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Review

Micro- and Nano-Plastics Contaminants in the Environment: Sources, Fate, Toxicity, Detection, Remediation, and Sustainable Perspectives

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Abstract: The continuous production and widespread applications of synthetic plastics and their waste present immense environmental challenges and damage living systems. Microplastics (MPs) have become of great concern in various ecosystems due to their high stability and decomposition into smaller fragments such as nano-plastics (NPs). Nevertheless, MPs and NPs can be removed from the environment using several physical, chemical, and microbiological methods. This study presents a comprehensive narrative literature review, which aims to explore the various types of MPs and NPs, their sources, fate, toxicity, and impact on human health and environment. To achieve this aim, the study employed a comprehensive literature review methodology. In addition, it summarizes various methods of sample collection and analysis techniques. Remediation strategies for MPs and NPs removal are assessed and compared. Furthermore, it highlights interlinkages between the sustainable development goals (SDGs)—specifically SDG 14—and plastic pollution. Overall, priority for research and development in the field of MPs and NPs impacts on ecological ecosystems is a must as this will enable the development of scientific polices driven by global collaboration and governance which in turn will develop tools and methodologies that measure the impacts and risk of plastic pollution.

Keywords: degradation of micro and nano-plastics; analysis methods; health and environmental impacts; remediation techniques; sustainable development goals (SDGs)

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1. Introduction

Plastic consumption is rapidly increasing worldwide, and the production increased from 365.5 metric tons in 2018 to 390.7 metric tons in 2021, which averages about a 7% increase [1,2] and is expected to double within the next two decades [3]. In addition, there are improper or illegal disposal methods for the waste that is produced. Therefore, the UN Environment Programme (UNEP) and globe-trotting countries are working on formulating a new legally binding global instrument—a convention—that aims to end plastic pollution across its full cycle in all environments in line with the sustainable development goals (SDGs). The potential effects of micro- and nano-plastics (MPs and NPs (MNPs))

on human health and the environment are of great concern because plastic enters every element of life and then disintegrates into smaller particles [4].

Natural resources that have gone through several chemical and physical reactions are used to make plastics. The most abundant plastic polymers are polyethylene (PE), polypropylene (PP), polystyrene (PS), polyvinylchloride (PVC), nylon (PA), cellulose acetate (CA), and thermoplastic polyester (PET). The two primary procedures for plastic production are polymerization and polycondensation, which fundamentally change the basic components into polymer chains [5]. The polymers must undergo further chemical procedures to be recycled into new types of plastic because this process is rarely reversible [6]. Plastics can be designed to meet a variety of application needs with industrial additives including colors, plasticizers, and stabilizers [7].

Environmental accumulation is increasing due to the chemical stability nature of plastics. When plastic waste is disposed of, it is subjected to biological, chemical, and environmental factors and will degrade into vast quantities of MPs (<5 nm) and NPs (<0.1 mm) [8–11]. In recent years, research has focused on investigating plastic waste and its impacts on the environment including MPs, all of which has been widely discussed in the scientific community and the public media. MPs in particular have been successfully detected, identified, and quantified using advanced analytical methods. However, the detection and quantification of NPs in the environment still require additional investigation. The most widely used analytical methods include visual inspection using microscopy; spectroscopy methods, such as surface-enhanced Raman spectroscopy (SERS); X-ray photoelectron spectroscopy (XPS); Fourier transform infrared spectroscopy (FTIR); mass spectrometry, such as pyrolysis-gas chromatography-mass spectrometry (Py-GC-MS); and light scattering analysis, for example, dynamic light scattering (DLS) [12]. The combination of microscopic methods with analytical approaches could be useful for the precise identification of MPs and NPs in natural samples. Moreover, it is important to search for innovative methods that are consistent, cost-effective, and can be implemented in any habitat [13]. To reduce the concentration of MPs and NPs in the environment, the treatment technologies should be optimized. Even though the remediation and removal of plastics from the entire water system are impossible. The discharge of plastics into the environment can be reduced with their removal from wastewater which is the main source of plastic pollution. Moreover, their presence in the environment brought up the need for remediation strategies and the existing methods have been classified into four categories: physical, chemical, biological, and nano-remediation.

Calls for institutional policies to enforce classifications of hazardous polymers have also been made [14]. Additionally, national policies should explicitly and systematically reflect environmental obligations [15]. However, very little research has been done on the quantities, types, and toxicity of NPs, as well as their effects on human health. For instance, one MP particle can decompose into billions of NP particles, indicating that NP pollution is widespread [16–18]. Since NPs can pass through biological membranes, it is likely that they pose greater harm than MPs. This review article is one of the few in literature that highlights the link between plastic pollution and the Sustainable Development Goals (SDGs).

This review aims to provide a comprehensive analysis of the production, behaviour, and degradation of MPs and NPs in the environment, as well as their toxicity and impact on human health in the literature. The review further summarizes and assesses the various techniques used for detecting and sampling of these particles. Besides this, the relationship between plastic pollution and SDGs is investigated. While providing a perspective for future research.

2. Method

To address the research aim, authors conducted a comprehensive review study using a literature review methodology. To gather information, the review process was started with internet searches, the widely recognized electronic databases were utilized such as Elsevier (sciencedirect.com), Scopus (scopus.com), Springer (springerlink.com), and Google

Scholar (accessed on August 2023). Besides that, the most relevant existing international publications such as UN reports. The focus was on MNPs' articles within the last 10 years, except for lack of recent literature. It took around four months to complete the research process. Our research had different goals and used varying approaches including descriptive techniques and gathering information from primary and secondary sources. We focused on studying the main issues related to plastic pollution, specifically MNPs, and their impact on human health, environment, and sustainability. This review comprised three stages: formulating research aims, selecting and evaluating studies, and analyzing the content and findings of the selected articles. The search terms used were "plastic(s) pollution", "microplastics" OR "MPs", AND "nanoplastics" OR "NPs". The results were filtered to include only peer-reviewed and scholarly articles. The filtering of published articles is based on the occurrence, sources, fate, toxicity, detection, remediation, and sustainability of MNPs.

The search was repeated for all possible results to make sure that all the related peer-reviewed and scholarly articles were obtained. To ensure the suitability of the selected articles, we considered research terms and their synonyms. Accordingly, we reviewed all articles that contained a term associated with plastic pollution in their titles or keywords, as well as all articles whose abstracts featured words related to research terms. Thus, this review provides a comprehensive perspective of the current academic debate on plastic pollution issues and its impact on human health and the environment. After analyzing the search results, they were categorized and presented in appropriate sections to cover this article's scope. Figure 1 summarizes the methodological process.

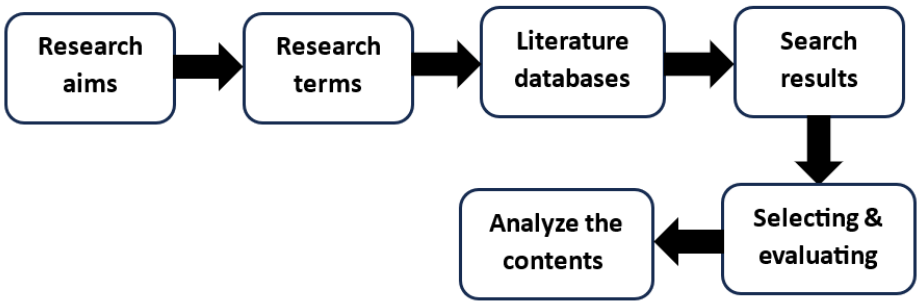


Figure 1. Research method of the literature review.

3. The Occurrence and Sources of Microplastics and Nanoplastics in the Environment

MPs and NPs can be classified into primary and secondary sources [19]; the primary are plastics produced at micronized scale, including domestic products, cosmetics, and medicine, while secondary are the result of the degradation of MPs by different processes such as mechanical (erosion, wave action), chemical (photooxidation, temperature, corrosion), and biological activities [20–22]. Furthermore, plastics are classified on their size into macro- (>25 mm; visible to the naked eye), meso- (<25–5 mm; visible under a light microscope), micro- (5 mm to 0.1 µm; separated under a microscope and identified using spectrometry), and nano- (<0.1 µm) plastics [23,24]. Manufactured plastics contain PP, PVC, PE, and PS as part of their chemical composition [25]. The plastic particles are found in various morphological forms (foam, fibers, pellets, and films), sizes, and colors (Figure 2).

The durability of plastic particles makes them highly resistant to environmental degradation as they readily adhere to hydrophobic persistent organic pollutants (POPs), which thus associating them with causing disease and death in numerous aquatic organisms. Remarkably, MPs and NPs are dispersed into the environment by many means such as landfills, sludge [26], discharge of wastewater treatment plants, food waste, terrestrial anthropogenic activities [27], personal care products (e.g., shower gels and shampoos), industrial abrasives (e.g., PS and plastic powder/fluff), residues from plastic processing and recycling plants [28], irrigation (lakes, rivers, reservoirs, and groundwater), street runoff and flooding [29].

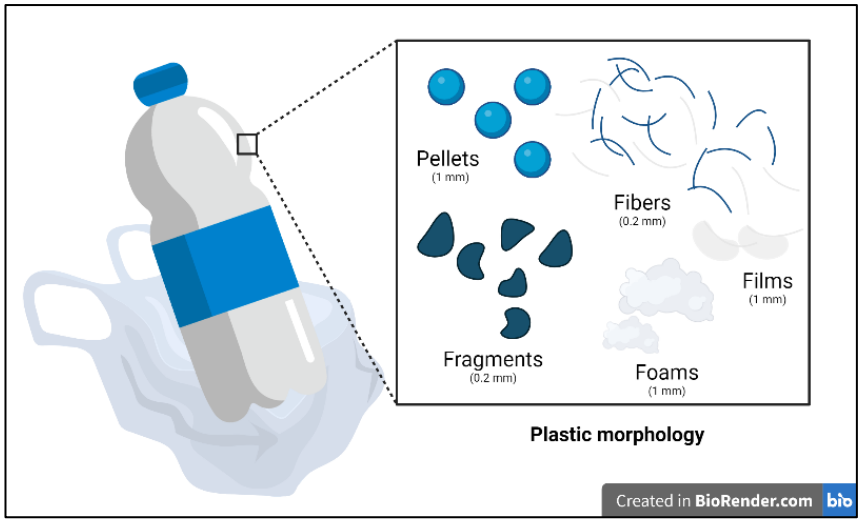


Figure 2. Plastic morphology.

The retention and transport of MPs and NPs in groundwater and soil are influenced considerably by their respective parameters (e.g., shape, size, density), soil media (texture, moisture, pH, temperature), and water flow (e.g., velocity, ionic strength, pH) [30]. Bioturbation is defined as interference in the deposition of soil and sediment due to living carriers of MPs and NPs from shallow soil layers to deep ones by ingestion and excretion of microbes [31]. Mites, collembolan, and certain mammals may spread MPs and NPs in soils via chewing, scraping, or even abrasion [32]. Those organisms (collembola, mites and digging mammals) could contribute to the generation of secondary MPs by crushing hard plastic fragments [33]. Many factors affect the quantity of deposition, preservation and transport of MPs and NPs including human activities, properties of particles (shape, size, and density), weather conditions, and environmental geography [34].

MPs and NPs are generated from land-based sources (80%) and sea-based sources (20%) [35]. Terrestrial ecosystems are the main source and transport paths of MPs and NPs into marine environments [36]. In addition, MPs and NPs have been detected in the atmosphere including indoor and outdoor environments [37] and arctic sea ice [38]. The main sources of MPs and NPs in the atmosphere are textiles production, attrition of rubber tires, household, and city dust [39], construction materials and waste incineration [40]. The indoor atmosphere has higher levels of MPs and NPs due to lower removal by dispersal mechanisms [39] which their concentration depends on room partition, ventilation, and airflow [41].

Other possible sources of MPs and NPs that enter the human food chain are the consumption of drinking water [42] bottled water [43], and commercial salt [44]. For instance, a study conducted in 14 countries on tap water and bottled water showed that 80% of the samples contained 4.34 plastic particles/liter, while another examined bottled water and revealed that 90% contained plastic pollutants [45,46]. Since MPs and NPs commonly escape filtration systems and are found in drinking water, removing plastics from water bodies in the size range of 1–10 µm has become a subject of concern [47]. Thus, MPs may enter the human body commonly through endocytosis and persorption.

The toxic chemicals are absorbed and accumulated on the surface of MPs and NPs, and their biomagnification poses a new risk to the biosphere in the long run [48]. Wastewater sludge, organic fertilizers, and agricultural plastic mulch films are some of the dominant sources of MPs and NPs in the environment [49]. However, many MPs and NPs derived from effluent discharge and agricultural activities pass through freshwater ecosystems, such as urban wetlands and natural rivers, to complete land-sea transport. As transition zones for substance exchange between terrestrial and aquatic ecosystems, wetlands may be essential in the environmental migration processes of MPs [50].

Evidently, MPs and NPs were observed in wetlands. For instance, analysis of sediment samples collected from 20 urban wetlands in Australia showed that MPs were observed at all wetlands with an average abundance of 46 particles/kg of dry sediment while plastic fragments accounted for 68.5% of all MPs found [50]. Another study conducted on coastal mangrove wetlands in China indicated that the abundance of MPs in mangrove sediment ranges between 8.3 and 5738 particles/kg with different MPs shapes including fibers, films, fragments, foams, and pellets [51]. It was concluded that the areas with intense human activity such as tourism, harbor transportation, and fisheries, and with dense vegetation intercept more MPs. In different areas of the Yellow River Delta wetland, MPs abundances ranged from 136 to 2060 particles/kg, where concentrations of PET ranged from 536 to 660 μg/kg, and the concentrations of polycarbonate (PC) ranged from 83.9 to 196 μg/kg [52]. This indicates that coastal wetlands are particularly at risk in trapping plastic waste since they are at the interface of terrestrial and marine systems and tidal wetlands are subject to plastic waste deposition, as they are within the vicinity of highly dense human population areas and activities.

Furthermore, PE MPs with sizes ranging from 0.96 to 1.57 mm were detected in some fish species common in the Arabian Gulf [53]. A study on MP pollution was carried out in Kuwait, which included analyzing 44 intertidal locations and 87 fish and mussels' gastrointestinal contents. The findings revealed that only a few MPs were detected in about 15 locations, but three pieces of MPs were detected in the gastrointestinal tract of the grouper of fish (locally known as Hamour); and the identified MPs were mainly PP, PE, and PS [54]. Habib et al., have reported that MPs concentration is highest in northern shores of the Arabian Gulf [55]. A study by Saif Uddin et al. conducted in 2020 indicated that 50% of the global wastewater influent remains untreated, which adds about 3.85×10^{16} MPs annually to the aquatic environments [56]. The study concluded that treating all produced wastewater before its release could lead to a 90% decrease in the current MPs input into aquatic systems.

MNPs are characterized by their persistence and accumulation in the environment. Thus, MNPs pollution negatively impacts the entire environment by contaminating the air, land, and water due to inadequate plastic waste management infrastructure, posing a threat to ecosystems and human health. MNPs change soil properties, harming biodiversity, and plant health. Wastewater effluent and sludge often contain significant quantities of plastic; thus, improper handling of plastic waste can cause plastic to enter terrestrial ecosystems, either directly or indirectly. Consequently, plastics can enter water and soil when effluent and sludge are used as fertilizer. As a result, water resources will be impacted.

4. Uptake and Bioaccumulation of Microplastics and Nanoplastics in the Human Body

Inhalation, ingestion, and skin contact (Figure 3) are the three main ways that MPs and NPs enter the human body [57,58]. Synthetic fabrics and rubber tires are among the MPs that can be inhaled through the air and come from urban dust [39]. MPs are consumed due to their prevalence in the food chain and water supplies [59]. MPs and NPs cannot travel through the skin membrane because it is too fine, but they can enter through wounds, sweat glands, or hair follicles [60]. Even though MPs and NPs are present in the human body through all three channels, the risk of absolute exposure is highest from environmental and seafood particles. This is because these settings are conducive to the long-term weathering of polymers, leaching of chemical polymer additives, residual monomers, exposure to contaminants, and the activity of pathogenic microbes [61–65].

4.1. Gastric Exposure

The most significant way that humans consume plastic particles is by ingestion [66]. Although there are no studies particularly examining the toxicity of NPs in people, there is evidence that MPs are being consumed through food and drink [46]. The discovery of plastic particles in human feces samples during initial examination confirms this [67]. Yet no research has investigated what happens to the MPs and NPs after they get into

the gastrointestinal (GI) system. It is important to investigate how the particles move through the GI tract and if they move past the gut epithelia or remain in the gut lumen. Given that the tight junction channels' important pores have a maximum functional size of about 1.5 nm, it is doubtful that MPs can penetrate at the paracellular level [68]. The possibility of their entering through lymphatic tissue and infiltrating the microfold (M) cells in the peyer's patches through phagocytosis or endocytosis is particularly probable [69]. Following intraperitoneal injections into mice, 1, 5, and 12 µm polymethacrylate and PS particles were observed to be phagocytosed by peritoneal macrophages [70,71], and the intestinal absorption was observed to be low i.e., 0.04–0.3% [72].

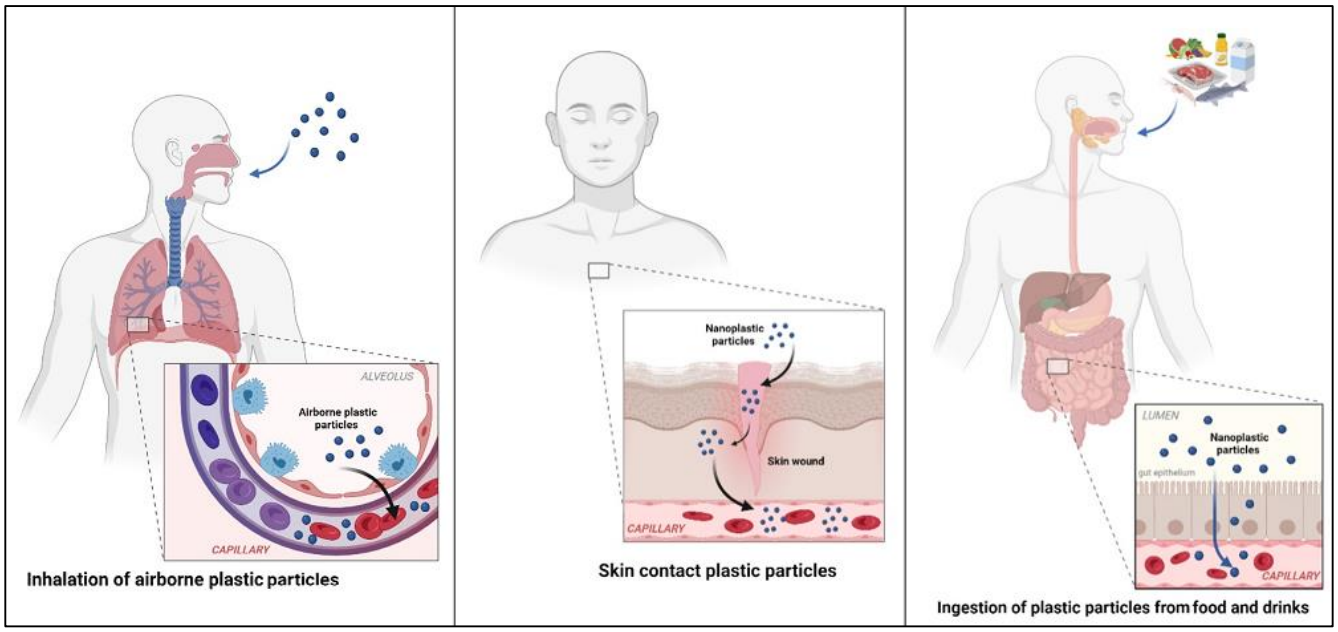


Figure 3. Ingestion, skin contact, and inhalation are the main routes for MPs and NPs to enter the human body (Created in BioRender.com).

In comparison to MPs (2–7%), the oral bioavailability level of 50 nm PS NPs is ten to one hundred times higher [73,74]. There is no clear relationship between the absorption, size, and structure of NPs, which is consistent with the findings for MPs [75]. Some studies have demonstrated that different in vitro intestinal models' ability to absorb NPs (50–500 nm) varies substantially, with rates ranging from 1.5 to 10% depending on the size, chemical composition, and type of model utilized [11,75,76]. NPs might change after being ingested, and this will affect how well and how quickly they can be absorbed. In general, nanoparticles may interact with a variety of substances in the GI tract [77], while a group of proteins known as a "corona" is known to surround them [78,79]. An in vitro model of human digestion has been found to modify the protein corona, which increases the translocation of nanoparticles [74]. A recent analysis looked at how dispersed organic materials interact with metal (oxide) nanoparticles and discovered that these interactions greatly affect agglomeration and deposition [80]. Furthermore, organic matter prevalent in water will stick to the surface of nanoparticles. More research should be conducted to fully understand the mechanisms involved in the uptake of MPs and NPs via the gastric route.

4.2. Pulmonary Exposure

Inhalation is the second most frequent way for people to be exposed to MPs and NPs. Airborne plastic particles, particularly from synthetic fabrics, are present in indoor spaces and can cause unintentional inhalation [81]. The lungs' alveolar surface area is about 150 m^2, and their tissue barrier is very fine. This barrier is permeable to nanoparticles and allows them to enter the capillary bloodstream [66]. Human health problems are caused

by the absorption of different particles, especially MPs and NPs, which have the potential to become deeply entrenched in the lung and either remain there on the alveolar surface or relocate to different areas of the body [81–84]. Hydrophobicity, surface charge, surface functionalization, protein coronas, and particle size are some of the variables that influence how MPs and NPs are absorbed and expelled from the lungs [85].

According to studies looking at PS particle absorption rates in alveolar epithelial cells in a lab setting, absorption varies with the size of the plastic particles [86–90]. Recent research on the inhalation of plastic particles by humans has found that urban areas' air fallout is a major source of the particles [40]. Dris et al. investigated the concentrations of MPs in the air inside and outside of two individual residences and one office building. They revealed that the indoor samples had a concentration of between 1 and 60 fibers/m^3, which was significantly higher than the outside samples' levels, which ranged from 0.3 to 1.5 fibers/m^3 [37].

4.3. Dermal Exposure

Another significant source of plastics is the health and beauty industry, particularly the body and face scrubs applied directly to the skin [13], the exposure is through the dermal application of nanocarriers for medication delivery. Small particle size and stressed skin conditions are crucial for skin penetration, despite no definitive data on the effects of nanocarriers [60]. There is currently no research that has examined how well NPs can penetrate the skin's outer layer. Thus far, one study documented nanoparticle penetration in small quantities via the skin [90].

The stratum corneum, the skin's outermost layer, serves as a barrier to protect the skin from harm, toxins, and microorganisms. Corneocytes make up the stratum corneum, which is bordered by lamellae of hydrophilic lipids such as cholesterol, ceramide, and long-chain free fatty acids [91]. Plastic particles could enter the body through sweat glands, skin wounds, or hair follicles, however, absorption through the stratum corneum by polluted water is deemed as uncommon because MPs and NPs are hydrophobic [60].

Plastic particles' entry into the body and subsequent distribution throughout the skin tissue was studied by Alvarez-Roman et al., where pig skin tissue and fluorescent PS particles with a diameter of 20–200 nm were used [92]. A confocal laser scanning micrograph of the skin showed that the concentration of 20 nm PS NPs was higher than that of 200 nm NPs in the hair follicles. To embed themselves into the deeper skin tissue, the particles need to pass through the stratum corneum, which neither was able to do. These results were confirmed by Campbell et al., who also found that PS particles with a diameter of 20–200 nm can only penetrate the skin's top layers at a depth of 2–3 μm [93]. Further, Vogt et al. found fluorescent PS nanoparticles with a diameter of 40 nm in the perifollicular tissue of skin explants that had undergone cyanoacrylate follicular stripping, and this research established that when particles were given transcutaneously, the langerhans cells then absorbed them [94].

Moreover, skin damage from UV exposure weakens the skin barrier [95] and causes an increase in the skin's penetration by different particles [96,97]. Common components in body lotions such as urea, glycerol, and hydroxyl acids improved the ability of nanoparticles to penetrate the epidermal barrier [98].

Kuo et al. highlighted the effects of oleic acid, ethanol, and oleic acid-ethanol enhancers on the transdermal transport of 10 nm zinc oxide nanoparticles by passing through the multilamellar lipid areas between corneocytes [99]. They found that each chemical had the potential to increase the ability of zinc oxide nanoparticles to penetrate the epidermal barrier. Bouwstra et al. established a three-layer "sandwich model" through crystalline structure analysis of different lipid lamellae compositions in stratum corneum samples obtained from human and swine sources [95]. This model presumably prevents big nanoparticles from penetrating healthy skin.

In conclusion, experiments conducted in vitro and in vivo have proven that MPs and NPs can enter the human body through the skin barrier. Nevertheless, the basis for all

these investigations is PS particle modeling. It would be beneficial to undertake additional research using environmental sample collection to completely comprehend the penetration properties of MPs and NPs as those samples could contain a range of plastic particles with various properties.

5. Toxic Effects of MPs and NPs on Human Health

Plastic particles can accumulate within human cells and cause various harmful toxicological effects at cellular and molecular levels [100], trigger the immune system, induce inflammation, oxidative stress, cytotoxicity, and generate reactive oxygen species (ROS). The severity of these effects depends on several factors, such as size, type, concentration, the shape of the plastic particle, and the type of cells exposed [101]. Table 1 summarizes the results of various studies that have investigated the effects of MPs and NPs on human cells.

Table 1. The effect of different NPs and MPs on different human cells.

Characteristics of Tested Particles	Particle Size	Target Cells	Effect of MPs and/orNPs on Organisms	Ref.
PS MPs	0.5, 1, and 5 μm	Human umbilical vein endothelial cells (HUVECs)	• Reduced cell viability. • Effects the ability of HUVECs to form tube.	[102]
PS NPs	100 and 500 nm	HUVECs	• Damaged the cell membrane. • Induced autophagy.	[103]
PS MPs	3 and 10 μm	Human intestinal cell line HT-29	• Reduced cell viability. • Increased reactive oxygen species.	[104]
PS NPs	50 nm	Human intestinal Caco-2 cells	• Changed the structure of the nucleus. • Changed the genotoxicity biomarkers.	[105]
PE, PP, PET, and PVC MPs	1–4 μm and 10–20 μm	Human intestinal epithelial cell line Caco-2	• Caused cytotoxicity.	[106]
PS NPs.	25, 100 and 1000 nm	Human small intestinal epithelium	• Increased epithelial permeability.	[107]
PS MPs	1 μm	Mice intestinal tissue and liver	• Damaged the intestinal and liver tissue. • Insulin resistance.	[108]
PE MPs and PCBs	40–48 μm	Human hepatoma cell line HepG2	• Remarkable lipidomic changes.	[109]
PS NPs	50 nm	rat hepatocyte	• Increased superoxide dismutase activity. • Increased malondialdehyde content. • DNA damaged.	[110]
PS NPs	25 and 70 nm	Human alveolar type II epithelial cell line A549	• Reduced cell viability. • Arrested cell cycle. • Upregulated transcription of pro-inflammatory cytokines. • Interfered protein expression related to cell cycle and pro-apoptosis.	[111]
PS MPs	1 and 10 μm	Human alveolar A549 cell line	• Disturbed cell metabolic activity. • Decreased cell proliferation. • Decreased Ki67 protein expression.	[112]
PS NPs	40 nm	Lung epithelial cells (BEAS-2B cell line)	• Reduced cell viability.	[113]
PS NPs	40 nm	Bronchial epithelium, pulmonary alveolar epithelial cells	• Reduced cell viability. • Altered gene expression. • Redox imbalance. • Increased proinflammatory mediators. • Induced cell apoptosis. • Destructed cell epithelial barrier.	[114]

Table 1. *Cont.*

Characteristics of Tested Particles	Particle Size	Target Cells	Effect of MPs and/orNPs on Organisms	Ref.
PET NPs	~62 nm	Human primary nasal epithelial cells	• Increased intracellular ROS. • Disrupted mitochondrial membrane potential. • Upregulation of LC3-II and p62 expression. • Changes in autophagy pathways.	[115]
PE MPs beads and fragments	Beads: 10, 50 and 100 µm; Fragments: 25–75 and 75–200 µm	Peripheral blood mononuclear cells	• Beads induced immune response and cell hemolysis. • Fragments caused cytotoxicity, inflammatory response, cell hemolysis, and produced ROS.	[116]
PS, PMMA, and PVC NPs	50–310 nm	Human monocytes and monocyte-derived dendritic cells.	• Higher release of cytokines.	[117]
PS NPs.	50 nm	Human peripheral blood lymphocytes	• High cell hemolysis. • Chromosomal damage. • Genomic imbalance. • Cytotoxicity.	[118]
PS NPs and functionalized PS pristine, PS-COOH, PS-NH2	100 nm	Mouse mononuclear macrophage (RAW264.7) cell line	• High cytotoxicity. • Induced reactive oxygen species production. • Changed the mitochondrial membrane potential. • Induced apoptosis in macrophage cells.	[119]
PS NPs	100 nm, 600 nm	Human gingival fibroblasts	• Increased inflammatory markers expression NF-κB, MyD88 and NLRP3. • lowered metabolic activity rate.	[120]
PS MPs	5–25, 25–75, 75–200 µm	Human dermal fibroblast, HeLa cell line, peripheral blood mononuclear cells (PBMCs) and KATO III cells	• ROS generation. • Cancer cells and fibroblasts cell death. • Released hemoglobin and lactose dehydrogenase.	[121]

Note(s): Microplastics (MPs), nanoplastics (NPs), Polystyrene (PS), polyethylene (PE), polypropylene (PP), polyethylene terephthalate (PET), polyvinylchloride (PVC), polychlorinated biphenyls (PCBs), polymethyl methacrylate (PMMA).

6. Methods of Microplastics Analysis

6.1. Visual Inspection Methods

Visual inspection techniques of MPs include, observations made by the direct visual method with the naked eye, using an optical microscope, and/or electron microscope, which are used to select, classify MPs, and observe the colour and size of the tested object [122,123] (Figure 4). These techniques are time-consuming and of low accuracy [124], in addition, the error rate is negatively related to the particle size [125].

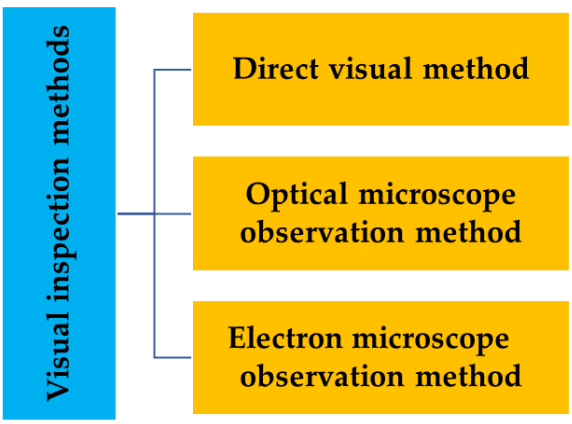


Figure 4. Classification of visual inspection methods.

The advantages of visual inspection method are easy to identify samples that include a significant amount of large MPs, giving a quick and affordable overall picture of their abundance. While the limitations are the samples' nature cannot be established, and the identification techniques must be combined.

MPs < 100 µm are difficult to identify or observe, even with a microscope [126–128]. Therefore, the development of technologies for the identification of MPs are crucial to attain more precise and effective results.

6.2. Thermal Analytical Methods

The classification of thermal analytical methods is presented in Figure 5.

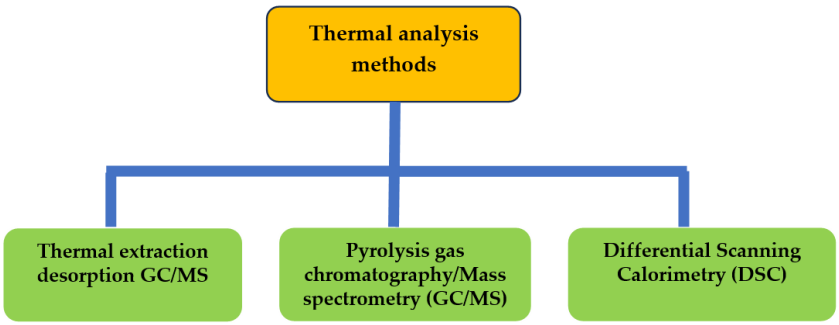


Figure 5. Classification of thermal analysis methods.

The Pyr-GC-MS, TED-GC-MS, and DSC approaches are mostly used to identify MPs in the environment due to their excellent detection accuracy. The advantages and disadvantages in addition to some important properties are summarized in Table 2. An overview of the application of thermal analytical techniques in detecting MPs is provided in Table 3.

Table 2. Comparison of thermal analysis methods in detecting microplastics.

Method	Advantages	Disadvantages	Sample Mass	Detection Limit	Ref.
Pyr-GC–MS	Different types of polymers, precise results, great sensitivity, and no sample preprocessing	Long processing times, sample degradation, high reaction temperatures, and manual placement.	0.5 mg	0.007 mg/g	[129,130]
TED-GC–MS	High sample mass, no blocking reaction cube, and no sample preprocessing	Excessive processing time, sample degradation, and high reaction temperatures	100 mg	-	[131,132]
DSC	Accurate results, widely applied technique, inexpensive and straightforward analysis	Long processing times, sample damage, substrate influence that is easy to see	3–15 mg	-	[133,134]

Table 3. An overview of the thermal analysis application in microplastics.

Method	Source of the Sample	Type of Sample	LOD	Sample Abundance	Ref.
Pressurized liquid extraction & Pyr-GC–MS	Soil and sediment	PE, PP	-	PE (3.3 ± 0.3 mg/g) and PP (0.08 ± 0.02 mg/g)	[135]
Pyr-GC–MS	Soil and sediments of freshwater	PE (fractionation ratio 15:2), PE (fractionation ratio 17:2), PE (fractionation ratio 18:2), PP, PS (pyrolysis product Sty), and PS (pyrolysis product aMeSty)	PE (fractionation ratio 15:2, 4800 µg/L), PE (Fractionation ratio 17:2, 2500 µg/L), PE (Fractionation ratio 18:2, 11,300 µg/L), PP (43,200 µg/L), PS (pyrolysis product Sty, 500 µg/L) and PS (pyrolysis product aMeSty, 1600 µg/L)	-	[136]
Pyr-GC–MS	Stomachs of marine fishes	PVC, PET, nylon, silica gel, and epoxy resin	-	-	[137]
Pyr-GC–MS	Surface water and wastewater	PS and PE	PS (30 µg/L) and PE (1000 µg/L)	-	[138]
Pyr-GC–MS and Nile red dye	Lagoon sludge	-	-	Fresh sludge (40.5 ± 11.9 × 103 particles/kg) and dehydrated sludge (36 ± 9.7 × 103 particles/kg)	[139]
Pyr-GC–MS and FTIR	Surface water	PVC, PP, and PE		0–110,000 particles/km^2	[140]
TED-GC–MS	Freshwater	PE, PS, PET, and PP	PE (20.0 µg/mg), PP (5.7 µg/mg), PS (2.2 µg/mg) and PET (18.0 µg/mg)	-	[141]
TGA, DSC	Wastewater	PE, PP, PET, PA, PES, PVC, and PU	-		[142]
DSC	Wastewater	PE, PP, PA, and PET	-		[143]
ATR-FTIR and DSC	Dutch beaches	-	-	-	[144]

6.3. Spectral Analytical Method

In comparison to visual recognition alone, the spectral analytical method yields more accurate information [8]. As of now, spectroscopic techniques can both, detect and verify

the composition of MPs. This is due to the spectral signal's ability to reflect the distinctive characteristic peaks that each type of MP produces. The polymer types of MP particles with a minimum particle size of 10 µm and 1 µm, respectively, have been determined using FTIR and Raman spectroscopy.

An overview of the advantages and limitations of spectroscopic analytical techniques are provided in Table 4.

6.4. Other Analytical Methods

The advantages and limitations of the most popular additional methods for analyzing MPs are provided in Table 5.

Scanning electron microscopy energy dispersive spectroscopy (SEM-EDS) is typically paired with vibration spectroscopy as an adjunct to the analysis to detect microplastics. There is not much research on the independent detection of MPs using SEM-EDS now, presumably because this technique cannot show chemical composition data [145]. There is not much research on the detection of MPs by High Performance Liquid Chromatography (HPLC), and the existing ones do not accurately identify the polymers. Therefore, more research is recommended. The combination detection of SEM-EDS and HPLC in the future may overcome the bottleneck of the existing MPs detection studies, based on the advantages and disadvantages analysis. Table 6 summarizes the findings on additional MPs analysis techniques.

Table 4. Advantages and limitations of spectroscopic analytical techniques.

Method	Particle Size	Advantages	Limitations
FTIR	ATR-FTIR can study particles >500 µm in size, while microscope coupled with FTIR can analyze particles <20 µm.	Nondestructive, reliable, quick, and credible. Significantly reduced analysis time using automatic FTIR imaging techniques like FPA, which enables the quick capture of thousands of spectra within an area using a single measurement.	Samples must be IR reactive; <20 µm may not provide interpretable spectra due to insufficient absorbance. Non-transparent particles are challenging to analyze. High in cost and needs skilled personnel to operate and process the data. The ambient matrix has an impact on the detection (e.g., biofilm growth on polymer), which makes it challenging to interpret the data. To get rid of IR active water, the sample needs to be processed.
Raman Spectroscopy	For particles >1 µm, the microscopy coupled Raman Spectroscopy (RS) approach is appropriate. For particles ranging in size from 1 to 20 µm, it is the only approach that works.	Enables the investigation of microscopic particles (1–20 µm) with excellent spatial resolution and relatively low sensitivity to water, analyze opaque and dark particles; perform fast chemical mapping, allowing for quick and automatic data gathering and processing.	Fluorescence from biological, organic, and inorganic contaminants interferes heavily and makes it difficult to identify MPs.Prior to analysis, the sample must be cleaned; crucial Raman acquisition parameters include wavelength, laser power, and photo bleaching. Micro-RS automated mapping is still being developed. The analysis by RS is time consuming.

Table 5. The most popular methods for analyzing microplastics: advantages and limitations.

Method	Particle Size	Advantages	Limitations
Scanning ElectronSpectroscopy	Analysis is possible for particles with diameters as small as a micron.	Creates a high-resolution picture of the samples.	High vacuum is required to cover the samples, and there is no precise identification data available.
Liquid Chromatography	The chemical extraction needs a sample size of several milligrams to carry out this examination.	Selected polymers have high recoveries.	Its uses are restricted to environmental samples since it is impossible to establish physical features, such as size information. Per run, only a few samples can be evaluated. By using this procedure, only particular polymers, such PS and PET, may be evaluated.

More detailed information about the above-mentioned analytical methods can be found in Supplementary Material.

6.5. The Evaluation of Analysis Methods

The main analytical technique used now is vibrational spectroscopy, which does not harm the sample and may reveal the physical and chemical properties of MPs. Additionally, widely analyzed MPs from water and soil mostly involve FTIR and Raman methods of vibrational spectroscopy. Research on airborne MPs has slowly begun to surface in recent years, but most of the work that has been published so far has concentrated on atmospheric deposition and a particular topic. Additionally, the fluorescence background can readily

affect Raman, which slows down its development. High spectral noise, spatial resolution, and a poor ability to identify water-containing materials are all characteristics of FTIR. Due to the destructive nature of the thermal analytical method's identification process, it is impossible to determine the quantity and shape of MPs. The main drawback of Pyr-GC-MS is that the sample mass is just 0.5 mg and MPs must be manually inserted in the pyrolysis reaction tube. To fully detect MPs, it is necessary to create a spectrum database of popular plastic types. TED-GC–MS improves the sample mass to 100 mg and overcomes the limitation of sample contamination from the reaction tube. However, high temperature, which can reach 1000 °C, hinders its development. DSC has a promising future in the analysis of MPs in water. However, this approach needs pretreatment and only effectively detects MPs of the type of PE and PP. In conclusion, the thermal analytical method's reaction temperature is high, and the leakage of MPs' combustion products contributes to environmental pollution.

Terahertz spectroscopy (THz) offers the qualities of solid penetration and high sensitivity, but the equipment is expensive and heavy, plus the spectrum signal-to-noise ratio is poor. High spectrometry imaging (HSI), whose images contain hundreds of small spectral bands from visible light to infrared and tens of thousands of pixel space, can directly offer samples of visual effects. As a result, we can swiftly determine the chemical make-up of MPs including other details like size, shape, and so forth, according to each pixel space. This technique offers a fresh approach to detecting MP pollution. However, this method's quick advancement is slowed down by difficult operation procedures and poor image quality. In addition, the machine learning technique for detecting MPs in conjunction with the spectrum analysis technique is still under development. Both HPLC and SEM-EDS are rarely utilized for MPs identification. Currently, SEM-EDS is mostly utilized to identify NPs. However, this approach does not offer information about the chemical composition of plastics. Additionally, HPLC may be modified to analyze huge samples. The chemical makeup of samples can theoretically be discovered. Currently, SEM-EDS have been used to identify PA, PS, PE, PP, and PVC in nature. Only their absorption content and amount have been determined. SEM-EDS must therefore be developed further.

Table 6. Summary of research findings on other analytical methods for microplastics.

Method *	Sample Source	Sample Type	Element Type	Sample Abundance	Ref.
SEM-EDS [1], polarized light microscope and μ-Raman [2]	Caspian Sea	-	C, O, Fe, Ba, Na, Si, and Al	-	[146]
SEM-EDS and μ-FTIR [3]	East Coast	PP, PE, PS, PET, PVC and PP-PE copolymer	-	--	[147]
SEM-EDS	Sediment	-	Cr, Ni, Cu, Zn, Pb, As, and Cd	-	[148]
SEM and XRD [4]	Aquatic environment	PA, PS, PE, PP, and PVC	-	-	[61]
Fluorescence microscopy, FTIR [5] and SEM-EDS	Beach	PE	-	45 ± 12 particle/kg to 220 ± 50 particles/kg	[149]
μ-FTIR and SEM-EDS	Beijiang River	-	-	178 ± 69 to 544 ± 107 particles/kg	[150,151]
FTIR and SEM-EDS	Sediment of Suhai lake	PE, PP, and PVC	-	24 ± 7 to 14 ± 3 particles/kg	[152]
HPLC-MS [6]	Pet food	PET	-	1500 ng/g to 12,000 ng/g	[153]

* Note(s): [1] Scanning electron microscopy energy dispersive spectroscopy, [2] Raman spectroscopy, [3] Microscope and fourier transform infrared spectroscopy, [4] X-ray diffraction, [5] Fourier transform infrared spectroscopy, and [6] High-performance liquid chromatography mass spectrometry.

The Raman spectrum's fluorescence background interference must be eliminated. Modern unconventional Raman spectroscopy techniques including face-off and nonlinear Raman spectroscopy can increase spectral data signal-to-noise ratios as well as Raman intensity. The increase in signal strength brought forth by nonlinearity, such as CARS and SRS, creates a new avenue for the investigation of MPs in real time. Strong signals in CARS and SRS are only produced by the desired molecular vibration patterns. As a result, fluorescence interference is reduced, data analysis becomes more accurate, and sample preparation is no longer required.

Due to its straightforward operation, FTIR technology performs better on MPs > 20 μm. The impact is greater than that of Raman spectroscopy, even though the detection limit is lower. Furthermore, the interference of fluorescence background in the Raman spectrum

is not a concern when using the FTIR approach. The THz technology can be improved in the future to make use of its high sensitivity and powerful penetration benefits. Given the size of existing THz and its primary use in the detection of MPs, the development of a portable THz is a future challenge. A new method for monitoring MP pollution is offered by the identification and qualitative method of HSI, despite its negative and low detection limit which only extends to 300 µm. Therefore, lowering the HSI technology's detection limit will enable real-time monitoring of MP pollution. SEM-EDS and HPLC are attractive options since they complement one other in identifying chemical components. The two approaches can likely be used for the identification of MPs since SEM cannot obtain the chemical composition while HPLC can. Currently, it is important to establish a consistent and unified standard detection method for MPs in diverse settings, such as different habitats. A variety of analytical and data processing techniques, such as machine learning, should be combined as much as possible for the detection and analysis of MPs to find a non-destructive, effective, and high-throughput detection method to lower the detection limit of the current spectral detection techniques.

7. Sampling of MPs and NPs in the Aquatic Environment

MPs and NPs are sampled through water and aquatic sediment collection plus biological specimens [154–156]. Multiple approaches for sampling MPs and NPs exist, each has its own advantages and limitations. Sampling method selection is dependent on multiple factors including the objective of the investigation, matrices to be sampled, available equipment and size limitation of target MPs [157,158]. Overall, sampling MPs from marine environments can be categorised into three approaches as indicated in Table 7.

Table 7. The categories of sampling approaches and methods.

Sampling Approach	Criteria	Application	Advantages	Limitations
Selective Sampling	Utilized when plastic items are large enough for identification with the naked eye, extracted directly from environmental matrices.	Beach sampling	Simple & straightforward	Size limitation of detectable MPs is high and less obvious items are easily overlooked particularly when mixed with other debris.
Bulk Sampling	Involves collecting the entire sample without decreasing its volume during the sampling.	Sediment sampling & occasional water sampling	Collects all MPs- and NPs present within the sample regardless of size and visibility.	Sample collection is relatively small in amount which may negatively affect sample representativeness
Volume-Reduced Sampling	Used when the entire volume of a bulk sample needs to be reduced by fast filtration during sampling; thus, only small fraction of the sample is being preserved for further analysis.	Water sampling	Covers large quantities or areas of samples.	Substantial loss of MPs and NPs may occur as most of the sample is lost/discarded due to fast filtration, which is evident in the MPs' size being smaller than the mesh size of sampling tool.

Furthermore, there are multiple sampling methods that can be employed for MPs and NPs in both water and sediment. Water samples can be collected either from the water column at specific depths or the surface. It is common to use manta nets (trawls) and neuston nets when sampling surface or near-surface water [157,159]. Their advantages include: (1) easy to use, (2) samples large volumes of water, (3) captures large number of MPs. However, certain limitations must be considered as: (1) they are expensive to acquire, (2) require a boat for use, (3) are time consuming, (4) samples are subjected to potential contamination by the tow ropes and the boat/vessel, (5) the lowest limit of MPs detection is 333 µm [157,160].

Commonly used equipment for water column sampling includes plankton nets for surface and near-surface sampling, bongo nets for deep water sampling, continuous plankton recorders (CPR), multiple opening-closing nets and near-bottom trawls [161–163]. These come with advantages and limitations, for example, plankton nets are: (1) easy and quick to use, (2) able to sample medium volumes of water, (3) have a small mesh size (~100 µm) allowing sampling in a short period of time (i.e., under a minute) and acquires MP concentrations 30 times higher than manta nets [164]). However: (1) they are expensive, (2) require

a boat, (3) require water flow for static sampling, (4) could get clogged or break, and (5) sample lower volumes of water in comparison to manta nets [157,165].

Other sampling tools include water intake pumps (e.g., shallow-water plankton pump (SPP), deep-water plankton pump (DPP) and submersible pump) and water collection bottles [166–168]. Water intake pumps enable sampling of large volumes of water effortlessly and provide a choice of mesh size. Nevertheless, they require equipment, and energy to work and are subjected to potential contamination by the tools, plus they could pose some difficulty when transporting them between sampling locations [154,157]. Results by Shi et al., showed that manta nets (trawls) and plankton pumps produced similar MPs abundance, however, the MPs characterization was significantly different. For example, the type of MPs in the plankton samples was dominated by fibers (>70%), whereas in the manta nets (trawls) it accounted for only 14.2% of the samples [159].

The most common mesh size is 333 µm, nonetheless, mesh sizes used in sampling tools vary from tens of microns to millimetres and MPs recovered from water bodies are influenced by the sampling tool's mesh size making data comparison difficult [158].

When resources are limited, manual sieving of water samples is occasionally conducted as sample collection is easy, it does not require specialized equipment or boat. Despite this, it is (1) laborious and time-consuming, (2) samples medium water volumes and (3) requires manual transfer of water using buckets [159]. Filtration of sieving (ex situ) is applied when conducting volume-reduced sampling, it is easy to collect samples, the sampled water volume is known and provides a choice of mesh size. Limitations include sampling of low water volumes; water samples require transportation to the lab for filtration, samples are subjected to potential contamination by the apparatus and is time-consuming depending on the mesh size [159].

Seabed sediment is regarded as a long-term sink for MPs and NPs whilst samples are acquired from the beach or seabed [156,166,169]. Beach sediment sampling is straightforward, easy to implement, allows rapid sampling and collection of large sample volumes. The main limitation is variation in the sampled area and depth. Sampling can be done horizontally (towards the water) or vertically (away) [164]. In addition, it can also be conducted along a transect in a defined area or within several separate zones [166,170].

To collect larger plastic particles (i.e., 1–5 mm), tools such as tweezers, forceps, metal shovels are used and/or directly by hand [158,171–173]. This would naturally lead to an underestimation of MPs presence since it excludes smaller-sized plastics, this is where bulk sampling is useful as it captures smaller-sized plastics in the sampled sediment. It is best to avoid sieving sediment samples as it could inflate the number of MPs due to its mechanical action that could create artificially more MPs [174].

Sampling marine sediment from the seabed entails either using a grab sampler, box core and/or gravity core, all of which are easy to use allowing multiple sample replicates [175–177]. Limitations include requiring a boat, variation with sampled area and depth, this can be tackled by collecting several replicates to acquire representative samples.

8. Remediation Strategies and Methods

The widespread MPs and NPs presence in the environment brought up the need for remediation strategies of these particles and the current methods have been classified into four categories: physical, chemical, biological, and nano-remediation (Figure 6) [178,179].

While the four categories of remediation techniques are well documented, there are instances where the remediation process can be simplified into three primary steps, i.e., primary, secondary, and tertiary treatment. This terminology is often used in wastewater (WW) recycling and in general, begins with physical or chemical treatments and continues with bioremediation and filtration [180,181]. Table 8 provides a literature summary of the types of plastics used in remediation methods, which can be referred to for further information.

Table 8. Examples of Remediation methods of MPs.

Material *	Type of Remediation	Used Techniques	Refs.
PE	Physical	Fe-Based Coagulation and UF	[182]
MPs	Physical	RO and Nanofiltration	[183]
Fiber MPs	Physical	UF	[184]
MPs	Physical	RO	[185]
MPs	Physical	Dynamic Membrane	[186]
polyacrylamide (PAM)	Physical	Sedimentation and Coagulation	[187]
PET	Physical	Primary Sedimentation	[179]
PS	Physical	Coagulation ($FeCl_3$, PAC) and Sedimentation	[188]
PS and PE	Physical	Coagulation with PAC and $FeCl_3$	[189]
PET/weathered PET and TC	Physical	Coagulation with $AlCl_3$	[190]
MPs	Physical	Pre-sedimentation, Coagulation, Flocculation, and Sedimentation, RSF	[191]
PE	Physical	Ultrasound Treatment	[192]
PET	Chemical	Photolysis	[193,194]
PE, PS, PET, and PVC	Chemical	UV Radiation	[195]
PE and PS	Chemical	TiO_2 Photocatalysts Under UV Illumination	[196]
LDPE	Chemical	(Pt)-Deposited ZnO Nanorods	[197]
PE	Chemical	Polypyrrole-Coated TiO_2 Catalysts Under Solar Radiation	[198]
PVC	Chemical	Electro-Fenton-Like System with TiO_2/C	[199]
PVC and PP	Chemical	Heterogeneous Photo-Fenton Degradation using ZnO Nanorods Coated with Oxide Layer and Fe0 Nanoparticles	[200]
PE, PS, PP, and PET	Chemical	Ozonation	[201,202]
Marine Plastics	Bioremediation	*Kocuria palustris* M16, *Rhodococcus* sp. 36, and *Bacillus* strains	[203]
PET	Bioremediation	*Ideonella sakaiensis* 201-F6 strain	[204]
Thermoset Polymers, PU	Bioremediation	*Bacillus*, *Pseudomonas*, and *Micrococcus*	[205,206]
LDPE	Bioremediation	*B. gottheilii* and *B. cereus*	[207,208]
PE	Bioremediation	*Penicillum*, *Aspergillus*, *Basidiomycota* and *Zygomycota*	[209,210]
LDPE and HDPE	Bioremediation	*Aspergillus* spp., *Penicillum* spp.	[211]
PE, PU, and PP	Bioremediation	*A. clavatus*, *A. oryzae* strain A5, *A. fumigatus*, and *A. niger*	[212,213]
PU	Bioremediation	*A. tubingensis*, *Monascus ruber*, *M. sanguineus*, *Monascus* sp., and *Pestalotiopsis microspora*	[214,215]
PET	Bioremediation	*Fusarium*, *Humicola*, and *Penicillium*	[216]
PAM and Small Size MP	Nanoremediation	Coagulation, Sedimentation and GAC Filtration	[187]
MPs	Nanoremediation	Green Nanoscale Semiconductors	[217]
MPs	Nanoremediation	Cellulose Nanocrystals, Chitin Nanocrystals, and Lignin-Zeolite Composite Nanofibers	[218]
MPs and NPs	Nanoremediation	IONPs with PDMS-based Hydrophobic Coatings	[219]
PE, PET, and PA	Nanoremediation	M-CNTs	[79]
PET	Nanoremediation	MXene/ZnxCd1-xS Nanocomposite Photocatalysts	[220]
LDPE	Nanoremediation	Deposited Platinum Nanoparticles on the Surface of ZnO Nanorods.	[197]
MPs	Nanoremediation	Carbon Nanosprings	[221]
MPs	Nanoremediation	Oxides-MnO_2 Core-Shell Micromotors	[222]
MPs	Bionanoremediation	Lysozyme Amyloid Fibrils	[223]

* Note(s): Ultrafiltration (UF), reverse osmosis (RO), polyaluminum chloride (PAC), rapid sand filtration (RSF), granular activated carbon (GAC) filtration, magnetic carbon nanotubes (M-CNTs), polyethylene (PE), microplastics (MPs), nanoplastics (NPs), polyacrylamide (PAM), polyethylene terephthalate (PET), polypropylene (PP), polystyrene (PS), tetracycline (TC), polyvinylchloride (PVC), low-density PE (LDPE), polyurethane (PU), High-Density PE (HDPE), polyamide (PA).

8.1. Physical Remediation Methods

Physical methods utilize filtration, sedimentation, magnetic separation, ultrasonic treatments, coagulation, and their combinations with different materials like graphene-based filters, where these methods may have limitations in eliminating all types of plastic particles [224–226].

Membrane filtration methods are used in secondary or tertiary treatment of WW and utilize methods with different pore sizes such as ultrafiltration, nanofiltration, reverse osmosis and membrane bioreactor. Removal of MPs depends on some parameters such as shape, size, and mass of plastic particles. Briefly, reverse osmosis (RO) is a widely used membrane filtration technique that applies pressure (10–100 bar) to force water molecules through a semi-permeable membrane, effectively removing MPs based on their size and weight [227]. Compared to other filtration methods, RO is particularly used for desalination, removal of heavy metals, and other impurities. Therefore, this method is generally used in water filtration [180,181]. Ultrafiltration

(UF) is another membrane filtration technique that operates in low-pressure (1–10 bar) and utilizes asymmetric pores between 1–100 nm [180]. This method allows the passage of water and smaller molecules while retaining MPs [223]. Nanofiltration (NF) technique lies between RO and UF in terms of pore characteristics and transport model [228]. It enables the separation of particles based on size and charge interactions. NF membranes have shown promising results in the removal of MPs (>0.005–0.02 µm) by effectively rejecting particles of larger sizes while allowing the passage of smaller molecules [181].

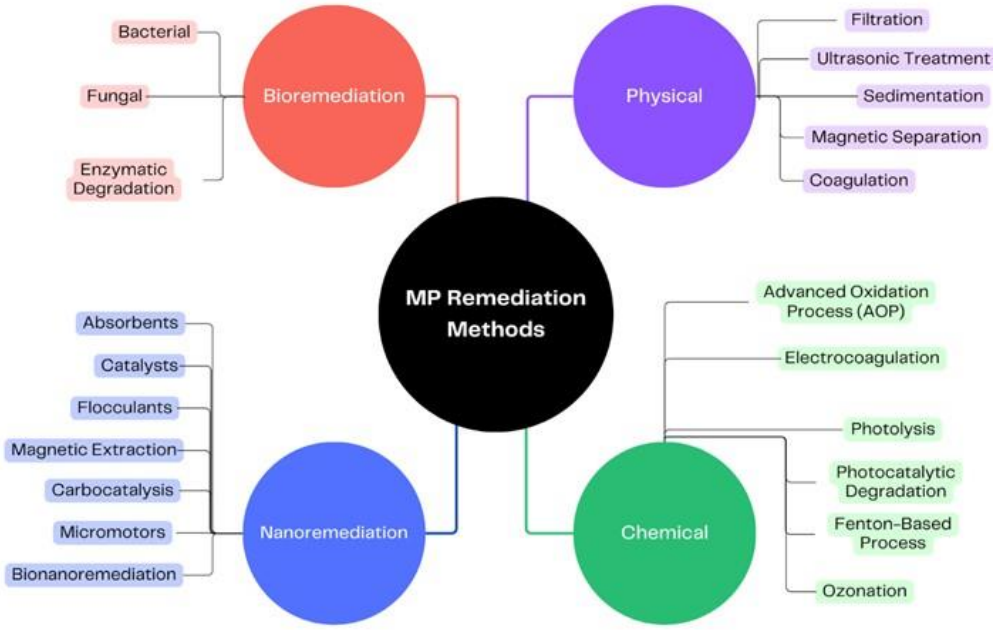


Figure 6. Schematic summary of MPs remediation methods.

The limitation of the filtration techniques is membrane fouling or contamination. Dynamic membrane (DM) technology is gaining popularity for WW treatment due to its affordability, easy maintenance, and low energy consumption [229]. Unlike traditional methods, DM utilizes the contaminants present in WW to form a filtration layer, eliminating the need for additional chemicals [230]. The cake layer that forms act as a secondary membrane, capturing particles and fouling particles as the WW passes through the supporting membrane. The use of a large pore-sized mesh or inexpensive porous material as the supporting membrane allows for low filtration resistance and minimal trans-membrane pressure, enabling gravity-driven operation without a vacuum system [181]. However, DM filtration has disadvantages related to fluctuating membrane performance. Excessive fouling and thicker cake layers can lead to a decline in membrane performance, while some MPs may bypass the formation of a filter cake [181].

Sedimentation is a simple physical separation technique that involves the settling of particles in a fluid using gravity, also, a cost-effective method for removing larger MPs. The principle of sedimentation is based on the difference in density between the MPs and the surrounding fluid, allowing the MPs to settle at the bottom of the tank or basin. Therefore, sedimentation can be an effective method for the removal of MPs from water. However, the removal of PP and PE MPs pose a challenge due to their lower density, which results in longer settling times compared to the water travel time. Consequently, these types of MPs may not settle effectively during the primary sedimentation process [179].

Coagulation is a widely studied approach for the removal of MPs and includes a crucial process utilized in water treatment to aggregate small particles into larger flocs and facilitate the adsorption of dissolved organic matter onto these particles. This allows for the subsequent removal of impurities through solid/liquid separation techniques. Over time, advancements in coagulation technology and the development of alternative coagulants

have expanded the options available for water treatment, allowing for more efficient and tailored processes to achieve high-quality treated water [231].

High-frequency sound waves generated by ultrasonic devices can cause physical and chemical changes in water, leading to the agglomeration and precipitation of MPs. Ultrasonic treatment has been shown to be effective in removing MPs from WW, surface water, and seawater. On the other hand, a new hybrid model with advanced oxidation process (AOPs) was suggested rather than a single usage of ultrasound in WW treatment [232]. In this way, the cost of the WW treatment can be minimized while maintaining effective cleaning-up processes. Ultrasonic treatment has also been shown to have other benefits, such as improving the performance of downstream WW treatment processes and reducing the amount of sludge produced during treatment. Cleaning sludge is an essential process because it is commonly utilized as fertilizer in agricultural fields, and when MPs are detected in this substance, it can result in soil pollution.

8.2. Chemical Remediation Methods

In WW treatment, chemical methods can be combined with other treatment techniques to completely clean up the MPs from the target environment. The extensive study of AOPs for the chemical treatment of contaminants back-dates to their proposal in the 1980s [233]. These processes involve various methods such as light, heat, plasma, sonication, and catalysts to effectively produce reactive oxygen species (ROS), commonly known as radicals, during the treatment process. Recently, AOPs have gained attention as effective methods for eliminating persistent contaminants in water by generating diverse ROS, including sulfate radical ($SO4\bullet-$), hydroxyl radical ($\bullet OH$) and chloride radicals, enabling them to readily break down a wide range of contaminants [199,234]. AOPs based on sulfate radicals have shown great potential for catalytic degradation of MPs, particularly those composed mainly of PE. AOPs offer advantages such as the removal of specific organic matter, enhancement of biodegradation, and complete conversion of hazardous pollutants.

While AOPs can be associated with high costs, utilizing them as a pretreatment for biodegradation, focusing on the surface degradation of MPs, can be a practical and environment-friendly approach [178]. AOPs have different types of processes originating from different sources like UV/photocatalytic reactions, ozone, and Fenton-based AOP.

Photolysis is a degradation reaction caused by light, particularly UV radiation, and it is the basis for all photo driven AOPs. Photolysis can be used alone or within AOPs for the degradation of plastics. When polymers are exposed to light, both physical and chemical changes occur in their structure [235]. Many organic polymers are sensitive to visible and UV irradiation [236]. The photolysis of plastics generally requires high irradiation energy. Different wavelengths of UV light can cause the scission of specific bonds in different polymers. Vacuum UV irradiation can also lead to the degradation of water molecules, resulting in the formation of highly reactive hydroxyl radicals and hydrogen radicals [237]. PET strongly absorbs UV irradiation below 315 nm, while PS is considered relatively stable when exposed to vacuum UV irradiation due to the energy transfer from the aliphatic backbone to the phenyl ring, which can distribute the absorbed energy to aromatic bonds and thermally released or by fluorescence [235].

In addition to the direct photolysis of plastics, photolysis is also applied to the degradation of pollutants in environmental pollution treatment facilities. Reactive intermediates and radicals, such as hydroxyl radicals, triplet organic matter, singlet oxygen, hydrated electrons, superoxide radical anions, carbonate radicals, and organoperoxy radicals, are generated through photolysis, especially under UV irradiation [238]. These reactive species can attack and decompose various recalcitrant contaminants. The physicochemical properties of plastics can be altered, leading to their decomposition [195]. Cracks can form on the surface of plastic samples, causing them to become rougher and eventually break down into smaller pieces ranging from nanometers to micrometers. Over time, the size of plastics or MPs can be further reduced to nano-sized particles.

Another UV-based technology called UV/H_2O_2 utilizes the reaction between UV light and hydrogen peroxide (H_2O_2) to generate hydroxyl radicals (•OH) [236]. This process offers an additional approach to the treatment of pollutants, and it can be used alone or in combination with other AOPs, utilizing various reactive species generated through UV irradiation.

In the context of decomposing recalcitrant contaminants, UV is commonly employed to activate photocatalysts, which generate ROS like hydroxyl radicals and superoxide radicals during photocatalysis. ROS attack MPs, leading to polymeric chain rupture, branching, crosslinking, and even mineralization into CO_2 and H_2O. This approach has been extensively studied for the removal of MPs in the environment [178,235,236]. It is a mature green technology that harnesses infinite and free solar energy, making it a promising eco-friendly and cost-effective treatment technique. Visible light-induced photocatalysis, a more environment-friendly technology utilizing solar light, has also been investigated. TiO_2 and zinc oxide (ZnO) have been widely used to develop visible light-active photocatalysts for degradation processes.

Fenton-based processes are widely utilized techniques due to their economic advantages, as they can be conducted at room temperature and atmospheric pressure. These processes involve electron transfer between peroxides, such as hydrogen peroxide (H_2O_2), potassium monopersulfate (PMS), or potassium persulfate (PDS) and ferrous ions (Fe^{2+}), resulting in the production of highly reactive hydroxyl radicals (•OH) which have demonstrated remarkable capabilities in decomposing persistent organic pollutants in water [239]. In the Fenton-like reaction, Fe^{2+} is replaced by ferric ions (Fe^{3+}). In the photo-Fenton reaction, UV irradiation is applied to enhance the reduction of dissolved Fe^{3+} to Fe^{2+} in the Fenton system. The electro-Fenton reaction involves the electrochemical generation of one or both Fenton reagents [240].

Ozonation is a widely used oxidation process that employs ozone (O_3) as the primary reagent. Ozone is highly reactive, with a strong oxidation potential, making it capable of directly oxidizing organic pollutants. This reaction can be further enhanced by UV irradiation, which generates additional oxidants such as H_2O_2 [235,241,242]. The combination of ozone and H_2O_2, known as the peroxone process, leads to the formation of hydroxyl radicals. Adding a catalyst, such as iron, further improves the production rate of hydroxyl radicals, resulting in more efficient polymer ozonation [242,243]. Various ozonation processes, such as conventional ozonation, UV/O_3, O_3/H_2O_2, and catalytic ozonation, have been developed to accelerate the decomposition of ozone into hydroxyl radicals [244]. Furthermore, ozonation processes can be modified and optimized to enhance the production of hydroxyl radicals and improve the overall efficiency of the treatment.

8.3. Bioremediation

Bioremediation is gaining attention for its advantages such as eco-friendliness, low cost, and low energy input. Basic categories for bioremediation are bacterial, fungal, and enzymatic degradations [179]. Chemical remediation techniques can also be combined with bioremediation because corrosion on the surface of MPs attracts microorganisms to be in these areas [245].

The usage of microorganisms to degrade MPs can be dependent on some parameters such as pH, temperature, and oxidative conditions [246]. By utilizing plastic fragments as the sole carbon source for energy and growth, recent technologies can be employed to predict the complete degradation and elimination of MPs [247]. The microbial degradation of plastic follows a series of steps. Firstly, biodeterioration occurs, which involves biological agents changing the physical and chemical properties of the polymer. This is followed by bio-fragmentation, where complex polymers are cleaved into simpler forms through the action of enzymes or acids. Microorganisms then incorporate these fragmented molecules through assimilation. Finally, the oxidized metabolites produced during degradation, such as CO_2, CH_4, and H_2O, undergo mineralization [246,247].

As mentioned earlier, UV radiation and photo-oxidation have been found to increase microbial degradation [248]. However, higher molecular weight plastic polymers pose a challenge due to their large fragments, which are difficult for microorganisms to take up. To overcome this, microorganisms employ two mechanisms: intracellular and extracellular degradation [249]. In intracellular degradation, microbes accumulate on the surface of MPs and hydrolyze the plastic into shorter chains whereas in extracellular degradation, bacteria secrete enzymes called hydrolases that break down complex polymers into simpler units, which can then be metabolized following which the mineralization process emerges.

Fungal degradation also plays a crucial role in the biodegradation of plastics. Also, fungi enzymatically convert the metabolic intermediate into metabolic byproducts [208,209]. Furthermore, there are some criteria to degrade MPs with fungal degradation which are surface area, molecular weight, hydrophilicity or hydrophobicity, crystallinity, functional groups, and chemical structure [210].

There are recent few attempts to use microalgae for the biodegradation of plastic. Exopolysaccharides (EPS) are synthesized by microalgae and enable them to colonize walls, rocks, and other substrates resulting in biodeterioration of the substrate. Surface charge, hydrophobicity, and electrostatic forces are the unique properties of EPS that bind to the substrate [250]. For example, the consortium of *Chlorella* sp. and *Cyanobacteria* sp. were found to deteriorate low-density polyethylene (LDPE sample), and this was confirmed by many chemical analyses like FTIR. The consortium was found to secrete various EPS. These EPS act as colonizing and degradative agents and convert polymers into monomers [251]. The factors that can affect the degradation process by microalgae include the type of polymer and the pre-treatment process such as UV, and heat. For instance, PP has raised severe environmental issues concerning its non-degradability. Sumat et al. investigated the ability of *Aspergillus terreus* (ATCC 20542) and *Engyodontium album* (BRIP 61534a) to break down PP and focused on the pre-treatment process. Polypropylene granule (GPP), film (FPP) and metallized film (MFPP) were pre-treated by either UV, heat, or Fenton's reagent. *A. terreus* incubated with UV-treated MFPP formed a high biomass yield. Additionally, surface morphological changes revealed consistent biodeterioration indication. Thus, *A. terreus* and *E. album* can grow on, change, and utilize PP as a source of carbon with pre-treatment aid, enhancing the biological pathways for plastic waste treatment [252].

Hydrolytic enzymes have been shown to be the major players in the biological degradation of polymers. Various enzymes, such as cutinases, lipases, esterases, carboxylesterases, and oxygenases, have been reported to modify and degrade a wide range of plastic fragments [253].

8.4. Nanoremediation

Nanomaterials can be used as absorbents, catalysts, and flocculants in the remediation process [254–256]. For example, activated carbon, traditionally used as a solid adsorbent, is effective due to its high porosity and large surface area [257]. There are different types of nano-flocculants, and their efficiencies vary based on the nature of polymers. For example, synthetic polymers, while highly efficient, are non-biodegradable and pose environmental burdens. Biopolymers, conversely, are water-soluble and biodegradable but less effective at low doses, however, the addition of nanomaterials to biopolymers can significantly enhance their performance [253].

Furthermore, magnetic extraction utilizing hydrophobic iron nanoparticles has shown high efficiency in recovering MPs from various environments [251]. Similar to photocatalysis, the degradation of plastics can be induced by carbocatalysis, where a carbon source is used for activating oxidation reactions. The combination of nanotechnology and bioremediation offers new possibilities for more efficient and cost-effective remediation methods [258,258].

9. Plastic Pollution in the Context of SDGs

Marine pollution is one of the main significant menaces to marine ecosystems [259], and a top priority environmental issue due to this crisis inherently transboundary. Thus, the United Nations is endeavouring to address it through the 2030 Agenda and its SDGs whereby SDG Goals 13, 14 and 15 aim to preserve and sustain marine and terrestrial ecosystems, natural habitats, biodiversity [260]. This can be achieved by global combined efforts, harmonized actions, and concrete coordination, and taking effective measures to tackle issues adequately and to mitigate environmental degradation. Continuous negative impacts will affect the health and resilience of land and marine ecosystems, which will lead to a loss or decline in biodiversity and pose severe threats to the sustainability of those ecosystems [259].

The continuous mass production of plastics and mismanagement of solid waste can cause serious environmental impacts [261]; around 80% of MPs pollution sources are from various land-based activities [33,262], and around 11% of the global plastic waste leaks into oceans and affects marine ecosystems [263]. Further, plastic consumption of non-biodegradable packaging materials during the COVID-19 pandemic has witnessed a significant increase of 40% [263]. Plastic pollution is related directly or indirectly to at least 12 out of 17 SDGs [264]. Thereby, SDG 14 (target 14.1) and SDG 15 (target 15.5) are intended for the conservation and sustainable usage of land biodiversity, oceans, and other water bodies; therefore, there is a need for urgent strong action to control waste generation sources. In this context, SDG 12 (target 12.5) aims to reduce waste generation via prevention, reuse, reduction, and recycling by 2030, and the role of industries is to adopt sustainable practices (target 12.6) and environmentally sound handling of chemicals throughout whole processes and avoid the significant damaging impacts (target 12.4). This will reflect on SDG 6 which addresses water quality (target 6.3), and intend to lessen pollution, increase recycling and safe reuse largely in an effort to improve water quality. As a result, SDG 3 (target 3.9) will witness a positive impact as it aims to significantly decrease the number of deaths and illnesses caused by hazardous chemical contamination from air, water, and soil pollution.

Concerning SDG 13, plastic pollution fosters greenhouse gas footprints and interferes with carbon fixation in marine ecosystems [265], where carbon sinks are essential in regulating global climate change [266]. Plastic emissions and greenhouse gases are closely linked to each other throughout the entire life cycle of plastics, contributing to the climate crisis [267]. Therefore, the Paris Agreement under the United Nations Framework Convention on Climate Change (UNFCCC) calls for sound management of the entire plastic lifecycle to attain net-carbon neutrality by 2050 [268]. Thus, SDG 9 (Target 9.4) which aims to promote resource efficiency and eco-friendly technologies, is best linked with SDGs 8, 12 and 13, which involve sustainable economic growth and industrial innovations. Hence, investing in sustainable materials and renewable resource technology efforts are crucial for achieving net-zero emissions [269].

Figure 7 summarizes the interlinkages among the SDGs, which are related directly and indirectly to SDG 14. Where SDGs 9 (promote innovative eco-friendly products), 12 (responsible waste management options), 13 (control greenhouse gas emissions), and 15 (manage land-based activities) are directly related to SDG 14, and to attain them at the global level, there is a need to enhance global partnerships through SDG 17. As a result, SDGs 2 (sustain food production), 3 (protect human health), 6 (conserve water quality), and 8 (promote sustainable economic growth) will be attained indirectly. Thus, this will lead to a resilient sustainable marine environment (SDG 14).

According to UNEP, the reviewing result of 18 international and 36 regional instruments is that "current governance strategies and approaches provide a piecemeal approach that does not adequately address marine plastic litter and MPs" [270]. This evidence raises the need for urgent global action to address the plastic pollution crisis; therefore, currently the UNEP with global countries are working on formulating a new legally binding global instrument—a convention—that aims to end plastic pollution across its full cycle in all

environments; and it focuses directly on SDGs 3, 6, 9, 12, 13, 14, and 15 through the monitoring and reporting framework. This new global instrument is a tailor-made combination of economic and environmental aspects to tackle plastic pollution [271].

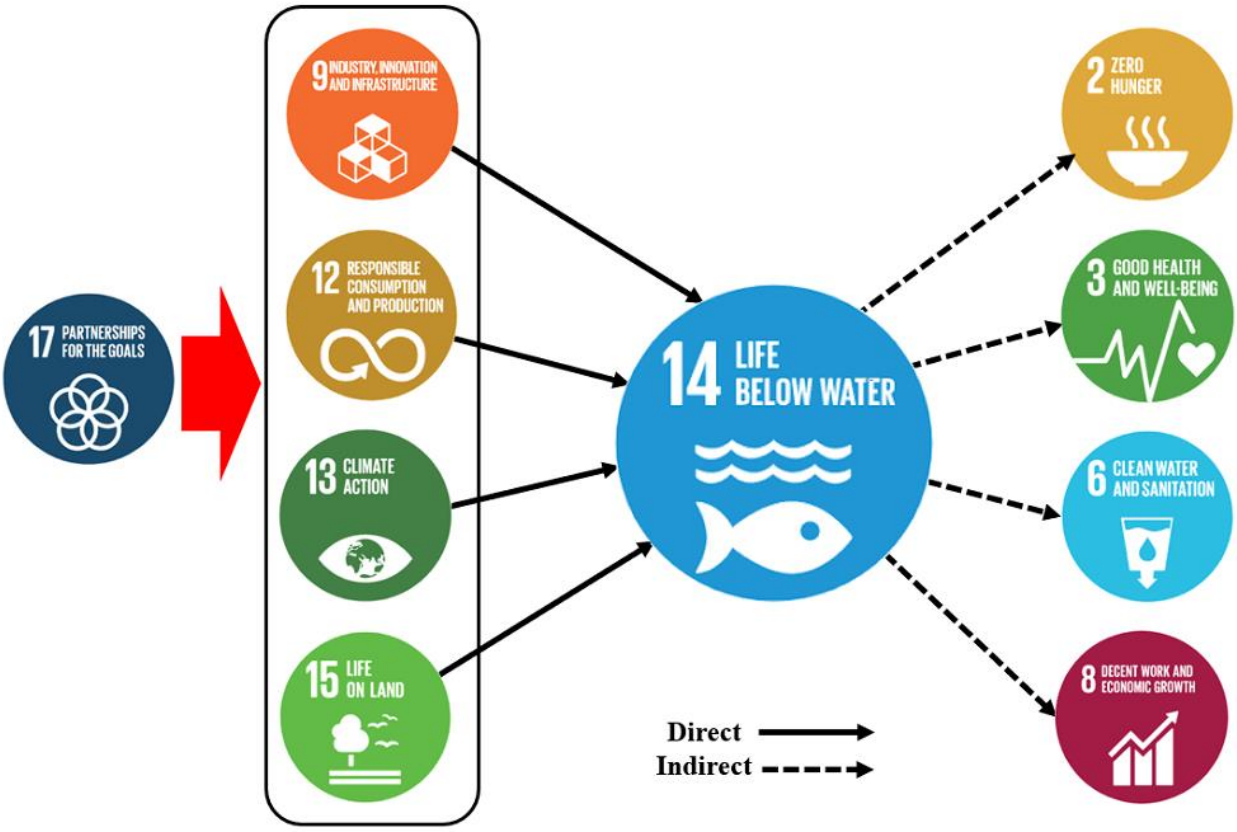


Figure 7. Sustainable Development Goal (SDG 14) and its association with other SDGs.

The key benefit of implementing a global instrument is its ability to enhance a common scientific base, which will lead to building a globally responsible and unified knowledge base towards a more efficient direction for policymaking processes and future research trends. Therefore, the starting point of tackling the plastic pollution issue is at the national level by enacting robust regulations and laws that limit or restrict single-use plastic products and monitoring plastic production and waste, raising awareness and education, and promoting investments in innovative technologies. In summary, there is no doubt that plastic pollution has significant negative impacts on terrestrial and aquatic ecosystems, and the SDGs framework presents a window of opportunity to address this issue from different aspects.

10. Future Prospectives and Recommendations

The issue of plastic pollution presents immense environmental challenges, and it is considered one of the main anthropogenic significant threats to the entire planet ecosystems, where the drastic increase in MPs and NPs in land and aquatic ecosystems will harm all environments. Thus, it is important to develop techniques and methods that analyze, identify, and monitor MPs and NPs sources across all the environmental components including soil, water, food, and other consumption products. It is important to acknowledge that there is a lack of comprehensive information and data availability on every aspect of the plastic lifecycle. There have been a few studies conducted on the various types of plastics and plastic products. Therefore, there is a need for international scientific projects to take place all of which require concerted, planned, and scalable efforts to transform plastic waste into a valuable resource. Also, further research should prioritize investigating

the transportation pathways of MPs and NPs in the environment to promote and ensure the health of both humans and the environment.

To achieve environmental sustainability, it is essential to rely on sound scientific research to guide policies and enhance the understanding of all parties involved. To fulfil the 2030 Agenda and attain its associated SDGs, collaborative and collective efforts are required across all levels, global, regional, and local whereby partnerships among all stakeholders (i.e., government, non-governmental organizations (NGOs), the private sector, academia, and civil society) must drive the process. Companies should use the SDGs as a valuable framework to change their current practices into those that are sustainable such as promote technological innovations, adopt cleaner production technologies, utilize eco-friendly components in their products and packaging, invest in the recovery of material, and reduce the use of harmful chemicals that harm human health and the environment.

Essentially, there is a crucial need for robust laws, regulations, and policies to reduce plastic usage at all levels national, regional, and international. Beyond this, there is a requirement, to increase public awareness and education, control plastic waste, encourage waste recycling, develop a synthesis of bioplastics products, ban products that contain MPs and NPs, ban single-use plastic packaging, promote reusable products, and enhance global cooperation. Thus, the urgent need arises for a legally binding international instrument to effectively manage and alleviate pollution caused by MPs and NPs in marine ecosystems and other environments. Plastic pollution has severe impacts, such as climate change, loss biodiversity, marine pollution, the loss of marine species and the degradation of aquatic ecosystems and coastal environment, economic losses, and human and environmental health.

In addition, it is important for the community to take on a societal responsibility by choosing to buy products that do not contain primary MPs, such as personal care items. This requires a shift in behaviours and habits and adopting new ones, which can be achieved through education and awareness on how to identify MPs and NPs-free products and safer alternatives. Moreover, there should be a focus on promoting principles of a circular economy by increasing public awareness (via open forums and trusted social media) about health hazards associated with plastic waste and the importance of effective waste management (avoid landfilling) to enhance natural resource efficiency, which includes encouraging reducing, reusing, and recycling in both the industrial sector (especially plastics manufacturers) and domestic settings.

At the global level, there is a necessity for coherence and synergy among the current agreements, including the UNFCCC, the Stockholm Convention on POPs, the Action Plan of International Maritime Organization (IMO) that address "Marine Plastic Litter from Ships", Basel Convention on the Control of Transboundary Movements of Hazardous Waste and their Disposal, and the International Convention for the Prevention of Pollution from Ships (MARPOL).

In conclusion, there should be a priority given to research and development concerning the impacts of MPs and NPs on the environmental ecosystems. It is important to develop policies based on science and driven by global coordination, collaboration, and governance through developing tools and methodologies that measure the impacts and menace of plastic pollution.

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