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Review Article

Study of microplastic accumulation in halophyte plants and macroalgae: A critical review

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ABSTRACT

Marine litter and microplastic contamination are severe dangers to aquatic ecosystems. The interaction between halophyte plants and micro/nanoplastics has recently gained attention. Halophyte plants and maritime macroalgae are capable of trapping substantial volumes of marine debris, leading to areas of buildup, known as 'sinks', of anthropogenic particles. The review of existing studies exposes that halophyte plants can serve as sinks for micro-nano plastics by absorbing them on their surface. Moreover, these plastics can be absorbed by plants. Plastic on the surfaces and within plant tissue can cause various harmful effects. The present review highlights an understanding of microplastic abundance, bioavailability, influencing factors, technological detection, and potential salt-tolerant plants for bioremediation. According to these findings, we advocate the addition of microplastic on halophyte plants and algae in prospective monitoring studies, describe acceptable methodologies, and advise doing exposure studies alongside risk assessments, strategies for preventing and controlling policies of these underestimated pollutants in vegetated coastal ecosystems and establishes a basis for future research.

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INTRODUCTION

Microplastic (MP) and nanoplastic (NP) are distributed in the environments worldwide. Plastics disintegrate slowly in natural ecosystems, therefore the accumulation of plastic contaminants has eventually become a concern [1]. Understanding the accumulation of plastic and its life cycle in the environment is crucial and requires frequent sampling over a long period [2]. Seeruttun et al. (2023) [3] estimated that the number of microplastics worldwide produced 350 tonnes in 2017, and approximately 4.8 to 12.7 million tonnes of various sizes entered the world's oceans and aquatic basins. Microplastics are numerous and likely irreversible repercussions of plastic pollution, including habitat disruption, harm to biota, and others [4]. Microplastic contaminant spans a family of contaminants, as plastic particles vary in chemical element, color, shape, size, and others [5]. The physicochemical characteristics of each plastic particle can be modified in various ways, driven by abiotic influences such as water salinity or UV light and biotic ones such as surface changes by microbes [6]. This weathering process might release plastic monomers and additives [6, 7]. Therefore, it is difficult to estimate the worldwide toxicity of microplastics and their compounds released into the environment [8].

Coastal ecosystems are unique and vital areas at the inter-

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section of marine and terrestrial processes [9], commonly known as mangroves, seagrasses, saltbush, saltmarsh, and macroalgae. Plants and algae represent 80% of Earth's total biomass, serving as a fundamental component in all ecosystems [10]. The accumulation of MPs can generate several complex harmful effects on plants, with the highest deposition in plant roots and germinating seed surfaces rather than being absorbed into the plants [11]. Plastic can accumulate in the environment for a long period, depending on its stability. Halophytes are plants that can survive and complete their biological cycles at salt concentrations above 100-200 mM NaCl without suffering significant negative impacts on their growth or development [12, 13, 14]. They could be a significant food source, particularly in coastal regions and areas with unfavorable environmental conditions [15]. Zhang et al. (2023) [16] demonstrated that halophytes accumulate sulfur, sodium, and chlorine during their growth period, indicating their ability to absorb various mineral nutrients selectively. Kiliç and Yücel (2024) [17] research has shown that MPs and macro-size plastics can be easily captured in invasive aquatic plants (Pontederia crassipes) due to their root structure. This may also contribute to their accumulation in halophyte tissues and trapping in algae.

Halophyte plants have shown potential as vegetation due to their ability to accumulate salts in their tissues, making them valuable plants for environmental management [18]. Such plants serve crucial functions in the carbon and oxygen cycles. They are essential pillars of the ecological balance, including climate regulation, preventing wind and sand erosion, soil and water conservation, and provisioning for biological habitats [1, 19]. The survival and vitality of halophyte plants serve as crucial bioindicators for assessing the overall health of aquatic ecosystems worldwide [20, 21]. Extensive MP research has been conducted in both marine and terrestrial environments. In recent years, the focus has mainly been on water, soil, air, animal, and terrestrial plants [22, 23, 24]. However, there needs to be more reviews on saltwater plants, making it essential to conduct a review on research concerning these plants. A review of the field's current situation is required. This paper analyzes relevant studies to discuss the following two aspects: the effects of MPs and NPs on halophyte plants and macroalgae and technologies for MPs detection in plants and algae. Furthermore, prospects for future study on this issue are presented for developing strategies to effectively manage and mitigate its effects and preserve these vital coastal ecosystems.

MATERIALS AND METHODS

The preliminary review of salt-tolerant plants and macroalgae included analyzing MPs articles published from 2014 to 2024 (Fig. 1a). Sixty-eight published articles on MP worldwide (Fig. 1b) were initially screened. All of the materials utilized here are from Internet databases. Multiple databases were used to discover relevant studies, examine data collected over a long period, and ensure that this evaluation appropriately reflects the most current advances in the field. Studies were found in the ScienceDirect, Scopus, PubMed, Springer, Nature, and MDPI databases. The keywords "microplastic", "plastic pollution", "marine litter", "accumulation", "microplastic analysis", "halophyte plant", and "algae" were used in the literature search. However, we independently screened microplastic-related research to ensure a complete literature collection because not all relevant literature can be retrieved using these words.

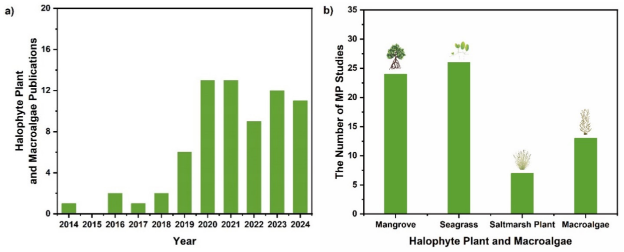

Figure 1. a) Publication trend on MP studies around 10 years; b) reviewed number of MP studies in saltwater plants and algae (retrieved on May 27th, 2024)

POTENTIAL SOURCE AND EXPOSURE ROUTES

Microplastic Distribution in Halophyte Plants and Macroalgae

Oceans are the ultimate sink for MPs, especially in the coastal environment, a habitat of salt-tolerant plants and macroalgae. In addition, the terrestrial ecosystem is a crucial recipient of plastics of any size. Due to the massive volume of anthropogenic waste [25], the terrestrial ecosystem is responsible for 80-90% of MPs in aquatic environments [26], maritime activities (marine aquaculture and ocean navigation) [27], tidal or wave action [28], airborne settlement [29, 30], and other sources such as atmospheric particulate deposition [31]. As mentioned earlier, salt-tolerant plants such as mangrove swamps, marshes, sloughs, and seashores are generally characterized by high biological productivity and organic matter levels. Therefore, MPs can be transported to these plants from multiple and complex sources. Compared to marine sources, terrestrial sources are estimated to contribute more significantly to the pollution of saltwater plants [32]. Generally, there are many sources of MPs. Fig. 2 mainly classified MP contamination pathways from land-into ocean-based sources in salt-tolerant plants.

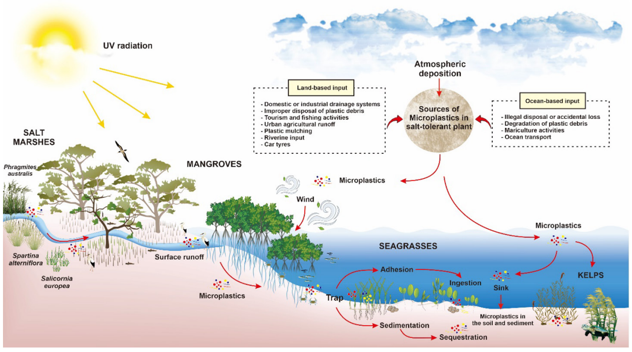

Figure 2. MPs contamination distribution pathway in the salt-tolerant plants and macroalgae

MPs enter the oceans through the breakdown of plastics, landfill leachates, illegal disposal or accidental loss, wastewater, sewage discharged into the atmosphere, agricultural runoff, tourism, fishing activity along the coast, and other sources propelled from beaches by winds and currents. As shown in Fig. 2, MPs are present in salt marshes, mangroves, seagrasses, and algae. They are also found in seawater, sediment, and land (including ice and freshwater) and are associated with various organisms. Several factors, including mechanical stress, washing, microbiological deterioration, and UV radiation damage, can produce microplastics [33]. Plastic debris is transported by rivers and lakes from far inland to the ocean, significantly contributing to ocean pollution. [34] calculated that between 0.8 to 2.7 million tons of riverine plastic are released into the ocean per year worldwide, with 1000 rivers being responsible for about 80% of these emissions. MPs in saltwater tend to collect slowly, primarily on coastlines with high human population density [35]. Ocean currents are essential for plastic waste's movement, dispersion, and accumulation [36]. Hydrodynamic parameters influencing MP transportation and sedimentation include turbulence, turbidity, current velocity, and residual circulation [37]. The distribution of MPs is also affected by their features, including particle size, surface alteration, and environmental circumstances such as pH, DOM, and light. However, quantifying these effects still needs to be expanded [38].

Uptake of Microplastics by Halophyte Plants

Bioaccumulation is the progressive increase in the concentration of a contaminant (compound) within an organism due to the uptake rate of the contaminant being more significant than its release [39]. The pattern of microplastic bioaccumulation is extensively studied across various trophic-level pyramids, especially in coastal and marine ecosystems [40]. Plastics form plastispheres that look similar to food sources for marine organisms. These plastisphere or aggregates form through microbial attachment, acting as a vector for the transportation of harmful bacterial species and phytoplankton on the plastic surface [41].

Plants primarily absorb both MPs and non-plastics through root hairs [42, 43]. In addition, some seedlings typically exhibit strong cell division and rapid nutrient translocation, enhancing the potential for nutrient and contaminant absorption. Due to their hydrophobic, dense, and high specific surface area properties, MPs easily adhere to root surfaces, subsequently absorbed and accumulated within plants, thereby affecting root metabolism [44]. Most studies on the impact of MPs on plants are conducted during the seedling stage with test particles on a submicron scale (<1 μm). Seedling roots can absorb small MPs (80 nm) and significantly inhibit plant growth and development [45, 46]. Larger particles can also accumulate in plant tissues, as demonstrated by [40]. The data summarized about methodology, study area, and MP features in Table 1 indicate MP contamination in 16 species of mangrove, 30 species of seagrass, five species of saltmarsh plant, and 25 species of macroalgae.

Particulate matter, including MP, must pass through various chemical and physiological barriers that determine the size exclusion limits (SELs) during plant absorption and translocation. The thickness and construction of these barriers vary depending on the species, growth stage, and environmental circumstances. Despite the modest SELs (<20 nm) of plant roots, it is widely acknowledged that plants can absorb very big nanoparticles (above 100 nm) [40]. MPs can penetrate the stele through epidermal gaps and then move to the plant's aboveground parts via the xylem through transpiration. During this process, the plant's transpiration force is critical to the absorption and transportation of microplastics. Another entry pathway is through the mode of crack entry, where the emergence of lateral roots on the primary root creates crack areas, and particles enter the circulation system through cellular gaps produced by the lateral root bulge area. Once entered into the vascular bundle, plants can absorb plastic particles from roots to stems through the vascular system and transpiration flow. Illustrations of the MPs entry process in plants are presented in Fig. 3.

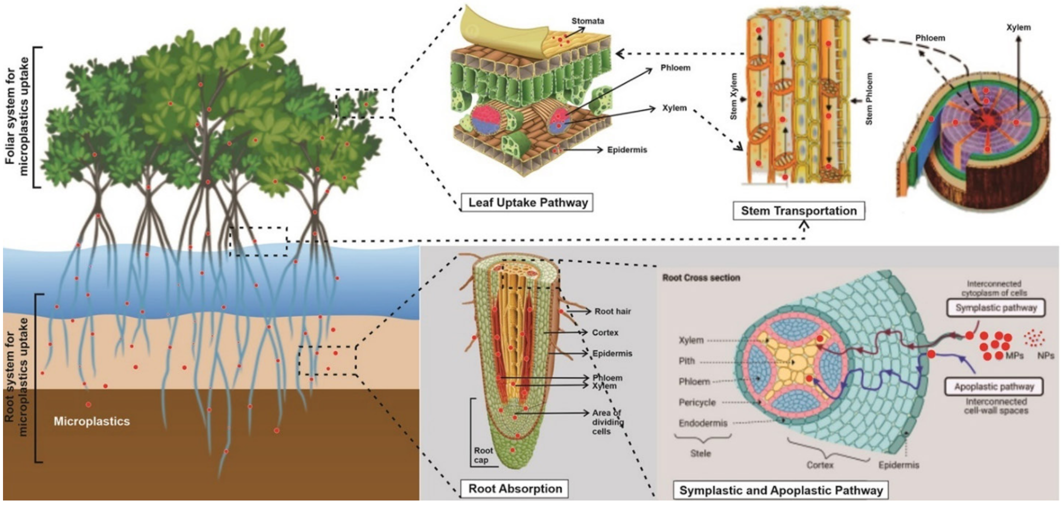

Figure 3. The uptake and movement of MPs in mangrove rhizospheres and non-rhizospheres underroot absorption pressure (Modified from [43, 47])

Table 1. Summary of MP contamination reported in salt-tolerant plants and macroalgae

Type of samples	Study location	Abundance	Types of MPs	Shape of MPs	Absorption	Ref.
Mangrove						
Mangrove and saltmarsh sediment	Singapore	36.8 ± 23.6 items.g-1 dry sediment	PE, PP, Nylon, PVC	FB, FL, GN	aerial root	[48]
Mangrove	Qinzhou Bay, China	15 to 12.852 items.kg-1	PS, PP, PE	FG, FB, Sphere	none	[49]
Mangrove	Colombia	31 and 2863 items.kg-1	PE, PS, Nylon	FG, FIL, PL, GN, FL, FO	pneumatophore	[32]
K. obovata	Saudi Arabia	9.3% ± 1.8% of all items, N = 1018	PS, PET	FG	pneumatophore	[50]
K. obovata, R. stylosa, B. gymnorhiza	Persian Gulf, Iran	19.5-34.5 items.kg-1	PE, PA	FB, FG	none	[51]
K. obovata	Beibu Gulf, China	Sediment & root hair zone: 70 ± 8 to 3967 ± 252 items.kg-1; rhizosphere: 127 ± 12 to 2607 ± 123 items.kg-1	PP, PET, PE	FB	root hair, rhizosphere	[63]
Mangrove	Mauritius	Ferney: 107.4 ± 76.42 items.kg-1 and Mahebourg: 140.2 ± 85.38 items.kg-1	PVC	FG, FB, PL, FL, FO	none	[3]
A. marina sediment	Sea of Oman	147.88 ± 99.24 items.kg-1	PE, HDPE, PS, PP, LDPE	FG, PL, FB	root	[64]
S. caseolaris, S. apetala, Aegiceras corniculatum, Acanthus ilicifolius, K. obovata	Seagull Island, China	1223 items.m-2.day-1 dry sediment	CA, Rayon	FB, FG, PL, FL	leaf	[65]
A. corniculatum	Nansha, Guangzhou, China	NA	PS, PMMA	NA	leaves of seedlings	[66]
Mangrove	The eastern coast of Thailand	2213.33 ± 1787.74 items.kg-1 dry sediment	PP, PE,	FB, FG	root	[67]
Rhizophora candle, A. marina, Excoecaria agallocha, A. corniculatum	Qinzhou Bay, China	1.76 n.g-1 to 15.45 n.g-1 and 0.74 n.g-1 to 3.28 n.g-1	PS, PP, PET, PC, Nylon	FB, FL, FG, BD, FO	leaf	[68]
Seagrass						
	Tyrrhenian Sea, Italy	NA	PS, PP, PE, PES, PVC, PU, ABS, PET, PA, PEST, Nylon, CA	FB	egagropiles	[69]

Type of samples	Study location	Abundance	Types of MPs	Shape of MPs	Absorption	Ref.
Thalassia testudinum	Turneffe Atoll, North America	NA	NA	FB, MBD	seagrass blades	[70]
Cymodocea rotundata	Barrang Caddi Island, South Sulawesi	NA	PE, PS, PP, Nylon	MFB, MFG	leaf tips, leaf base	[71]
Endocladia muricata, Pelvetiopsis limitata	Sonoma County, California	E. muricata: 2.5 to 24.3 items.g-1, P. limitata: 0.58 to 8.0 items.g-1	NA	NA	none	[72]
Zostera noltii, Zostera marina, Cymodocea nodosa, Caulerpa prolifera, saltmarsh Sporobolus maritimus	Ria Formosa lagoon, Portugal	1.3-17.3 macroplastics 100 m-2, 18.2-35.2 items.kg-1	NA	FB, FL, FO, FG, MBD	shoot	[73]
Enhalus acoroides	Xincun Bay and Li'an Bay, China	Xincun bay: 93.3 ± 15.3 items.kg-1 dry sediment, 196.7 ± 16.1 items.kg-1; Li'an bay: 267.1 ± 60.5 items.kg-1 dry sediment, >780.2 ± 147.0 items.kg-1 dry sediment	PE, PP, PA, PS	FB, FG, PL, FL, FO	leaf, root, rhizome	[74]
Seagrass	Rameswaram island, India	Water: 24 ± 9 to 96 ± 57 items.L-1; sediment: 55 ± 21 to 259 ± 88 items.kg-1	PS, PA, PE, PET, PVC, PP, CP, PU, PEST, PVA	FB, FL, FG, FO	blades, root	[75]
Z. marina L.	Orkney, Scotland	4.25 kg-1 ± 0.59 SE	PE, PP, PA, PS, PU, PTT	FB, FG, Flake	blades	[76]
E. acoroides, Thalassia hemprichii	Barrang Lompo island, Makassar	E. acoroides: 0.10 ± 0.02 items.cm-2; T. hemprichii: 0.24 ± 0.05 items.cm-2	NA	LN	leaf	[77]
C. serrulata, C. rotundata, Sargassum ilicifolium, T. hemprichii, Padina sp.	Singapore	0.051 items.cm-2, 0.060 items.cm-2, 0.036 items.cm-2, 0.012 items.cm-2, 0.007 items.cm-2, 0.029 items.cm-2	NA	MFB, MFG	blades	[78]
P. oceanica	NW Mediterranean	Sediment: 79.61 ± 1.99 items.g-1; pseudofeces: 52.59 ± 1.22 items.g-1	PET, Nylon, PE, PVC	FB, FG	none	[79]
P. oceanica	Spanish Mediterranian coast	3819 items.kg-1, 2173 items.kg-1, 68-362 items.kg-1	PVC, PU, PS, VC, PE, PTFE, EVA, HDPE, LDPE	FB, FL	root, rhizome	[80]

Type of samples	Study location	Abundance	Types of MPs	Shape of MPs	Absorption	Ref.
Zostera japonica, Halophila beccarii, Halophila ovalis, A. corniculatum, A. marina	Guangxi, China	17.68 ± 8.10 to 611.75 ± 81.52 items.kg-1 dry sediment	PE, PP, PS, PVS, EPDM, PA	FB, FG, PL, FL, FO	shoots, branches, trunks, aerial roots	[81]
Z. marina	Baltic Sea, Estonia	72,1 ± 9,1 g per 50 mL	PVC	FB, FL, Angular, other (incl. round, oval, etc.)	none	[82]
Cladophora	Laurentian Great Lakes	32 ± 10 items.g-1, 34 ± 22 items.g-1	PE, PET, PAN, CA	MFB	none	[83]
Z. marina, Ulvaceae, Gracilariaceae	Northern Adriatic Sea	0.16 to 330 items.g-1	PS	FB	none	[84]
Z. marina, Zostera noltii	Southern England and Wales	215 ± 163 items.kg-1 dry sediment, 221 ± 236 items. kg-1 dry sediment	NA	FB, FG, FL, Fiber bundles	shoot to the tip, leaf	[85]
C. nodosa, Caulerpa cylindracea	Ligurian Sea, Italy	NA	HDPE	FG	root, rhizome, internodes, shoot, apical meristem	[86]
C. nodosa	Italy	68 µg.L-1 (4.5 × 1012 items.L-1 and 9.8 × 108 items.L-1)	PS	FG	root, rhizome, shoot, leaf	[87]
Zostera capensis	South African Estuary	91 (SD = 85) items.kg-1, 99 (SD = 102) items.kg-1, 83 (SD = 63) items.kg-1, 89 (SD = 58) items.kg-1, 94 (SD = 106) items.kg-1 dry sediment	NA	FB	leaf	[88]
Z. noltii, C. nodosa, Sporobolus maritimus	Cádiz Bay, Sothern Spain	Spring: 14.8 ± 2 items 1000.m-2; summer & winter: 12 ± 1.6 and 11.1 ± 1.3 items 1000.m-2; autumn: 8.7 ± 1,3 items 1000.m-2	NA	FB	none	[89]
Halophila ovalis	Swan-Canning Estuary, Perth, Western Australia	1000 ± 100,37 items.kg-1, 972 ± 92,19 items.kg-1	PE, PP	FG, FB	blades	[90]
P. oceanica	Germany	NA	NA	NA	canopy, shoot	[91]
H. ovalis, Halophila spinulosa, Halophila decipiens, Halodule uninervis	North-eastern shores of Singapore	12.65 ± 0.04 items.g-1 dry sediment, 69.65 ± 0.189 items.g-1 dry sediment	PET, PA	FB, FL, FO, FG, PL, Fiber bundle	canopy	[92]

Type of samples	**Study location**	**Abundance**	**Types of MPs**	**Shape of MPs**	**Absorption**	**Ref.**
Seagrasses, saltmarshes	United Kingdom	300 items.L-1	PVC, PET, PA	FB, FG, Flake	stem, blades, branches, leaves	[93]
Saltmarsh Plants						
Spartina alterniflora	Southeast Zhejiang, China	9600-130725 and 200-4350 n.m-2	PS, PE, PP, PU, PA, PC, PET, PVA, PVC, ABS	FG, FB, PL, FO	none	[94]
S. alterniflora, Phragmites australis	Dafeng Elk National Nature Reserve, China	2.97 ± 2.73 items.g-1; 5.39 ± 6.58 items.g-1	PET, CP, PE, PP, PA, PAN	FB, FG, FO	none	[95]
S. alterniflora	Bahía Blanca Estuary, Argentina	> 20,060 items.m-2	HDPE, LDPE, PP, PS	FG, FL, FB, PL, FO	none	[96]
Salicornia europaea	Shawan County, China	28.00 ± 5.29 item.kg-1 to 1426.67 ± 136.49 items.kg-1	PE, PP	FB, FL	Root	[97]
P. australis	Lima Estuary, Portugal	NA	PE	FG, FB	root, rhizome	[98]
Macroalgae						
Fucus vesiculosus	Helgoland, North Sea	NA	PS, PA	MBD, FG, FB	thalli	[99]
Kelp	Southern California, USA	NA	NA	NA	none	[100]
Ulva prolifera	Yellow Sea, China	4603.3 ± 1167.2 items.kg-1 dry sediment	PS, PET	FO, FL	branches	[101]
U. prolifera	Yellow Sea, China	NA	PE, PET, PS, PA, PP, rayon, PVC, PEU, (PE-PP)	MBD, FL, FG, FO, FB	thalli	[102]
Pyropia yezoensis, U. prolifera, Ulva pertusa, Sargassum homeri, Cladophora sp., Undaria pinnatifida	Haizhou Bay, China	Culture periods: 0.17 ± 0.08 items.kg-1 fresh weight, non-culture periods: 1.04 ± 0.32 and 1.86 ± 0.49 items.L-1	PR, Rayon, PP, PS, CP, PE-PP, PET, PAN, Nylon, PS&PAN&PMMA, PMMA	FB, FO, FL	branches, thalli	[103]
Furcellaria lumbricalis, Cocctylus truncatus, Polysiphonia fucoides, Cladophora rupestris, Cladophora glomerata	Russian sector	2.6 ± 1.0 items.individual-1, 5.2 ± 1.8 items.individual-1	PP, PVC, PE, PES/PET, CE	FG, FL, FB	blades, thalli	[104]

Type of samples	Study location	Abundance	Types of MPs	Shape of MPs	Absorption	Ref.
Rhodophyta	Spain	NA	NA	NA	thalli	[105]
Ulva sp., Ulva lactuca, Ulva flexuosa, Ulva intestinalis, Gelidium pusillum, Colpomenia sinuosa, Phycoclidia acanthophora,	Hongkong	3.15 ± 6.82 fibers.g-1 dry sediment, 1.74 ± 3.79 fragment.g-1 dry sediment	PE, PP, PA, PS, PET, PVC, PE/PP	FB, FG, PL, FO, FL	thallus	[106]
U. prolifera, U. lactuca, Gracilaria lemaneiformis, Chondrus ocellatus, Saccharina japonica	The eastern coast of China	Macroplastics: 0 to 201.5 items.kg-1 dry sediment; mesoplastics: 0 to 1178.0 items.kg-1 dry sediment; MPs: 0 to 355.6 items.kg-1 dry sediment	PS, PE, PET, Rayon	FB, FO, FL	branches	[107]
Gelidium corneum	San Lorenzo Beach (Gijón, Asturias)	NA	PET, PEI, PES, PA	GN, FB	none	[108]
Caulerpa lentilifera, Gracilaria tenuistipitata	Qiuhai Lake, China	100 mg.L-1	PA, PS	Microspheres	none	[109]
Polysiphonia morrowii, Blidingia Minima, Ceramium rubrum, Ulva spp.	Argentina coastal area	38.20 ± 53.74 items.L-1, 7 ± 2.44 items.L-1	CE, PTFE, PP, PET, PE, PA, PES, PAN	FB, FG, FL, PL	thalli	[110]
U. lactuca	Southwest England	7.5 items.g-1 to 110 items.g-1	Rayon, Cotton Acrylic, PET, PE, PA, PP, PU, Nylon	FB, BD, FG	none	[111]

PS: Polystyrene, PP: Polypropylene, PE: Polyethylene, PU: Polyurethane, PA: Polyamide, PC: Polycarbonate, CA: Cellulose Acetate, CP: Cellulose Propionate, CE: Cellulose Ether, VC: Vinyl Chloride, BR: Polybutadiene/Butadiene Rubber, PET: Polyethylene Terephthalate, PES: Polyethersulfone, PVC: Polyvinyl Chloride, PVA: Polyvinyl Acetate, PTT: Polytrimethylene Terephthalate, PVS: Polyvinyl Sulfide, PAN: Polyacrylonitrile, PEU: Polyether Urethane, EVA: Ethylene Vinyl Acetate, PLA: Polyactic Acid, PBS: Polybutylene Succinate, PEI: Polyetherimide, ABS: Acrylonitrile Butadiene Styrene, PEST: Polyester, LDPE: Low-Density Polyethylene, PTFE: Polytetrafluoroethylene, EPDM: Ethylene Propylene Diene Monomer, PES/PET: Polyester (Polyethylene Terephthalate), PMMA: Polymethyl Methacrylate, HDPE: High-Density Polyethylene, PP-PE: Polypropylene-Polyethylene (blend), FB: Fiber, MFB: Microfiber, FG: Fragment, MFG: Microfragment, FO: Foam; PL: Pellet, GN: Granule, BD: Bead, MBD: Microbead, FIL: Filament, LN: Line, NA: Not Available.

Mangrove

The mangrove ecosystem is one of the world's most valuable marine habitats, both economically and ecologically. Indonesia's mangrove forests currently cover 3,364,076 hectares, contributing about 23% of the global mangrove forest area and serving as home to 45 out of 75 valid mangrove species worldwide [112]. Mangroves effectively store long-term carbon inside their sediments, with an estimated global storage of 12 billion metric tons. Mangrove ecosystems are crucial for mitigating climate change and carbon sequestration. Coastal wetlands such as mangrove forests can absorb carbon 4-5 times more effectively than tropical terrestrial forests. This ecosystem provides various services such as coastal protection, pollution control, and habitat for a large number of fauna, which are essential components of the food chain [113]. The trapped MPs by mangroves hinder the tree and neighboring animals by impeding gas exchange and emitting toxic compounds [50, 114]. Many benthic organisms live within the mangrove forest, such as crustaceans and clams, which have deposit-feeding capabilities, thus increasing the chances of these organisms ingesting MPs that settle in the mangrove sediment [114].

Seagrass

Seagrass meadows and beds offer valuable ecological services such as nitrogen cycling [115], and carbon sequestration [116], and support commercial fisheries [41]. These grazing grounds provide habitat, food, and shelter to a variety of related herbivores such as fish, gastropods, dugongs, and turtles [117]. Seagrass meadows also serve as a significant trap of particulate matter like MPs due to their particle-trapping abilities [88]. Recently, MP presence has been reported in environmental samples of Padina sp., T. hemprichii, T. testudinum, S. ilicifolium, E. acoroides, C. rotundata, and C. serrulate [22, 78]. [82] investigated surface water in seagrass beds containing 0.04 to 1.2 MP/L, and the sediments of the seagrass beds had 0 to 131 MP/50 mL sediment-water suspension. [70] and [90] found microfibers and microbeads encrusted on epibiont communities on T. testudinum and H. ovalis seagrasses. Marine herbivores can easily consume MPs in the ecosystem by preying on seagrasses [41], which MPs enter the lower trophic levels of coastal food chains. This accumulation of MPs may expose the seagrass flora and fauna to anthropogenic pollutants. Furthermore, MPs may leach toxins from the environment, including PAHs, PCBs, and DDTs, contaminating benthic organisms in seagrass beds. MPs collected in the seagrass beds could also potentially harm humans through the food chain [118].

Saltmarsh plant

Salt marsh plants, such as S. alterniflora, S. europea, and P. australis are known for their capability to trap suspended particles from water and appear to enhance salt marshes' ability to capture plastic materials [94]. [95] found that the abundance of MPs in P. australis reeds (5.39 ± 6.58 items.g-1) was higher than in cord grass S. alterniflora (2.97 ± 2.73 items.g-1). Reeds may have broader leaves and longer fibrous stalks, making it more straightforward for plants to absorb and hold MPs in the environment. Furthermore, there is S. europea which has diverse ecological values, including fresh consumption, fodder source to feed cattle, production of edible oil and salt, as well as applications in industry, biofuel, and the press cake [15, 119]. This plant has phytoremediation and biofiltration capabilities for pollutants from industrial or aquaculture systems in coastal or inland areas [120, 121, 122]. Genus Salicornia can be categorized into three main groups: phytoextractors, phytostabilizers, and phytodegraders. The pythoextractors absorb and transport pollutants to the shoot for accumulation, excretion, or exudation, while the phytostabilizers stabilize pollutants within the root system or rhizosphere. Phytodegraders break down pollutants into insoluble or nontoxic compounds [123, 124].

Macroalgae

Macroalgae are primarily linked to rocks or other substrates and play an essential ecological role in coastal environments [35], such as sediment stabilization and offering habitat for epifauna and infauna [100, 125]. They are also used as animal feed and human nourishment [125, 126], suggesting that MPs in macroalgae can be transferred to animals and humans through the food system. Four plastic-trapping mechanisms (wrapping, twining, embedding, and attachment) on or in macroalgae were revealed, explaining why the plant has such a strong potential to trap MPs. Twinning and attachment are the two main ways U. prolifera catches polymers. It is easier to separate from the thalli than embedded and wrapped ones; therefore, the plastic trapping changes with the migration path [102]. [110] found macroalgae acquire a more significant proportion of high-density polymers (PAN, PMMA, CE, PES, and PE) detected in six species such as U. intestinalis, U. rigida, U. flexuosa, C. rubrum, P. morrowii, B. minima. [99] investigated that the F. vesiculosus retains suspended MPs on the surface and proved that seaweeds are an efficient pathway for MPs to reach marine benthic herbivores like common periwinkle L. littorea. [108] identified PEI and PE from G. corneum collected near sandy substrates. [104] also identified microfibers on filamentous algae like C. rupestris, C. glomerata, and P. fucoides. The report values for MP concentration in macroalgae differ between the algae species shown in Table 1 due to their varying ability to hold plastic particles. Coastal macroalgae are successfully employed as the most effective biomonitors of MP fiber contaminants in the coastal zone [111]. Macroalgae tend to accumulate MPs, resulting in biomagnification, making them sensitive biomarkers of environmental conditions.

Types of Microplastics

Several researchers have studied the type of MPs in various halophyte plants and algae, and these review studies may provide valuable insights into the distribution of MPs in these ecosystems. [126] indicated a high tolerance plants to MPs, which can be a potential bio-trapper for MPs. Fig. 4a represents the primary forms of MP contamination in salt-tolerant plants and maritime macroalgae identified in the reference studies. MPs were quantified and categorized by type (fibers, fragments, films, foams, beads). Fibers (29%) were the dominant type of MP in field investigations, followed by fragments (24%) and films (14.2%) due to terrestrial material transport. Water currents and tide patterns contribute to dispersing fibers in salt-tolerant plant habitats. Fibers frequently released from textiles have unique environmental impacts [127]. These fibers can configure marine species, causing physical injury and potentially affecting ecosystems if consumed [128]. Fragments from the mechanical deterioration of more significant plastic items contribute to extensive contamination and constitute a direct physical hazard to marine life [64]; their accumulation in sediments and coastal regions may have distinct biological implications in those areas [129]. Other forms such as pellets, foams, granules, microbeads, and filaments almost equally follow films. The majority of these fibers were identified in seagrass (37.2%)

(Fig. 5). Plastics are made of synthetic materials, including polyethylene, polystyrene, polyethylene terephthalate, polypropylene, polyamide, polyvinyl chloride, and nylon. Plastics are also made from semi-synthetic polymers, such as cellulose derivatives [35]. The percentage of different types of MP polymers during the recent year has been described in Fig. 5. Due to its commercial worth and availability, PE (15.8%) is commonly used as MPs in experimental studies. Compared to other MPs like PA, PE, and PP harmed archaeal communities in the sediment of mangrove ecosystems [130, 131]. PS harmed macroalgal physiology [40]. Natural environment contamination studies have revealed that macroalgae are simultaneously exposed to various MPs. [104, 106] and [108] identified a combination of PE, PET, PS, and PP, with PE and PS being the most prominent.

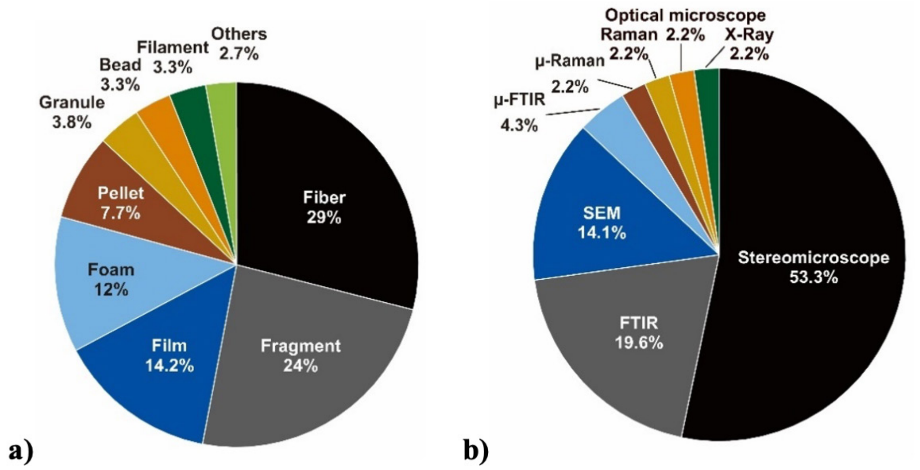

Figure 4. a) The shape of MP contaminations; b) Technological for MP detection in salt-tolerant plants and macroalgae

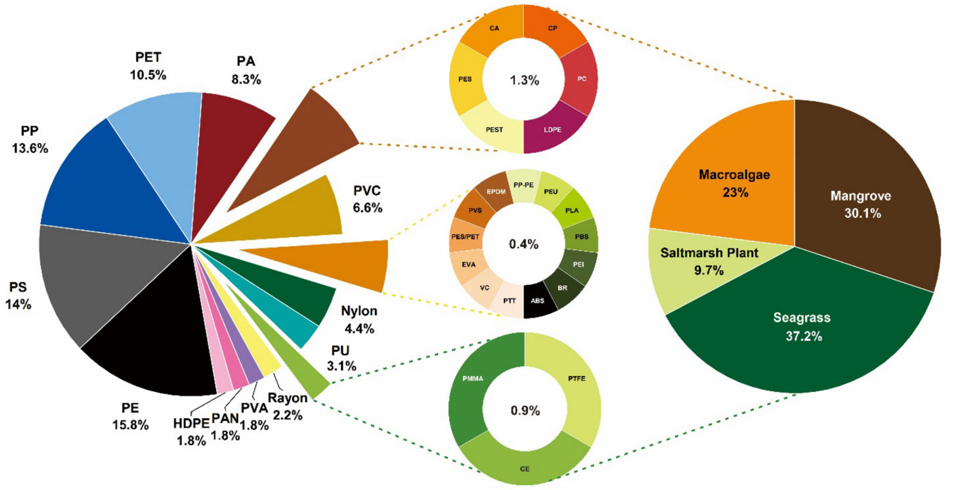

Figure 5. Percentage of MPs polymer type in salt-tolerant plant and macroalgae

Environmental Factors Influencing MPs' Bioavailability

Environmental factors are crucial for plant growth and survival, especially halophyte plants. Environmental factors encompass external elements that influence adsorption by altering the properties of MPs and organic pollutants or indirectly alter heavy metal chemical speciation, transport, and the fate of MPs [132, 133].

Salinity

Salinity is an important factor influencing the bioavailability of MPs in the marine environment. Salinity can influence the adsorption mechanism by altering the potential of electrostatic contact and the ion exchange capacity of MPs and organic pollutants. A greater quantity of Na+ may severely compete against cation exchange sites on the surface of MPs, leading to diminished organic pollutant adsorption [134]. [135] examined the adsorption of sulfamethoxazole by various types of MPs such as (PP, PA, PET, PVC) and observed that Na+ adhered more easily to negatively charged MPs via electrostatic interaction, displacing hydrogen ions from acidic groups with Na+, blocking hydrogen bond formation and decreasing the uptake capacity. [136] and [137] indicated that excessive salinity could have a salting-out impact on organic pollutants in solution, lowering their solubility and enhancing their adsorption onto MPs.

Temperature

The temperature significantly influences the abiotic and biotic ageing processes of MPs. Temperature can influence the kinetic energy of polymer molecule chains, affecting the dynamics of numerous physical processes and chemical reactions in abiotic processes. Temperature influences catalase, neutral phosphatase activities [138], and the adsorption process primarily by altering the composition of MPs [139]. In general, an optimal temperature exists for the adsorption mechanism. When ambient temperatures are below this optimum, raising the temperature increases the fluidity and solubility of organic pollutants. It decreases the adsorption energy of the endothermic process, therefore improving the adsorption [140]. [141] showed that 25^{0}C was the ideal temperature for adsorbing three synthetic musks on polypropylene. Warmer temperatures exacerbated MP toxicity, and although this effect was observed only at concentrations not currently found in nature, these concentrations are feasible in pollution hotspots due to pulse pollution events or deteriorating environmental contamination in the future [142].

pH and ion strength

The pH primarily influences the adsorption by affecting the electrical characteristics of MPs, i.e. zeta potential [143]. pH can change MP's zeta potential and heavy metal precipitation. The MP zeta potentials decrease with rising pH value. At the same time, some metals' precipitation occurs in environments with pH > 7 [133]. The increase in pH value enhanced the adsorption quantities of Ni, Co, Zn, Cd, Pb, and Cu onto MPs [144]. Conversely, the adsorption of Cr6+ onto MPs was observed to reduce the positive charge on their surface [145]. Ionic strength can be modified with the surface charge, MP aggregation, sorption site, and heavy metal activity. MPs are inhibited by increasing ionic strength [144, 146]. High ionic strength can enhance heavy metal competition for sorption sites on MPs, decreasing heavy metal solution activity concurrently [147].

Dissolved Organic Matter (DOM)

DOM is a naturally occurring organic compound capable of enhancing the stability of MPs, modifying their surface characteristics, altering desorption capacities, and significantly affecting the adsorption of organic contaminants on MPs [132, 148]. For example, the absorption of Cu, Pb, Ag, and Cr on MPs was increased by organic matter [149, 150]. This occurs because the organic matter that exists naturally adhering to the surface of MPs can enhance the binding with heavy metals. These enhancements could also be attributed to more adsorption sites and functional groupings on the MP surfaces [133]. Furthermore, the enhancement of DOM was observed to mitigate the toxicity of Ag+ and plastic nanoparticles to D. magna [150]. These findings suggested that organic matter modulated the desorption/adsorption, accumulation, and toxicity dynamics of pollutants associated with MPs.

Surfactants

Surfactants are molecules possessing both lipophilic and hydrophilic structures, typically engaging with different phases with diverse chemical dissolution properties [151]. As a hydrophobic substance, MPs are easily combined with the hydrophobic end of surfactants, altering their physical and chemical properties, consequently changing MPs' migratory and adsorption properties and potentially raising ecological and environmental concerns [152], [153]. The combination of surfactants with MPs is posed to aid the separation of MPs from water utilizing biodegradable organic reagents in flotation processes. The adsorption of biodegradable organic pollutants on MPs by flotation emerges as a highly effective approach for MPs removal from aquatic environments. Additionally, multiple studies have highlighted surfactants' ability to accelerate the desorption rate of organic contaminants from MPs [154]. [155] observed significant enhancements in the desorption rate of chemical compounds from PE and PVC facilitated by surfactants during the desorption process.

TECHNOLOGICAL TECHNIQUES FOR DETECTING MPS AND NPS

No standard method exists for identifying and measuring the MPs [156]. Due to scientific limits, there are considerable discrepancies between the data discovered for the levels of MPs or NPs in various samples (Fig. 4b). The biggest impediment is the need for an established methodology for MPs or NPs characterization, detection processes, and preparation of samples [157]. Researchers have studied numerous methods, including microscopy, py-GC/MS, spectroscopy, nuclear techniques, and flow cytometry. The MP analysis consists of several phases: sampling, processing, and analysis (identification, characterization, and quantification).

Microscopic Examination

Fluorescent Microscopy

A fluorescent microscope integrates the ability of a light microscope to magnify objects with the ability of chemicals to emit fluorescence. This approach has a 78% accuracy rate when analyzing the samples for MPs [158]. For staining MPs, various dyes (rose bengal, acridine orange, neutral red, rhodamine B, trypan blue, and Nile Red (NR)) have been investigated [159]. Fluorescence tracking of particles could be a better method. Still, it is one of the best currently accessible technologies for tracking non-metallic nanoparticles, such as protein interaction, cell signaling events, or distinguishing spectrally overlapped fluorophores [160]. The chemical incorporation of fluorescence dyes into the polymer network reduces the risk of dye leaching [31]. Due to its strong affinity, higher fluorescent intensity, and quicker processing time, NR is the dye that is better suited for MP staining among the ones that have been researched. The environment's hydrophobicity affects the fluorescence of NR, which is hydrophobic by nature [161]. Other drawbacks of the NR staining method include its propensity to co-stain lipids in MP samples tainted with organic debris [162].

Scanning Electron Microscopy (SEM)

SEM examination was most helpful in obtaining high-resolution particle surface structure properties of the material and elemental composition signatures. This technique utilized a picture by scanning the material's surface with a relatively short electron beam [163]. Furthermore, Energy-dispersive X-ray spectroscopy (EDS) can be combined with this method to evaluate the composition of MPs. Combining SEM with EDS can be determined by size, shape, and morphology of MPs. Furthermore, SEM-EDS can eliminate non-plastic particles and analyze prepared samples to identify potential MPs based on their elemental signatures and surface properties. SEM images revealed typical cracks associated with environmental exposure and pigment particles consistent with manufacturer materials [163]. [31] identifies the presence of plastic beads in the plant tissues based on size and morphology. However, this method cannot fully determine whether the observed particles are PE, PP, or others.

Spectroscopy

FTIR Spectroscopy

These are the spectroscopic methods that are most frequently applied to MP analysis. The measurement of the infrared radiation that MPs absorb forms the basis of the FTIR analysis. The infrared spectrum serves as a sample's fingerprint and aids in identifying functional groups because various compounds are composed of distinct atoms. This method works with liquid, solid samples, and gaseous materials [164]. A microscope is necessary for the localization of smaller particles, but FTIR can identify MPs. Progression of FTIR research, such as μ-FTIR could rapidly identify the morphological and chemical properties of MPs without harm (not appropriate for detecting particle sizes <10 μm) [165]. The method's accuracy and efficiency have grown with machine learning and automated spectra evaluation [166]. The asymmetric vibrations of polar groups are best studied by FTIR spectroscopy, whereas the symmetric vibrations of non-polar groups are better studied by Raman spectroscopy [167, 168].

Raman Spectroscopy

Raman imaging is an analytical technique utilized to determine molecular structure by investigating the vibrational frequencies of molecular bonds present in the sample [169]. This technique is particularly suitable for analyzing MPs at the micron-sized size with improved sensitivity to non-polar functional groups and reduced water interference with a resolution of 1 μm [165, 168]. The ability to identify MPs without modification is lowered in conventional Raman spectroscopy. Custom-designed μ-Raman spectroscopy allows for imaging, size quantification, and characterization of MPs [169]. By employing spherical gold nanoparticles (14 to 46 nm) to boost the scattered signal, [170] could detect plastic particles at concentrations below 10 μg/mL utilizing surface-enhanced Raman scattering techniques [171] classified MPs based on their size (<100 μm, 100 to 500 μm, 500 to 1000 μm, and >1000 μm), colour, shape, and type using 3D Raman spectroscopy without consideration of composite fractions in mangrove sediment.

X-ray Photoelectron Spectroscopy (XPS)

XPS is a susceptible and particular technology that evaluates the elements present on the surface of a sample, not only general chemical information but also on the surface, tiny areas, and depth distribution when examining electronic materials and detecting MPs [172, 173]. This method can identify and detect components and their binding condition in the material based on the photoelectric effect. Samples are exposed to X-ray radiation, which causes the sample surface to emit photoelectrons [162]. XPS can only analyze the top few nanometers of a surface that demands a high vacuum [174]. MP oxidation can improve organic contaminant adsorption and increase MPs' function as contaminant vectors in the aquatic food chain. They did this by using XPS and other techniques to determine the adsorption characteristics of PP and HDPE for different pollutants.

Gas Chromatography and Mass Spectrometry (GC-MS)

GC-MS simultaneously monitored and quantified the mixed films [156]. The pyrolysis technique was paired with gas chromatography and mass spectrometry as a thermoanalytical approach to predict the chemical structure of MPs, concentration, and quality of the particles. However, the quantity and particle size of the MPs are inadequate [175, 176, 177]. This combination cannot count or provide size and shape information since MPs are thermally destroyed throughout the process. In another study, [178] developed ten plastic polymers: PS, PVC, nylon-6,6, PE, PP, PMMA, NBR, PET, ABS, and PC using this method as a new technology that allows the low-level and exact identification of MPs in environmental samples [179] successfully identified and quantified PE, PS, PP, PVC, and PMMA in seafood using Py-GC/MS analysis.

Flow Cytometry

Flow cytometry is a well-known technology for quickly and automatically examining cells and particulate compounds in aqueous samples [180, 181]. Detection of MPs using flow cytometry was pioneered in 2016 [182], with the advantage that it can discriminate MPs from false positives (e.g. bacteria) and detects particle size ranges from 0.2 to 100 μm using fluorescence straining, thus covering the low range of MPs (< 1 μm) [183, 184]. This approach is primarily used with liquid samples, where MPs are passed under a light beam one at a time, and the scattering and fluorescent intensity of the particles are identified by an accurate photomultiplier tube. Flow cytometry assessed and classified the samples depending on their size. In another study, it can also quantify plastic particles between 0.6-15 μm [162]. [185] showed this approach to identify polyethylene MPs with 70% efficiency, PS and PVC with 96% efficiency with 90s time analysis, which is significantly faster than spectroscopy.

Nuclear Technique

Radiotracer methodologies are extensively utilized for troubleshooting due to their advantages over conventional tracking methods [186]. While the conventional technique needs intricate processes and a large number of animal subjects, the nuclear method provides an accurate, sensitive, and real-time technique using radiolabeled micro-nanoplastics as a tracer [187]. The presence of radionuclide activity can facilitate the monitoring of specific components of MPs that can harm the environment [188, 189], thereby assisting in assessing plant responses, investigating mechanisms, and understanding the subtle interactions between plants, MPs, and other pollutants at a sub-microscopic level. Detecting MPs within plants presents a technical challenge due to their diminutive size and resemblance to biomass constituents.

The radiotracer should have the least or zero radiochemical toxicity to avoid any radiological threat to the operator, public, and environment [186]. [190] discovered a production method for Iodine-131 radiolabeled polyvinyl chloride (PVC) as a possible radiotracer of MPs bioaccumulation and biodistribution studies in organisms due to their stability radiochemical purity assessment [191] investigated the uptake of 137Cs on milkfish (C. chanos) from aquaculture farms in Jakarta Bay via seawater pathways experiment. Bioaccumulation studies of 65Zn and 137Cs in M. micropterus from Jakarta Bay were also investigated via the water pathways. A high-resolution gamma spectrometer equipped with a high-purity germanium (HPGe) detector was utilized to determine the radioactivity concentrations of these tracers [192], and a gamma spectrometer with NaI(Tl) detector to analyze Cd accumulation in P. viridis through food pathways [193]. [194] exposed 14C-radiolabeled 24 nm and 250 nm polystyrene NPs in mollusk (P. maximus) using autoradiography, which analyzed conduct 6 hours later, revealed that 250 nm NPs accumulated in the intestine, whereas 24 nm particles were disseminated throughout the body.

POTENTIAL EFFECT OF MPS ON HALOPHYTE PLANT

The toxicity of MPs was investigated using a variety of marine organism models, including oysters, nematodes, and zebrafish. Early research on MPs' toxicity concentrated mainly on marine organisms including, vertebrates and invertebrates [195, 196]. The impact on halophyte plants is predominantly unexplored, as most research focuses on terrestrial plants. MPs toxicity factors can be classified as physical, chemical, and biological components [194]. Because of the chemical and physical characteristics of salt-tolerant plants, the impact of plastics could damage their residents through enhanced bioavailability and have the potential to alter the functioning of the ecosystem. Coastal wetlands plants not only capture and confine MPs but can also constrain plant growth by influencing soil composition, nitrogen transport, pollutant adsorption and transport, hazardous release, and microbial populations [197]. Plastics, the majority of which are inert, are not easily degraded in coastal wetlands and can be exploited as a carbon source. Despite that, as plastic debris gradually degrades into tiny plastic pieces, plant-interrooted microorganisms can exploit these MPs as a carbon source, changing the functional features of plants [198].

Bioaccumulation of MPs and NPs affects various marine organisms by changing activities such as reproduction, growth, feeding, and survival, as well as the behavior of fish and filter-feeding organisms [118]. Several studies indicate that MPs can potentially influence phytotoxic effects on the structure and function of salt-tolerant plants [199, 200]. Interaction between mangrove roots and polystyrene (PS) polymers may restrict the transfer of energy and substances, leading to decreased nutrient uptake and light penetration [201, 202]. This interaction can cause damage to the cellular structure through puncturing, as well as morphological alterations such as the thickening of cell walls and deformation of thylakoids. Moreover, it disrupts nutrient cycles by inhibiting nitrogen fixation by diazotrophs, elevates toxin levels that interfere with metabolic processes, and inhibits microbial activities [203]. Fig. 6 summarizes microplastic effects on halophyte plants and maritime macroalgae observed in review studies.

MPs significantly increased the dry weight of the root and shoots, the relative growth rate, and the decrease in the main shoot length in M. spicatum (1753) and Elodea sp. [204]. Recent studies also indicate adverse effects on the growth of microalgae and terrestrial plants; tiny microplastics (200 nm) and nanoplastics adsorbed on roots compile in plant tissues and eventually translocate to shoots [40], causing toxicity, increased oxidative stress, obstruction of light and nutrient entry, turbidity of the water, DNA damage, changes in gene expression, reduced photosynthesis, inhibition of seed germination, and affecting the shape and thickness of root and leaf cell membranes [87]. [103] showed that the floating macroalgae can spatially and temporally influence plastic dispersion via their trap and release. The impact of MPs on plants, including halophytes, gets more problematic in saline conditions. Salinity and MP pollution stress damage numerous essential plant activities like respiration, photosynthesis, antioxidant defence mechanisms, nutrient absorption, and transfer. The most prominent consequences found in published research [1, 123]. The risk-level criteria for MP pollution are showed in Table 2.

Table 2. The risk-level threshold for microplastic contamination [205]

Risk category	I	II	III	IV
Polymer index values	< 10	10 to 100	101 to 1000	> 1000
Pollution load index values	< 10	10 to 20	20 to 30	> 30

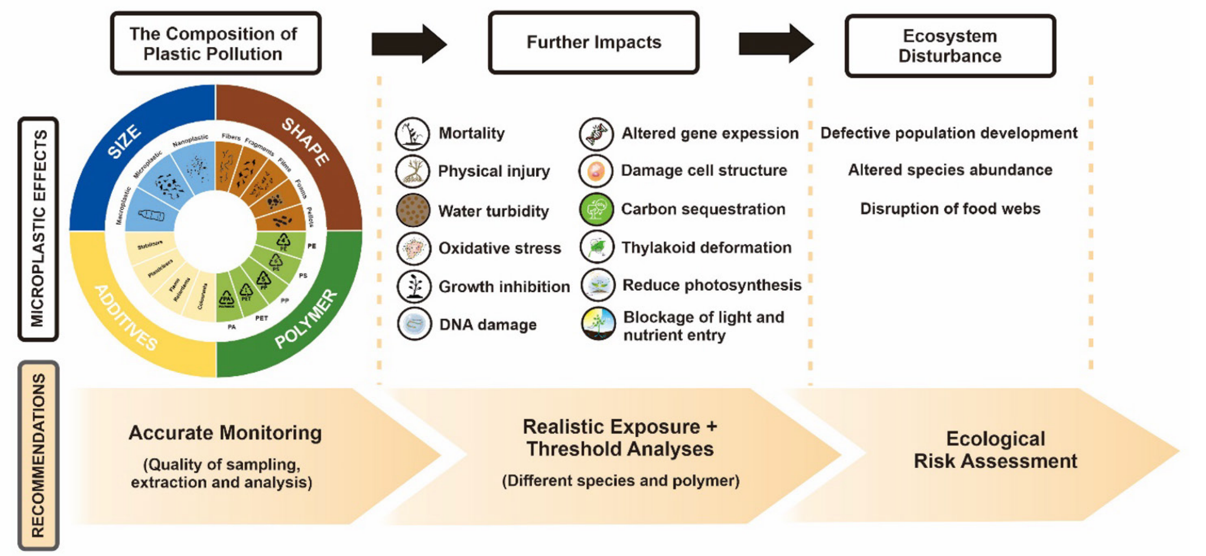

Figure 6. Summary of microplastic effects on halophyte plants and maritime macroalgae observed in review studies

POTENTIALS OF HALOPHYTE PLANTS AND MACROALGAE: BIOREMEDIATION OF MPS

Multiple plants with various taxonomic characteristics can be utilized for successful phytoremediation of MP [206]. Seaweeds (F. vesiculosus) can retain suspended MPs on their surfaces. Aquatic plants are unaffected ecologically by nano- and microplastics at environmentally realistic concentrations. These plant systems could be explored further for MPs bioremediation potential [84, 99]. Seagrasses, aquatic macrophytes, and their accompanying bacteria may be promising candidates for MPs bioremediation in marine and brackish environments [206]. MPs are further fragmented into nanoplastics, which are even more challenging to detect and remove. Advances in modeling and monitoring tools are critical for tracking MP migration, accumulation, and hotspots. These tools enable focused cleanup activities and guide future mitigation approaches.

CONCLUSIONS AND PERSPECTIVES

The current review emphasized microplastic pollution, its degradation, technological approaches, and the interaction mechanism for negatively impacting the halophytic plant and macroalgae. The constant accumulation of MPs in the environment inevitably causes environmental issues and health emergencies. Currently, the study of MP contamination is restricted not only to rivers, oceans, and other water-based ecosystems but also to coastal environments and various other ecosystems. There has also been an increase in the depth of study. Considering the study of MPs on salt-tolerant plants, dissimilar investigations admitted numerous gaps, including the incidence of MPs on wild mangroves and mechanisms of MPs on plant tissue for reducing theirs. At the same time, other research emphasized the distribution, quantity, characteristics, and consequences of MPs on plants and algae. This review summarizes a new tool for investigating MP toxicology that is predicted to address the difficulty of accurately quantifying MPs in plants and algae, hence providing a basis for understanding and evaluating the MPs' toxicity in the body.

Research on MP contamination in coastal environments, especially salt-tolerant plants and macroalgae, still needs to be improved. According to this, the subsequent research directions should be taken to create comprehensive pollution assessment methods and integrate them into routine monitoring of the environmental schemes. The ecological risk assessment framework for MP pollution in the coastal environment needs to be clarified. The United Nations Environment Programme has linked the magnitude and seriousness of MP contamination to climate change. However, concerning the coastal environment as a risk evaluation is still needed to build a comprehensive MPs contamination assessment system and environmental monitoring protocols. The majority of research on MPs and their impact on ecosystem services takes place in laboratory settings, where the ecological conditions significantly diverge from the genuine environment. MPs have nanometer-sized particles, making measuring nanoplastic concentrations in the actual environment challenging. Consequently, additional research is needed to ascertain the effects of MPs on ecosystem functions in the field environment. Creating strategies for preventing and controlling policies for MP pollution in coastal environments to identify the primary sources of contamination, reduce MP emissions and pollution from the root, eliminate the source of MP deterioration, and investigate factors for aggravating MP pollution in coastal environments based on the current research.

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DATA AVAILABILITY STATEMENT

The authors affirm that the data supporting the study's conclusions may be found within the article. Upon a reasonable request, the corresponding author can provide raw data that supports this study's findings.

AUTHOR'S CONTRIBUTIONS

Meita Eka Fara: Writing – original draft, Writing – Review & editing, Methodology, Conceptualization, Visualisation, Validation. Muslim Muslim: Writing – review & editing, Validation, Supervision. Miftakul Munir: Writing – review & editing, Conceptualization, Validation, Supervision.

CONFLICT OF INTEREST

The authors state that there are no known conflicts of interest or personal relationships that could have influenced the work presented in this study.

ETHICS

There are no ethical concerns about publishing this manuscript.

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