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REVIEW ARTICLE

The under-investigated plastic threat on seagrasses worldwide: a comprehensive review

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Abstract
Marine plastic pollution is a well-recognised and debated issue affecting most marine ecosystems. Despite this, the threat of plastic pollution on seagrasses has not received significant scientific attention compared to other marine species and habitats. The present review aims to summarise the scientific data published in the last decade (January 2012–2023), concerning the evaluation of plastic pollution, of all sizes and types, including bio-based polymers, on several seagrass species worldwide. To achieve this goal, a comprehensive and critical review of 26 scientific papers has been carried out, taking into consideration the investigated areas, the seagrass species and the plant parts considered, the experimental design and the type of polymers analysed, both in field monitoring and in laboratory-controlled experiments. The outcomes of the present review clearly showed that the dynamics and effects of plastic pollution in seagrass are still under-explored. Most data emerged from Europe, with little or no data on plastic pollution in North and South America, Australia, Africa and Antarctica. Most of the studies were devoted to microplastics, with limited studies dedicated to macroplastics and only one to nanoplastics. The methodological approach (in terms of experimental design and polymer physico-chemical characterisation) should be carefully standardised, beside the use of a model species, such as *Zostera marina*, and further laboratory experiments. All these knowledge gaps must be urgently fulfilled, since valuable and reliable scientific knowledge is necessary to improve seagrass habitat protection measures against the current plastic pollution crisis.

Keywords Marine plastic pollution · Seagrass · Stress response · Accumulation · Field monitoring · Laboratory experiments

Introduction

Plastic litter is nowadays found from the most highly anthropized coast to the most remote regions, in all shapes and sizes (Bergmann et al. 2015). Starting from the post-war period, with the fast increase in the human population and the ever-increasing plastic global demand, a massive quantity of plastic waste is produced every day. To date, according to IUCN (2021)the amount of synthetic polymer production has reached over 300 Mt/year, and about 50% of this is intended for the manufacture of single-use plastic items, such as straws (Gao and Wan 2022), carrier bags (Bergmann

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et al. 2015; Xanthos and Walker 2017), food packaging, wrappers, cutlery and containers (Luo et al. 2022). Additionally, up to 12 Mt of plastic materials enter the oceans each year, giving rise to the well-deserved definition of the current plastic pollution issue as a "planetary crisis" (IUCN 2021). A lack of public awareness, in conjunction with a poor plastic waste management policy, caused the spread of plastic debris, threatening marine ecosystems worldwide (Derraik 2002; Xanthos and Walker 2017). To address this pressing issue, several studies, to date, have explored and delved into aspects of plastic pollution, such as the impact of plastic debris interaction with ecosystems and the consequences of plastic ingestion by marine wildlife including studies on marine mammals like whales and invertebrates like bivalves and sea urchins (Bergmann et al. 2015; Poeta et al. 2017; Ward et al. 2019; Valente et al. 2019, Viel et al. 2023). Nevertheless, limited literature is available on the effects of plastic on seagrass meadows, despite their great ecological importance and high economic value (Bonanno and Bonaca 2020; Gerstenbacher et al. 2022).

Seagrasses are marine plants that branch out by structuring extended and intricate meadows in shallow coastal waters worldwide, with the Antarctic area being the only exception. Seagrass meadows are well-known key coastal habitats that furnish, at a global scale, a broad range of ecosystem services, including coast preservation against erosion, nursery areas for juvenile fishes, recruitment areas, biodiversity hotspots and carbon intake (Nordlund et al. 2018; Bonanno and Bonaca 2020). With their sophisticated tangled structure, seagrass meadows act as a trap for marine litter, forming a relevant sink for macro- and microplastics (MP) (Goss et al. 2018; Jones et al. 2020; Gerstenbacher et al. 2022). Recent evidence has shown that plastic pollution can affect marine seagrasses by producing adverse and possibly hazardous multiple impacts on the seagrasses' growing rate and photosynthetic efficiency, also altering their oxidative status (Jones et al. 2020; Menicagli et al. 2022). Particularly, plastic microparticles can adhere to the surface of seagrass leaves, threatening associated epiphytic communities and the marine food chain (Jones et al. 2020).

Three reviews were recently published (Bonanno and Bonaca 2020; Gerstenbacher et al. 2022; Walther and Bergmann 2022) on some specific issues regarding plastic pollution in seagrass habitats. Gerstenbacher et al. (2022) provided the current state of knowledge on MP impact on seagrasses, epiphyte assemblage and substrate-associated community. Walther and Bergmann (2022) concentrated on an integrated comparison of four under-investigated marine ecosystems worldwide, including seagrass meadows. Bonanno and Bonaca (2020) emphasised the absence of a seagrass-focused legislative framework, as well as standardised protocols and dedicated guidelines for comparable data collection.

The aims of the current review are to:

(i) Perform a comprehensive collection of available data about the occurrence and impact of plastic pollution on seagrass meadows, on a global scale
(ii) Critically explore the current and available methods for the investigation of plastic pollution in seagrass habitats
(iii) Highlight strengths and weaknesses and propose pathways for upcoming research

Materials and methods

A detailed systematic literature review has been conducted with the use of the scientific databases: "Scopus" (https://www.scopus.com) and "ISI Web of Science" (http://apps.webofknowledge.com). Additional research has been carried out on Google Scholar (https://scholar.google.com). All significant and valuable published studies on the subject have been examined during the period between 2012 and 2023.

Two parallel analyses have been conducted by combining "microplastic" with "seagrass" and "plastic litter" with "seagrass", to ensure the inclusion of all plastic litter sizes related articles. Boolean logic has been applied to keywords as follows: [(Microplastic*seagrass)* OR plastic litter* OR marine plastic pollution* OR biodegradable plastic* OR seagrass communities* OR *Posidonia oceanica** OR trapping effect* OR coastal ecosystems* OR marine vegetation* OR biota* OR sediments*, OR microfibers* OR bioaccumulation* OR stress response* OR effect*] AND [(Plastic litter* seagrass) OR marine plastic pollution* OR biodegradable plastic* OR seagrass communities* OR *Posidonia oceanica** OR trapping effect* OR coastal ecosystems* OR marine vegetation* OR biota* OR sediments*, OR microfibers* OR bioaccumulation* OR stress response* OR effect*] (Fig. 1).

This research resulted in a total of 63 full-text articles. Each study has been consulted, and an eventual screening has been carried out to guarantee that all the publications considered were strictly related to plastic pollution on seagrasses.

A total of 33 not pertinent articles have been excluded, and 26 articles have been selected for the final literature analysis. Only research articles were taken into consideration, in this study, and the three reviews found on the topic were excluded but are summarised in the introduction (see the "Introduction" section) (Gerstenbacher et al. 2022, Walther and Bergmann 2022; Bonanno and Bonaca 2020).

After the screening, although the range was from January 2012 to January 2023, all valuable articles were

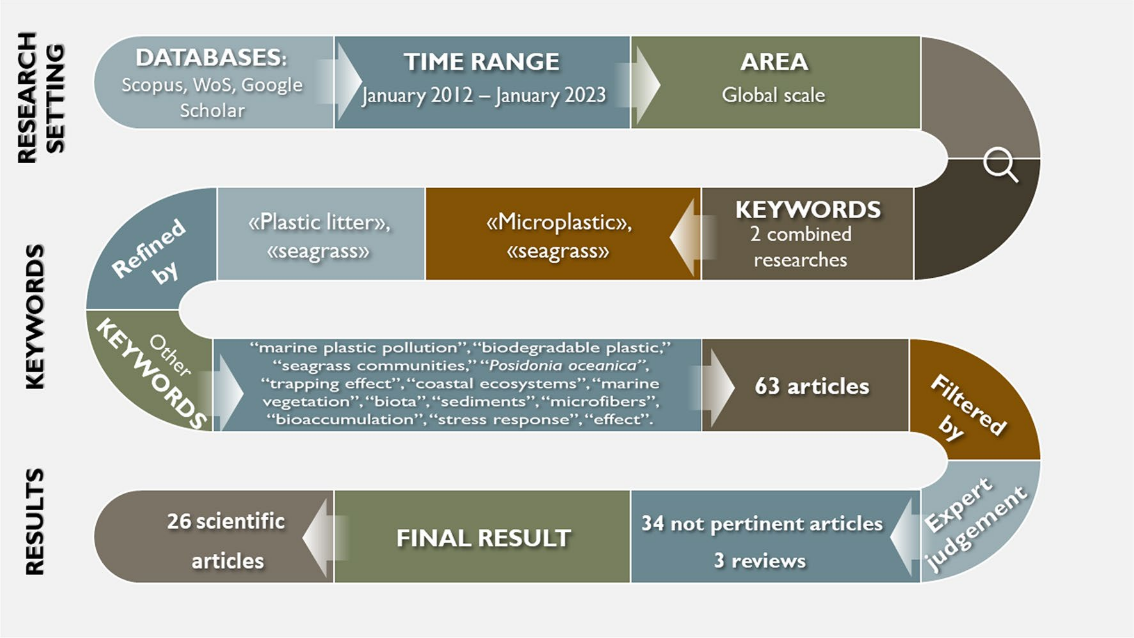


Fig. 1 Bibliographic research workflow conducted on Scopus, Web of Science and Google Scholar in the range time January 2012–January 2023

published in a restricted time range, from 2017 to 2023. A workflow representing the details of the bibliographic research is reported in Fig. 1. Eventually, the results of the literature search have been ordered and arranged in Supplemental Materials (Table S1).

After article selection, a detailed and deep analysis of the literature collected has been carried out, in order to give prominence to all the aspects pertaining to plastic pollution on seagrasses and particularly considering (i) the research approach (monitoring studies in situ or controlled exposures in the laboratory), (ii) the spatial–temporal trend, (iii) the species-specific accumulation, (iv) the type of experimental design, (v) the type of polymers and their concentration in situ, and (vi) the evaluation of potential biological effects by laboratory studies.

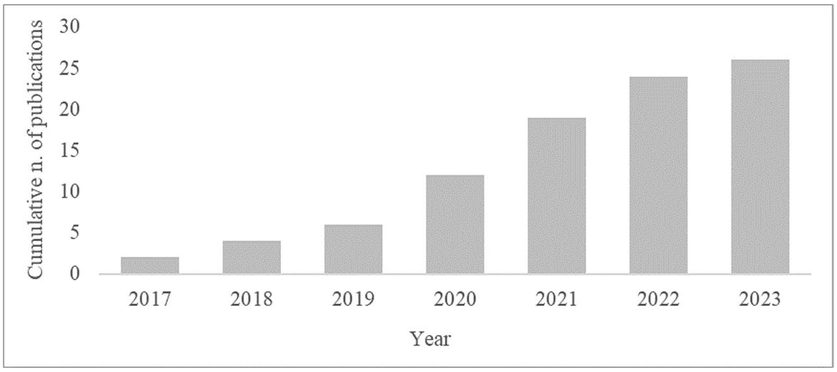
Results and discussion

Trend in time and research approach

The first publication that fully satisfied the requirements of our bibliographic research was released in 2017, despite a significant amount of plastic and MP studies on the other environmental compartments and ecosystems being published much earlier. However, the research related to plastic pollution in seagrasses showed an exponential increase from 2017 to date (Fig. 2).

Over the years, several methodologies, such as in situ analysis and controlled laboratory experiments, have been developed. A total of 22 studies have been conducted in the natural environment ("in situ", see the "In situ studies" section), while 5 experiments were set in a controlled

Fig. 2 Global cumulative trend of scientific publications related to plastic pollution on seagrasses within the time range 2017–2023



environment (laboratory, see the “Laboratory studies” section). Only Zhao et al. (2022) adopted both approaches investigating MP accumulation on meadows (*Zostera marina* Linnaeus, 1753) and unvegetated sites by in situ trials and the Polystyrene MP sedimentation rates in laboratory conditions.

As reported in Fig. 3, most of the studies, both in situ research (left) and laboratory experiments (right), investigated MP (less than 5 mm), but it is frequent that a single study can include more than one plastic size. It is worth to note that only seven studies (in situ) are focused on macroplastic and only two of the five researches conducted in a controlled environment are targeted on macro-bioplastic (Balestri et al. 2017) and nanoplastic (Menicagli et al. 2022).

In situ *studies*

Investigated coastal areas, seagrass species and plant parts

The collected data covered 15 countries, with a distribution that varies from one to five papers per country: the studies were rather confined to limited sites, especially belonging to the Indian Ocean and to the Mediterranean Sea, with an evident under-investigation of the remaining areas (Fig. 4), despite the occurrence of seagrass worldwide and the apparent plastic pollution condition (Sanchez-Vidal et al. 2021).

The hereby considered in situ studies investigated 15 different seagrass species, with 10 studies regarding more than one species or mixed composition seagrass beds, focusing on the analysis of seagrass sediments, leaves, canopies and debris (Fig. 5). The most studied seagrass species is

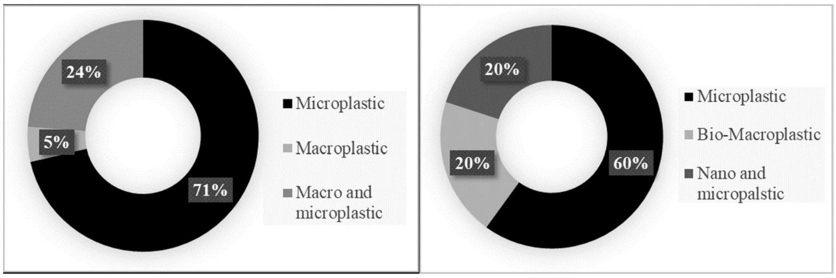


Fig. 3 Graphic illustration of the investigated areas within the studies selected for the present review. The different particle sizes investigated within in situ (left) and in laboratory (right) studies are reported as pie charts and frequencies indicated

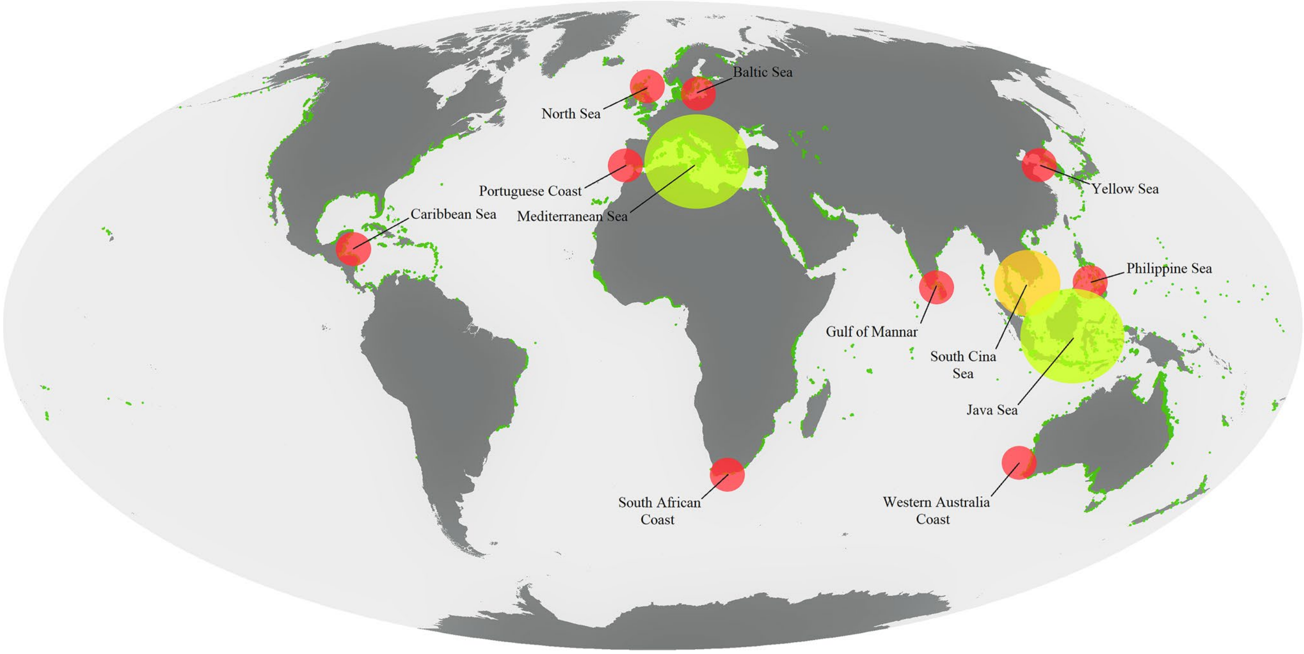
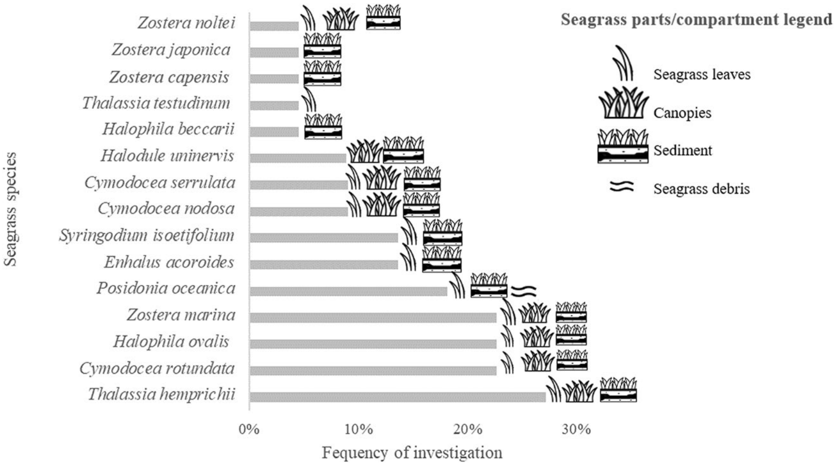


Fig. 4 Graphic illustration of the plastic particle sizes investigated within the studies selected for the present review. Green areas along the coasts represent seagrass distribution worldwide (map credit: https://data.unep-wcmc.org/datasets/7). Bubbles represent the studies across oceans and seas, and different colours and dimensions refer to numbers of studies per area (legend: yellow = 5 studies; orange = 3 studies; red = 1 study). Multiple studies carried out in the same area were aggregated according to the sea in which they are located. The investigated areas refer to seagrass sampling sites and not the research institute's provenience

Fig. 5 Graphic illustration of the investigated seagrass species within the studies selected for the present review. The 15 seagrass species investigated in the studies are listed by increasing frequency of investigation, and details about the plant parts or compartments analysed are reported. Icons provided by https://icons8.com



Thalassia hemprichii (Ehrenberg) Ascherson, 1871, after 3 species *Cymodocea rotundata* Asch. and Schweinf, *Halophila ovalis* (R. Brown) Hooker f., 1858 and *Zostera marina* Linnaeus, 1753, equally present in the literature, and followed by *Posidonia oceanica* (Linnaeus) Delile, 1813; *Enhalus acoroides* (Linnaeus f.) Royle, 1839; *Syringodium isoetifolium* (Asch.) Dandy; *Cymodocea nodosa* (Ucria) Asch; *Cymodocea serrulata* (R. Brown) Ascherson and Magnus, 1870; *Halodule uninervis* (Forssk.) Asch; *Halophila beccarii* Ascherson, 1871; *Thalassia testudinum* K.D. Koenig, 1805 and eventually other three species belonging to *Zostera* genus: *Zostera capensis* Setchell, 1933, *Zostera japonica* Ascherson and Graebner, 1907 and *Zostera noltei* Hornemann, 1832.

The different parts of the plant and substrate have not been investigated with the same frequency. Acknowledging that a single study can inspect multiple parts of a seagrass, 68% of the studies were carried out on superficial sediments sampled within the seagrass meadows, exploring the seagrass's ability to act as a sink and accumulate plastic in the sediment. The 36% of the surveys analysed the blades—calculating the number of items per unit of area of the leaf or the average number of items per blade—since plastic items have the capacity to adhere to seagrass blades (Goss et al. 2018; Priscilla et al. 2019). Plastic presence on seagrass leaves could have numerous effects, representing a potential hazard for marine food webs (Sawalman et al. 2021). Particularly, Goss et al. (2018) investigated the role of *T. testudinum* in acting as an intermediary between plastic items and benthic marine food webs. Microfibers have been found on their blades with a significant frequency of occurrence, encrusted with epiphyte assemblages, potentially altering the global health status of the seagrasses and affecting the feeding interaction of the associated community. Additionally, deposited plastic fragments may affect the reproductivity potentialities by inhibiting flowering and/or fruit and seed dispersion (Gallitelli and Scalici 2022), highlighting the importance of the seasonality on the plastics' effects on vegetation as well (see Gallitelli and Scalici 2022b, and references therein). Anyway, further research, conducted in a controlled laboratory facility, is discussed below (see the "Laboratory studies" section). Indeed, to date, few (not exhaustive) investigations occur in the literature about the real effect of MP deposition on the seagrass (see below the "Experimental designs" section).

The remaining studies involved canopies (22%) and seagrass debris (18%), by evaluating the contribution offered by seagrass meadows in trapping plastic items in proximity to the coasts. This analysis had been carried out by means of transects (Gaboy et al. 2022; Navarrete-Fernández et al. 2022; Rasyid et al. 2022) and replicated plots (Cozzolino et al. 2020). Limited data are related to seagrass fragments deposited along the Mediterranean coasts by marine currents. Pietrelli et al. (2017) recorded, for the first time, the occurrence of plastic items within *P. oceanica* spheroids and egagropiles, by suggesting that plastic materials—especially fishing nets and lines—could negatively affect the natural process of egagropile formation. On the other hand, Sanchez-Vidal et al. (2021) considered the plastic trapping capacity of *P. oceanica*, as described for mangroves (Martin et al. 2020) and riverine riparian vegetation (Cesarini and Scalici 2022). They pointed out a new "ecosystem service" provided by these aquatic habitats. Indeed, vegetation in general may be damaged by plastics, but macrophytes and algae may provide a service by trapping plastics which may (i) spread worldwide and (ii) generate secondary nanoplastics after their environmental deterioration, even if little is known about the global patterns of plastic retention and remobilisation by vegetation through different habitats.

Experimental designs

The experimental designs used to investigate the effect of plastic pollution on seagrass within the 22 studies selected for the present review are various and pursue several approaches. To compare the studies and highlight the most common approaches and main gaps, we identified five major different experimental design categories: (i) before/after pollution, (ii) control/impact site, (iii) protected areas, (iv) multi-habitat and (v) vegetated/bare areas (Fig. 6).

Considering the "before/after pollution" design, two studies investigated seagrasses through temporal observations with respect to plastic pollution. The first one evaluated *P. oceanica* trapping capacity, by comparing the plastic pollution immediately after the dry season and after the rainfall period, finding that macroplastic abundance after heavy rainfalls had tripled its value (Navarrete-Fernández et al. 2022). The latter used a reliable soil age-depth chronologies technique to evaluate plastic pollution over the last century within different sites. The results pointed out that plastic pollution in meadows was negligible until 1970, while the highest average value of plastic concentration was recorded during 2012 (Dahl et al. 2021).

The "control/impact site" design has dealt with the choice of study areas in proximity or far from disturbance sources, such as wastewater discharges or landfills. For instance, Boshoff et al. (2023) found that threadlike MP displayed a significant difference in abundance between a polluted site and a low anthropogenic pressure site, while other MP types did not show differences among the investigated locations.

The "protected areas" design regarded studies conducted within marine areas subject to a certain degree of protection from human disturbances. Although the frequency of studies conducted in protected areas is not negligible, only Dahl et al. (2021) directly compared MP occurrence between protected and not protected areas and found a lower abundance of MP, but not completely absent, within the marine protected area investigated. Nevertheless, the rest of the studies highlighted the presence of plastic pollution, even if conducted within protected areas (Pietrelli et al. 2017; Goss et al. 2018; Cozzolino et al. 2020; Jones et al. 2020).

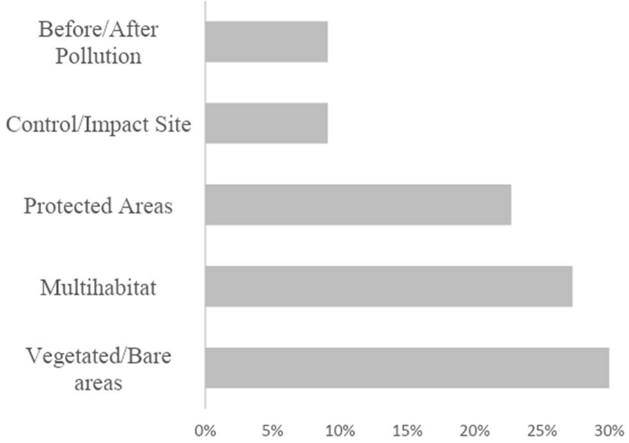


Fig. 6 Graphic illustration of the experimental designs used within the studies selected for the present review. Different experimental designs applied to investigate the effect of plastic pollution on seagrasses are summarised, and their frequency within the studies is reported as bar chart (since a single study can adopt numerous methods, repetitions within the individual design categories can occur)

"Multi-habitat" design focused on the comparison of plastic pollution among seagrass meadows and other habitats, such as coral reefs, mangroves and macroalgae. Among this sampling design cluster, Seng et al. (2020) have found a significantly higher MP load in seagrasses than in macroalgae. Another study (Renzi et al. 2018) compared the plastic trapping capacity of *C. nodosa* meadows, at Amphioxus sands and Mäerl beds in the Northern Adriatic Sea, but differences were not significant, and they concluded that further studies are needed to deepen the habitat influence on plastic pollution occurrence.

The "vegetated/bare areas" design represented one of the most widely used methodologies with more than 30% of the studies employing it. It focused on the comparison between plastic item abundance within seagrass meadows and the surrounding unvegetated areas, to evaluate seagrass plants trapping capacity. A series of interesting results, in some cases contrasting, have emerged. Three studies evaluated the trapping capacity of several seagrass species and found comparable abundance of MP between vegetated and adjacent bare sediments, while macroplastics were absent in the unvegetated areas (Boshoff et al. 2023; Cozzolino et al. 2020; Wright et al. 2023). On the other hand, other three studies showed that MP abundance was significantly and positively correlated to the presence of the seagrasses (Huang et al. 2020; Jones et al. 2020; Zhao et al. 2022). On the contrary, Tahir et al. (2020) found no correlation between MP abundance and seagrass cover percentage. More information in terms of plastic concentration in seagrass meadows and unvegetated areas is reported in the next section (see the "Plastic item characterisation and concentrations" section).

It is worth to note that a further 30% of studies have not been included in any category because they generally concern plastic pollution in seagrass habitats but did not show a specific experimental design. This suggests that the rationale behind the studies could be better developed, including a more detailed experimental design.

Out of the 22 studies conducted in the marine environment, only 5 provided water sampling, and 15 included the collection of sediment samples. Indeed, plastic pollution on the sea surface and into the water column is still difficult to assess: as floating plastic items tend to accumulate with specific patterns on the sea surface; hence, the sampling may not accurately represent the actual condition of the whole marine surface, and an intensive sampling effort would be needed (Cole et al. 2011; Welden and Lusher 2017).

We can summarise that the approaches evaluating the occurrence of plastic pollution are the most common within the 22 studies considered for the present review. Another common approach was the investigation on the role of seagrass meadows as plastic sink and seagrass trapping capacity. Given the key ecological role of seagrass meadows, these coastal habitats should be included in the assessment of plastic debris accumulation, and further research, including experimental studies, is needed to shed more light on the issue. However, since seagrass trapping capacity seems extremely inconstant and strongly dependent on plastic size, habitat and tide, it should be carefully evaluated, considering this variability (Cozzolino et al. 2020). Moreover, since plastic pollution has become a widespread phenomenon, a clear limitation in this approach is due to the actual absence of pristine areas (not contaminated by plastics) to be identified as a proper reference site (control).

Although in marine ecosystems, there is a generalised agreement in considering seagrass to be able to trap plastics by several pathways (see Datu et al. 2019; Cozzolino et al. 2020; de los Santos et al. 2021; Sanchez-Vidal et al. 2021; Navarrete-Fernández et al. 2022), an evaluation of the possible direct effects of plastic pollution on biota and their consequences on ecosystem services, at population (meadows dynamics) and individual (eco-physiological descriptors) level, is completely lacking in these in situ studies. Also, in this case, the absence of control sites or the difficulty of applying specific chronological techniques represents a limitation to be considered. Furthermore, seagrasses are recently experiencing several pressures worldwide, mostly deriving from their proximity to highly anthropized areas. Therefore, the actual effect of plastic pollution on seagrasses cannot be separated from the other factors that contribute to damaging the seagrass with possible cumulative effects (Gerstenbacher et al. 2022).

Plastic item characterisation and concentrations

As previously mentioned (see Fig. 3 and the "Investigated coastal areas, seagrass species and plant parts" section), in the present review, most of the studies detected MP, and only a few focused on macroplastics, sometimes including more than one plastic size.

Regarding the size measurements, many different techniques have been applied in the reviewed studies. For macroplastics, almost all studies perform standard measurements, also using microscopes except for Navarrete-Fernàndez et al. (2022) which uses ImageJ. For MP, there is a great heterogeneity of methods, and many studies involve the use of image software (e.g. Huang et al. 2020; Jones et al. 2020; Wright et al. 2023). Nevertheless, a considerable number of studies do not specify the measurement methods at all (e.g. Boshoff et al. 2023; Priscilla et al. 2019; Tahir et al. 2019), and it is common that to refer to multiple dimensions together as "size classes" is considered.

Among studies focusing on MP, in Cozzolino et al. (2020), plastic particles in *C. nodosa* and *Z. marina* ranged from 4925 to 45 µm, but the most frequent size was 0–1000 µm, with a frequency of occurrence of 57.8%. Similarly, in Kreitsberg et al. (2021), the most abundant size class in *Z. marina* sediments is once again 0–1000 µm. Huang et al. (2021) divided MP particles into size classes, discovering that in seagrass beds, the prevailing size was 125–250 µm, subsequent to 250–500 µm and 63–125 µm. On the contrary, according to Navarrete-Fernàndez et al. 2022, the most abundant size class in *P. oceanica* beds is between 1 and 2.5 mm (56.25%), followed by those from 2.5 to 5 mm (31.25%) and from 0.5 to1 mm (12.5%), consistently with another research (Wright et al. 2023) indicating that the most abundant plastic particle size ranges from 1.23–50 µm (78.5%) in *H. ovalis* beds.

Concerning the studies regarding macroplastic, the only one which is exclusively concentrated on macroplastic (Gaboy et al. 2022) takes into account the density of the items/m^2 and the total mass per site rather than the dimension. Other studies (Navarrete-Fernàndez et al. 2022, Cozzolino et al. 2020, Pietrelli et al. 2017) reported an array of heterogeneous values of abundances regarding size classes. The reported most abundant size categories for the studies aforementioned are, respectively, less than 50 cm and from 10 to 50 cm after heavy rainfalls, from 0.5 to 10 cm (55.6%) and from 1 to 1.5 cm.

Only 55% of the studies included an effective and proper polymer characterisation (see Supplemental Materials, Table S1 for details); most of them focused on a representative subsample of the total collected items (e.g. Wright et al. 2023; Kreitsberg et al. 2021; Sanchèz-Vidal et al. 2021). Moreover, some studies (e.g. Navarrete-Fernandez et al. 2022; Jones et al. 2020) have limited their analysis to a subsample exceeding an established size (e.g. more than 1.5 mm in size; only items between 100 and 5000 µm), and comparisons to reference materials recorded in libraries can be also included. Although a detailed description of the methods for the chemical characterisation is not always provided, analyses are generally conducted with spectroscopy techniques, mainly using Fourier transform infrared spectroscopy (FTIR) with an attenuated total reflection (ATR) accessory, with different spectrum ranges and scan rates (for detailed method descriptions see Huang et al. 2021 and in Jeyasanta et al. 2020).

As clearly illustrated in Fig. 7, the polymer composition of the plastic items found in the natural environment had a synthetic origin, and even among the most recent publications, bio-based polymers were never found or considered. Polyamide (PA6), polyethylene (PE) and polystyrene (PS) were the most abundant polymeric substances found

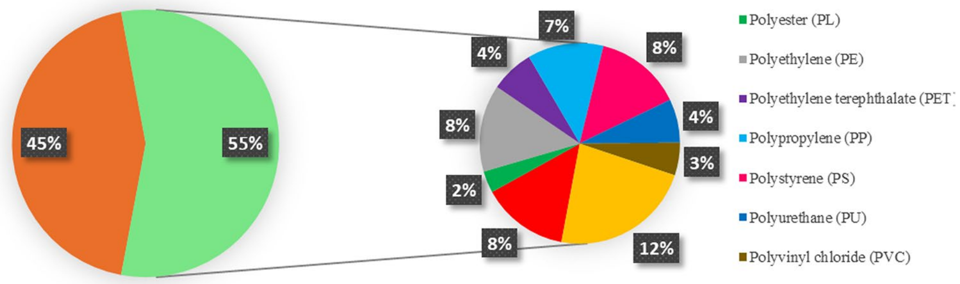


Fig. 7 Graphic illustration of the polymer characterisation within the studies selected for the present review. Left pie chart: percentage of papers which made (green) or not (red) a proper polymer characterisation ($n=22$). Right pie chart: different polymers identified

among seagrasses worldwide (frequency of occurrence F.O. = 8%), immediately followed by polypropylene (PP) (F.O. = 7%). Furthermore, a significant slice of the pie chart is represented by polyethylene terephthalate (PET, 4%), polyurethane (PU, 4%), polyvinyl chloride (PVC, 3%) and polyester (PL, 2%). Ultimately, the portion "others" includes the less common polymers, only appearing in one study each (F.O. < 0.8%).

Although bio-based polymer deployment is getting more and more widespread (Manfra et al. 2021; Balestri et al. 2017), still, little information has emerged for bio-based plastic, limited to laboratory-controlled experiments (see the "Laboratory studies" section).

A huge variability of data on MP concentrations (see Supplemental Materials, Table S1) has emerged due to several factors: (a) the investigated seagrass species, (b) the parts of the plant where values were measured, (c) the measurement units in which they are expressed, (d) the polymer type, (e) the particle size and (f) the substrate (vegetated, not vegetated) of plastic adhesion in presence of seagrasses.

The studies highlighted a certain variability in plastic abundance, even at small spatial scales, with a strong correlation to meteorological events or to proximity to larger human population densities (Huang et al. 2020; Navarrete-Fernández et al. 2022; Boshoff et al. 2023). These issues should be taken into consideration for the design of future studies aiming to monitor plastic pollution in seagrass habitats.

The results in terms of concentration are highly variable and not simple to compare in surveys analysing sediment too. Based on recent research findings, the presence of seagrasses is not a significant variable considering MP abundance in the sediment (Wright et al. 2023). Huang et al. (2021) evaluated seagrass meadows and mangrove forest's ability to stock MP in the sediments. Three species (*H. beccarii*, *H. ovalis* and *Z. japonica*) have been considered, and the seagrass mostly composed of *H. beccarii* showed, by contrast, a great rate of MP accumulation and the major variety of MP—in terms of colour and size—compared to the bare sites. Jones et al. (2020) also highlighted that the presence of seagrasses is a significant factor which can increase MP load in the sediment.

Three of the studies hereby considered carried out a detailed comparison of plastic concentrations between seagrasses. The first paper reported an average value of 0.10 ± 0.02 items/cm^2 for *E. acoroides* leaves and 0.24 ± 0.05 items/cm^2 for *T. hemprichii* blades, by identifying the differences between the two species' epiphytic community in factors related to leaf morphology and subsequently physical reaction to wave action (Sawalman et al. 2021). The second one showed that *C. rotundata* displayed the highest number of MP per single blade ($n=4$), while *C. serrulata* had the highest density of MP per square centimetres, followed by *C. rotundata* and *T. hemprichii* (Seng et al. 2020). Cozzolino et al. (2020) pointed out that *Z. noltei* exhibited the utmost abundance of particles per surface area on seagrass leaves, even though the frequency of occurrence was higher in *Z. marina*, which had a higher surface area among all the considered species. On the contrary, MP load in the vegetated sediments of the two species was not statistically different. Furthermore, research found 4.25 (± 0.59 SE) unit per *Z. marina* seagrass blades (Jones et al. 2020), while another one showed a mean concentration of 185 particles/cm^2 on *C. rotundata* leaves, with no significant difference in sediment MP contents between the two species (Priscilla et al. 2019).

Laboratory studies

The laboratory studies ($n=5$) accounted for 19% of those analysed in this review, all between 2017 and 2022 (Table 1); three focused on MP, with sizes from a minimum value of 0.5 µm (Menicagli et al. 2022) to a maximum of 5 mm (Zhao et al. 2022; de Los Santos et al. 2021) and one targeted on macro-bioplastic (Mater-Bi derived from vegetable oils and corn starch) (Balestri et al. 2017) and one on nanoplastic (polystyrene nanoparticles 30 nm with a density of 1.06 g/cm^3) (Menicagli et al. 2022).

In these studies, plastic particles with a pre-established size were used, and suppliers of the polymers were reported; only Balestri et al. (2017) used the bio-plastic bags cut into equal pieces. Surprisingly, none of the laboratory studies

Table 1 Laboratory exposure studies ($n = 5$) considered in the present review, displaying the type of polymer used and the selected concentration

References	Polymers	Concentration
Menicagli et al. 2022	Polystyrene (PS)	Overall: $68\ \mu g \times l^{-1}$, NPs 34.5×1012 items $\times\ l^{-1}$, MPs 9.8×108 items $\times\ l^{-1}$
Zhao et al. 2022	Polystyrene (PS)	320 items $\times\ ml^{-1}$
de Los Santos et al. 2021	Polypropylene (PP), polystyrene (PS), polyamide (6 PA), polyethylene terephthalate (PET)	From 0.90 to 1.34 $g \times cm^{-3}$
de Smit et al. 2021	Polyethylene (PE)	2.5 mm items 0.06 items $\times\ l^{-1}$ 0.5 mm items 2.22 items $\times\ l^{-1}$
Balestri et al. 2017	Biodegradable polymer	14 cm × 14 cm, 0.48 ± 0.04 g D.W., 20 μm of thicknesses

carried out particle size measurements, except for Menicagli et al. (2022) who validated the actual size of the particles by inspecting them with a scanning electron microscope (SEM).

Recently, two research projects studied the trapping capacity of seagrass (*Z. marina* and *E. acoroides*), using a hydraulic flow simulator (De Los Santos et al. 2021; de Smit et al. 2021). The first study used four seagrass distribution densities and several concentrations of 4 polymers (PA, PP, PS and PET) that mainly represent marine debris in coastal habitats worldwide. Generally, canopy trapping ability was positively correlated with shoot density and flow velocity. Specifically, high-density polymers, such as PA and PET, were more susceptible to retainment by *Z. marina.* This result was helpful to clarify the aggregation and distribution patterns of several types and densities of synthetic polymers within *Z. marina* canopies. de Smit et al. (2021) utilised PE particles of two sizes and two concentrations and showed that the leaf surface-to-volume ratio exhibited a positive correlation with the MP retainment capacity. Moreover, sediments also detained MP of one to two orders of magnitude higher than the one captured in the canopy-forming structures. Balestri et al. (2017) was the only study entirely focused on biodegradable polymers, by observing the effects of commercialised bio-plastic bags on *C. nodosa* in several environmental-simulated conditions. After a designated 6-month exposure to bio bag square pieces, they observed that roots propagation, vegetative spreading and competition levels, within and between species (in the presence of *Z. noltei*), were altered in *C. nodosa*. Moreover, leaf morphology and disposition changed in *Z. noltei*. It has been concluded that biodegradable polymers buried in the sediments can slowly degrade and alter the geochemical properties of the environment, potentially generating several repercussions on species growth and mutual relationships, representing a future threat to coastal habitats.

Zhao et al. (2022) evaluated the influence of *Z. marina* epiphytic bacterial assemblages on MP sinking in the seawater by laboratory exposure, by choosing 320 particles/ml concentration. The laboratory outcomes, in line with field ones, were that the eelgrass plays a fundamental role in MP sequestration from seawater, also secreting a white agglomerate which promotes MP sedimentation. Among the wide variety of seagrass species, *C. nodosa* and *Z. marina* appeared to be the most frequent species chosen for the controlled experiments, as widely distributed and fast-developing species (de Los Santos et al. 2021; Menicagli et al. 2022). Moreover, recently, several laboratory studies have been strongly criticised for the employment of overabundant amounts of MPs, often much higher than the ones found in natural environments (Cunningham and Sigwart 2019). In particular, de Smit et al. (2021) underlined that the chosen particle densities are three orders of magnitude greater than those in the natural waters where *E. acoroides* was sampled.

Even though nanoplastics presence, in the marine environment, had been observed earlier in field surveys (Ter Halle et al. 2017), the analysis of nanoplastic contamination effects on seagrasses started in 2022. Menicagli et al. (2022) deeply investigated the influence of micro- and nano-PS particles on the growth rate and the physiological functioning of *C. nodosa* during short-term exposure. Several parameters (i.e. including vegetative recruitment, oxidative conditions and photosynthetic performance) have been pondered to assess the global response of the seagrass. After 12 days of high-concentration exposure to PS, negative effects, such as photosynthetic proficiency reduction and pigment concentration enhancement, have been registered on *C. nodosa* shoots. Furthermore, it has been emphasised that nanoplastic impact can be attributed to their capacity to penetrate and be incorporated within plant tissues; hypothesis was confirmed by scanning electron microscopy (SEM).

Main gaps and future research recommendations

This review collected and critically summarised the scientific literature regarding the threat of plastic pollution on seagrass habitats, highlighting the knowledge gaps and research efforts that need to be addressed.

The available literature about plastic pollution in seagrass habitats was relatively scarce; moreover, considering an entire decade of investigation (from 2013 to 2023), no studies were published before 2017, highlighting the very recent efforts dedicated to this topic. This review highlighted a high degree of heterogeneity in the published data, in terms of the investigated areas, the seagrass species and the considered plant parts, the experimental design and the type of polymers analysed, both in field monitoring and in laboratory-controlled experiments. The investigated areas around the world are still limited and scattered despite the global distribution of seagrasses. Most data emerged from Europe, and little or no data on plastic pollution are available for North and South America, Australia, Africa and Antarctica. Most of the studies selected in the present review were devoted to microplastics, considering a wide dimensional range, with limited studies dedicated to macroplastics and none to nanoplastics (except for one laboratory-based experiment). Furthermore, the polymer characterisation is not always provided, and bio-based polymers were poorly investigated. Concerning the experimental designs, the predominant approaches evaluated the plastic presence in seagrass and their trapping capacity, while the consequences of plastic pollution in seagrass ecosystems, including the health and viability of associated communities, are relatively recent and unexplored fields of research. The methods employed and units of measure (see the "Plastic item characterisation and concentrations" section and Table S1) appeared as not homogeneous affecting the comparisons especially during environmental monitoring activities.

We believe that an attempt to standardise methods for the identification/quantification and physico-chemical characterisation of plastics is urgently required. Such standardisation can be achieved by increasing experimentation under laboratory-controlled conditions, using environmentally relevant plastic concentrations. The laboratory approach is particularly convenient, also allowing to (i) make up for the lack of control sites (not contaminated by plastics) in the field studies and (ii) disentangle the actual effect of plastic pollution from the other several pressures that seagrass meadows are experiencing worldwide. We suggest to always include an effective and proper polymer characterisation both in the field and in laboratory studies, providing a thorough description of the methods employed. In particular, to standardise size measurements, the use of image software analysis is recommended, and for chemical characterisation, the use of Fourier transform infrared spectroscopy (FTIR) with an attenuated total reflection (ATR) accessory is effective, with appropriate spectrum ranges and scan rates.

In this scenario, we also suggest to select a common model species to be used for exposition trials, namely, *Z. marina*: this species has a circumglobally distribution and is the most widely studied seagrass (with > 3000 articles), already considered a marine model system for exploring adaptation under rapid climate change (Ma et al. 2021 and references within). Furthermore, *Z. marina* is one of the three most studied species, with more data available, accounting for both in situ and in laboratory studies, analyses of both environmental matrices (sediments and water), leaves and canopy as part plant investigated, a more comprehensive polymer characterisation compared to the others and the highest number of regions investigated.

Additionally, since microplastic effects on seagrass are reported (e.g. change in growth rate and physiological functioning; photosynthetic proficiency reduction and pigment concentration enhancement; alteration in roots propagation, vegetative spreading, and competition rates; change in leaf morphology and disposition; disruption of species growth and so on: Balestri et al. 2017; Menicagli et al. 2022), it could be useful to apply risk analysis approaches (Burgman 2005) to this sector. In detail, preparing conceptual frameworks that facilitate the relationship between threats (i.e. MPs), pressures (e.g. alteration mechanisms and related variables) and targets (changes in metrics relating to the status and fitness of seagrass species) would be pivotal. For example, the application of threat-pressure-target causal chains (Salafsky et al. 2002, 2008; Margoluis et al. 2009), already used on many conservation targets (AlHirsh et al. 2016; Bauer et al. 2022; Giovacchini et al. 2022), but still little used in marine environments, can be useful to reduce, through schematic approaches, the complexity of information in this disciplinary sector. This approach is also useful for assigning sets of indicators at each step of the threat-target causal chain (pressure indicators for threats, state and impact indicators for targets), following a DPSIR approach (Maxim et al. 2009), yet applied in marine ecosystems (Atkins et al. 2011; Patricio et al. 2016).

In conclusion, the existing literature demonstrated that plastics are pervasive within seagrass meadows, and although the mechanisms of their accumulation are still under-explored, research must pivot towards exploring the dynamics and effects of this accumulation in seagrass ecosystems at individual, population and community level. However, the methodological approach (in terms of experimental design and polymer physico-chemical characterisation) should be carefully standardised in order to increase comparability among studies and, in the long run, to support more targeted waste management approaches. Furthermore, using a model species, such as *Z. marina*, and conducting controlled laboratory experiments are strongly recommended approaches.

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CB: writing—review and editing—and data elaboration.
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