mukwei lagoons, Ghana, showing a moderate negative correlation between core depth and MP abundance, with higher abundances at ~10 cm depth (30–40 items 100 cm^{-3}), suggesting in situ plastic breaking. Pradit et al. (2022) have studied MPs in sediment cores from mangroves in Songkhla Lagoon, Thailand, finding an enrichment of MPs within the 0–4 cm layer (~5–39 items cm^{-2}) and a decrease towards greater depths. These authors suggested a deposition and integration of MPs in mangrove soils favored by the action of tides, tree roots, and biological and physical processes (Pradit et al., 2022).

3.6.3. Water renewal and residence time

MP pollution was related to the renewal time of water in the lagoons, as pointed out by Cozzolino et al. (2020) in Ria Formosa Lagoon, Portugal. They attributed the low macroplastic pollution in this lagoon to its high renewal rate thanks to exchanges through inlets directly connecting to the open sea. Waite et al. (2018) mentioned that in the Mosquito Lagoon, United States, 50% renewal of water requires between 200 and 300 days and, therefore, the MPs that enter this lagoon may reside for rather long periods. In Ahe, Manihi, and Takaroa lagoons, French Polynesia, Gardon et al. (2021) observed areas of MP accumulation in the surface water, created by waves, winds and hydrodynamic factors that are mainly determined by water flows through the inlets connecting the lagoons to the open ocean. They found higher MP abundances in the water in the southern area of Ahe and Takaroa, and in the northern part of Manihi, eased by the influence of the prevailing wind, the level of sheltering with respect to the inflow and outflow of water across the inlets, and lower water renewal (34, 76, and 130 days of residence time, respectively; Gardon et al., 2021). In Rio Lagarto Lagoon, Mexico, water circulation is dominated by the tides in the entrance area and by the winds in the inner lagoon, the latter creating a nearly permanent force driving the lagoon's water seaward thus exporting MPs to the ocean (Quesadas-Rojas et al., 2021).

3.6.4. Interactions with other pollutants and organisms

Waste discharges from domestic and industrial activities contribute MPs and several other pollutants, such as pesticides, hydrocarbons, polychlorinated biphenyls, and heavy metals, among others, which can be adsorbed by MPs. Concentrations of 0.04–0.26 mg $\sum$PAHs kg^{-1}, 0.11–0.34 mg $\sum$PCBs kg^{-1} and 0.70–1.58 mg $\sum$OCPs kg^{-1} dry weight have been reported in Lagos Lagoon, Nigeria, with lindane (α, β, γ, δ), endosulfan II and endrin present in MPs (Fred-Ahmadu et al., 2022a). In this same lagoon, Fred-Ahmadu et al. (2022b) referred to the presence of metals such as Al, As, Cd, Cr, Cu, Fe, Pb, Mn, Ni, Se, Tl and Zn associated to MPs. $\sum$PAH, $\sum$OCP, Al, As, Cd, Cr, Cu, Fe, and Mn were comparatively higher in MP foams whereas Pb, Ni and Zn showed a preference for hard MPs (i.e., PE, PP and PVC) (Fred-Ahmadu et al., 2022a, b). Photooxidative weathering, biofilm formation and hydrogen−containing precipitates are processes promoting interactions between MPs and other pollutants in the surrounding environment (Fred-Ahmadu et al., 2022a, b).

Microorganisms also interact with MPs in coastal lagoons, colonizing such particles and forming biofilms. In a study on the diversity and structure of microbial communities, both attached to MPs and free−living, in Laguna Madre, United States, Pinnell and Turner (2020) have discovered that the communities adhered to PET MPs were significantly more diverse than the free−living communities. The three most abundant lineages were the family Melioribacteraceae (order Ignavibateriales, class Ignavibacteria), a non−cultivated genus of Cyclobacteriaceae (order Cytophagales), and the genus Candidatus Electrothrix (family Desulfobulbaceae, phylum Proteobacteria; Pinnell and Turner, 2020). In this very same lagoon metagenomics have been used to analyze the variations in antibiotic resistance gene content in biofilms associated to MPs, with an abundance of 3.05 copies per 16S rRNA in PET and Pseudomonas as the main host of these genes (Sun et al., 2021). Microbial diversity in has been also evaluated in MPs incubated in Xincun Lagoon, China, with the finding of potential plastic biodegraders and no potential pathogens (Shi et al., 2022). Meanwhile, Faruk et al. (2021) have observed diatoms, coccoliths, dinoflagellates, bacteria, bryozoans, barnacles, Asellote isopods, and marine worms adhered to MP surfaces in the Küçükçekmece Lagoon, Türkiye, using scanning electron microscopy.

The transfer of MPs in coastal lagoons to aquatic organisms has occurred primarily by ingestion. In Ciénaga Grande de Santa Marta, Colombia, Garcés-Ordóñez et al. (2022) have noticed that MPs in the digestive tract of nine analyzed fish species share the same characteristics as those present in waters and sediments, with fibers and fragments of the same colors being the most abundant in all these compartments. Similarities in polymer composition, colors, and shapes of mainly fibers and fragments allowed Wakkaf et al. (2020b) to confirm MP transfer from water to mussels in Bizerte Lagoon, Tunisia. Also, MPs (mainly fragments) in the water and in pearl oysters from Ahe, Manihi, and Takaroa lagoons in French Polynesia have the same polymer composition, colors, and shapes (Gardon et al., 2021). Individual particle sizes, amongst 20 and 200 μm, fit with those retained by the oysters when feeding. MPs in the water were also able to adhere to the outer skeleton of corals as observed for fibers in lagoons of the Xisha Islands, China, by Ding et al. (2019).

4. Microplastic pollution in coastal lagoons compared to other environments

In coastal lagoons, like in other environments, MP pollution levels in their environmental compartments (i.e., water, sediments, and organisms) varied depending on the distance to and the intensity of pollution sources, which generally include poor management practices of domestic and industrial waste, tourism, fishing, aquaculture, port activities, and river discharges, among others (Deng et al., 2021; Garcés-Ordóñez et al., 2021; Orona-Návar et al., 2022; Ding et al., 2022).

Though extreme care is required when trying to compare results from MP studies in different habitats, including for instance methodological aspects and transfer functions from numbers to mass (Weiss et al., 2021), we attempt here to provide a broad perspective of the situation of coastal lagoons with respect to other habitats in terms of MP pollution.

4.1. Microplastics abundance in waters

Higher MP abundances (up to 24,000,000 items m^{-3}) were reported in lagoonal waters than those reported in surface waters in other coastal habitats including mangroves. This was well illustrated by data from coastal waters in the Colombian Caribbean and Pacific (0.01–8.96 items m^{-3}; Garcés-Ordóñez et al., 2021), southern China (3800–7800 items m^{-3}; Ding et al., 2022), and other areas in Brazil, Mexico, Peru, and Argentina (0–33,373 items m^{-3}; Orona-Návar et al., 2022). MP densities in mangroves within estuaries, bays and gulfs in Brazil, China, Iran, Indonesia, and Jamaica were also lower (0.14–5531 items m^{-3}), as reported in the review by Deng et al. (2021). In Vietnam, Strady et al. (2020) have measured and compared MP abundances in water from different aquatic environments and have found that Thai Nai Lagoon (3.2–4.1 items m^{-3}) contained lower abundances than most rivers and lakes, and higher abundances than most bays and reservoirs. In Türkiye, Faruk et al. (2021) noticed lower abundances in estuarine (26,790 items m^{-3}) and fresh water (30,770 items m^{-3}) of Küçükçekmece Lagoon compared to adjacent marine waters (37,370 items m^{-3}). Also, MP abundances in Küçükçekmece Lagoon were higher than the ones in some lakes (1800–5500 items m^{-3}), estuaries (1500–4000 items m^{-3}) and bays (1500−30,000 items m^{-3}) around the world (Faruk et al., 2021).

4.2. Microplastics abundance in sediments

MP abundances in sediments within coastal lagoons in the reviewed studies (0.24–7960 items kg^{-1}) were almost identical to those reported for mangrove sediments (2–7900 items kg^{-1}) by Deng et al. (2021). Mangroves are commonly associated to lagoons and estuaries in tropical and subtropical areas and are important MP traps (Deng et al., 2021). The range of MP abundance in lagoons was higher than the one reported from beaches in different places of Latin America and the Caribbean (0–4200 items kg^{-1}; Orona-Návar et al., 2022) and much higher than in beaches from the Northwestern Mediterranean Sea (12–187 items kg^{-1}; Constant et al., 2019) but was lower than in sediments from the southern coast of China (2600–10,000 items kg^{-1}; Ding et al., 2022).

Ghayebzadeh et al. (2021) observed that MP abundance in the Anzali Lagoon (342 items kg^{-1}) in the Caspian Sea, Iran, was lower than abundances recorded in the estuarine sediments of the nearby Lavandvil, Sardabroud, Chalus, Mian Rud, Haraz, Babol and Tajan rivers (406–916 items kg^{-1}) and higher than in the estuarine sediments of the Talesh, Jireh Bagh, Chamkhaleh, Talar, Black, Neka, and Gorgan rivers (46–305 items kg^{-1}). In Nigeria, Fred-Ahmadu et al. (2022b) found fewer MPs in Lagos Lagoon sediments (292 items) than on adjacent coastal beaches (3388 items), which also showed higher concentrations of metals (Al, Ca, K, Mg, and Na) than the MPs from the lagoon. Concentrations of $\sum$PAHs, ΣPCBs, and ΣOCPs were equally higher in beach MPs than in the one from the lagoon (Fred-Ahmadu et al., 2022a).

4.3. Microplastics abundance in fish

Fish was the group of organisms in which MPs have been most studied in coastal lagoons and in other marine, estuarine, and freshwater environments (Azizi et al., 2021; Zazouli et al., 2022). MP abundances in the digestive tract of fish from coastal lagoons in the reviewed literature ranged from 0 to 53 items ind.$^{-1}$, which was higher than in fish from bays, estuaries, lakes, rivers, and the open ocean reported in Zazouli et al. (2022). It was also higher than the abundance found by Azizi et al. (2021) in their review of MPs in freshwater fish (0.15–40.9 ind.$^{-1}$ items). MP abundances in lagoon fish were notwithstanding lower than in marine fish (0.02–136 items ind.$^{-1}$; Zazouli et al., 2022) and in fish from mangroves (0–511 items ind.$^{-1}$; Deng et al., 2021).

5. Key issues and future research on microplastic pollution in coastal lagoons

The reviewed studies mentioned 135 key issues about MP pollution in coastal lagoons. We have organized and integrated these issues into 15 overarching issues and future research lines referring to methodological questions, assessment/monitoring of pollution, dynamics, and impacts and prevention or environmental management (Table 5).

Methodological aspects represented 13% of the identified issues, amongst which the standardization of sampling and analytical methodologies for MPs in the different environmental matrices of coastal lagoons stands out (Table 5). This relates to the difficulties in comparing results over broad spatial scales and to the necessity of implementing some low-cost, highly reliable MP monitoring techniques as discussed in section 3.2. The availability of equipment and human and economic resources to carry out systematic studies in highly vulnerable areas is another important limitation in many countries. For instance, Gbogbo et al. (2020) indicated the lack of analytical capabilities to analyze polymer composition as a problem. Within the reviewed studies polymer composition was not analyzed in 37% of them (Table 3). The training of new researchers and technicians is another crucial factor limiting the ability to generate knowledge in many regions of the world. Scientific collaboration is essential to overcome these and many other barriers, as highlighted in the SDGs (United Nations, 2015). Research networks and citizen science initiatives aiming at strengthening the technical capacities across countries, organizations and individuals also are of the utmost importance to develop regional research programs on MPs in coastal areas, especially in developing countries where the social perception of the benefits of protecting natural environments often is less extensive than in more advanced countries.

Assessment and monitoring aspects represented 72% of the identified issues, mainly pointing at the need to advance the knowledge of the ecological, economic, and social impacts of MP pollution, as well as their toxicity for aquatic species and risks for human health (Table 5). This focus is understandable given that coastal lagoons are areas of high production of seafood, which is an important nutrition source for the lagoon coastal communities (Abidli et al., 2019; Badylak et al., 2021; Calderón et al. 2019; Garcés-Ordóñez et al., 2022). Although progress has been made in understanding MP dynamics in lagoons, the reviewed studies indicated the relevance of, specifically, advancing knowledge on processes that influence MP distribution (e.g., Chico-Ortiz et al., 2020; Cozzolino et al., 2020; Piarulli et al., 2020; Badylak et al., 2021), absorption of organic and inorganic pollutants by MPs (e.g., Fred-Ahmadu et al., 2022a, 2022b; Olarinmoyec et al., 2020), bacterial hosts harboring antibiotic resistance genes (e.g., Sun et al., 2021), bioaccumulation and biomagnification (e.g., Waite et al., 2018; Renzi et al., 2020; Sfriso et al., 2021), physiological responses (e.g., Ding et al., 2019; Dantas et al., 2019; Illif et al. 2020; Cozzolino et al., 2021; Lin et al., 2021), the role of plant communities as potential MP sinks (e.g., Cozzolino et al., 2020), and bioindicators of MP pollution (e.g., Wakkaf et al., 2020b; Renzi et al., 2020).

Prevention and management represented 15% of the main outstanding issues identified. Environmental education was one of the points that received most mentions (Table 5), highlighting the need to develop general educational programs and activities targeting the key actors (e.g., coastal communities, fishermen, manufacturers, and environmental managers) such as, for instance, clean-up days. Knowledge transfer to generate awareness about the state of MP pollution and its potential ecological, social, and economic impacts should deserve priority (Dantas et al., 2019; Bayo et al., 2019; Chico-Ortiz et al., 2020; Wakkaf et al., 2020a). Additionally, the development and implementation of policies aimed at changes in production patterns, the building or improvement of the infrastructure for the management of domestic and industrial waste, and the reduction of the pollutant load in the lagoons were mentioned (Garcés-Ordóñez et al., 2019; Wakkaf et al., 2020a; Bayo et al., 2020; Faruk et al., 2021; Lorenzi et al., 2021).

Finally, the hypothesis that coastal lagoons are important sinks for MPs clearly emerges from this review, which is to be tested in future studies. Contributing to this point would also clarify whether coastal lagoons are a temporary or permanent sink for MPs, while taking into account their typologies, environmental differences because of latitude

Table 5
Main outstanding issues and future research lines on microplastic pollution in coastal lagoons identified in the current review. The shaded column Rep.-1 shows the fraction of the total key issues and future research (n = 135) mentioned in the reviewed studies grouped in each aspect; and the shaded column Rep.-2 shows the fraction of the total key issues and future research for each aspect. These shaded columns provide an indication of the relevance of the different aspects, as measured by the times each is mentioned in the reviewed studies. Rep.: representation.

Aspects	Rep.-1	Issues and future research	Rep.-2
Methodological	13%	Difficulties in comparing amongst MP studies due to methodological differences.	20%
		Under or overestimation of MP abundances resulting from differences in methodologies.	10%
		Limited or no access to FTIR analyses for polymer identification.	25%
		Need to find and implement low-cost methodological solutions for MPs identification and monitoring.	10%
		Need to implement a standard protocol for sampling, processing, counting, and reporting on MPs.	35%
Assessment and monitoring	72%	Need to monitor processes influencing the dynamics of MPs and associated contaminants.	10%
		Convenience to identify indicator species for MP pollution.	10%
		Need to assess ethological, physiological, and toxicological effects of MPs on aquatic species.	20%
		Necessity to assess ecological, economic, and social effects and impacts of MP pollution.	30%
		Considering human health risks derived from the consumption of MPs in seafood.	20%
		Need to establish monitoring schemes integrating waters, sediments, and organisms.	5%
		Request to track bacteria in biofilms on MPs, and especially those harboring antibiotic resistance genes	5%
Prevention and management	15%	Develop and implement awareness rising and educational strategies on MP pollution.	52%
		Implementing policies to prevent plastic pollution, including improved waste management.	43%
		Find a solution to the issue of too limited to non-existing financial resources to support MPs monitoring efforts.	5%

(and thus climate setting), and acting natural (e.g. regime and amount of river discharges, hypopycnal vs. hyperpycnal flows from such discharges) and anthropogenic processes (e.g. fishing, aquaculture, dredging, waste disposal) that could influence the entry, transport, abundance, impacts, recirculation and final fate of MPs in these and in connected environments. To address these issues, regular MP monitoring would be required so that robust time series on their abundance, characteristics and sources could be achieved. Knowing the variations of MP contents and composition in sediments in a variety of sub-environments (e.g., in shallow vs. deeper zones, or in vegetated vs. non-vegetated zones) is pivotal to understand their cycling in coastal lagoons together with residence times, would these be days, months or decades.

6. Conclusions

Research on MP pollution in coastal lagoons has made significant progress especially in the last few years, increasing background knowledge and providing much needed building blocks to achieve a global overview of this problem. The scientific literature on MPs in waters, sediments and organisms from coastal lagoons report higher abundances where these ecosystems suffer from human pressures such as urban development, aquaculture, fishing, and other high intensity activities. In contrast, most lagoons in protected natural areas record lower abundances of MPs. Even though most studies in coastal lagoons address single environmental matrices, an overall similar predominance of MP characteristics in waters, sediments and organisms already emerges in terms of physical (e.g., shape and color) and chemical (e.g., polymer composition) properties.

Coastal lagoons are highly vulnerable to MP pollution, due to their characteristics of limited water exchange, shallow depth, and high anthropogenic pressure. This causes large amounts of MPs to accumulate in these water bodies, predominantly those of secondary MPs such as fibers and fragments in water, sediments and organisms that have been studied. In addition, the levels of MP pollution in coastal lagoons are higher than those reported in freshwater bodies, river estuaries, reservoirs, and oceans, and similar to the abundances reported in mangroves, underscoring that these systems are highly threatened by this type of pollution.

Besides the findings summarized above and like in other settings such as rivers and oceans, studies on MP pollution in coastal lagoons suffer from methodological dissimilarities in terms of sampling devices and strategies, size classes addressed, and reagents used in separation protocols. In many places, access limitations to spectroscopy techniques to identify polymer composition and corroborate the particles nature also hampers progress.

For the reasons above, future research and monitoring plans must encompass a fully integrated approach, as it will facilitate a much-improved understanding of the dynamics of MPs in coastal lagoons, including feedbacks between water, sediments, and organisms, subsequently easing the implementation of sound, science-based mitigation measures. Networking and scientific alliances can play a pivotal role in minimizing current weaknesses that prevent further progress, so that (i) common sampling and analytical methods and protocols are applied at least at regional level, including access to critical analytical tools, (ii) sound comparisons of results can be made, and (iii) indicators and thresholds on MP pollution in coastal lagoons are defined.

Credit author statement

Ostin Garcés-Ordóñez: Conceptualization, Methodology, Validation, Formal analysis, Investigation, Resources, Data Curation, Writing - Original Draft, Writing - Review & Editing, Visualization, Supervision, Funding acquisition. **Juan Saldarriaga-Velez:** Conceptualization, Methodology, Investigation, Writing - Original Draft. **Luisa Espinosa:** Resources, Writing - Review & Editing, Project administration. **Miquel Canals:** Conceptualization, Validation, Resources, Writing - Review & Editing, Visualization, Supervision. **Anna Sánchez-Vidal:** Validation, Writing - Review & Editing. **Martin Thiel:** Conceptualization, Validation, Resources, Writing - Review & Editing, Visualization, Supervision.

Declaration of competing interest

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

Data availability

Data will be made available on request.

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Appendix A. Supplementary data

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