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Microplastics and Nano-Plastics: From Initiation to Termination

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Abstract

Following the advent of the Industrial Revolution, plastic pollution has been a serious environmental issue while micro- and nano-plastics have been a cynosure of researchers' attention in the twenty-first century. This is due to the improved knowledge of its ecotoxicological effects and the global pushforward towards sustainability. There is a growing concern that the increasing presence of microplastics and nanoplastics (MNPs) in aquatic habitats poses a threat to marine life, and it is predicted that nanoplastics will be just as ubiquitous as macro- and micro-plastics, but far more destructive to living organisms due to their ability to infiltrate cells. Recent research has shown that marine and freshwater biota become entangled with plastic litter, which disrupts the ecosystem. Aquatic creatures are known to absorb and deposit these new pollutants in their digestive systems, as has been documented in several studies. More recent research has also examined their co-occurrence and toxicity with other emerging contaminants, including their prevalence and effects in food, air, and soil. Using articles extracted from a six-year period from Scopus, ACS Publications and Google Scholar, this review explores the origins, fates, occurrence in the food chain, exposure routes, cellular interactions of microplastics and nano-plastics, in addition to the ecotoxicological impacts, analytical methods, and the potential remedies for combating pollution and toxicity. Ultimately, this review is a comprehensive, updated addendum to available reviews on micro- and nano-plastics.

Keywords

Microplastics, Nano-Plastics, Occurrence, Transport, Toxicity, Environmental Health, Remediation

1. Introduction

Globally, plastic consumption is increasing annually, with current estimates indicating plastic output surpassing 365 million tons in 2020 (Chen et al., 2022). In light of the fact that plastic permeates every area of life (Zhu et al., 2021), and eventually degrades into smaller particles (Bastyans et al., 2022), the potential effects of micro- and nano-plastics (MNPs) on the human body and the environment have become a worldwide source of concern (Briffa, 2021; Kumar et al., 2022; Liu et al., 2022; Saravanakumar et al., 2022; Wagner & Reemtsma, 2019). Plastics are manufactured from natural materials that have gone through several chemical and physical transformations. Polymerization and polycondensation are the two basic processes employed, in which the core constituents are essentially converted into polymer chains (Shrivastava, 2018). For recycling purposes, the polymers must undergo additional chemical operations (Liu et al., 2017). Plastics may be designed to meet specific application needs using industrial additives (Ambrogi et al., 2017). However, typical plastics are chemically stable, and as a result, environmental buildup is rising. Thompson and his group (Thompson et al., 2004) coined the term microplastics after discovering minuscule plastic particles in beach sediments in the United Kingdom in 2004. Subsequently, microplastics studies, and more recently, nanoplastics have grown into popularity, and some scientists have emphasized the importance of having a unified definition of the terminologies (Hartmann et al., 2019; ter Halle & Ghiglione, 2021).

The urgency of tackling plastic pollution in the context of climate change has been recently emphasized by studies by Manno, Peck, Corsi, and Bergami (2022). Plastics are a major environmental and global hazard, responsible for the majority of pollution accumulation and have spread across marine, freshwater, and terrestrial ecosystems (Haegerbaeumer et al., 2019; Mattsson et al., 2018; Prata et al., 2019; Xu et al., 2020). Goods such as cosmetics, paints, fabrics, biomedical and cleaning products include plastics that degrade into microplastics and ultimately nanoplastics once they are exposed to the environment (Mattsson et al., 2018; Prüst et al., 2020). Today, human tissues have been found to have MNPs (Rolsky & KeLkar, 2020), and single-use plastics have been referred to as a major factor for the proliferation of plastic and MNPs in various ecosystems (Yee et al., 2021). Microplastics are defined as plastic pieces with a diameter of less than 5 mm that exhibit potential to bioaccumulate and biomagnify (Kumar et al., 2020; Lehner et al., 2019; Li et al., 2018). A secondary report by Kumar et al. (2021) stated that in 2016, the European Union (EU) recovered roughly 30 million metric tons of plastic waste, of which 31%, 42%, and 27% were recycled, repurposed for energy generation, and re-dumped on landfill sites, respectively

(Kumar et al., 2021). The improper handling and disposal of household and commercial plastic trash is the primary source of contamination in the natural environment (Mattsson et al., 2018). The prevalence of microplastics in coastal habitats has been extensively proven (Gallo et al., 2018; Kane & Clare, 2019; Wu et al., 2019). For nanoplastics, several researchers set a maximum size restriction of 1000 nm (Cole & Galloway, 2015; Gigault et al., 2018), while others set the size ranging from 1 - 100 nm (Ferreira et al., 2019). NPs provide a greater danger than MPs due to their ease of entry into cells. The difficulty in isolating and identifying NPs, as well as their ubiquity in the environment, has been largely disregarded so far (Kumar et al., 2021). As a result, the physical presence and health hazards posed by NPs may be underestimated (Kumar et al., 2021). This study explores the latest findings on MNPs. In particular, the origins, fates, occurrence in the food chain, exposure routes, cellular interactions of microplastics and nanoplastics, in addition to the ecotoxicological impacts, analytical methods, and the potential remedies for combating pollution and toxicity are provided. This review, therefore, aims to 1) present the current state of research on microplastics/nanoplastic and give an extensive overview of microplastic/nanoplastics abundance in ecosystems, and 2) identify research gaps to direct future research priorities. In this paper, microplastics and nanoplastics are jointly referred to as MNPs. In this paper, microplastics and nanoplastics are jointly referred to as MNPs.

2. Bibliometrics Exploitation: Methodology

Screening paradigm adopted by Rahman et al. (2021) and Araújo et al. (2021) was used with modification as a guide for the retrieval of documents for this study. An electronic search of articles published in ACS Publications, Scopus, and Google Scholar using a combination of keywords was conducted. In retrieving documents from ACS Publications, search query contained the keywords "microplastics; nanoplastics; toxicity; environmental health", producing a preliminary number of documents. This was subsequently refined to articles from January 2018 to December 2022. This yielded 70 documents. Manual exclusions were made to retain, explore and exploit relevant articles. From Scopus database, keywords in the search query were "microplastics; nano-plastics; toxicity", from 2018-2022. Following manual exclusion, only thirteen documents were screened out. Seven documents were manually included from Google Scholar, based on keywords such as "graphene; biochar; adsorption; microplastics; nanoplastics"; all within the year 2017-2022. Generally, the literature search was limited to articles published in the English language from 2017 to 2022. **Table 1** summarizes the activities leading to the retrieval of final documents for this paper.

3. Origins, Fates, and Occurrence in the Food Chain

Figure 1 shows sources and Fate of MNPs in the Environment. MNPs are

Table 1. Summary of literature search.

	ACS Publications	Scopus	Google Scholar
Keywords	Microplastics; nano-plastics; toxicity; environmental health	Microplastics; nano-plastics; toxicity	Graphene; biochar; adsorption; microplastics; nanoplastics
Period	2018-2022	2018-2022	2017-2022
#Documents	70	58	N/A*
Final #Documents	38	48	7

N/A: Numerous articles initially available, but manual inclusion was executed.

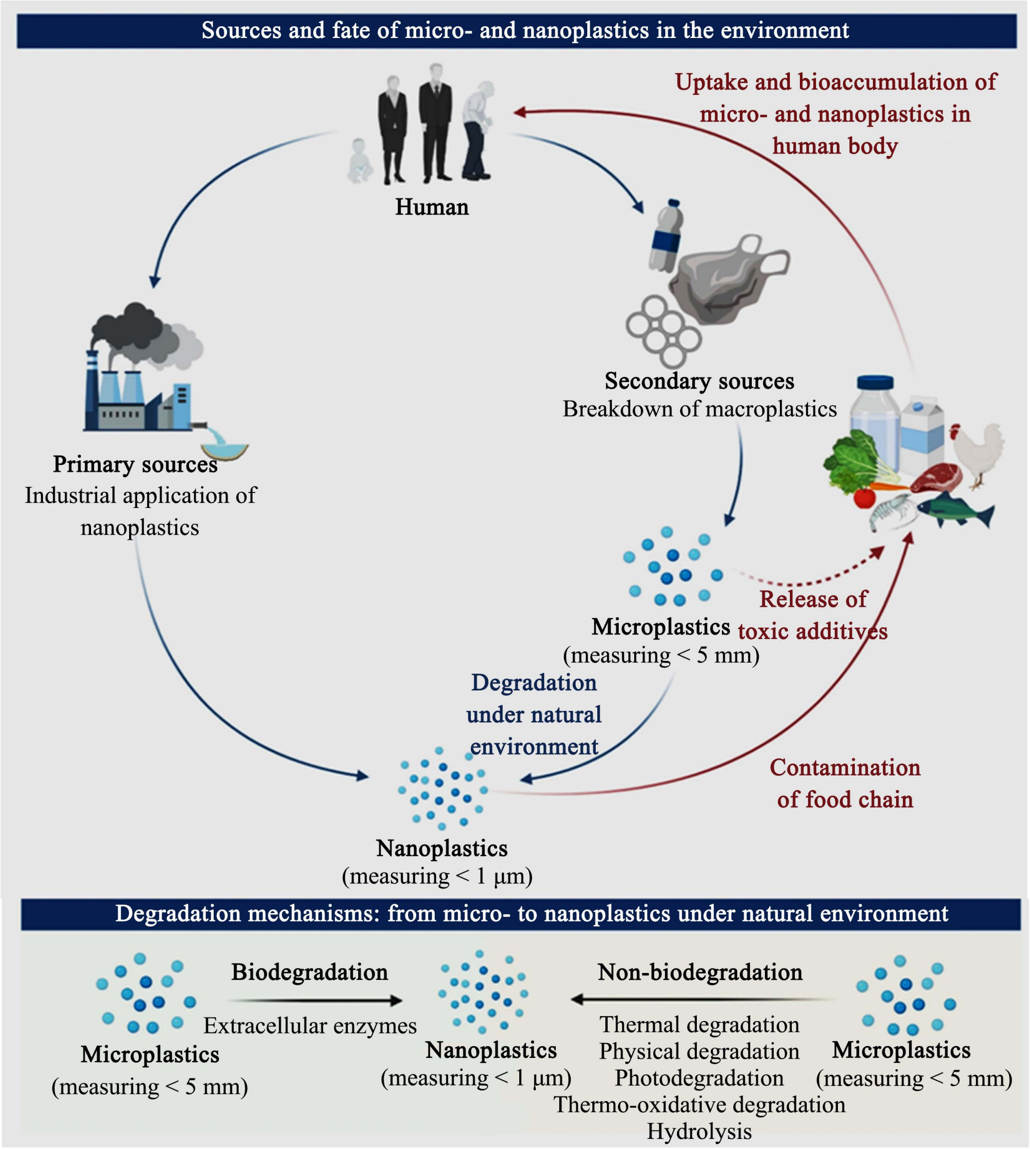

Figure 1. Sources and fate of MNPs in the environment (Reproduced from Yee et al. (2021); no permission required).

formed when large polymers are fragmented (Horton et al., 2017). External pressures, such as freezing and thawing of plastics in the maritime environment, may cause mechanical degradation of plastics (Kumar et al., 2021). Plastics may be mechanically degraded when they come into contact with pebbles and sands due to wind and waves (Liu et al., 2020b).

To break down most plastics, free radical-mediated reactions are required, which are induced by sun irradiation (Liu et al., 2019b). Polystyrene is the fourth most common plastic type used globally and annually (Gaspar et al., 2018), and recent studies have demonstrated that ultraviolet radiation may cause polystyrene nanoparticles (NPs) to agglomerate, affecting their distribution and bioavailability in the environment (Wang et al., 2020b). Thermolysis and hydrolysis are other types of mechanisms that could degrade plastics. Furthermore, plastics are biodegradable, that is, micro-organisms can disintegrate them (Zhang et al., 2021a), and the disintegration rate can be measured (Kumar et al., 2021; Zhang et al., 2021). According to Brownlee (2021), about 2.5 megatons of plastic are conveyed from freshwater to ocean on an annual basis and are derivatives of domestic and industrial products. MNPs are widely used in the electronics, plastic goods, automotive, textile, 3D printing, personal care and cosmetics sectors (particularly toothpaste and exfoliating products) (Zahin et al., 2020) and can be discharged into soil, affecting the soil environment. Since it is unknown how many MNPs exist in the environment, scientific researchers are attempting to develop mathematical models that will aid them in understanding the fates of MNPs in the environment (Wu et al., 2019).

MNPs have been discovered in virtually all environmental segments (soil, air, and water), and they can induce ecotoxicological effects on organisms and their microbiota (Santos et al., 2022; Singh et al., 2022). **Figure 2** shows sources and Distribution of Plastic Particles in the ecosystems.

MNPs are often a byproduct of some manufacturing processes. In drug manufacturing, NPs helps to foster drug delivery (Zahin et al., 2020). Globally, the rate at which microplastics are being released into the environment seems to be unstoppable, with long-term ramifications for water quality, biodiversity, and conservation (Angnunavuri et al., 2020). Managing plastics in the environment and guaranteeing successful intervention policies and practices involves knowledge of their origins, transportation, and fates, as well as regional and worldwide cooperation and multidisciplinary study (Anbumani & Kakkar, 2018; Brewer et al., 2021; Peng et al., 2017; Siegfried et al., 2017). Effluents have been reported to be a major contributor to MNPs transport to the aquatic ecosystem (Haegerbaeumer et al., 2019).

Soil is home to many microbes and biota (Nizzetto et al., 2016). It is widely used in Africa, where agriculture is the main sector (Šilhánková, 2018). Apart from the fact that plastic particles increase soil carbon, nutrition, and microbial activity, they may affect water, biodiversity, and ecosystem function (Angnunavuri et al., 2020). Disposal of garbage inefficiently and natural calamities might produce secondary microplastics (Westphalen, 2017). According to a study by

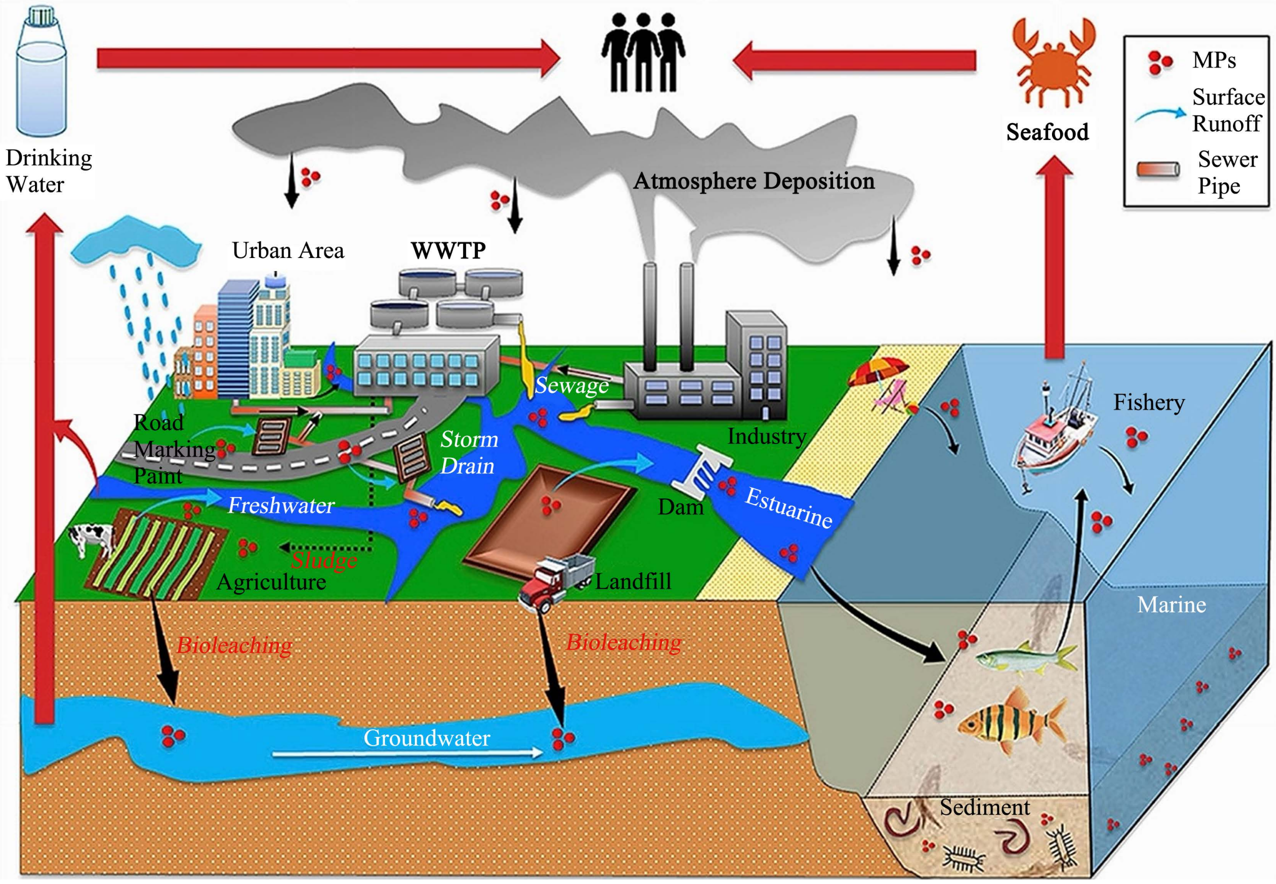

Figure 2. Sources and distribution of plastic particles (Reproduced from Wu et al. (2019) with permission).

Ganguly & Ariya (2019), it was established that in the years to come, MNPs emissions may have a role in cloud-formation and hence anthropogenic climate change.

Marine, riverine, and lake systems contain around 12.5 million metric tons of plastic garbage yearly (Williams et al., 2019). Particles of plastic in water may function as microbe transporters (Oberbeckmann & Labrenz, 2020; Siegfried et al., 2017). Plastic particle sedimentation in water may be caused by microplastic fouling and colloidal properties (Haegerbaeumer et al., 2019). About 2000 particles/L were found in Nigerian interior riverine systems (Wirnkor et al., 2019). Plastic particles operate as sinks for persistent, bioaccumulative, and toxic contaminants, possibly contaminating water.

Airborne MNPs have been found in rural places far from human impact owing to long-distance wind and dust dispersion (Allen et al., 2019), and in some urban areas in Asia (Dehghani et al., 2017) and Europe (Klein & Fischer, 2019). Plastics degrade quicker in the air than in saltwater, and in direct sunlight (Biber et al., 2019). Chemical volatilization and minimal diluting impact may cause larger indoor concentrations of atmospheric plastic particles (Biber et al., 2019; Lim et al., 2021). Drying of fabrics, tire defects, incinerators, and abrasives are identified as substantial sources of air microplastics (Sobhani et al., 2020). MNPs may also absorb and emit air contaminants (CIEL, 2019), resulting in new microbial biomes and poisons.

Numerous studies have revealed that MNPs reach the human food chain in a variety of ways: by animal consumption in their natural habitat (Santillo et al., 2017), contamination during food manufacturing processes (Karami et al., 2017), or leaching from food and beverage packaging (Mason et al., 2018; Nikova et al., 2022). MNPs have been found in honey, sugar, and all sorts of fish (Devriese et al., 2015). After plant species, mass concentration and size of nanoplastics, exposure period and pathway, negative effects are most frequently linked to toxicity measures (Dang et al., 2022). Analysis of tap, bottled, and spring waters using FTIR spectroscopy revealed the presence of microplastics in all of these water sources (Yee et al., 2021). Subsequent research to ascertain the existence of MNPs in a variety of foods including seafoods are being explored (Jinadasa et al., 2022). MNPs were detected in scientific experiments on polystyrene drinking cup lids as the material degraded (Lambert & Wagner, 2016). Additionally, there are a variety of goods that include industrially made MNPs, which will degrade into plastic debris in the oceans and on land, ultimately entering the food supply chain (CONTAM, 2016). Photolysis contracted the size of microplastics by 31%, and further towards an overall 99.9% reduction in form of nanoplastics, and this brought about free radical formation coupled with the leaching of organic additives (Wang et al., 2020c).

4. Potential Routes of Exposure to the Human Body

MNPs may enter the human body via three main routes: ingestion, inhalation, and skin contact. The subsections below encapsulate the salient points.

4.1. Ingestion

This is the major route of exposure to the human body. According to a research conducted by Cox et al. (2019), persons who drank exclusively bottled water to fulfill their minimum water consumption ingested extra 9×10^4 particles, compared to just 4×10^3 particles for those who drank only tap water. Even more MNPs are found in the dust that settles on food containers, serving dishes, and packaging (Catarino et al., 2018). Particles of polyethylene-terephthalate (PET) and other types of synthetic polymers were found in food and the environment (Toussaint et al., 2019). As reported by Yee et al. (2021), human feces samples were initially analyzed, and it was discovered that plastic particles were being expelled, confirming the idea that people are absorbing these particles through food and drink. These findings, together with studies on ingestion absorption in environmental models, demonstrate unequivocally that people will consume MNPs on a daily basis (Ge et al., 2018). However, few investigations have been conducted on the fate of MNPs after they reach the gastro-intestinal (GI) tract (Yee et al., 2021). Once eaten, nanoparticles undergo alteration, which affects their absorption capacity and kinetics (Yee et al., 2021).

4.2. Inhalation

Inhalation is the second most probable way of human MNPs exposure (Yee et al., 2021). Indoor airborne plastic particles from synthetic fabrics cause accidental inhalation (Stapleton, 2019). Humans can be exposed to polluted aerosols from ocean waves or airborne fertilizer particles from dry wastewater treatments (Lehner et al., 2019). A large surface area of the lungs allows MNPs to pass through and enter the capillary blood stream, allowing MNPs to travel throughout the human body (Lehner et al., 2019). Inhaling plastic particles may cause pulmonary irritation. Recent research on human inhalation of plastic particles indicates that urban air fallout is a substantial source (Dris et al., 2016). Nanoplastics have the tendency to cross the gut barrier (Magrì et al., 2018). The research of Brandon et al. (Brandon et al., 2021) on insect mediated mechanism of plastic degradation revealed that the mealworm, *T. molitor* and its gut microbiome expedite plastic biodegradation, coupled with respiration. In an examination of indoor air samples, it was estimated that 33% were of petrochemical origin, with the major component being polypropylene and the remainder being cellulose (Dris et al., 2017). According to Prata (2018), the typical human absorbs an average of 78 MNPs daily by inhalation, however, Vianello et al. (2019) revealed that a lethargic individual may inhale approximately 270 MNPs daily. These discrepancies are unsurprising, given that the calculations were based on particle characteristics, sampling methods, and a variety of other variables, including surface cleaning regimens, seasonal fluctuations, equipment, and general air quality (Prata et al., 2020). The size, density, hydrophobicity, and surface charge of particles may all have an effect on their deposition and absorption via the respiratory system, with smaller and lighter particles reaching deeper into the lungs (Rist et al., 2018).

4.3. Skin Contact

MNPs exist in personal care products, particularly body and face washes (Hernandez et al., 2017). Another important exposure pathway is dermal nano-carriers for medicine administration (Yee et al., 2021). Skin penetration is determined by microscopic particle size and strained skin (Schneider et al., 2009). Although no research has examined nanoplastics ability to penetrate the skin's surface, one study detected textile nanoparticles crossing the epidermal barrier (Som et al., 2011). The outer layer of the epidermis protects the skin against injury, toxins, and bacteria, and consists of corneocytes surrounding hydrophilic lipid lamellae (Bouwstra et al., 2001). In spite of the fact that MNPs are hydrophobic, plastic particles may enter the body via sweat ducts, wounds, or even hair follicles (Schneider et al., 2009). Some researchers have ascertained that polystyrene particles up to 200 nm in size may penetrate 2.5 meters into the dermis (Campbell et al., 2012). Due to the potential mutagenic or carcinogenic risk of the monomers employed in its production, PS is among the most toxic polymers (Ru et al., 2022). In vitro and in vivo studies have proved that MNPs can cross the skin barrier into the human body (Yee et al., 2021). In general, it is well established that plastic materials employed in surgical operations and prosthetic body parts trigger foreign body responses, resulting in inflammation (Rahman et al., 2021). MNPs were demonstrated to promote inflammation in mice when they were introduced subcutaneously in vivo (Van Tienhoven et al., 2006). Schirinzi et al. (2017) revealed that cutaneous exposure to MNPs produces oxidative stress in human epithelial cells. Although investigations have only relied on the use of polystyrene, subsequent research exploring other types of MNPs would provide insight into the penetration potentials of MNPs in general (Yee et al., 2021).

5. Cellular Interaction

Cytotoxicity tests conducted by Liu et al. (2021) have indicated that smaller particles can more easily migrate cells than larger ones. MNPs are absorbed and then react with cells depending on their physiochemical properties and/or the organelles they come in contact with (Mahmoudi et al., 2011). There is a lack of information on the cytotoxicity of MNPs to vascular endothelial cells, despite the fact that the vascular endothelium is one of the most critical target organs that immediately interact with the MNPs once they reach the blood circulation system (Lu et al., 2023). MNPs absorb proteins from the body and form protein coronas (Treuel et al., 2014). Unlike MNPs that are exposed, those that react with cells are generally already enveloped by a protein corona (Cao et al., 2022), further modifying the properties of MNPs (Tenzer et al., 2013), and causing cellular interactions and enhanced toxicity (Nasser & Lynch, 2016). MNPs of PS easily permeate lipid bilayer membranes, inducing alterations in membrane structure and eventually affecting cell function (Rossi et al., 2014). Uptake inhibition experiments on ~40 nm PS particulates in human colon fibroblasts and bovine oviductal epithelial cells revealed a clathrin-independent uptake mechanism (Fiorentino et al., 2015). In adenocarcinomic human alveolar basal epithelial cells, up to 50 nm particles of PS were found intracellularly (Salvati et al., 2011). MNPs can adversely affect the generation of ATP in living systems (Trevisan et al., 2019). Although it has been demonstrated that nanoplastics can be hazardous to plants, it is not yet known how they can induce neurotoxicity, especially in higher animals. Nanoplastics may be inhaled through the nose and deposited in the brain, where they cause cell damage and behavioral changes (Liu et al., 2022).

6. Toxicological Impacts of MNPs with Its Additives

6.1. On Living Organisms

Toxic elements and compounds have been found to be adsorbed on MNPs owing to the unique high functionalized surface area characteristic to the particles (Bradney et al., 2019). Some of these compounds are dioxins, antibiotics, polycyclic aromatic hydrocarbons (PAHs), and heavy metals (Baysal & Saygin, 2022;

Kumar et al., 2021; Tang et al., 2022). Heavy metals, akin to MNPs, can be routed to humans via food consumption (Idris et al., 2020; Olubusoye et al., 2021), and it has been linked to the development of several fatal illnesses that plague modern society (Osobamiro et al., 2019).

Bisphenol A, phthalate, triclosan, bisphenone, organotin, and brominated flame retardants are currently recognized to be hazardous chemical additives in plastic that are known to be harmful to human health (Ryan, 2015). While it is unknown if these compounds leak straight into living tissues, some additives like Bisphenol A have been discovered to be consumed by marine biota (Chen et al., 2020; Koelmans et al., 2014), Absorption of this leachate frequently used in lining food and beverage cans, can induce endocrine problems and adversely affect human health (Ryan, 2015). In particular, associated health risks may include, cytotoxicity (Gopinath et al., 2021), neurotoxicity (Han et al., 2021; Varsou et al., 2021), immunotoxicity, reproductive toxicity (He et al., 2021), or even carcinogenicity (Gao et al., 2021). Yip et al. (2022) have tested and predicted the possibility of MNPs transfer from mother to offspring. Studies conducted by Mohamed Nor et al. (2021) revealed that the average intake rates of MNPs in adults and children are 600 ng per capita per day and 550 ng per capita per day, and empirical data aligns with simulated MNP levels in feces. In a recent study by Pestana et al. (2021), microplastics capacity in acting as a vector for a couple of microcystin analogues was demonstrated. The toxicity of plastic recorded was approximately 140 μg/g. Ašmonaitė et al. (2018) investigated whether contaminated polystyrene microplastics of 250 μm average diameter, when ingested, resulted in hepatitis alteration in rainbow trout. Ultimately, ingestion of high-level contaminants had no hepatic damage in the fish. Ingestion of MNPs from hydrologic surgical masks by copepods and the subsequent decline in their fecundity have been reported (Sun et al., 2021b). According to a recent study conducted by Teng et al. (2022), polystyrene nanoparticles harm zebrafish by inhibiting growth, causing intestinal inflammation, and restricting their ability to mature. These effects are closely related to the disruption of the control of the brain-intestine-microbiota axis (Huang et al., 2022; Teng et al., 2022).

6.2. On Soil Environment and Aquatics

According to some reports, the prevalence of MNPs in the digestive systems of microorganisms is owing to their tiny size and shape, which enables them to be readily eaten and collected in the digestive systems of non-discriminating feeders that mistaken for food (Wang et al., 2020a). Understanding the environmental behavior of MNPs is crucial, since the aquatic with the soil environment is the main sink of these particles (Benson et al., 2022; Yadav et al., 2022; Yuan et al., 2022; Zhang et al., 2022).

Due to the high surface-to-volume ratio of MNPs, they are toxic to soil bacteria, fungus, and microorganisms, disrupting the food chain and microbial population. MNPs will have a detrimental effect on the emission of N_2O, a significant greenhouse gas (Ren et al., 2020), hence contributing to global warming and climate change. On the plus side, decomposing MNPs release carbon into the soil, helping microorganisms grow. In temperate climates, MNPs can absorb sunlight and boost soil temperature, enhancing microbial activity, root nutrient intake, and growth rate (Khalid et al., 2020). However, as MNPs decompose, the additives are released into the soil and can accumulate in plants (Boots et al., 2019). Zhang et al. (2021b) found that the roots were the most affected, followed by leaves and then the stem. MNPs also harm plants' photosynthetic mechanism (Li et al., 2020). Due to their larger root systems, older trees and plants have higher levels of MNPs (Khalid et al., 2020). MNPs can transport contaminants from roots to stems and leaves via the vascular system (Ebere et al., 2019). In comparison to chemical plastic polymers, biodegradable plastics seem to represent a larger danger to seed and plant development (Dong et al., 2022; Iqbal et al., 2020). Wang et al. (2022) in their recent investigation conclude that the buildup of MNPs and the accompanying damage in plants might have serious consequences for agricultural yield, food safety, and quality, posing a threat to human health.

He et al. (2018) studied the interaction of MNPs with bacteria. They particularly explored these particles contributed to the transportation and deposition behaviors of *E. coli* in sandy environments at a pH slightly below neutral. It was discovered that at high ionic potential, MNPs elevated bacterial transport in a sandy environment. In a study by Shiu et al. (2020) on the effects of MNPs on the microbial community, the authors concluded that marine phytoplankton showed high sensitivity to MNPs and activate their exopolymeric constituents in coping with the stress derived from pollution. Liu et al. (2020a) reported that the presence of humic acid in a unicellular green alga situated in freshwater environment largely reduced the toxicity of smaller microplastics, but not of the larger ones. SEM images revealed that humic acid corona formation onto the surface of plastic particles, thereby reducing the affinity of microalgae, and ultimately limiting the potential adverse impact. A similar study was carried out by Fadare et al. (2020), using *Daphnia magna* to assess the impacts of fluvic acid and humic acid on MNP toxicity and corona formation. After a week exposure period, it was observed that the presence of humic acid mitigated gene expression while the high upregulation of all the genes were noticed with fulvic acid. Fulvic acid availability resulted in high protein adsorption on MNPs in the culture medium and homogenates of the species, whereas the presence of humic acid recorded a lower adsorption. Another study by Pikuda et al. (2019) assessed acute toxicity potentials of polystyrene MNPs (coupled with 0.002 M sodium azide- Na_3N- acting as antimicrobial preservative) on *D. magna*. Results did not show any correlation of acute toxicity with the particles but with sodium azide alone. However, significant disruption in the swimming behavior of *D. magna* was observed. While MNPs can be clogged by embryonic chorions, they have the capacity to adversely alter the early development of aquatic organisms (Duan et al., 2020). Zhu et al. (2019) explored different types of microplastics including polystyrene (PS) and phenol-formaldehyde resin (PF), aging them under controlled photolysis. They observed the presence of environmentally persistent free radicals (EPFRs) on the irradiated PS and PF, detected by electron paramagnetic resonance spectroscopy. MNPs have the potential to adsorb heavy metals and other emerging contaminants like PFAS and antibiotics, and this can culminate in co-toxicity of organs. MNPs in freshwater ecosystems might contribute to eutrophication, and in turn pose an adverse effect to human health (Feng et al., 2020). Nanoparticle leaching leads to modification in hydrophobic nature of its membrane, surface coarseness, pure water absorbency, and salt-rejection properties (Kajau et al., 2021). While H_2O_2 is commonly used to control cyanobacterial harmful algal blooms, its effects could be altered by specific contaminants (Guo et al., 2021). In fact, Guo et al. (2021) have reported that nanoplastics limited the degrading power of H_2O_2 on cell abundance and microcystin production.

7. Analyzing Micro- and Nano-Plastics

The first step in analyzing MNPs is separation from components that could interfere with its identification when subjected to relevant instruments. For example, a cost-effective way of separating MNPs from soil samples is density separation which involves the use of salt solution to float and recover MNPs (Allouzi et al., 2021). Oil-extraction protocol has been reported to be an effective approach, with more than 95% recovery rate (Crichton et al., 2017). Magnetic separation technique has been used to separate MNPs in sediments and water samples, with recovery rate exceeding 75% (Grbic et al., 2019). Size exclusion chromatography is also an important method for separating MNPs from samples (Allouzi et al., 2021). The challenges associated with identifying and measuring MNPs in soil samples limits the understanding of its fate and distribution in terrestrial environments (Allouzi et al., 2021). Lai et al. (2021) used pretreated acid digestion with a mix of 5 millimolar nitric acid and 40 millimolar hydrogen fluoride to eliminate coexisting inorganic nanoparticles from MNP-polluted water sample. The method exposes researchers to a plausibly efficient method for initial separation of MNPs from major to minor interferences. Polypropylene happens to be the most prevalently detected MNPs in waterbodies, and the use of oil-in-water emulsion strategy, with sodium cholate acting as a surfactant, has helped to easily assess its probable origin and synthesis routes (Cassano et al., 2021).

Analytical Methods: Pros and Cons

Several analytical methods have been employed for analysis of plastic (**Figure 3**). While the existence of a variety of techniques makes initial MNP_s separation possible, there exists a fundamental problem with identifying and analyzing them by their characteristics (Allouzi et al., 2021).

FTIR and Raman Microscopy can help determine the morphology of MNPs, but the analytical size is rarely below 0.5 mm for the former and rarely below 1 μm for the latter (Allouzi et al., 2021). This means that analyzing nanoparticles

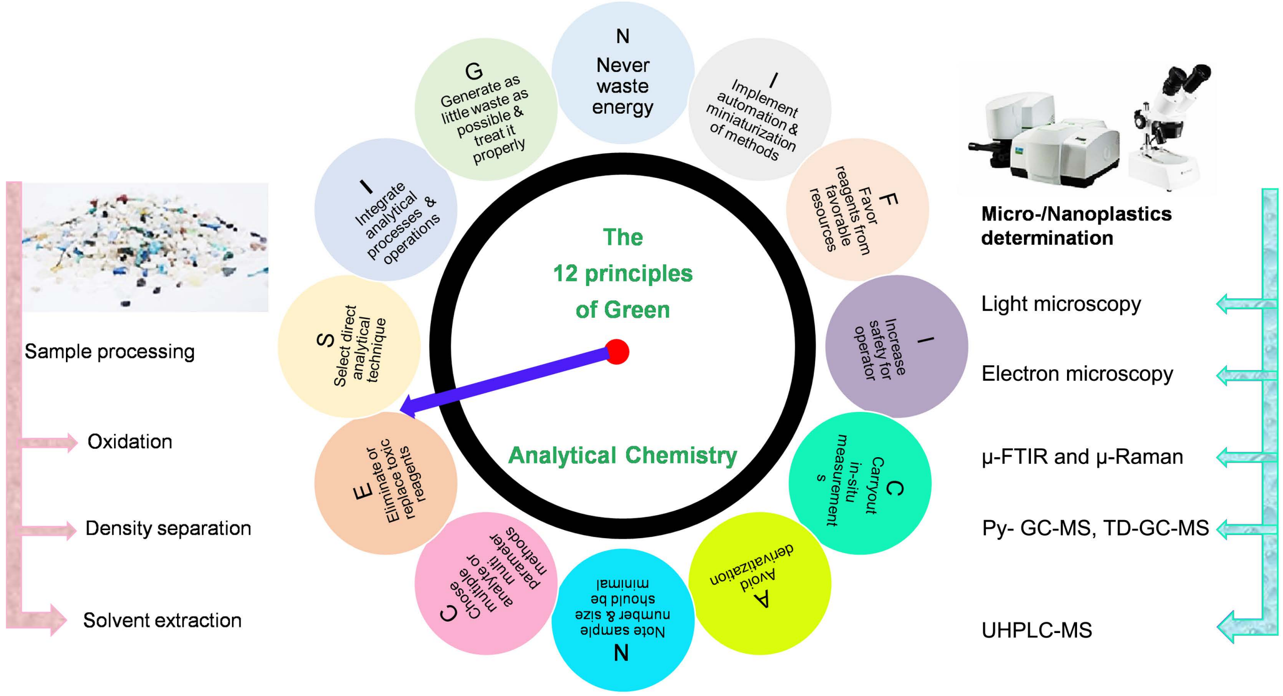

Figure 3. Analytical methods for MNPs. Adapted from Pico et al. (2019) with permission.

might be difficult. Although this analytical method is relatively simple, former measures faster than the latter. Although scanning electron microscope (SEM) is a useful instrument for describing minute fragments of plastics as the surface area of the sample is observed in detail, the disadvantage of SEM is related to its time-consuming attribute with respect to sampling (Renner et al., 2018).

The above methods may not be effective if they are utilized singly. By complementing with mass spectrometer, the distinct types of MNPs can be quantified and analyzed. The drawback is mainly related to high cost. Pico et al. (2019) emphasized the qualities of pyrolysis coupled gas chromatography mass spectrometer (Py-GCMS) including low detection limit, high sensitivity, requiring no sample preparation and having negligible sample interference. Alkaline digestion coupled with protein precipitation has been successfully used for extraction of MNPs from tissues of water creatures, followed by the use of Py-GCMS (Zhou et al., 2021). Studies and analysis of nanoparticles is still scanty in literature due to its size which makes detection and quantification rather challenging.

Scanning electron microscopy/energy dispersive X-ray spectroscopy (SEM/EDX) is capable of generating high-resolution imaging of MNPs and analyzing their elemental characteristics. This enables the MNPs to be differentiated from other solid particulates (Eriksen et al., 2013). Oliveri Conti et al. (2020) carried out extraction of MNPs from vegetables and fruits and analyzed the samples using SEM/EDX. Results showed that apple was the most contaminated fruit while carrot was the most contaminated vegetable, with the smallest size of MNPs (1.50 microns) detected in carrot samples. Due to the smattering associated with the degradation process of microplastics to nanoplastics, Mekaru (2020) dispersed about 200 nm PS in deionized water, agitating them by either rotational mixing, shaking, and flowing. Using the field emission scanning electron microscopy, results show that the sizes and shapes of these particles were altered after one-week physical degradation at room temperature.

Although FTIR spectroscopy is time-consuming and costly, it is non-destructive to the materials and enables automated mapping. Additionally, it can detect particles as small as 10 microns. It operates on the basis of energy adsorption by functional groups on the surface of microplastics (Shim et al., 2017). FTIR is a robust and versatile technology since it may be employed in the attenuated transverse reflection (ATR) mode to identify particles larger than 0.5 mm in diameter or in the transmission mode to detect microplastic particles of 15 microns (Klein et al., 2018). The major drawback of FTIR spectrometry is its proclivity for producing erroneous findings when the polymer's surface has been subjected to chemical modifications (Abuwatfa et al., 2021).

Raman spectrometry increases the capability of detection down to 1 micron due to the instrument's usage of shorter excitation wavelengths (Shim et al., 2017). The approach proved successful in identifying PS microplastics with a diameter of 3 - 31 μm. Additionally, the study demonstrated that zooplankton species were capable of ingesting 2 - 31 μm of microplastics, specifically PS beads. Additionally, fluorescence microscopy was employed to visualize microplastics consumed by a variety of zooplankton species (Cole et al., 2013). Pinto da Costa et al. (2019), Ivleva (2021), and Das et al. (2021) have recently reviewed both quantitative and qualitative analysis of MNPs, and have recommended critical studies into the analysis of nanoplastics.

8. Remedies for Combating MNPs Pollution and Toxicity

8.1. Effective Waste Management

Researchers have categorized plastics according to their recycling qualities, with recyclable plastics being more ecologically friendly and economically beneficial in areas with powerful recycling programs (Angnunavuri et al., 2020). Besides recycling and prohibitions, financial incentives for plastics disposal schemes have resulted in improved and more environmentally friendly, packaging and sanitation (Angnunavuri et al., 2020). Plastic waste accumulation has been attributed to changing consumer paradigms, behaviors, and inadequate retrieval and treatment infrastructures in a number of developing nations (Godfrey et al., 2019; Liu et al., 2019a). Developing nations are frequently burdened by severe social and infrastructure demands, rendering them incapable of connecting sound waste management policies with national development ambitions. As a result, the plastic threat is more severe in low- and middle-income nations, as indicated by the spreading of streets and waterways, overflow from trash dumps, increased plastic content in municipal solid waste, contamination of shorelines and beaches, and pollution of aquatic systems (Williams et al., 2019). Africa has been identified as a hotspot for the buildup of unmanaged and mishandled plastics, second only to the Middle East. Waste not properly managed has catastrophic effects for the humanity. Flooding and outbreaks of waterborne sickness have been recorded (Knoblauch et al., 2018; Williams et al., 2019). Waste plastics have brought harmful populations of bacteria and chemical compounds into aquatic ecosystems, gradually altering their biodiversity (Hu et al., 2019). Aquatic species have been entangled and destroyed by humongous plastics, and coral ecosystems have perished as a result (Surfrider Foundation, 2013). According to Abdolahpur Monikh et al. (2022), the European Commission is updating its proposed definition of nanomaterials and other legislative processes that would affect the future regulation of plastics and purposely created MNPs.

8.2. Biotechnological Upcycling

Plastics' persistence in the environment as a result of insufficient activity of catabolic enzymes continues to imperil aquatic and terrestrial ecosystems (Huerta Lwanga et al., 2018; Thiel et al., 2018). Simultaneously, the chemical sector depletes crude oil and fossil fuel resources to generate 90% of its products (Sarkar et al., 2022). Addressing these difficulties will require a shift away from traditional to unconventional carbon and energy sources, with plastics playing a crucial role in the circular economy as an input and output (Sarkar et al., 2022).

Due to the single-use nature of plastics and the inadequacy of recycling processes, 4 gigatons of carbon are contained in 80% of plastics manufactured globally (Geyer et al., 2022). Exceptionally high-performance fiber-reinforced plastics made from deconstructed PET (reclaimed PET) and renewable and readily accessible monomers enable the upcycling of PETs, the most widely manufactured polyesters (Rorrer et al., 2019). Integrating thermochemical degradation with biological upcycling processes enables the utilization of carbon sources in plastic trash for a circular economy that is sustainable (Wierckx et al., 2019). Concerned users are championing the minimization of single-use plastics, as a result, some manufacturers are striving towards the creation of new plastic packaging to supplant popular conventions (Hernandez et al., 2019). Depending on the chemical bonds present in the polymer, enzyme-mediated hydrolysis of plastics is critical for biodegradation. The bacterium's low capacity to breakdown PET is due to the necessity for elevated heating rates for enzymatic hydrolysis. This limitation can be solved by rational protein engineering (Song et al., 2019). Advanced knowledge of microbial metabolic pathways and genome editing techniques can assist in overcoming significant obstacles associated with biotechnological upcycling of plastic wastes (Blank et al., 2020).

8.3. Adsorption Techniques

Techniques for removing MNPs from the environment include but are not limited to biodegradation, adsorption, catalytic, photocatalytic, coagulation, filtering, and electrocoagulation, adsorption via the use of sustainable bioproducts seems more promising due to its cost-effectiveness and easy of application (Sharma et al., 2021). Sustainable bioproducts such as biochar and graphene materials have proven to have higher porosities and surface areas particularly when modified. The hydrophobic nature of nanoplastics can be determined using dye adsorption method which expunges the uncertainty instigated by assessing the surface area of nanoplastics dispersed in liquid phases (Li et al., 2022). The successful removal of nanoparticles of polymethyl methacrylate and polyvinyl acetate from water medium through $CaCO_3$ co-precipitation approach has been conducted, with efficiency as high as 99% (Batool & Valiyaveettil, 2020). Due to the enormous amount of oxygen atoms on the surface of graphene oxide (GO) as well as its distinctive functional groups such as -COOH, graphene oxide is an efficient adsorbent (Sheng et al., 2018). Yuan et al. (2020) have proposed the use of lysozyme amyloid fibrils- a bio-based flocculant- for the removal of MNPs from water. This substance has the capacity to flocculate and precipitate the particles and is up to 98% efficient. On the basis of the adsorption capability of 3-D reduced GO, a recent study conducted showed that its maximum adsorption capacity on PS MNPs was ~620 mg/g at a pH 6 and 2 hours of residence time (Yuan et al., 2020). Chitin-based sponges impregnated with GO and oxygen-doped carbon nitride successfully removed various modified PS MNPs with a removal efficiency of 72% - 92% at a concentration of 1 mg/L in water (Sun et al., 2021a). As it turns out, the adsorbent used in this experiment could be biodegraded and reused, Chen et al. (2021) removed MNPs from a water system using sugarcane bagasse-derived biochar. The results indicated that biochar created at 750˚C had a much greater MNP removal rate of 99%. Following the sorption experiment, FTIR analysis was performed to demonstrate MNP sorption on the biochar. The spectra were analyzed using Thermo Scientific Nicolet iS5 FTIR Spectrometer equipped with an ATR in the wavelength range 4000 - 500 cm^{-1}.

8.4. Use of Natural Products

While it is recommended that clinical tests be carried out on potential ameliorative natural products for combating toxic effects of emerging contaminants in humans (Oluyori et al., 2020). Chen et al. (2021) have demonstrated that Canidin-3-glucoside, a natural anthocyanin can prevent induced toxicity of nanoplastics due to its antioxidant and tissue-protective properties.

9. Conclusion

This paper has successfully explored important aspects on MNPs as an emerging contaminant and emerged threat. MNPs have an adverse impact on the environment and living organisms. Furthermore, because inconsistent size categories and terminology can misguide researchers and readers, thereby compromising advancement in research and mitigation endeavors, it is pivotal that future research classifies and specifies MNPs. Finally, to reduce the adverse impacts of MNPs on various components of all ecosystems, regulation and awareness should be instigated, coupled with improved environmental protection education, locally, nationally, and globally.

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Conflicts of Interest

The authors declare that they have no competing interests.

Authors' Contributions

Oluwafemi Awolesi performed data gathering and analyses and was a major contributor to the manuscript. Peter Oni revised and edited the manuscript. Beatrice Arwenyo revised, edited and provided guidance all through the project. All authors read and approved the final manuscript.

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List of Abbreviations

Micro- and Nano-Plastics (MNPs)
European Union (EU)
Nanoparticles (NPs)
Polyethylene-Terephthalate (PET)
Gastro-intestinal (GI)
Polystyrene (PS)
Polycyclic aromatic Hydrocarbons (PAHs)
Phenol-Formaldehyde resin (PF)
Environmentally Persistent Free Radicals (EPFRs)
Pyrolysis coupled Gas Chromatography Mass Spectrometer (Py-GCMS)
Scanning Electron Microscope (SEM)
Scanning Electron Microscopy/Energy Dispersive X-ray spectroscopy (SEM/EDX)
Attenuated Transverse Reflection (ATR)
Graphene Oxide (GO)