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Navigating microplastic-related challenges in the Arabian Gulf: Prospects of artificial intelligence and bioremediation

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Abstract

Microplastics (MPs) have emerged as contaminants of growing concern due to their widespread distribution, high mobility, and ability to act as vectors for pollutants in marine ecosystems. This review examines MP contamination in the Arabian Gulf, one of the world's most environmentally vulnerable semi-enclosed seas. The Gulf's extreme conditions, including high salinity, elevated temperatures, restricted water circulation, and intensive coastal development, promote MP accumulation and biological exposure, increasing potential risks to marine organisms, aquaculture, and human health. Conventional detection and quantification techniques, including Fourier-transform infrared (FTIR) and Raman spectroscopy, as well as pyrolysis–gas chromatography/mass spectrometry, are critically assessed with emphasis on limitations related to size detection thresholds, analytical throughput, and processing efficiency. The review highlights artificial intelligence (AI) as a transformative approach for MP analysis. Machine-learning algorithms applied to FTIR and Raman spectral data improve polymer classification accuracy, whereas computer-vision models such as U-Net and Mask R-convolutional neural network enable automated particle segmentation and sizing. These tools reduce manual bias, enhance reproducibility, and facilitate high-throughput analysis across laboratories. Meanwhile, eco-friendly bioremediation strategies are reviewed. Microorganisms, algae, and aquatic plants have demonstrated the ability to adsorb, colonize, or partially degrade MPs, offering sustainable alternatives to conventional remediation methods. However, the effectiveness of these biological approaches under the harsh environmental conditions of the Arabian Gulf remains limited. Finally, this review proposes a Gulf-specific roadmap that includes standardized monitoring protocols and shared spectral and image databases to support AI-based detection, interlaboratory proficiency testing, and pilot-scale bioremediation studies tailored to regional conditions.

Keywords: Microplastic; Arabian Gulf; Marine pollution; Artificial intelligence prediction; Artificial intelligence in pollution management; Machine learning; Bioremediation; Aquatic ecosystems

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1. Introduction

1.1. History

The history of plastics can be traced back over a century, with significant developments in our understanding of their environmental impact. In 1972, Carpenter and Smith[1] published a study that marked an early examination of marine plastic pollution. In the early 1980s, small-scale research and case studies began highlighting the detrimental effects of plastic in the ocean. By 1988, governmental policies were implemented to prevent ships from discharging plastic waste into marine habitats, driven by concerns over the impact of plastic on marine life.[2]

Further insights into the role of plastic deformation in the cracking process of metallic materials were discussed by Wang *et al.*[3] in 1998. However, it was not until 2004 that serious discussions and analyses specific to microplastics (MPs) emerged, primarily led by Thompson *et al.*[2,4] Their study introduced the term "microplastics" to describe these minuscule plastic particles, sparking a significant increase in research interest.[5]

The growing awareness of the MP issue led to a research revolution after 2004. In a milestone event, the National Oceanic and Atmospheric Administration organized the First International Research Symposium on the Occurrence, Effects, and Fate of Microplastic Marine Debris, during which MPs were well-defined as plastic particles <5 mm in diameter.[6]

To date, numerous studies have underscored MPs as a global threat to various living organisms, including potential effects on human respiratory health,[7] the well-being of aquatic life, such as fish,[8] and even microbial communities.[9] These findings emphasize the need for continuous research and proactive measures to address MP pollution.

Plastics, in general, are characterized as long chains of high molecular-weight organic polymers.[10] The significant components of plastics' organic composition are derived from fossil fuels, reflecting the recurring hydrocarbon-based chemical structures that constitute plastic polymers.[11]

The inception of plastics marked a significant advancement in materials science, with early household products made from materials such as bakelite, a phenol-formaldehyde thermoset, representing one of the earliest synthetic plastics produced in the 20th century.[12] Subsequently, after World War II, plastic production experienced exponential growth, with annual production reaching approximately 5 million tonnes in the 1950s.[13] This accelerated production trend continued, dramatically increasing, reaching 359 million tonnes by 2018. Global plastic production is projected to continue increasing, reaching 590 million tonnes by 2050 (Figure 1).[14,15]

Plastics possess various unique characteristics, making them highly desirable for consumers and industrial applications. These attributes include strength, cost-effectiveness, extended durability, lightweight properties, resistance to corrosion, and flexibility.[16] These inherent qualities have facilitated the incorporation of various plastic polymers, such as polyethylene (PE), nylon, polystyrene (PS), and polypropylene (PP), in diverse roles such as fillers, plasticizing agents, antimicrobial components, adhesives, and coloring agents. This versatility enhances plastic performance and accessibility for end-users.[17]

1.2. MPs classification: A closer look

MPs encompass a wide array of particle sizes, shapes, and polymer types.[18] These plastic fragments can be categorized by size into several groups: Macroplastics (over 25 mm), mesoplastics (5–25 mm), and MPs (<5 mm).[19] Interestingly, small-scale plastic particles were detected in aquatic habitats as early as the 1970s before they were formally recognized and labeled as MPs.[20] To date, any fragments smaller than 5 mm are referred to as MPs,[21] and it is well understood that plastic particles can continue to degrade into even smaller sizes, eventually producing nanoplastics.[22]

Other than size categorization, MPs are generally categorized into two main classes: primary and secondary MPs.[23] Primary MP particles are intentionally manufactured at the microscale. They can be found in products such as scrubs, handwashing soaps, cleansers, toothpaste, and biomedical products.[24] These particles, especially those with diameters between 1 μm and 5 μm, tend to be spherical and are typically composed of materials such as PP, PS, or PE.[25] Notably, some of these particles can bypass filtration systems during sewage treatment and enter freshwater environments, posing a threat to various living organisms.[26]

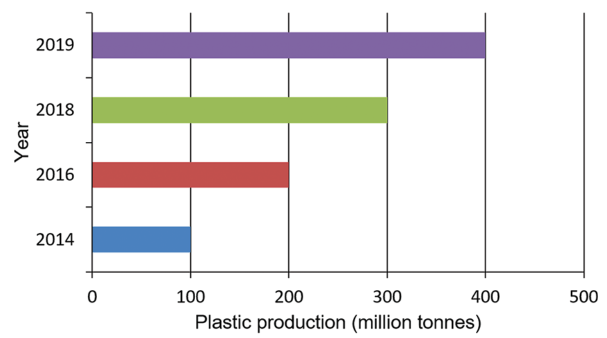

Figure 1. Global plastic production (million tonnes) has steadily increased from 2014 to 2019. Image created by the authors.

Meanwhile, secondary MPs are formed when larger plastic waste is fragmented.[27] Physical forces and ultraviolet (UV) radiation from the sun play a role in breaking down larger plastics into micro- and nanoparticles.[28] Exposure to waves, sunlight, and high temperatures can make plastics brittle, rendering them more susceptible to fragmentation.[29]

The main objective of this study is to shed light on the MP issue in the Arabian Gulf as an example and evaluate its negative impact on marine ecosystems and human health. We discuss promising methods for monitoring, detecting, and mitigating the risk of MPs, highlighting the central role of artificial intelligence (AI) in improving detection accuracy and the potential of bioremediation strategies as an eco-friendly tool to address this environmental threat, with particular applicability to the Arabian Gulf. In addition, we highlight how these innovations can be integrated into broader resource management and governance strategies, such as Circular Economy approaches, to help mitigate the region's growing plastic dependency. With rapid urbanization, high consumption patterns, and heavy reliance on single-use plastics shaping daily life, the challenge is both urgent and complex. By connecting technological tools, such as AI-powered monitoring, with policy measures that promote recycling, sustainable waste practices, and eco-friendly product design, this study suggests a practical and forward-looking pathway for building stronger, more resilient environmental governance across the Arabian Gulf. This compelling analysis underlines the pressing nature of the MP pollution crisis, proposing innovative solutions that can guide policymakers and shape future research endeavors in marine conservation.

The methodology for this review involved a systematic survey of literature on MP contamination in marine environments, emphasizing the Arabian Gulf. Articles from 2000 onwards were retrieved by searching scientific databases such as the Web of Science, Scopus, and PubMed. The focus was on peer-reviewed articles discussing MP types, sources, impacts, and remediation. Information on study location, MP concentration, and remediation effectiveness was extracted and compiled. The data were synthesized narratively to present an updated overview of MP pollution and potential solutions.

1.3. MPs in the Arabian Gulf

The MP issue has garnered increasing global attention. Recent evidence suggests that MPs are found in different habitats around the globe, such as the deep sea of the western Pacific Ocean,[30] the Indian Ocean,[31] and the Atlantic Ocean.[32] However, there has been relatively little focus on MPs in the Gulf Cooperation Council countries, particularly in the Arabian Gulf region of Saudi Arabia. The Arabian Gulf, a geologically young sea basin, boasts rich and diverse marine habitats, including mangrove forests, seagrass beds, and coral reefs.[33] This unique region is surrounded by eight countries: Saudi Arabia, Qatar, Oman, the United Arab Emirates (UAE), Kuwait, Bahrain, Iraq, and Iran.[34]

Several factors contribute to the Arabian Gulf's relevance as a setting for MP research. First, it receives minimal river inflow into the Gulf.[35] Second, rainfall is limited between October and January.[36] Third, the region experiences high salinity (44 practical salinity units) and extreme thermal variations, with surface seawater temperatures ranging from 20°C in spring to 38°C in summer.[37] Given the impact of global warming on seawater temperature, the Gulf's environment has become a focal point for researchers studying climate change.

Despite these favorable conditions, limited studies have assessed the presence of MPs in the Arabian Gulf, particularly from the perspective of Saudi Arabia (Table 1).[38-44] One such study analyzed 18 MP particles—13 isolated from sediments and 5 from seawater [38]. Their findings revealed the ubiquitous presence of MPs in beach sediments and surface seawaters along the coast of Qatar. PP and PE polymers dominated the MPs in intertidal sediments and seawater samples. Furthermore, fibers, measuring 1–5 mm in size, represented the dominant type of particle in all samples, comprising 93.8% of the total isolates.

Naji *et al.*[39] examined the presence of MPs in several types of shellfish found in the coastal waters of the Arabian Gulf. Their study confirmed the presence of MPs through Fourier-transform infrared (FTIR) analysis with common polymers, including PE, polyethylene terephthalate (PET), and nylon. Notably, their study highlighted fibers and microfibers as the most prevalent shapes of MPs in the marine environment and shellfish.

A study investigated the bioaccumulation,

Table 1. Timeline of the significant stages in microplastic research in the Arabian Gulf

Time	Location	Sample source	Reference
2017	Qatar	Sediments/seawater	37
2018	Arabian Gulf	Shellfish	38
2019	Arabian Gulf	Fish, crab, prawn	39
2020	Kuwait	Fish, sediments	40
2021	Arabian Gulf	Sediment and bivalve	41
2022	United Arab Emirates	Sediment and oysters	42
2023	East of the Arabian Gulf	Sediments	43

biomagnification, and potential human exposure to MPs in the muscles and gills of five commonly consumed species (including three fish, one crab, and one prawn) from the Arabian Gulf.[40] Among the species examined, *Penaeus semisulcatus* and *Epinephelus coioides* had the highest (average of 0.360 items/g muscle) and lowest (average of 0.158 items/g muscle) levels of MPs in their muscles, respectively. Interestingly, the number of MPs extracted from the gills exceeded that from the muscle tissue. Calculations of the trophic magnification factor and biomagnification factor indicated that MPs did not biomagnify within the edible portions of the marine food web in the Arabian Gulf. Contrary to prior beliefs, MPs experienced dilution rather than concentration in seafood's edible parts. Assessing the human intake of MPs highlighted potential risks associated with seafood consumption, particularly for individuals with a seafood-heavy diet.

Saeed *et al.*[41] studied MP influences in Kuwait's coastal areas using several sampling techniques to collect data. For example, sediment samples were taken from 44 intertidal locations, short trawls were conducted at 40 sites to gather samples from the water, and the gastrointestinal contents of 87 fish and mussels were examined to assess the ingestion of materials. MPs were identified using Raman spectroscopy, and contrary to expectations, the results revealed a relatively low presence of MP particles. Only 37 MPs were found in beach sediments at 15 locations, and seawater trawls detected MPs in just 2 samples from Kuwait Bay and 2 from the southern areas. In biota, only three pieces of plastic were recovered from the gastrointestinal tracts of Hamour fish. Moreover, they found that the most common MPs were PP, PE, and PS. While MP levels in Kuwait were lower than in neighboring areas, they were comparable to those in Qatar and Oman.

Jahromi *et al.*[42] investigated heavy metals and MPs in coastal sediments and edible bivalves along the Arabian Gulf in the Hormozgan province. Sampling sites were strategically selected to represent industrial, urban, and protected forest areas. The results indicated heavy metal concentrations in sediments were generally below typical geological baseline values, except for nickel (Ni) and cadmium (Cd). Furthermore, areas with significant human activity, such as ports, exhibited elevated concentrations of several heavy metals. The study identified a moderate environmental risk associated with arsenic (As), cobalt, zinc, and copper (Cu). However, it concluded that health risks from heavy metals in bivalve consumption were generally low, except for As, which posed a potential carcinogenic risk. Regarding MPs, the predominant type identified was fibrous, with lengths ranging from 100 to 250 μm, primarily composed of PET and PP.

Al Hammadi *et al.*[43] examined MP pollution in the UAE oyster bed ecosystems. They assessed MP levels in sediment and oysters from five coastal sites, considering abundance, shape, size, color, and composition. MPs averaged 191.7 ± 95.5 MPs/kg of dry weight in sediment samples, whereas in oysters, it was 101.2 ± 93.8 MPs/kg. MPs were found in all sediment samples and 51% oysters, with no clear correlation between sediment and oyster MP levels. Fibers were the primary MP shape (93%), and black was the most common color (53%). This study, the region's first investigation into oyster bed MPs, highlights the widespread presence of MPs in sediment, necessitating further research into sources and management to protect the marine ecosystem.

In a more recent study, Ali *et al.*[44] aimed to be the first to assess MP pollution in Saudi Arabia's east coast sediment, specifically at beaches in four cities: Khafji, Jubail, Dammam, and Salwa. Samples were collected from high and low tide zones. A total of 586 MP particles were found, with an average size of 1.55 ± 0.94 mm. Most particles (77%) were with a size smaller than 2 mm. The MP levels exhibited a range of values, with the low tide region ranging from 5.5 ± 1.55 to 21.2 ± 0.68 particles/kg and the high tide region ranging from 6.3 ± 4.05 to 16.5 ± 4.98 particles/kg. Transparent (34%) and blue (30%) were the predominant colors, whereas fibers (96%) were the most common shape. PET was the common polymer type in fibers, whereas PE and high-density PE were prevalent in fragments and filaments.

Nevertheless, comprehensive datasets on MP abundance, polymer typology, and degradation behavior within the Arabian Gulf are notably limited, highlighting an urgent need for systematic, region-specific investigations that account for its distinct hydrographic and climatic characteristics.

2. Impacts of MP pollution on the marine ecosystem

Saudi Arabia's aquaculture sector has shown remarkable growth, with total production reaching approximately 140,000 tonnes in 2023, reflecting a 56.4% increase compared to previous years.[45] Shrimp (66,000 tonnes) and Nile tilapia (45,000 tonnes) dominate aquaculture output, driven by intensive marine and freshwater farming practices. However, the sector may face significant challenges due to MP contamination in the Arabian Gulf, a major production area. MPs threaten the health and reproduction of key species and compromise water quality, impacting aquaculture sustainability and regional food security. These risks emphasize the urgent need for monitoring and mitigation strategies tailored to the Gulf's unique environmental conditions.

2.1. Impact on aquatic life

Marine organisms consuming MPs can experience severe physical harm, including digestive blockages, reduced feeding efficiency, and internal injuries. These impacts have been documented across various species, from plankton to top predators. For example, an increasing trend of MP ingestion, including PE and PP, has been observed globally in commercially important fish species (*Acanthopagrus latus* and *E. coioides*) from the Arabian Gulf.[46,47] MPs tend to accumulate in the digestive tracts of plankton and small fish, impairing nutrient absorption and disrupting metabolic processes, adversely impacting growth and reproduction.[48]

In the Arabian Gulf, economically valuable species face heightened risks due to high levels of plastic pollution predominantly originating from fishing gear, domestic wastewater, and industrial activities.[47,49] These MPs disrupt physiological functions and introduce contaminants such as heavy metals and persistent organic pollutants, exacerbating their impacts. Recent studies have highlighted that MPs in the region are dominated by fibers and fragments, commonly ingested by fish, mistaking them for prey.[46,49] The ingestion of MPs by these species poses significant threats to fisheries production and food security.

Furthermore, the trophic transfer of MPs within marine ecosystems can result in the bioaccumulation of contaminants, leading to cascading ecological effects.[48,49] This emphasizes the need for rigorous research to quantify MP ingestion rates and assess long-term ecological consequences in the Arabian Gulf. Strategic policy measures targeting plastic waste reduction and improving wastewater treatment systems are essential to mitigate these risks.[47,48]

MPs are ubiquitous in marine environments and linked to biochemical disturbances in aquatic organisms. They interact with cellular processes, disrupting metabolic pathways and overall organismal health. Understanding these biochemical interactions is essential for assessing the broader ecological implications of MPs in marine ecosystems.

Recent studies have demonstrated the extent and complexity of these disruptions. For example, adult zebrafish exposed to high-density PE and PS MPs exhibited altered gene expression, notably impacting immune system functions and epithelial integrity.[50] Histological assessments further revealed increased neutrophils in the gills and intestinal epithelium, suggesting vulnerabilities in defense mechanisms and altered energy utilization due to MPs exposure.

MPs exacerbate biochemical risks in the Arabian Gulf by acting as vectors for hazardous substances, including heavy metals and endocrine disruptors.[48] These contaminants amplify physiological stress, resulting in oxidative damage, diminished immune responses, and cellular dysfunction. Such impacts may jeopardize marine food web stability and ecosystem health in this unique and vulnerable region.[49,51]

Moreover, oxidative stress caused by MPs is a primary biochemical concern. MPs promote the generation of reactive oxygen species, leading to lipid peroxidation, protein denaturation, and DNA damage.[52] These processes impair organism health and disrupt trophic interactions, amplifying ecological consequences across marine systems.[53]

The dual role of MPs as physical and biochemical disruptors underscores the urgency of further research, particularly in regions such as the Arabian Gulf, where unique environmental conditions may exacerbate these impacts. Identifying Gulf-specific biomarkers for oxidative stress and immune dysfunction could aid in effectively monitoring and mitigating these risks.

MPs are ubiquitous across marine ecosystems and pose substantial risks to the reproduction and growth of marine organisms. When ingested, MPs can release harmful agents that disrupt endocrine systems and inhibit reproductive success in marine species.[54,55] These disturbances have cascading effects on population dynamics and marine ecosystem stability. Studies have highlighted the reproductive challenges faced by key species. For example, MPs have been shown to impair oyster reproduction by interfering with gamete development and larval growth.[54] Similarly, zooplankton exposed to MPs experience feeding disturbances that reduce reproductive output, threatening their critical role in the marine food web.[56]

In the Arabian Gulf, unique environmental conditions such as high salinity and elevated temperatures may exacerbate the reproductive impacts of MPs on local species. A study has reported significant MP ingestion among commercially valuable species, including shrimp and groupers, potentially leading to reproductive challenges such as reduced fecundity and growth disturbances.[57] Although specific data quantifying these effects are sparse, the ecological implications of chronic MP exposure underline the urgent need for targeted research in the region.[57,58]

Marine turtles are particularly vulnerable to MP ingestion, which has been documented to cause gastrointestinal blockages, reduced stomach capacity, and mortality. Such outcomes indirectly affect turtle populations by limiting reproductive potential and disrupting nesting success.[59] These findings highlight the urgent need for targeted research in the Arabian Gulf to evaluate the long-term reproductive consequences of MPs on ecologically and economically significant species.

Exposure to and ingestion of MPs by marine organisms have prompted various behavioral shifts. For example, post-MP consumption, zooplankton have been observed to alter their swimming behaviors, increasing their susceptibility to predators.[60] Similarly, when exposed to MPs, mussels exhibit diminished mobility and compromised defensive reactions.[61] Research on gastropods links MP interactions with various adverse effects, from developmental issues to behavioral shifts.[62]

The proliferation of MPs, especially in delicate areas such as coral reefs and benthic habitats, is also a growing concern. Reports indicate that MPs injure corals, hampering their growth, smothering entire communities, and transmitting toxic substances.[63,64] Furthermore, MPs serve as vectors for detrimental pathogens, potentially altering benthic community structures and threatening their diversity.[65] These extensive damages (Figure 2) highlight the urgency of addressing this rising menace to uphold marine ecosystem health.[66]

2.2. Responses and adaptive mechanisms

Marine organisms exhibit a range of responses to MP exposure. Recognizing these intrinsic tactics can offer valuable insights for devising holistic solutions.

Mollusks, such as oysters, have been observed to incorporate MPs into their shells as a potential defense mechanism.[67] According to a study by Onyena *et al.*,[68] essential marine organisms such as phytoplankton and zooplankton alter their feeding habits to avoid MP-rich areas. Several other studies have investigated the impact of MPs on the feeding of phytoplankton and zooplankton.[69-74] The effects depend on various factors, including size, shape, concentration, organism species, and polymer type. Table 2 concludes the most significant findings. These studies indicated that at elevated concentrations of spherical MPs, algal consumption of certain organisms, such as cladocerans, diminished. In contrast, realistic microfiber concentrations (5.7–9.0 fibers/mL) do not inhibit diatom clearance in calanoid copepods or doliolids, regardless of observable ingestion and egestion through fecal pellets. Most promisingly, recent research hints at the capability of certain marine species to biodegrade MPs courtesy of unique enzymes or metabolic processes.[75]

These findings could pave the way for biotechnology-based solutions to combat MP pollution. One such initiative includes incorporating Ballast Water Treatment Systems (BWTSs) filtration chambers in vessels, as previously suggested.[76] This would prevent MPs from being further spread during ballasting procedures. However, the utilization of BWTS has several drawbacks, including unsustainability from both economic and environmental perspectives. For example, factors such as the use of UV, particularly in high turbidity conditions, and maintenance

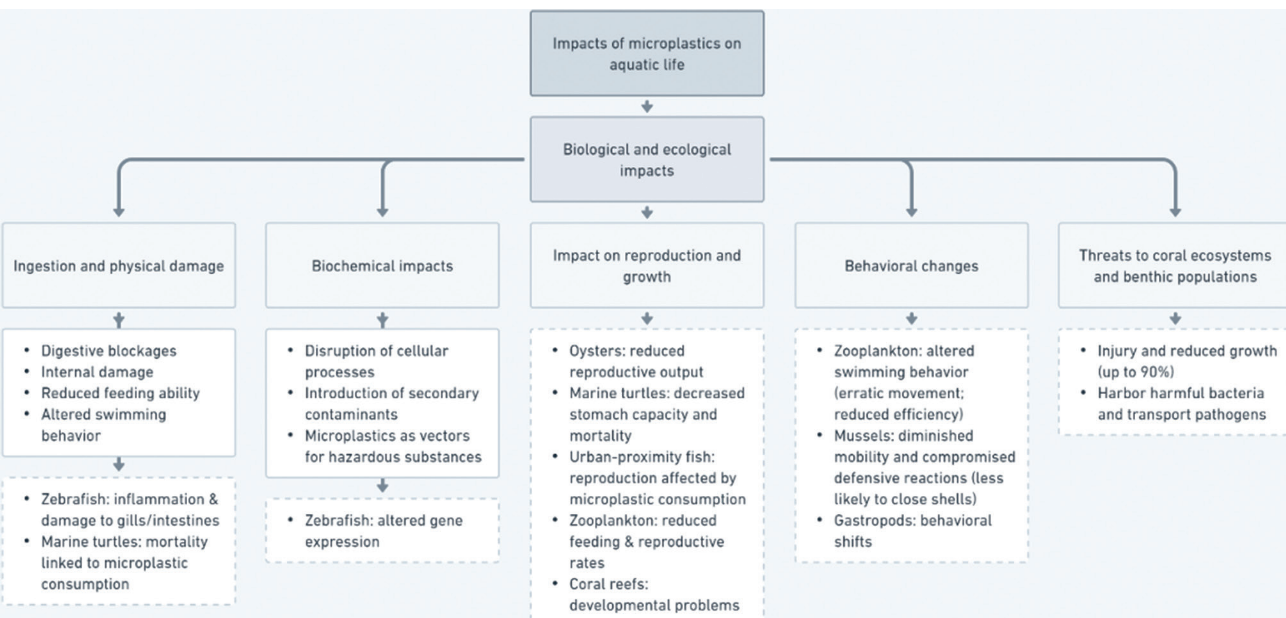

Figure 2. Comprehensive overview of microplastic (MP) impacts on aquatic life. The flowchart summarizes various MPs' effects on marine organisms (solid square), detailing specific consequences and citing relevant research examples (dashed square). Flowchart created by the authors.

Table 2. Experimental studies quantifying MP effects on zooplankton feeding behavior

Study	Species/System (most impacted)	MP type consumed/tested	Particle size (μm)	Concentration	Exposure duration	Feeding effect	Quantitative change
Cole *et al.*[69]	*Centropages typicus* (copepod)	Fluorescent PS beads	7.3	0, 4,000, 7,000, 11,000, 25,000 particles/mL	24 h	Significantly decreased algal ingestion rate in a dose–response relationship when concentrations of MPs increased (>4,000 particles/mL)	Not specified
Scherer *et al.*[70]	*D. magna*	Fluorescent PS spheres	1, 10, 90	3, 30, 300, 3,000 particles/mL; for 90 μm, the highest tested concentration was 300 particles/mL	2 min for *D. magna* (as short-term experiments with a concentration of 100 particles/mL)	Concentration- and size-dependent ingestion; *D. magna* excludes 90 μm; co-exposure to natural particles (e.g., algae, sand, and leaf) reduces ingestion and enhances egestion	Up to 6,180 particles/h ingested
Malinowski *et al.*[71]	*Daphnia dentifera*	Fluorescent PE microspheres	27–32	Various concentrations: • Low: 2.38×10^{-8} mg/L • Medium: 0.023 mg/L • High: 162 mg/L	24 h	Significantly reduced algal consumption (gut algae) at high concentrations (grazing capacity declined)	Lower gut algae content at high MP exposure; effect consistent with reduced ingestion. (% coverage, assessed by fluorescence)
	Arctodiaptomus dorsalis					No significant difference (decrease at medium (p=0.011) and high (p=0.003) concentrations compared to Control 1)	Not specified, but a notable decrease compared to the control
Yin *et al.*[72]	*D. magna* and *S. kingi*	PE	32–38	0, 0.4, 2, and 10 mg/L	21 days	Reduced grazing capacity and reproductive impairment due to increasing levels of the ingested MP, while no significant effects on feeding behavior were observed in *S. kingi*	*D. magna*: significantly reduced reproductive capacity, including a decline in the number of neonates and their body size. (quantitative values not detailed). The parameters in all treatments rapidly declined on day 13
Montoya *et al.*[73]	Marine microbial and phytoplankton communities (pelagic mesocosms)	Mixture of PS (1.04–1.09 g/cm^3), PE (0.89–0.95 g/cm^3), PP (0.85–0.92 g/cm^3), PVC (1.16–1.41 g/cm^3), and PET (1.34–1.41 g/cm^3)	20–1,000	100 pieces/L (20 per polymer)	NA (not a zooplankton feeding test)	MPs indirectly increased phytoplankton biomass and benefited photosynthetic efficiency via shifts in bacterial and phytoplankton assemblages and NH_4^+cycling (ecosystem functional response, but not a zooplankton grazing assay)	Enhanced chlorophyll a biomass (R^2=0.33, P<0.01), NH_4^+ (R^2=0.27, P<0.01), and photosynthetic efficiency (R^2=0.31, p<0.05)
Köster and Paffenhöfer[74]	*E. pileatus* (calanoid copepod) and *D. gegenbauri* (doliolid)	Nylon microfibers	Width=10 μm; length = ~300 μm (mean 336 μm, with rare up to 1.45 mm)	5.7–9.0 fibers/mL (similar to diatom *R. alata*)	• *E. pileatus*: 18 h (initial), then 6.0–6.1 h • *D. gegenbauri*: 6.0–6.1 h • Both at 20°C on a plankton wheel in 960 mL bottles (5 individuals/bottle)	• At~7 fibers/mL, no significant effect on diatom clearance • Fiber clearance *by D. gegenbauri* was greater than that of *E. pileatus,* while the ingestion of their food (*R. alata,* diatom) was 10 times more than the ingestion of fibers	Clearance rate of *E. pileatus* for *R. alata* (21.4 mL/individual/h), compared to (13.1 mL/individual/h) for fibers; in contrast, *D. gegenbauri* had a higher clearance rate for fibers (27.2 mL/individual/h) than that for *R. alata* (18.7 mL/individual/h). In addition, the number of fibers per pellet was 3.5 for copepods and 3–16 for doliolids

Abbreviations: *D. gegenbauri*: *Dolioletta gegenbauri*; *D. magna*: *Daphnia magna*; *E. pileatus*: *Eucalanus pileatus*; MP: Microplastic; PE: Polyethylene; PET: Polyethylene terephthalate; PP: Polypropylene; PS: Polystyrene; PVC: Polyvinyl chloride; *R. alata*: *Rhizosolenia alata*, *S. kingi*: *Scapholeberis kingi.*

costs are considered significant factors in energy consumption.[77,78] Moreover, carbon dioxide emissions that can be generated from BWTSs[79] and persistent toxic chemicals, such as the formation of disinfection by-products, are further environmental challenges.[80] These observations emphasize the dual nature of the solutions needed to alleviate the consequences of MP pollution in our oceans, encompassing natural adaptations and human-driven interventions.

2.3. Environmental impacts of MP contamination

2.3.1. Influence on water quality

Marine water quality is fundamental for maintaining marine biodiversity and habitat well-being. MPs have been shown to harm various elements of water purity, leading to increased water cloudiness and hindering light penetration crucial for aquatic plant life, such as influencing the process of microalgal photosynthesis. Moreover, MPs play a role in introducing pollutants into marine waters.[81-83] Intriguingly, previous studies by Liu *et al*. and Pestana *et al*.[84,85] have linked MPs to the proliferation of harmful algal blooms. In a broader context, a study by Hale *et al*.[52] highlighted the compounded threats of MPs to marine life and its food chains, from zooplankton to finfish.

2.3.2. Sediment quality deterioration

The omnipresence of MPs in marine sediments raises alarms due to sediments' importance in marine ecosystems. Previous studies by Kane and Clare, Barrett *et al*.[86,87] have detailed the widespread occurrence and retention of MPs in marine sediments. Delving into the repercussions for bottom-dwelling organisms, MPs' negative impacts were discussed.[56,88] Another study, Waldschläger *et al*.[89] further pointed out potential geophysical changes induced by MPs.

2.3.3. Disruption of nutrient cycles

For marine ecosystems, nutrient cycling is vital. It has been discussed how MPs can adversely affect nutrient dynamics by disrupting the nutrient cycles within the plant–soil system.[90,91] For example, MPs have been found to have a direct and/or indirect impact on the essential nutrients, such as magnesium and potassium, necessary for chlorophyll synthesis in plants.[90] MPs disrupt the plant–soil nutrient dynamics by altering soil nutrient availability, enzyme activities, and functional microbial communities, compromising the natural nutrient cycles essential for sustainable agriculture and land use.[91] Moreover, another study by Gerstenbacher *et al*.[92] has provided insights into the effects of MPs on seagrass and aquatic nutrient balances. MPs impede light and gas exchange, increasing toxin concentrations and disrupting metabolic processes. It has been reported that specific MPs, such as polyurethane foam and polylactic acid, can enhance nitrification and denitrification processes. Moreover, polyvinyl chloride (PVC) inhibited both these processes, highlighting the differential impacts of MPs on sedimentary nitrogen cycling.[93]

2.3.4. Persistence and potential irreversibility

The long-lasting nature of MPs poses persistent challenges. The studies by Amelia *et al*.[55] and Ma *et al*.[94] emphasized the enduring threats of MPs, especially their toxicological effects. Global perspectives by Ziani *et al*.[51] and Yang *et al*.[95] highlighted the near-impossible removal of MPs. Pourebrahimi and Pirooz[96] foresaw long-term ecological shifts due to MP pollution. MPs, resulting from the degradation of larger plastic materials, have become pervasive pollutants in marine environments, where their ability to adsorb and transfer other harmful pollutants poses significant challenges to their effective removal and management.

2.3.5. Bioaccumulation and transfer of MPs in the food chain

The prevalent presence of MPs in marine ecosystems has severe implications for bioaccumulation and their movement through food webs. Organisms such as plankton, foundational to marine food webs, are particularly vulnerable.[54,59] Li *et al*.[88] have detailed the dangers of MP transfers to higher trophic organisms. At the end of many marine food chains, humans also face risks from MP consumption via seafood.[66]

2.4. Pollutants associated with MPs and their impact

In addition to their intrinsic dangers, MPs are a significant problem due to their propensity to serve as carriers for various environmental contaminants. MPs are inclined to bind with diverse toxins within aquatic systems, from heavy metals and persistent organic pollutants to harmful microbes. Such relationships amplify the ecosystem risks of MPs, enabling the transfer of these toxins into marine life and, subsequently, apex predators, including humans. Addressing these dual threats requires an in-depth understanding of the relationship between MPs and the myriad pollutants they may carry. This section elucidates this intricate relationship, considering the modes of attachment, ecological implications, and potential health consequences.[55,95,97]

2.4.1. Introduction to the concept of MPs as pollutant vectors

MPs, abundant within marine ecosystems, mainly result from the breakdown of larger plastic items. Their persistent nature and expansive surface area bolster their potential to adsorb toxins.[59,95,98] Agboola and Benson[99] detailed the critical interactions between MPs and organic pollutants, emphasizing the significance of physisorption and chemisorption. Tragically, these pollutants might alter their bioactivity when attached to MPs, introducing enhanced risks for marine organisms.[100] As MPs navigate marine environments, they scatter these pollutants, potentially extending the reach of these toxins.[54] Recognizing MPs as carriers of these pollutants is pivotal for comprehensive risk assessment and informed remediation tactics.

2.4.2. Types of pollutants associated with MPs

The relationship between MPs and pollutants has gained significant attention due to its amplifying effect on ecological consequences. MPs, especially PVC and PP, can adsorb heavy metals such as lead, Cu, and Cd, emphasizing the potential environmental risks. Moreover, persistent organic pollutants present long-lasting challenges for marine environments, with MPs depicted as carriers of these pollutants.[17,98,101]

2.4.3. Mechanisms of association

The relationship between pollutants and MPs entails complex physicochemical interactions, predominantly governed by adsorption and desorption processes. Agboola and Benson[99] distinguished physisorption and chemisorption as the main drivers behind these interactions. Factors such as MP properties, pollutant type, and surrounding environmental conditions, including pH and salinity, influence these interactions, for example, influencing As adsorption on MPs.[75] The large surface of MPs provides numerous binding sites, further enhancing their pollutant-carrying capacity.[98]

2.4.4. Bioavailability and trophic transfer

Analyzing the relationship between pollutants and MPs is critical to understanding their marine ecosystem implications. Once attached to MPs, pollutants can infiltrate aquatic food chains, leading to bioaccumulation and ecotoxicological impacts on marine organisms. This underscores their potential adverse effects on human health through dietary exposure, with varied toxin accumulations due to differential ingestion rates among marine species.[54,88,102] The tendency of hydrophobic toxins to prefer specific MPs and become bioavailable post-ingestion poses substantial threats.[98] Recognizing the risks, research by Agboola and Benson[99] suggested enhanced bioavailability of MP-bound pollutants than those freely present. Costa *et al.*[103] documented evidence of these pollutants even in brief food chains, highlighting the bioaccumulation risks in top predators.

2.4.5. Ecological and health risks

The intertwining of MPs and pollutants poses multifaceted ecological and health challenges. Adverse effects on marine organisms due to toxins such as organic pollutants and heavy metals are evident,[17,64] ranging from oxidative stress to developmental irregularities. The risk of toxin magnification across food chains is particularly emphasized by Bhuyan.[102] From a human health perspective, toxin exposure through seafood ingestion is concerning. Research has demonstrated potential health impacts of MPs, from hormonal imbalances to DNA damage.[65,102]

2.5. Human health implications of MP contamination

The pervasive presence of MPs in marine ecosystems has invoked heightened scrutiny due to the potential health risks for humans. These minute fragments originate from the disintegration of larger plastic pieces. They are integrated into numerous trophic levels, presenting potential channels for human contact primarily through seafood consumption and inhalation of airborne MPs.

Current studies have continually illustrated the health risks associated with such exposures. Evidence suggests that MP consumption might lead to cellular anomalies, including endocrine system disruptions.[104] Moreover, MPs serve as carriers for various pollutants, further exacerbating health dangers and even posing risks of disease transmission.[55]

2.5.1. Introduction to the human health context

Since MPs are ubiquitous in the marine environment, assessing their potential entry into the human diet is crucial. As has been outlined in an earlier study,[17] MPs can invade various marine segments, resulting in their accumulation in organisms that humans consume. Furthermore, a study by Chen *et al.*[105] revealed that besides seafood, humans could also encounter MPs by inhaling airborne particles or through water consumption, highlighting the importance of expansive research.

2.5.2. Routes of exposure

Humans primarily encounter MPs via three routes: consumption, inhalation, and, to a lesser degree, direct skin contact. Seafood, especially from significant fishing regions such as China, bottled water, and atmospheric MPs originating from urban areas are potential sources of exposure.[17,102,104] Kiran *et al.*[17] pointed out the inhalation risk of atmospheric MPs from urban areas. Skin absorption from MPs in cosmetics and personal care products is another channel that warrants further exploration.[95] Meanwhile, nanoplastics may enter through physical piercing and endocytosis/phagocytosis.[17]

2.5.3. Bioaccumulation and toxicology

Bioaccumulation refers to a living organism's gradual concentration of substances, such as MPs and associated pollutants. MPs can accumulate in human tissues and act as transporters of organic chemicals, indicating potential health risks when these chemicals are ingested[99,104]. The toxins binding to MPs might enhance their availability in the body, leading to heightened adverse health reactions, including endocrine system disturbances.[106]

2.5.4. Endocrine disruption and other biological effects

The binding propensity of MPs to various contaminants has raised concerns about their physiological impact on humans. MPs can transport chemicals that disrupt the endocrine system, leading to potential hormonal imbalances. Certain plastic additives can also induce cellular stress and inflammation, potentially compromising cellular well-being.[107,108]

2.5.5. Public health perspective

MPs' widespread environmental presence highlights potential community health dangers, including their ability to transport marine pollutants and the associated risk of disease transmission, primarily through seafood consumption. Therefore, ensuring water quality, especially in urban aquatic systems, is paramount.[55,100]

The pervasive impacts of MPs extend beyond biological disruptions in marine organisms to broader environmental, ecological, and human health challenges. MPs alter nutrient cycling, destabilize food webs, and accumulate as pollutants in aquatic habitats, amplifying risks to biodiversity and ecosystem functioning, particularly in vulnerable regions such as the Arabian Gulf. Furthermore, their role as vectors for harmful substances, such as heavy metals and endocrine disruptors, adds another layer of ecological and public health complexity. Addressing these interconnected challenges requires a detailed understanding of MPs' environmental pathways and impacts, which are explored in the following sections.

These widespread impacts of MPs on marine ecosystems underscore the urgent need for innovative solutions, such as AI-driven detection and bioremediation strategies, to mitigate their effects, particularly in vulnerable regions such as the Arabian Gulf.

3. Traditional techniques for MP detection and identification

Before utilizing methods for counting and distinguishing MPs, a range of preparatory steps is typically undertaken. The preparation of MP samples is influenced by their environmental origin, such as marine, terrestrial, and atmospheric contexts[109]. Standard procedures, including sampling, density separation, filtration, sieving, digestion, and visual categorization, are applied across different sample types to isolate MPs from other particulate matter in the Arabian Gulf.[44,110]

Additional procedures are incorporated based on the distinct characteristics of the sample under investigation. For example, atmospheric MPs can be collected passively from environmental degradation or via an air pump directing the air toward a sensor. The critical step post-collection involves separating MPs from organic materials to reduce analysis disruptions.

In marine contexts, MPs are usually collected through pumping systems or with a Manta trawl, a specialized net for aquatic sampling. MPs within the 1–5 mm range are typically examined through direct observation or microscopic techniques, contingent on operator expertise.[111] Due to these requirements, automating the identification and quantification of MPs to facilitate environmental risk evaluations presents challenges. Therefore, enhancing MP detection focuses on shortening analysis time, maintaining the integrity of MP samples, implementing on-site real-time assessments, and advancing automated identification technologies.[112]

Optical imaging methods are prevalent to detect MPs, as they influence light in various ways, including reflection, absorption, transmission, diffraction, scattering, and creating interference, which are determined by their optical attributes. The following subsections discuss the main optical imaging techniques.

3.1. Microscopy methods

Microscopic imaging provides essential details on MPs' morphological structure and surface texture. The selection of microscopy techniques is contingent on MP size: Optical microscopy for MPs under 1 mm, stereomicroscopy for MPs between 0.1 and 1 mm, and scanning electron microscopy for MPs smaller than 0.1 mm, despite its low throughput. Polarized light optical microscopy is utilized to identify MPs in wastewater by leveraging the anisotropic optical properties of specific polymers such as PE, PP, and PET.[113]

3.2. Spectroscopic analysis

Spectroscopic analysis is critical for the nondestructive, precise, and accurate chemical characterization of MPs, distinguishing them based on spectral signatures. FTIR and Raman spectroscopy can reveal MP chemical makeup and structure. However, Raman spectroscopy distinguishes itself by providing higher spatial resolution. The micro-FTIR and micro-Raman spectroscopies enable the identification of smaller MPs with specific detection capabilities for various polymers. Challenges include specific sample preparation to avoid fluorescence in Raman spectroscopy and the requirement for dehydrated and regularly shaped samples for practical FTIR analysis.[114]

3.3. Thermal analysis

Techniques such as differential scanning calorimetry and thermogravimetric analysis (TGA) assess physical and chemical properties based on thermal stability. These are considered destructive and require skilled operation. They are helpful for bulk samples and often complement spectroscopic methods. TGA, combined with other analytical methods such as FTIR, enhances the specificity of MP material identification.[115] Table 3 summarizes commonly used analytical techniques for MP identification and characterization, highlighting their size detection limits, cost, and analysis speed.[116-121]

In summary, the identification and analysis of MPs involve a combination of microscopy for morphological assessment and spectroscopy for chemical characterization, each with specific applications and limitations. Thermal analysis provides additional physical and chemical data, while alternative methods such as fluorescence staining offer the potential for simpler identification, albeit with their challenges. The following section focuses on AI and bioremediation technologies as promising and highly applicable approaches for researchers studying the Arabian Gulf.

4. Artificial intelligence and bio-remediation technologies

4.1. Introduction to artificial intelligence

At its core, AI is the domain of computer science that endeavors to emulate human intelligence processes through the design and development of algorithms. These algorithms let machines carry out activities that traditionally necessitate human intellect, such as visual perception, speech recognition, decision-making, and language translation. The following four distinct phases have marked the evolution of AI. It started with the early foundations phase, in which the seeds of AI were sown in the 1940s and 1950s. Alan Turing, a pioneering computer scientist, introduced the Turing test as a criterion of intelligence, suggesting that a machine could be considered "intelligent" if it could imitate a human to the point of being indistinguishable from one. This was followed by the knowledge-based systems phase in the 1970s, which witnessed the rise of expert systems, attempting to mimic the decision-making of human experts by encoding knowledge in rule-based systems.[122] The machine learning phase gained momentum in the late 1980s and 1990s, and the focus shifted to developing algorithms that could learn from data. The machine learning subfield enabled computers to improve task performance through experience.[123] The deep learning phase and the recent renaissance in AI, particularly in the 2010s, have been powered by advances in neural networks and deep learning. Inspired by the human brain's architecture, these systems have significant advancements in image and speech recognition, as demonstrated by the notable success gained by Goodfellow *et al.*[124] in 2016.

4.2. Challenges of artificial intelligence in marine MP applications

Despite rapid progress, applying AI to marine MPs faces two immediate hurdles. First, data standardization, where models trained on FTIR/Raman spectroscopy and microscopy data require large, well-labeled, standardized datasets with consistent metadata (polymer, size class, morphology, weathering state, additives, and imaging/spectral settings). Lack of shared schemas and benchmark splits leads to overfitting and irreproducible

Table 3. Comparative summary of microplastic analytical techniques

Technique	Size detection limit (μm)	Cost	Analysis speed	Reference
Optical microscopy	≥1,000	Low	Fast	116
Stereomicroscopy	100–1,000	Moderate	Moderate	117
Scanning electron microscopy	<100	High	Slow	118
Polarized light optical microscopy	50–1,000	Moderate	Moderate	119
Fourier-transform infrared spectroscopy	10–20	High	Moderate	116
Raman spectroscopy	~1	High	Slow	120
Differential scanning calorimetry	Bulk sample	Moderate	Moderate	121
Thermogravimetric analysis	Bulk sample	Moderate	Moderate	121

results. We recommend Gulf-wide templates for sample preparation, spectral/image formats, and labels, as well as interlaboratory ring trials and model cards with uncertainty calibration. Second, generalization, where domain shift—caused by the Arabian Gulf's high salinity, temperature, biofouling, oxidation, and distinct polymer use—can degrade accuracy for models trained elsewhere. Transfer learning, domain adaptation (e.g., feature alignment), self-supervised pretraining, and synthetic data augmentation can mitigate shift, but require external validation on Gulf field samples and stress-testing across salinity/temperature gradients. Practical guardrails include holding out Gulf test sets, reporting calibration error, and publishing inference latency to ensure edge/boat-side deployability.

4.3. Promising artificial intelligence application domains in MP research

4.3.1. MP detection and classification

MPs from diverse everyday products, with varied chemical structures and shapes, can be visualized through scanning electron microscopy and other advanced microscopy methods,[125] making these methods suitable for utilizing recent advancements in AI applications for images.

Image segmentation techniques distinguish specific MP images from background visuals and other particles. While automated identification and classification techniques have excelled in medical imaging, applying these methods to MP imaging remains challenging due to the nuances in size class distribution, which is highly sensitive. Several studies have been conducted on MP detection and identification. For example, a combination of holographic imaging and transfer learning using convolutional neural networks (CNNs) has been explored and shown to improve the results.[126]

In a 2019 study, Mukhanov *et al.*[127] employed ImageJ software to convert red, green, and blue (RGB) images into binary formats, enabling the classification of MPs into four morphological categories—rounded, irregular, elongated, and fibers—using a combination of infrared spectrometry and Raman spectroscopy integrated with a hyperspectral imaging system. Similarly, Serranti *et al.*[128] utilized multivariate image analysis and designed analytical techniques to identify the type and morphology of plastics. Although these advanced imaging methods have achieved accurate classification, their widespread application is limited by high costs and accessibility challenges. Meanwhile, Gauci *et al.*[129] applied a least-squares approach to assessing MP size and surface textures from samples collected in Malta in the Central Mediterranean. They further analyzed color metrics by calculating mean square error across RGB channels. While these techniques demonstrate efficiency in tasks such as edge detection and area estimation, they rely heavily on pre-configured algorithms and subjective human interpretation. As a result, there remains a pressing need for integrative and standardized methodologies, leveraging advancements in AI to enhance MP detection and classification accuracy.

In the study by Shi *et al.*,[130] scanning electron microscopy was utilized to capture images of MPs from everyday products (Figure 3). A deep learning method was employed to quantify and categorize MPs using a hand-labeled dataset containing 237 images of MP particles (fragments or beads) sized between 50 μm and 1 mm and fibers approximately 10 μm in diameter. For quantification, the U-Net and MultiResUNet deep learning models were used for semantic segmentation. Both models surpassed traditional computer vision methods, achieving a high average Jaccard index above 0.75. In another study, Ronneberger *et al.*[131] merged the U-Net with object-aware pixel embedding to further quantify densely packed and intertwined fibers. A modified VGG16 neural network was used for categorizing by shape, achieving a remarkable 98.33% accuracy. New images can be segmented and categorized accurately using these trained models in seconds, a more efficient and cost-effective process than manual methods. As datasets expand, this approach could aid in identifying and measuring MPs in environmental samples in subsequent studies.

Recent studies have shown that 1D-CNNs enhance Raman/FTIR classification under noise/weathering;[132] U-Net-family models deliver pixel-accurate masks for sizing;[133] Faster/Mask R-CNN support high-throughput detection in brightfield and UV;[134,135] and holography/phone-microscopy enables rapid, low-cost screening. These findings underscore the need for Gulf-specific datasets and external validation.

4.3.2. MP quantification

Quantifying MPs is essential for tracking their progression and predicting their actions. Traditionally, this task has been both time-consuming and reliant on costly instruments. Several studies have introduced deep learning-based architectures designed to automatically enumerate and categorize MP particles, ranging from 1–5 mm, captured in photos from digital cameras or smartphones with a resolution of 16 megapixels or more. They employed several algorithms, such as the U-Net neural networks,[131] which are designed for object detection and classification.

The quantification of plastics from images falls under object detection.[136] In object detection, not only is the object identified, but its position within the image is also determined using a bounding box. Notable deep

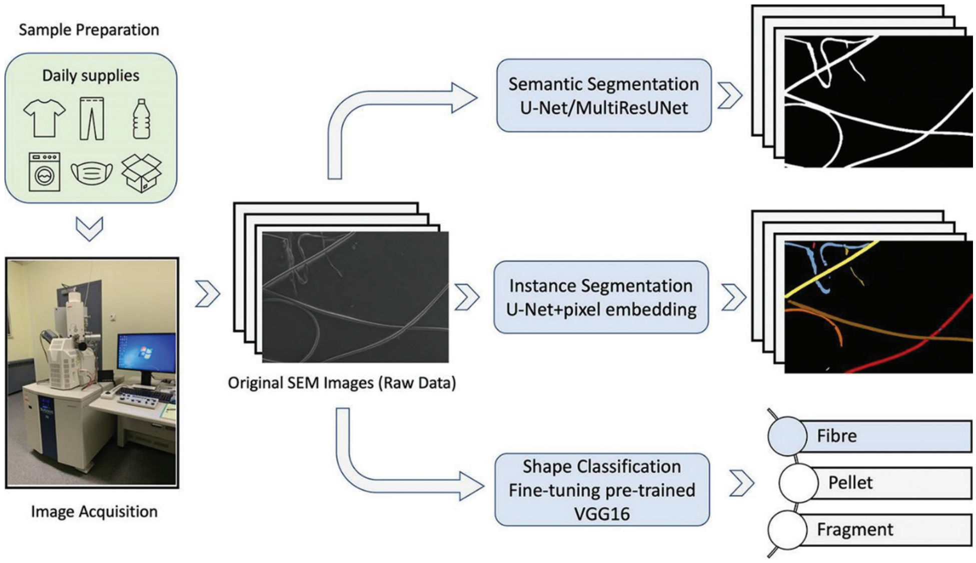

Figure 3. Segmentation models for microplastic image analysis. Adapted from Shi *et al.*[130]

learning architectures that utilize bounding boxes include algorithms such as Fast Region-based CNNs (RCNN),[137] You Only Look Once,[138] and Single Shot MultiBox Detector.[139] These methods excel in scenarios where the primary objective is determining the object's location and frequency in an image.

However, for MP classification, pinpointing the exact pixels of the particle is crucial, especially for size estimation. This requirement makes object instance segmentation or semantic segmentation techniques more appropriate, as they detect the object and categorize each pixel according to its corresponding object class. Some prominent deep learning architectures for this purpose include Fully CNN,[140] Mask-RCNN,[141] and U-Net.[131]

A particular study has demonstrated AI applications in both quantifying and classifying MPs.[142] In that research, the initial phase of the proposed framework utilized the U-Net neural network for segmenting particles within images. Once these particles were singled out, the subsequent phase employed the VGG16 neural network to categorize them into three primary types: fragments, pellets, and lines. These categories were chosen due to their prevalence within the specified size range, as described in Figure 4.

4.3.3. MP monitoring

Achieving effective MP monitoring is a pivotal long-term objective to grasp the impact and progression of MP contamination comprehensively. Despite its importance, current research in this field is notably demanding in terms of time and effort. Present monitoring methods involve collecting, processing, and manually examining vast sample quantities, but these methodologies lack uniformity and standardization. It is essential to understand the movement patterns of MPs to improve monitoring effectiveness, allowing for optimizing the placement and application of monitoring instruments. There is a growing interest in establishing high-throughput and automated monitoring systems to streamline the analysis of MP distribution on a grand scale. One promising approach is employing models to study MP behaviors, providing deeper insights into their distribution, origins, endpoints, and movement trajectories. For example, modeling has demonstrated its potential in pinpointing optimal global locations for effective plastic waste collection.

Though modeling offers insights into certain MP behaviors, it is grounded in tangible data concerning MPs' observed and measured attributes. The complexity within model equations is imperative to truly encapsulate the intricate dynamic forces that steer inertial particle movement. Machine learning and deep learning models can address these numerous challenges that involve vast data, thereby optimizing efficiency.[143] Specifically, image-centric machine learning has been pivotal in material science, assisting in analyzing extensive image sets to decipher the correlation between material structures and their properties.[144]

4.3.4. MP source tracking

In the context of MPs, pinpointing the source of pollution becomes essential, whether it stems from industrial activities, consumer goods, or waste disposal methods. Given the intricate nature of MP dispersal, which is shaped by elements such as aquatic flows, wind directions, and human interventions, there is a pressing need for sophisticated analysis methods. Through machine learning, scientists can identify potential origins of MP emissions and anticipate areas of future buildup. This knowledge guides precise remediation actions and policy decisions to curb additional contamination. Wu *et al.*[145] employed random forest, multilabel decision trees, and support vector machines, which are all supervised machine learning algorithms, to determine the origins of the contaminants by analyzing data such as physicochemical properties.

4.3.5. MP data aggregation

A pressing issue arises from the vast and varied types of data, making data preprocessing challenging. Preprocessing the enormous variety of MP imagery, especially regarding data scaling, can be difficult when preparing it for use with deep CNN algorithms. Depending on the specific deep CNN algorithm used, it is essential to rescale the extensive MP imagery datasets, which come in various ranges, units, and scales, to ensure they match the required standardization and prerequisites. As illustrated in Figure 5, this preprocessing stage constitutes a critical component of the overall machine learning workflow for the MP analysis platform. The sheer volume of this data adds to the complexity, making it a significant hurdle in the automated processing of high-volume imagery.

5. MP biodegradation

MP contamination can be controlled or even eliminated in specific circumstances through biodegradation. Biodegradation is a natural process by which organic compounds in the environment are broken down and converted to simpler compounds, mineralized, and redistributed back to the environment.[146] It not only applies to organic compounds but also to some inorganic complexes, such as macroplastics and MPs. Biodegradation of MPs involves fragmentation into smaller sizes and, eventually, mineralization, a process entirely driven by microorganisms.[147] It occurs almost everywhere in the biosphere, including the soil rhizosphere, aquatic environments, and landfills.[148] There is growing exploration of microbial degradation as a promising, eco-friendly method for removing MPs from the environment.

The typical microorganisms associated with the biodegradation of MPs include bacteria, fungi, and algae.[149] These microorganisms vary in their mode of MP degradation and the type of polymers they degrade, as shown in Table 4.[150-158] The fungal class, for example, has been reported as a common candidate for bioremediation

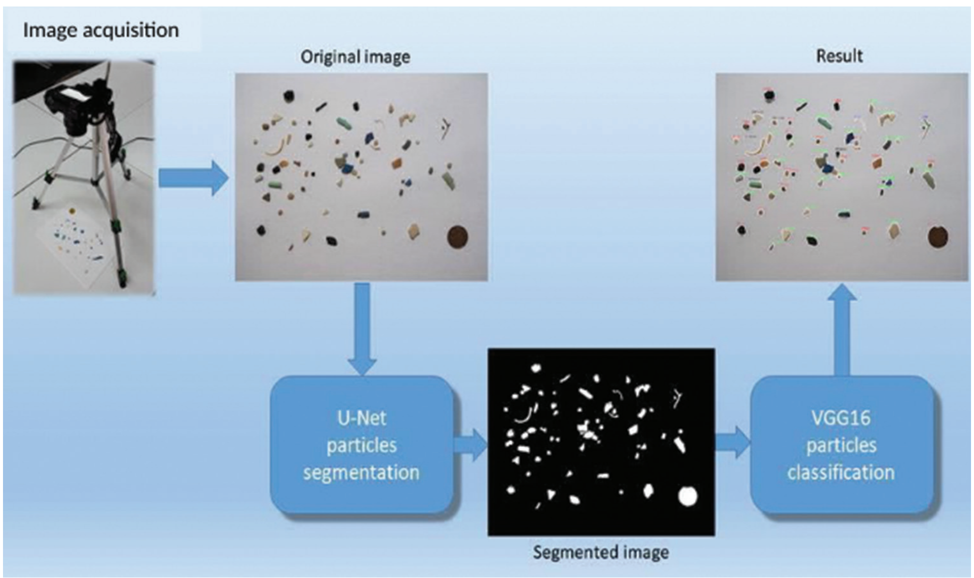

Figure 4. An example model showcases the quantification and classification of three primary MP types. Adapted with permission from Lorenzo-Navarro *et al.*[142] Copyright 2020, Elsevier.

Figure 5. The primary machine learning workflow for developing the microplastic analysis platform. Image created by the authors.

Table 4. Examples of bacteria, fungi, and algae in the biodegradation of plastics

Biodegrading microorganism	Example	Type of plastic	Reference
Bacteria	*Staphylococcus aureus*	PE	150
	Bacillus gottheilii	PE, PP, PET, and PS	151
	Bacillus subtilis	PE	152
	Pseudomonas aeruginosa	PE	153
Fungi	*Penicillium* species	PHB	153
	Pestalotiopsis microspora	PUR	153
	Zalerion maritimum	PE	154
	Aspergillus species	PE	155
Algae	*Anabaena spiroides*	PE	156
	Spirulina species	PE and PP	157
	Phaeodactylum tricornutum	PET	156
	Chlamydomonas reinhardtii	PET	158

Abbreviations: PE: Polyethylene; PET: Polyethylene terephthalate; PHB: Poly-3-hydroxybutyric acid; PP: Polypropylene; PS: Polystyrene; PUR: Polyester polyurethane.

in almost every ecosystem due to its diverse environmental adaptability as well as the capacity to secrete a wide range of enzymes and amino acids, such as manganese peroxidase, laccase, aspartate, histidine, serine, and lignin peroxidase, that can degrade macroplastics and MPs until mineralization.[159] According to Ameen *et al.*,[160] some fungal mycelia discharge extracellular enzymes that aid in breaking down plastics into small pieces (oligomers, dimers, and monomers), which are subsequently absorbed by the fungi and mineralized with the help of internal enzymes. The success of fungi in the degradation of plastics has also been associated with producing numerous polysaccharides and proteins that enable them to attach to plastic surfaces and secrete extracellular enzymes that help disintegrate the plastics.[159] The common fungi that have been used in the biodegradation of plastics include *Penicillium* species, *Pestalotiopsis microspore, Zalerion maritimum, Aspergillus* species, *Phanerochaete chrysosporium*, *Trametes versicolor,* and white rot fungi. These fungal species' degradation ability varies with the type of plastics and the duration taken to break down the plastics. For example, *Penicillium* species and *Z. maritimum* have been reported to break down the PE MPs, whereas *Aspergillus* species can break down the high-density PE plastics.[161]

Apart from fungi, bacteria are also known to play a significant role in the degradation of plastics in the environment.[151] Like fungi, bacteria also secrete both intracellular and extracellular enzymes that aid in the degradation of plastics. These enzymes include hydrolases, xylanase, depolymerases, protease, and chitinase.[159] The commonly used bacteria for MP biodegradation belong to the genera *Bacillus*, *Rhodococcus*, *Escherichia,* and *Pseudomonas.*[151] *Bacillus* species are the most researched bacteria in bioremediation, with different species showing variations in their degradation efficiencies. For example, *Bacillus cereus* has been shown to degrade PE, PET, and PS plastics, leading to weight losses of 1.6%, 6.6%, and 7.4%, respectively. Meanwhile, *Bacillus gottheilii* has been reported to degrade the same polymers, leading to weight losses of 6.2%, 3%, and 5.8%, respectively. *Bacillus subtilis,* on the other hand, has been reported to degrade high-impact PS, resulting in 23% weight loss. Other bacterial species, for example, *Pseudomonas aeruginosa* and *Penicillium simplicissimum,* have also been reported to degrade PE plastics, resulting in 20% and 7.7% weight loss, respectively.[162] Studies have also shown that different bacterial species can be combined to have a synergistic effect on MP degradation. A significant example is the combination of *Actinobacteria* and *Firmicutes,* which led to the degradation of low-density PE plastics by 60% in 3 weeks.[163]

Algae are also categorized as microorganisms that are capable of degrading plastic materials. These microorganisms produce toxins that effectively break down polymeric materials.[164] Like fungi and bacteria, microalgae species degrade different MPs at varying rates. For example, *Anabena spirodes* takes 45 days to degrade 8.18% of PE plastics. Other microalgae associated with the degradation of plastics include *Spirulina* species, *Phaeodactylum tricornutum*, *Chlamydomonas reinhardtii*, *Cryptomonas* species, and *Phormidium lucidum* (Table 4).[159]

Irrespective of the microorganisms involved, the biodegradation of MPs occurs through a sequence of steps, starting with biofilm formation, deterioration, fragmentation, assimilation, and mineralization (Figure 6). Biofilm formation occurs on the surface of the plastic, where microbes attach to the surface, reducing the hydrophobicity of the plastic[165]. Deterioration of the plastic occurs due to biofilm formation and the release of extracellular enzymes or toxins by microorganisms, leading to the fragmentation of plastics into monomers, oligomers, or dimers[166]. Assimilation involves taking up fragmented plastic molecules by microorganisms, converting them to soluble organic compounds with the help of intracellular enzymes. The last process of converting MPs to carbon dioxide, water, and methane is mineralization.[159]

Environmental factors and plastic properties drive the efficacy of MP biodegradation. Environmental factors such

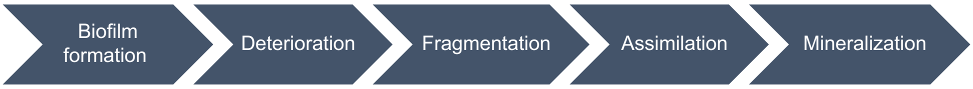

Figure 6. Illustration of the steps in microplastic biodegradation. Image created by the authors.

as oxygen level, pH, sunlight, and temperature directly or indirectly affect biodegrading microorganisms' growth, enzymatic production, and performance.[29] The abiotic environmental factors also affect the plastic decomposition rate as they affect these compounds' chemical composition. For example, a study by Gutiérrez-Silva *et al*.[167] showed that an increase in UV light and moisture led to an increased hydrolysis rate of poly (butylene adipate-co-terephthalate)-thermoplastic starch blends and, consequently, the rate of polymer biodegradation. Another study by Katarzyna Świderek,[168] showed that biodegradation of PET is directly affected by pH levels, as acidic conditions (pH 5) induced the hydrolysis of the two ester bonds forming bis-(hydroxyethyl) terephthalate, whereas only one ester bond was hydrolyzed in neutral and alkaline conditions (pH 7 and 9). Plastic properties such as molecular weight, crystallinity, shape, and size affect the polymer deposition rate. Polymers with high molecular weight, such as high-density PE, decompose gradually compared to low-density PE.[159] Other factors, such as crystallinity and the composition of co-polymers, affect the degradation rate as they determine plastic microbial accessibility and water.[169]

In the Arabian Gulf, extreme environmental conditions such as high salinity and elevated temperatures (>30°C) may limit the effectiveness of many plastic-degrading microorganisms. For example, halophilic bacteria such as *Halomonas profundus* and *Marinobacter hydrocarbonoclasticus* have shown plastic-degrading potential in saline environments, whereas thermophilic species such as *Thermobifida fusca* and engineered *Clostridium thermocellum* have demonstrated efficient PET degradation under elevated temperatures.[168,170] These findings suggest that the selection of native or adapted halo- and thermotolerant strains, as well as the development of engineered enzymes, is critical for effective biodegradation under Gulf conditions. Recent advances in protein engineering have enabled the development of thermostable PET hydrolases such as IsPETase and Cut190 variants, which retain high catalytic efficiency under elevated temperatures typical of the Gulf environment.[171,172] Direct evolution and computational enzyme design are further enhancing the substrate range and stability of these enzymes, opening new opportunities for scalable bioremediation strategies tailored to extreme marine ecosystems.

6. Conclusion

The widespread presence of MPs in marine environments poses a complex environmental and health issue. Beyond direct physiological effects, MPs may disrupt marine ecosystems, including reproduction in marine organisms and, consequently, food-web dynamics. Furthermore, consuming seafood contaminated with MPs may pose health risks to consumers. A multifaceted approach, including thorough research, is needed to address this problem. In addition to proactive legislative actions to reduce plastic waste, developing AI-powered technologies will improve monitoring and detection.

To implement this agenda, we propose a staged roadmap linking standards, shared data, validated AI, and field-tested bioremediation to policy uptake. Short-term actions establish common protocols and a regional repository; medium-term efforts deploy pilots and low-cost sensing; long-term measures embed AI- and nature-based solutions into coastal management and plastics policy. Measurable targets—including a 50% reduction in coastal MP concentrations within 10 years, repository growth to >1 million labeled spectra/images, and region-wide monitoring coverage—provide accountability while fostering international collaboration and academic–industry consortia.

Addressing MPs with particular emphasis on cutting back on single-use plastic bags is a global steady movement to control the contamination of ecosystems. While limited policies directly target primary MPs (e.g., bans on microbeads), interventions such as bans, fees, and taxes on plastic bags have gained traction globally. Many European nations have implemented widespread tariffs for plastic bags, greatly decreasing consumption. As effective efforts of Gulf nations to protect local, including marine environments, the UAE, through the Ministry of Climate Change and Environment, plans to implement a full ban on single-use plastics on January 1, 2026.[173] Similarly, the efforts on MPs in Saudi Arabia's marine environments, including the Arabian Gulf Sea, have been emphasized in a number of relevant national and international reports. According to the Minister of Environment, Water, and Agriculture, Saudi Arabia has joined the Alliance to End Plastic Waste in the Ocean and the World Ocean Council on a global scale.[174] As sustainable innovation is promoted locally in Saudi Arabia, plastic has been recycled in road construction to improve quality and lower costs.[175] While significant progress has been made through these initiatives, enforcement issues and unequal implementation remain challenges, especially at the national level. Although its efforts are mainly concentrated on more general environmental projects, Saudi Arabia has been making progress in combating plastic pollution. For example, the Saudi Green Initiative prioritizes environmental sustainability, aiming to preserve 30% of Saudi Arabia's land and marine regions by 2030. This initiative includes the national efforts that indirectly support the reduction of plastic waste and pollution in marine environments, such as waste management and afforestation projects. Second, innovative solutions such as cleaning robots have been implemented in Saudi Arabia to reduce plastic waste along coastlines. Red Sea Global, a developer of regenerative tourism destinations, leads programs to promote clean beaches and sustainable practices.[176] Such coastal cleanliness and sustainability efforts also support Saudi Arabia's broader Vision 2030 objectives for developing a sustainable tourism sector.[177] Third, recent life-cycle assessment evidence from Saudi Arabia indicates that advanced waste management strategies, including pyrolysis and mechanical recycling, can lessen the environmental impact of plastic waste.[178] These strategies seek to reduce dependency on landfills and produce high-quality recycled products, emphasizing a transition toward a circular economy concept.[169,178] Public awareness and responsible consumption can also play vital roles in mitigating this growing environmental challenge.

These national and regional initiatives align with general global perspectives that highlight advanced 2D nanomaterial-based treatment solutions and the crucial role of atmospheric transport and deposition as primary routes for MP exposure, underscoring the necessity for comprehensive, cross-media mitigation strategies.[179,180]

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The authors declare they have no competing interests.

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Consent for publication

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Further disclosure

During the preparation of this work, the authors used Grammarly and ChatGPT to improve language clarity. The authors reviewed and edited all content to ensure accuracy and take full responsibility for the final manuscript.

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