sustainability

Review

You Are What You Eat: Microplastics, One Health, and Our Global Food System

Gerald Shurson [1,*] and Mary Kosuth [2]

[1] Department of Animal Science, University of Minnesota, St. Paul, MN 55108, USA
[2] Institute on the Environment, University of Minnesota, St. Paul, MN 55108, USA; kosu0003@umn.edu
* Correspondence: shurs001@umn.edu

Abstract

Despite societal benefits derived from the many uses of plastics in our daily lives, plastic pollution has become another One Health crisis that has resulted in microplastic (MP) and nanoplastic (NP) contamination of all aspects of our global food production system and requires urgent attention. According to Plastic Europe, 99% of all plastics are made from fossil fuels but only 9% are recycled, which has created a major environmental injustice problem associated with geographic disparities for disposal. Plastic polymers slowly degrade to MPs and NPs in the environment and adsorb and transport other toxic environmental contaminants that compound their detrimental effects on all components of ecosystems and human health. Our global food system represents the culmination of MP contamination in the environment and is the major route of human exposure to MPs and NPs, but there are no comprehensive guidelines to avoid unhealthy consumption of contaminated food and drinking water; numerous analytical, data interpretation, and risk assessment challenges; and no international treaties to end plastic pollution. This comprehensive review is intended to provide a synthesis of disparate threads of vast amounts of scientific information across multiple disciplines to improve our understanding and action for addressing this complex One Health problem.

Keywords: agriculture; ecosystems; environment; food production; human health; livestock; microplastics; nanoplastics; One Health; plastic pollution

1. Introduction

Many scientific experts and environmental and public health organizations have pronounced that plastic pollution and microplastic (MP) and nanoplastic (NP) contamination in the environment has become a global One Health crisis [1–5]. According to the World Health Organization, One Health is defined as "an integrated, unifying approach that aims to sustainably balance and optimize the health of people, animals, and ecosystems" [6]. This means that the health of humans, domestic and wild animals, plants, and all components of ecosystems are closely connected and interdependent [1]. As a result, our global food system is the culmination of widespread MP contamination in air, soil, water, plants, animals, and marine and terrestrial ecosystems that is threatening the health of ecosystems, animals, and humans [1–5,7,8]. Food is the primary route of MP exposure in humans [9,10]. This led us to choose the title "You Are What You Eat: Microplastics, One Health, and Our Global Food System" for this comprehensive critical review and synthesis of the vast amount of scientific information on the detrimental effects of plastic, MP, and NP pollution on the health and sustainability of ecosystems, food production, and human health.

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Academic Editor: Md. Shahinoor Islam

Received: 30 April 2026
Revised: 6 July 2026
Accepted: 14 July 2026
Published: 18 July 2026

Understanding the complexity of the role of MPs and NPs on One Health requires systems thinking and integration of information across disciplines. Everything and everyone are connected to this urgent One Health and sustainability problem. Because of the widespread detrimental effects of MPs and NPs on One Health, a science-based and coordinated global strategy to overcome this extremely complex problem needs to be developed and implemented. Specifically, it will require using a transdisciplinary approach to develop policies that prevent further environmental contamination by identifying hotspots or point sources (e.g., biosolids from wastewater, plastic mulching for weed and moisture control, polymer coated urea fertilizer) and finding alternative biodegradable products as substitutes and developing and implementing effective solutions to minimize the effects of this One Health problem. It will also require significant investment in research to develop and implement various remediation and removal approaches of MPs and NPs in the environment [11].

Scientists must also take a more active role in translating and communicating this complex information to a wide variety of audiences if there is any hope for motivating and inspiring changes in behavior at all levels of society to overcome this One Health problem. To date, all published reviews on this topic have focused on various subsets of information rather than providing a comprehensive holistic summary of the challenges and potential solutions for addressing this global One Health problem. Therefore, our goal in writing this review article is to provide a critical synthesis that comprehensively captures the scope, sources, and consequences of MP and NP contamination on the many components of our global food production system on human and ecosystem health; describe the analytical and regulatory challenges that need to be overcome; potential bioremediation and mitigation strategies; behavioral changes to minimize daily MP and NP exposure; and specific knowledge gaps that need to be addressed. Our intent is that by critically reviewing, summarizing, and synthesizing this breadth of information, it can be used in guiding decision making of government policies and for increasing corporate responsibility in all industries to reduce plastic use, end plastic pollution, and begin managing this overwhelming global One Health problem. By providing a comprehensive information resource to a broad audience of scientists, environmentalists, ecologists, health care professionals, agri-food business professionals, farmers, policymakers at all levels of government, communities, and citizens around the world, it is our hope that it will help persuade changes in corporate and consumer behavior to take more urgent action to reduce plastic use, overcome the social and environmental injustices associated with its disposal, and develop global agreements and technologies to mitigate its widespread contamination and detrimental effects on One Health.

2. Materials and Methods

To achieve our goals in writing this comprehensive critical review, we chose to rely extensively on previously published systematic, scoping, and critical reviews (n = 197) of peer-reviewed articles that used common search engines such as PubMed, Scopus, and ScienceDirect to obtain original references on numerous (n = 26+) topics and scientific disciplines involving plastics, MPs, and NPs rather than duplicate these search processes. We used GoogleScholar, which is the largest multidisciplinary index, to search broadly for peer-reviewed, systematic, scoping, and critical review articles and original research studies between September 2025 and April 2026. We also used Ovid MEDLINE, which covers the same core data as PubMed, but also provides advanced and complex search capabilities to identify relevant citations in biomedicine, life sciences, nursing, and allied health between January 2026 and April 2026. We used more than 48 key words, terms, and variations that included microplastics, nanoplastics, plastic, One Health, agriculture, aquaculture, marine ecosystems, terrestrial ecosystems, environment, atmosphere, water, soil, plants, crops, fruits, vegetables, livestock, poultry, fish, seafood, shell fish, meat, milk, eggs, food, food packaging, toxicology, regulations, risk assessment, animal health, human health, economy, government policies, environmental justice, recycling, disposal, environmental contamination, degradation, analytical methods, heavy metals, antibiotic resistance, toxic environmental chemicals, bioremediation, and biodegradable plastic alternatives.

Documents from plastic manufacturers (i.e., Plastics Europe) were included to accurately report quantities of plastics being produced globally. Reports from various reputable public media sources were considered if they reflected relevant information. Additional publications were obtained by reviewing and identifying references cited and cross-referenced in systematic and scoping literature reviews, meta-analyses, data summaries, and numerous articles. Extensive literature searches were conducted to identify peer-reviewed articles on types and chemical composition of plastics used in various consumer products and the effects of human and animal exposure MPs and NPs on organs, body fluids, and physiological systems and mouse studies. Additional searches were conducted to identify scholarly articles involving plastic recycling, laws and regulations, remediation techniques for contaminated water and soil, and actions to minimize exposure to biosolids, wastewater, anaerobic digesters, compost, and animal manure.

3. The Fossil Fuels Industry Is the Main Cause of Our Plastic Pollution Problem

About 99% of all plastics are made from fossil fuels [12], and as a result, they are a major contributor to GHG emissions, ecosystem pollution, chemical leaching, habitat destruction, and loss of biodiversity [13]. The fossil fuels industry is directly involved in plastic manufacturing and is increasing investments in plastic production capacity to try to maintain demand for fossil fuels as global economies shift away from using fossil fuels for energy [14]. Initially, plastics were made from fossil fuels byproducts and waste, which made them very inexpensive, and because global fossil fuel subsidies were $7 trillion in 2022, they remain artificially inexpensive [15]. Furthermore, according to United Nations Trade and Development Calculations, plastic and rubber tariffs have declined dramatically from 34% in 1990 to 7.2% in 2020, while tariffs on natural alternative materials have remained steady [16]. These subsidies make virgin materials less costly than recycled material. In 2024, 89.8% of plastics manufactured globally were made from virgin fossil fuel feedstocks. If mechanical and “chemical” recycled plastics are included in that total, 99.4% of plastics were made from fossil fuels in 2024 [12].

Plastic production and use have always been based on the linear “take–make–use–dispose” model, which means waste is and always has been the end of useful life outcome. As Lloyd Stouffer, the editor of Modern Packaging stated in 1956, “The future of plastic is the trash can” [17]. The development of single-use plastic items such as plastic bags, bottles, and straws became a widespread convenience, but consumers were unaccustomed to this practice and had to learn to discard them after a single use [18]. New plastic inventions were introduced to society very gradually and their emergence was not necessarily fueled by consumer demand. There was no point at which the public was informed and able to weigh the pros and cons of using consumer products made from plastic. There were no opportunities for “consumer sovereignty” or consumer feedback. Although disposability has always been important to the plastics industry to enable continuous demand and production, it is now even more important to the fossil fuel industry as they experience dramatic shifts in demand away from fuel use.

The fossil fuels industry began exploring new ways to remain viable and profitable once pressures to reduce GHG emissions began to influence demand. Over the past decade, fuel efficiency standards have improved, battery technology has advanced, the cost per kWh of renewable energy has decreased precipitously, and transportation modes are shifting toward electric vehicles. These factors reduce demand for fossil fuels. In 1978, nearly half (49%) of U.S. energy came from petroleum, but in 2023, that proportion decreased to 38%. In 1950, coal comprised 37% of America's energy supply but today it makes up only 9%. Only natural gas, which is an important feedstock for plastics, has increased its share from 18% in 1950 to 36% in 2023 [19]. In fact, natural gas developments resulted in the U.S. becoming the largest producer and exporter of ethane [20], which is used to make ethylene, a necessary feedstock for low-density polyethylene (LDPE), linear LDPE, high-density polyethylene (HDPE), polyethylene terephthalate (PET), polyvinyl chloride (PVC), and polystyrene (PS).

Fossil fuel companies are aware of these trends, and in response, they plan to continue to invest even more in plastic production. A headline from the 2025 British Petroleum (BP) Energy Outlook report reads, "The use of oil as a petrochemical feedstock becomes an increasingly important component of oil demand". And a quote obtained directly from that report, that fully articulates this idea, "The outlook for oil demand is shaped by two, counteracting forces: the diminishing role of oil in road transport as vehicles become more efficient and are increasingly electrified; offset by the more persistent use of oil as a feedstock in the petrochemicals sector, predominantly for the production of plastic" [14]. In fact, BP anticipates that 95% of its future growth will come from plastics [21]. All economic forecasts predict future growth in global plastic production. Currently, plastic production consumes 8% of global petroleum, but plastics are expected to consume 20% by 2050 [22].

All around the world, plastics offer convenience and low-density durability for a reasonable price while contributing to local waste streams. Markets in developed nations are saturated, which is why geographically, the fastest growing markets are in the developing nations of Asia, Africa, and South America [23]. In the Philippines, single-use sachets are an affordable means for packaging snack foods and personal care products, but once discarded they make up over half of the plastic trash that communities must manage [24]. The increasing reliance on single-use plastics may even stymie municipal developments. For example, the use of single-use plastics in healthcare is allowed in clinics and hospitals with limited financial resources to avoid investment in reliable electrical and clean water infrastructure needed for the sterilization of reusable medical instruments [25]. Furthermore, many low- and middle-income nations are not well equipped to collect, sort, and dispose of plastic. As a result, many of these countries are struggling with the tradeoffs between the endemic use of single-use disposable plastic versus plastic waste colonialism, which involves exporting waste from high-income countries to low-income countries. For example, there are more than 300 hectares in the remote Atacama Desert in Northern Chile where global textile waste has been dumped [26]. Even in high-income nations, such as the United States, plastic manufacturing facilities, feedstock transport corridors, landfills, and incinerators are often located in low-income communities and communities of color, leading to disproportionate exposure of these populations to plastic pollution and health problems.

Lack of adequate waste management systems and infrastructure to encourage collection, segregating, and recycling plastic waste has resulted in improper disposal in landfills, waterbodies, or being burned or buried which results in widespread environmental contamination. Burning releases harmful emissions into the atmosphere. As a result, fossil fuel extraction and refining for plastic production substantially contributes to GHG emissions, air and water pollution, ecosystem and habitat destruction. Now we have a One Health crisis with no easy solutions.

4. The Life Cycle of Plastics

4.1. Plastic Production

Annual global plastic production exceeded 100 Mt (million tonnes) in 1989 [27] and exceeded 400 Mt in 2022 [28]. Cumulatively, this results in an amount of total global legacy plastic of 11,000 Mt [12,29,30]. Due to a rapid increase in growth, more than half of all plastics ever made emerged during the past 15 years [31]. Plastics are manufactured from synthetic or semisynthetic organic polymers by polymerization of single monomer molecules linked to two or more polymers by covalent bonds [32]. The length and structure of these polymers determine the specific physical and thermal properties of plastics including elasticity, strength, durability, transparency, insulation, and others [33]. Plastic polymers are classified into three categories based on their properties and include (1) thermosets such as polyurethane (PU) and epoxy resins, (2) thermoplastics such as polyethylene (PE), polypropylene (PP), PVC, PET, PS, and polyamides (PA), and (3) elastomers which include neoprene, silicone, and rubber [32]. In addition to the polymers from which they are derived, most plastics also comprise different types of chemical additives that improve various properties such as flame retardants, plasticizers, thermal and UV stabilizers, acid scavengers, lubricants, pigments, biocides, and antioxidants [34].

The defining characteristic that distinguishes plastics from all other fabrication and construction materials is the ability to customize them. The manipulation of synthetic polymers on a molecular level enables the production of plastic materials with nearly any physical properties desired. In addition to customization, the other two major attributes that plastics offer are low density (lightweight) and durability.

The evolution of plastic production and use in agriculture and food production began in 1907 when Bakelite was invented by Leo Baekeland for use in manufacturing various mechanical equipment, electrical insulators, telephones, and food processing tools [35]. The use of PVC for irrigation pipes and food packaging began in the 1920s, followed by PE (plastic film to extend shelf life and protect crops) and LDPE (silage bags, greenhouse covers, drip irrigation systems) production and use in 1933. The production of PET containers and packaging emerged in 1941, followed by PE (1950), PP (1951), and HDPE (1953) which were used in plastic films, food storage, packaging, containers, and water tanks [35]. It was not until the 1980s and 1990s that the biodegradable polymers of polylactic acid (PLA) and polyhydroxyalkanoates (PHA) emerged as reduced environmental impact plastic alternatives for use in food packaging and mulch films, with PLA becoming more widely used in the 2010s for biodegradable food packaging and compostable agricultural films to promote sustainability [35].

4.2. Societal Benefits of Widespread Plastic Use

Lauded for being lightweight, durable, inexpensive, and customizable, the plastics industry has found numerous plastic applications in all countries around the world. Plastics have become a major part of our daily lives, and it is difficult to imagine our world without them. Plastics are used in all sectors of industry and society, which are dominated by packaging followed by building and construction, automotive, electrical and electronics, medical devices, and leisure products [36]. They are also used to make numerous consumer products along with synthetic textile fibers, coatings, adhesives, and sealants [36]. Plastics provide numerous societal, human health, and environmental benefits, including the following: packaging to protect food and product from contamination and prevent waste to spare resources; light weight packaging saves fuel and decreases emissions during transport; use in water systems and storage ensures clean water; low-density plastics can replace metal or ceramics in cars and airplanes and save fuel and decrease emissions; use in protective clothing and safety equipment helps prevent injuries; and plastic medical products such as tubing, disposable syringes, and prothesis improve human health [36].

Although plastics are used in numerous applications in all types of sectors, the greatest demand for plastic is for packaging applications [37]. About 40% of plastic use worldwide is for food packaging, which is expected to increase in the future due to population growth, food delivery, low cost, longer shelf life, and single-use cutlery and packaging for take-out and fast-food meals [33]. However, despite these benefits, many of the chemicals used to manufacture plastics are highly toxic and are major One Health concerns [38]. In addition to the large amounts of plastics used in food packaging, about 12.5 Mt of plastics are used in crop and livestock production, forestry, and fisheries, representing about 3% of total annual global plastic production [33]. Fernández-Arribas et al. [33] provide several examples of different uses of plastic products in agriculture:

- Bags used for seed and fertilizer transport and storage.
- Mulch and films to reduce weed growth, water evaporation, enable ensiling of forages for long-term preservation.
- Greenhouse and tunnel films and nets to protect plants, extend cropping seasons and enhance yields.
- Irrigation tubes, pipes, and driplines to optimize water use.
- Bottles and containers for transport and storage of liquid pesticides, herbicides, fertilizers, and fuel.
- Seeding trays for plant propagation.
- Plant and tree protectors from animal and weather damage and create microclimate to enhance plant growth.
- Nets, ropes, traps, and twines used to catch and farm aquatic species, and connecting and pulling livestock, loads of crops, and equipment.
- Coatings on fertilizers, seeds, and plants to protect, regulate chemical release, and improve seed germination.
- Textile protection to protect crops from extreme temperatures.
- Tree labels for identification.
- Ear tags for livestock identification.
- Insulating cages for aquatic animals.

4.3. End-of-Life Options

Despite efforts in many countries to recycle plastics and reduce environmental pollution, only about 9% is recycled, with about 91% of total plastic production disposed in landfills, incineration, or directly discarded into the environment [39,40]. Unfortunately, a very high proportion of plastic applications have a very short useful life, such as single-use plastic water bottles, cutlery, and drinking straws, before they are disposed. Despite many communities in high income countries encouraging or even mandating plastic recycling, the quantity of plastics found in municipal solid waste has increased from <1% in the 1960s to >10% in the 2000s [41]. Microplastics are released into the environment from both disposal in landfills [42] and mechanical recycling [43]. As a result, MPs and NPs are produced [44] and have contaminated all aspects of ecosystems including soil, water, air, plants, animals, and humans. A lack of awareness of environmental impacts, the mismanagement of plastic waste, and other factors have led to massive accumulation in the environment [45].

4.3.1. The Fallacy of Plastic Recycling

Citizens in Western countries have been erroneously led to believe that the plastic they use is recycled and reused in the country where they live. The truth is that most of the plastic waste is exported to poor countries with insufficient infrastructure to adequately process and dispose of it. Consumers in wealthy countries enjoy the many conveniences of plastic in their daily lives with little consideration of the resources and environmental costs associated with making it and the devastating effects it is having on the global environment once it is discarded. In "Waste Wars—The Wild Afterlife of Your Trash", investigative journalist Alexander Clapp teaches us about the many hidden and little-known insights about the fate of plastic "recycling" [46]. The global collection, transport, distribution, and disposal network for plastic and other toxic waste is an atypical and informal industry generally driven by unscrupulous individuals in low-income countries seeking profits by operating in family networks using makeshift warehouses with only smart phones and internet access to monitor market prices. These entrepreneurs have identified legalistic loopholes in international trade laws to exploit differences in definitions between "waste", "scrap", and "resources", and the limited inspections of containers filled with waste that arrive in ports. In fact, illegal plastic trafficking was estimated to be a trillion USD annual business in 1992, but now it is 40 percent greater than previously thought and is more valuable than the combined worth of the global weapons, timber, and wheat trade [47,48].

Petroleum companies have done a masterful job of greenwashing and disguising what really happens to plastics under the guise of recycling [49]. According to a report on "Fraud of Plastic Recycling" from the Center for Climate Integrity, the plastics industry convinced the public on the disposability of plastic in the 1950s and 1960s; promoted incineration and landfilling as "solutions" to plastic waste in the 1960s and 1970s; promoted plastic recycling in response to public backlash in the mid-1980s; began a coordinated campaign to make "investments" and promise recycling in the mid-1980s to mid-1990s; continued promising recycling despite limitations in the 1990s before relenting on its commitments when its campaign was successful and public pressure subsided in the mid-1990s to mid-2010s; and a resurgence of public pressure to address plastic waste beginning again in 2015 to now [50].

Plastic and other wastes are exported from wealthy countries to low-income countries through businesses and global commerce that actually profit from it. Rich countries want to get rid of all their trash as far away as possible because they do not want to deal with waste in "my backyard". China was a major recipient of plastic and other wastes for many years until 2018 when it informed the world that it was no longer accepting waste, which was then diverted to countries in Southeast Asia [50]. This led to the emergence of 250,000 waste brokers operating in the United Kingdom alone and without legal permits to collect up to £70 for every tonne of plastic that was collected for "recycling". About 85 percent of this plastic was illegally shipped to Turkey to be recycled [51], with more than 750,000 tonnes of old plastic from European countries shipped to Turkey for "recycling", making Turkey the greatest recipient of plastic on the planet [46]. Ironically, this was occurring at the same time that Turkey had proclaimed itself to be a zero-waste nation. While it was never intended to recycle this enormous amount of plastic back to its original form, some plastic was cleaned, shredded, and chemically modified through an energy-intensive, toxin-emitting recycling process into polyester that can be used to manufacture various types of fabrics used by consumers. However, much of this plastic was burned as an inexpensive or "free" fuel source in cement factories, while that which was deemed too dirty or of minimal value was dumped in the countryside and burned, releasing toxic fumes, or allowed to slowly break down into MP and NP particles and contaminate soil and surface waters.

Fundamentally, a linear economy cannot grow infinitely if it is based on the manufacture of consumer goods that are fabricated from finite raw materials. Consequently, we must evolve into a circular economy where wasted materials are reused and recycled to produce the next generation of materials [52]. However, plastics were not designed to be recycled. Although some synthetic polymers can be converted into post-consumer goods, such as the amalgamation of plastic film and wood fiber to make decking and outdoor furniture, these products exemplify downcycling, which means these items have been removed from the circular economy and will ultimately be disposed in landfills or incinerated. Another missing part of this "recycling" story is "Have we reduced the use of more fossil fuels to produce more plastic?" Plastic recycling has often been touted as a way to reduce demand for raw materials and to keep fossil fuels in the ground [53]. However, there is no evidence that current plastic recycling is slowing resource extraction in any measurable way. This may be due to the small scale of recycling, or it may be due to the Jevons Paradox, where material savings are simply reinvested into new markets to feed endless economic growth [54].

4.3.2. Plastic Disposal

End-of-life options begin with collection and sorting followed by recycling (mechanical recycling, chemical and energy recovery), incineration (release of carbon dioxide and carbon monoxide), landfilling, and littering [34]. Globally, less than 10 percent of plastic waste is recycled [55], with the greatest proportion of plastic waste either landfilled or burned. Both landfilling and littering lead to chemical, mechanical, and biodegradation, fragmentation into MP and NP particles, and subsequent mineralization [34]. Burning releases carbon dioxide and methane which contribute to global warming, but several toxic pollutants are also released that contribute to numerous human health effects including carbon monoxide (asphyxia, nausea, fatigue), dioxins (carcinogenicity, endocrine disruption), furans (genotoxicity, liver damage), polycyclic aromatic hydrocarbons (cancer, cardiovascular disease, infertility), volatile organic compounds (cancer, organ damage), hydrogen cyanide (highly toxic asphyxiant), nitrogen oxides (chronic bronchitis, exacerbates asthma), sulfur dioxide (cardiovascular disease, stroke, exacerbates asthma), heavy metals (damages nervous system), and particulate matter (black carbon; cardiovascular disease, lung cancer) are also released [56]. As a result, the practice of open burning has become an urgent global health issue [57]. Open burning of plastics has been linked to free-range eggs contaminated with polychlorinated dibenzo-para-dioxins, dibenzofurans, and polychlorinated biphenyls [58]. Emissions including polycyclic aromatic hydrocarbons and dioxins have been associated with skin lesions, cancer, immunological disorders, birth defects, and increased risk of cardiovascular disease, respiratory problems, and neurological disorders [56]. Black carbon is particulate matter that is produced from incomplete burning of plastic, and when it is inhaled, it is linked to increased risk of asthma and birth defects, respiratory and cardiovascular diseases, neurotoxicity, adverse childbirth and development outcomes, epigenetic changes affecting the immune system and susceptibility to diseases, and premature death [59–63]. Black carbon is the fraction of soot that absorbs light and is considered to be one of the greatest contributors to climate change after carbon dioxide [64]. The ash remaining after burning plastics contains dioxins, heavy metals, and other toxic chemicals that contaminate soil, groundwater, and ecosystems [65].

4.4. Environmental Injustice of Plastic Disposal and Pollution

The environmental and health costs of plastic manufacturing and disposal are not evenly distributed across populations. Unfortunately, the responsibility for managing plastic waste is disproportionately placed on people and geographical locations least responsible for producing it [66]. People living in communities in countries in the global south (e.g., South and Southeast Asia) are subjected to increased vector-borne diseases, clogged drainage systems, reduced tourism, and increased exposure to toxic compound produced from burning plastics for heat or cooking because of a lack of adequate solid waste management systems [67]. As efforts continue to negotiate and develop a global

https://doi.org/10.3390/su18147361

plastic reduction and management treaty, justice-oriented governance strategies need to be developed that include interdisciplinary solutions based on social science approaches, account for dynamic changes in geopolitics of managing plastic waste and develop effective methodologies for monitoring progress [68]. Dauvergne [69] proposed five justice principles that should be used to guide negotiators, policymakers, and implementers during the development and implementation of an international plastics governance treaty which include the following:

- Acknowledge that plastic pollution disproportionately affects vulnerable populations in low-income countries and strive to achieve distributive justice.
- Commit to procedural justice to ensure that indigenous people and those in marginalized communities can fully participate in plastics governance.
- Avoid rules, incentives, and market mechanisms that violate human rights and promote social inequities while aiming to achieve environmental justice at all levels of governance.
- Impose strict and effective regulatory controls that require corporate transparency and accountability for plastic pollution and environmental injustices.
- Provide technical and financial assistance to enable marginalized populations to transition to a non-polluting global plastics economy by placing the economic burden on countries that contribute most to plastic pollution and have the capacity to effectively mitigate it to prevent further indebting low-income countries.

4.5. Degradation to Micro- and Nanoplastics

Degradation of plastic is slow but constant, and it occurs through mechanical degradation (wind, waves), photodegradation, thermo-oxidative, hydrolytic and biodegradation processes [70]. Plastics are very resistant to complete degradation and vary depending on the type of plastic and environmental conditions (sunlight, oxygen, moisture, temperature) of exposure [71,72]. Complete mineralization of plastics and MPs requires unique environmental conditions [73]. Degradation of plastics in packaging waste occurs by mechanical (collision, abrasion, freezing, thawing), thermal (broken polymer chains, formation of free hydroxyl and alkoxy radicals), photo (UV radiation, oxygen exposure, ozone, oxides, metals compounds), chemical (pH and salinity in aqueous environments), and biological (bacteria, fungi, insects) degradation processes that cause fragmentation into macroplastics, followed by MPs and NPs, which can undergo further decomposition to small molecular compounds including CO_2 or CH_4 [74]. Yasir et al. [35] classified the various biodegradable and non-biodegradable polymers used in agriculture and food production sectors (Table 1).

Table 1. Biodegradable and non-biodegradable polymers used in agriculture and food industries.

Biodegradable Polymers Agriculture	**Non-Biodegradable Polymers Agriculture**	**Biodegradable Polymers Food Industry**	**Non-Biodegradable Polymers Food Industry**
Polylactic acid (PLA)	**Polyethylene (PE)** [1]	Polylactic acid (PLA)	**Low-density polyethylene (LDPE)** [1]
Polyhydroxyalkanoates (PHA)	**Polypropylene (PP)** [1]	Polyhydroxyalkanoates (PHA)	**High-density polyethylene (HDPE)** [1]
Polybutylene adipate terephthalate (PBAT) [1]	**Polycarbonate (PC)** [1]	**Polybutylene adipate terephthalate (PBAT)** [1]	**Polyurethane (PU)** [1]
Polycaprolactone (PCL) [1]	**Polyethylene terephthalate (PET)** [1]	**Polycaprolactone (PCL)** [1]	**Polypropylene (PP)** [1]
Polyhydroxyester (PHE)	**Polyvinyl chloride (PVC)** [1]	Polybutylene succinate (PBS) [2]	**Polyethylene terephthalate (PET)** [1]
	Polyurethane (PU) [1]		**Polyvinyl chloride (PVC)** [1]
	Acrylonitrile-butadiene-styrene (ABS) [1]		**Acrylonitrile-butadiene-styrene (ABS)** [1]

[1] Polymers in bold are derived from fossil fuels. [2] PBS can be derived from either fossil fuels or renewable sources.

https://doi.org/10.3390/su18147361

According to World Wildlife Fund Australia (https://wwf.org.au/blogs/the-lifecycle-of-plastics/) (accessed 10 January 2026), 20 years are required to completely degrade plastic bags, 30 years for take-away coffee cups, 200 years for plastic straws, 400 years for 6-pack plastic rings, 450 years for plastic bottles and cups, and 500 years for disposable diapers, coffee pods, and plastic toothbrushes. However, through exposure to UV radiation, thermal oxidation, and hydrolysis, plastics physically break down into smaller fragments classified and micro- (<5 mm) and nano- (<1 µm) plastics which can persist in the environment indefinitely [75]. Because of their smaller size, NPs are more toxic and have greater detrimental effects in the environment because they have the ability to penetrate biological barriers and are more difficult to analyze and study than MPs [74,76,77].

Plastic particles found in the environment are classified by size, with macroplastics being the largest (>1000 mm), followed by midrange mesoplastics (5000 µm to 1000 mm), MP (1 to 5000 µm), and NP particles (<1 µm) that are not visible to the naked eye [35]. The term "microplastics" was first established in 2004 and they have been defined as synthetic solid particles or polymeric matrices that are regular or irregular in shape and range in size from 1 µm to 5 mm from primary and secondary manufacturing processes and are insoluble in water [78]. Primary MPs are intentionally produced as small particles such as in abrasive beads used in blasting media to remove paint, gentle exfoliants in personal care products, or a precursor to other products (e.g., pre-manufactured plastic nurdles used in blow molding), while secondary plastics are produced by fragmenting or shedding from large plastic products, such as fibers from a sweater or tiny particles from a plastic buoy [79]. Plastic particles < 1 µm are considered NPs [80].

Nanoplastics are a greater health concern than MPs for several reasons. They are more abundant and reactive than MPs, with a higher surface-to-volume ratio that enables NPs to penetrate living cells to reach more remote locations [77]. Nanoplastics in the environment are more heterogenous in particle size, shape, surface properties, reactivity, and contain small amounts of additives which cause them to have different interactions with light and organic matter which affect their mobility and degradation rates compared with synthetically engineered NPs [77].

There are seven categories of plastic that make up nearly three-quarters (74.4%) of the industry's manufacturing base. In 2024, these plastics were polypropylene (PP; 19%), low- and linear low-density polyethylene (LDPE and LLDPE; 13.9%), polyvinyl chloride (PVC; 12.8%), high-density polyethylene (HDPE; 12.1%), polyethylene terephthalate (PET; 6.2%), polyurethane (PU; 5.3%), and polystyrene (PS; 5.1%) [12]. The chemicals in MPs and NPs consist of additives and monomeric and oligomeric raw materials originating from plastics, along with chemicals adsorbed on surfaces from the surrounding environment [81]. Therefore, in addition to the polymeric matrices, MPs also contain many types of additives including plasticizers (improve flexibility, durability, and stretchability of polymeric films), flame retardants, antioxidants (delay oxidative degradation when exposed to ultraviolet light), heat stabilizers (prevent thermal degradation when foods are processed at high temperatures), slip agents (provide lubrication, antistatic and antistick properties, reduce melt viscosity), curing agents, foam blowing agents, biocides (resist microbial growth), soluble colorants and organic and inorganic pigments, fillers, reinforcements, and residual or unreacted monomers and oligomers [34]. Release and migration of these additives, including residual and unreacted monomers and oligomers, can occur from packaging materials into foods [34,82,83]. Heavy metals are also used as additives in plastic polymer products as flame retardants (Sb oxide, Al oxide, Zn borate, Cl, Br), inorganic pigments and colorants (Al, Ba, Mn, Zn, Pb, Cr, Co, Cd, Ti), ultraviolet light and heat stabilizers (Al, Ba, Pb, Cd, Sb, Sn, Ti), and biocides (As, Cu, Sb, Sn, Hg) [77].

However, due to proprietary rights, the plastic industry is not required to disclose the types of chemical additives used to manufacture plastic products. To circumnavigate this barrier, a digital repository has been created to list and track the possible chemicals that are used in plastic manufacturing, which currently comprises a total of 16,325 chemicals [84]. Of this total, about 26% (4219 chemicals) are known to be hazardous, while another 66% (10,726 chemicals) have no hazard data [84].

5. Reasons Why Micro- and Nanoplastics Have Become Another One Health Crisis

Because of the significance of plastic pollution and MP and NP contamination on environmental, animal, and human health, our scientific understanding of the multiple dimensions of these detrimental effects is improving and has led to it being designated as a One Health crisis [1,4,5]. Plastics, MPs and NPs are found in all environmental matrices including oceans, freshwater, soil, and air [85]. Eleven billion tonnes of plastic have been estimated to have accumulated in the environment by 2025 [86]. The greatest amount of plastic pollution is found in the Northern Hemisphere, in and around urban areas, and in marine environments [87]. Plastic represents about 75% of litter in marine environments [88] where it accumulates on coastlines and beaches [89], shorelines of remote islands [90], the Atlantic Ocean surface [91], the western Pacific Ocean [92], deep sea sediments [93–95], and Arctic Sea ice [96]. Microplastics have also been found in very remote locations including snow on the Austrian Alps [97,98], in the French Pyrenees [99], Mount Everest [100], glaciers of the Tibetan plateau [101], and the hadal sediments of the Mariana Trench, which is the deepest part of the Earth's oceans [102]. Micro- and nanoplastics are found in freshwater [103–106], groundwater [107,108], snow [97,109,110], sea and glacier ice [111–113], peat [114], soils [115–117], sediment [118], terrestrial and aquatic biota [119–122], and the air [86,99,123–126].

Although most of the One Health focus on plastic pollution and the toxic effects of MPs and NPs are on ecosystems, plastic pollution also has a significant effect on GHG emissions and climate change. In fact, GHG emissions occur at every stage of the plastic life cycle, beginning with extraction and transportation of petroleum raw materials, manufacturing processes, waste treatment and disposal in the environment [127]. Additional GHG emissions occur from unintended consequences of pipeline leakage, land use, loss of forests as a natural carbon sink, and decreased carbon fixation capacity of oceans associated with plastic pollution [127]. Both recycling and incinerating plastic waste release substantial amounts of GHG [127]. Based on current and projected GHG emissions from plastic production and disposal, cradle-to-grave emissions may exceed 56 gigatons by 2050, which is about 10 to 13% of the remaining global carbon budget available to prevent catastrophic events associated with global warming [127]. In oceans, microplastics may disrupt carbon sequestration by compromising the photosynthesis capability of phytoplankton and disrupt the biological pump that brings carbon-rich fecal pellets to settle on the ocean floor [127]. Furthermore, Arctic sea ice contains concentrations of MPs several orders of magnitude greater than found in highly contaminated surface waters of the Pacific Gyre, and as this global sink of MPs continues to melt as a result of climate change, their release into the ocean will have additional effects on ecotoxicity [96]. Finally, although individual particles that are suspended the atmosphere are small, thousands of kilotons of tire and brake wear particles are collectively released every year and drift to snow-covered regions, threatening to reduce Earth's ability to reflect solar radiation [128].

https://doi.org/10.3390/su18147361

Microplastics and NPs can serve as sources, carriers, and sinks of many types of environmental pollutants [129]. Many of the additives (e.g., phthalates, bisphenol) used in plastics are released during degradation [130] and are major health concerns because results from studies suggest that they are carcinogenic and endocrine disruptors [131]. Heavy metals and persistent organic pollutants are commonly adsorbed on MPs. Microplastics and NPs allow the colonization of fungi, bacteria, and viruses in biofilms [132]. Burning plastics releases numerous toxic chemicals into the atmosphere including dioxins, furans, polycyclic aromatic hydrocarbons (e.g., benzopyrene), volatile organic compounds, nitrogen oxides, ozone, sulfur dioxide, phthalates, bisphenols, heavy metals (i.e., mercury, lead, cadmium), and fine particulate matter [56,57,133]. Many of these compounds are linked to a wide range of health problems including cancer, reproductive and developmental problems, organ damage (especially lungs, heart and kidneys), cardiovascular disease, and metabolic problems.

Microplastics are toxic pollutants because they not only contain toxic polymers and chemicals within their physical structure, but they can also adsorb a wide variety of toxic chemicals that are present in the environment [134,135]. Microplastics act as carriers for organic compounds in aquatic environments [136], and have been shown to adsorb halogens (bromine), numerous potentially toxic metals (aluminum, arsenic, cadmium, chromium, cobalt, copper, iron, manganese, nickel, lead, titanium, zinc), and several organic pollutants such as polychlorinated biphenyls (PCBs), polyaromatic hydrocarbons (PAHs), organochlorine pesticides (i.e., dichlorodiphenyltrichloroethane, hexachlorocyclohexane isomers, chlordanes, cyclodienes, mirex, hexachlorobenzene, hopanes), polybrominated diphenyl ethers (PBDEs), per- and polyfluorinated alkyl substances (PFAS) found in numerous consumer products, aliphatic hydrocarbons, bisphenol A (BPA) widely used in food and beverage containers, and octylphenols and nonylphenols used as additives for plastics and other products including laundry and dish soaps and paint [137–139]. These interactions are a result of relatively high sorption capacities of MPs that enable the bioaccumulation and transfer of numerous chemicals throughout the environment [140]. Furthermore, antibiotics present in aquatic environments can adsorb MPs, alter the bioaccumulation and toxicity of antibiotics to aquatic organisms, and enrich antibiotic-resistant genes in the surrounding environment [141]. Although several studies have shown that MPs can adsorb and concentrate many organic and inorganic contaminants, acting as vectors to facilitate their bioaccumulation throughout the food chain, their role as a vector of transferring pollutants into organisms is controversial [142].

Micro- and nanoplastics in the atmosphere can also serve as carriers for microorganisms, including bacteria and viruses, which may facilitate the spread of diseases and antibiotic-resistant bacteria in the environment [143–145]. There is concern that the plastisphere [146], the term used to describe the plastic surface microhabitat that hosts a microbial community, may act as a site for the development of antimicrobial resistance [147–149]. Recent evidence indicates that MPs actively facilitate the evolution and spread of antimicrobial resistance [150]. Three common types of MPs (polystyrene, polyethylene, polypropylene) used in food packaging, ranging in size from 0.5 mm to 10 µm, were incubated with *Escherichia coli* for 10 days in the presence of clinically relevant levels of four widely used antibiotics (ampicillin, ciprofloxacin, doxycycline, streptomycin) to determine if the bacteria developed antibiotic resistance [150]. Results showed that regardless of type, size, and concentration, MPs facilitated multiantibiotic resistance in the four antibiotics for *E. coli* within 5–10 days of exposure. The resistance induced by MPs and these antibiotics was stable after antibiotics and MPs were removed from the bacteria. These findings indicate that MPs actively contribute to development of antimicrobial resistance, which persists after MP and antibiotic exposure, and even in the absence of antibiotics, challenging results from previous studies that suggested that MPs are only passive carriers of resistant bacteria. Therefore, MPs appear to have an important and active role in the evolution of antibiotic resistance. Plastisphere biofilms provide an ideal, persistent surface for bacterial colonization where densely packed bacteria make it easier for them to share antibiotic-resistant genes [151,152]. These dense bacterial communities on MPs increase the rate of horizontal transfer of resistant genes [151]. Furthermore, MPs are hydrophobic and can absorb antibiotics and heavy metals from the environment which creates selective pressure to actively promote the growth of resistant bacteria [153,154]. Microplastics can influence the evolution of antibiotic-resistant infections even in the absence of pre-existing antibiotics [150].

Numerous agriculture production-related practices contribute to extensive plastic pollution in agricultural land, including plastic mulching materials, pesticide bottles, and coating urea used as fertilizer [155]. As a result, MP and NP pollution, especially from PE and PU, on agricultural lands is now a major threat that alters the physical and chemical characteristics of soil and interferes with water retention and nutrient cycling [156]. The microbial community of rhizospheres of plants is altered which prevents root growth [157]; oxygen depletion occurs which makes soils less fertile; and nutrient uptake by plants is reduced [158]. Plastic additives can leach out of plastic and contaminate soil, groundwater, surface water, and drinking water sources, and adversely affect microorganisms to reduce biodiversity and ecosystem functioning [159]. Chemicals such as chlorinated dioxins and furans from chlorinated plastics can be mixed with water sources and are the most harmful [160]. Plastics also combine with agrochemicals which increase toxicity of pesticides and exacerbate environmental pollution [156]. Therefore, plastics interact and facilitate exposure to many types of toxic compounds which are hazardous in food and agriculture production systems, drinking water, animal- and plant-derived foods, and human health.

Animals ingest plastics that can cause impaction in digestive systems, and absorption of MPs and associated toxic chemicals affects growth, reproduction and health [4,36,161]. Bioaccumulation in livestock and poultry leads to human consumption of MPs from contaminated meat, milk and eggs [162], which are further contaminated during food processing, packaging, and handling before consumption by humans [33]. Various chemical additives in plastics are released from food packaging and during environmental degradation processes that also contaminate food and water, and upon ingestion, have been associated with additional health problems including chronic inflammation, cardiovascular diseases, endocrine disruption, reproductive problems, disrupted brain development, cognitive function and neurodegenerative diseases, and cancer in humans [163]. Microplastics ingested from contaminated food and water, inhaled, and absorbed through skin may be associated with inflammation, oxidative stress, and reproductive, respiratory, and digestive problems as well as cancer [4,5,163]. Gomez Souza et al. [164] proposed using a data-driven framework and approach to create a Harmfulness Score for quantitatively ranking the environmental and biological risks associated with MP pollution. This framework involves three interconnected strategies for standardizing terminology, metrics, and metadata; integrating the Harmfulness Score into regulatory frameworks to substitute high risk polymers with lower risk polymers to reduce ecotoxicological impact while maintaining most of the functionality across applications; and using consistent environmental assays to evaluate polymer and nanoparticle interactions. Although some remediation technologies have been developed, such as coagulation, membrane bioreactors, sand filtration, adsorption, photocatalytic degradation, electrocoagulation, and magnetic separation, they have not been extensively implemented [165].

6. One Health and Circularity Effects of Microplastic Contamination in the Environment and Our Global Food System

Air, water, and soil are essential for life and the production of food, but the ever-increasing plastic production and pollution that is occurring around the world is threatening these life-giving resources. Plants that produce fruits, vegetables, and crops for animal and human consumption accumulate MPs and NPs from air, water, and soil, which leads to health concerns for food-producing animals and contamination of meat, milk, and eggs. Plastic used in food packaging exacerbates MP and NP contamination in food and drinking water. The presence of slowly degradable MPs and NPs in animal manure and biosolids from sewage treatment results in the reintroduction of them to agricultural soils and water sources through land application as an essential circularity practice to recycle wasted nutrients. However, MPs and NPs appear to serve as carriers for pathogens, antibiotic-resistant genes, heavy metals, and persistent organic pollutants, which can cause additional adverse health effects on microbiomes, soil, plants, animals, and humans.

6.1. Air

Microplastics are particulate matter that can contaminate ambient air as suspended particulates capable of transboundary movement [166], and can be inhaled and penetrate lung tissue depending on particle size [167]. Airborne MP particles can fall from air, settle on surfaces, and accumulate over time, which contributes to dust load and deposition in terrestrial and ocean environments [168], or they can be resuspended depending on particle size, weight, and aerodynamic properties [124,169]. Both indoor and outdoor dust accumulation can be a sink for many types of contaminants including MPs [166]. Studies have shown outdoor airborne MP concentrations to range from <1 to >1000 particles/m^3, deposition rates between 0.5 and 1357 MP particles/m^2/day, and dust concentrations ranging from 2 to 477 particles/g depending on the environment sampled [166]. The main types of MP composition found in air, deposits, and dust are PET, PE, and PP, with the addition of PVC from road dust and PA in outdoor dust [166].

The greatest atmospheric deposition rates of plastics occur over oceans (especially the Pacific Ocean and Mediterranean Sea), and the greatest atmospheric MP deposition rates in terrestrial environments have been shown to occur in the United States, Europe, Middle East, India, and eastern Asia [170]. Although MPs comprise <1% of aerosol deposition on terrestrial environments, they contribute more than 50% to the atmospheric deposition over oceans, and re-emission sources are the main contributors to the atmospheric burden of MPs [170]. However, more information is needed for temporal deposition of aerosol MPs across different landscapes; differences in marine, agriculture, road, household, and industry emissions among regions; and aerodynamic properties of various types of plastic fibers, films, and particles [170].

Although the amount of airborne particles from various sources is unknown, they are produced by wind abrasion and have been found in air and water interfaces (i.e., sea spray), resuspended aerosol particles from motorized vehicle tire wear and nail salons, vent exhaust from mechanical drying of synthetic material, areas of landfill, and from human activity while wearing synthetic clothing [166]. High concentrations of MPs have been reported in indoor air samples resulting from breakdown of consumer, domestic, and construction products, and wearing face masks increases, rather than decreases, human exposure to MPs [171]. However, there is a lack of standardized methods for sampling and analysis of airborne MPs [171]. Because of the capability of MPs and NPs to be transported long distances by air, they are in a perpetual loop of deposition, resuspension, and ecosystem contamination that has become a serious public health issue [172,173].

https://doi.org/10.3390/su18147361

6.2. Water

The generation, cycling, and distribution of MPs and NPs in the atmosphere are intertwined with the plastic pollution, degradation, and distribution in oceans, surface freshwater (lakes, rivers, and streams), groundwater, and land [99]. Precipitation in the form of rain and snow acts like a global conveyor belt that transports MPs through the atmosphere and deposits them in aquatic and terrestrial ecosystems through a process known as wet deposition [109,174,175]. The amount of precipitation and direction and intensity of wind significantly affect MP distribution [176,177] in all types of habitats, ranging from mountains to maritime and metropolitan areas [178]. There is also evidence that the type of precipitation (rain versus snow) influences the abundance of microplastics washed out from the atmosphere [179]. The increasing frequency and intensity of extreme weather events that cause torrential rains, extensive flooding, typhoons, and monsoons resulting from climate change facilitate plastic fragmentation from intense abrasion forces and redistribute larger and more varied types of plastic particles by agitated waves [178,180–182]. Results from a meta-analysis of published data showed that floods and storms (28%), wind and tidal waves (21%), typhoons (18%), and monsoons (18%) account for 85% of MP transport globally [178]. The long-range transport and deposition of synthetic particles to high elevations, such as alpine glaciers, is also concerning because many inhabitants rely on glacial melt as a source of fresh water for drinking. According to a 2025 United Nations World Water Development Report, approximately 2 billion human inhabitants depend on these freshwater reservoirs [183].

Among all types of water environments, the abundance and characteristics of MPs have been most studied in seawater, especially in Asian countries like China [184]. Microplastics have been found in numerous seas and oceans around the world, including the Atlantic, Pacific, Indian, Arctic, and Antarctic Oceans, and the Mediterranean, Baltic, Arabian, Barents, Kara, White, South China, and Nordic Seas [184]. Concentrations of MPs are greater along shorelines and semi-enclosed bays than in open seas [185–189], but MPs generated on land also flow into marine ecosystems from rivers [190]. Sources of MP contamination in seawater include mariculture buoys and facilities, paint chips from ships and ports, fishing gear and nets, thermohaline water structure, and swimming beaches [184]. About 80 to 90% of MPs found in marine environments originate from terrestrial sources [191]. As expected, concentrations of MPs are greatest in areas with high population density [192,193] and sewage treatment sites [194,195], and all types, shapes, and sizes of MPs have been detected in marine environments [184]. It is concerning that plastics in marine environments serve as a reservoir for metal resistance genes and antibiotic resistance genes [196].

Compared with seawater, there is limited information regarding MP contamination in freshwater sources. Sources of MP contamination in freshwater are directly affected by the surrounding land environment and include tire wear, asphalt sealant, and cigarette butts on highways and roads; mulching, irrigation water, and sludge application to soil in agriculture systems; rainfall, wind, typhoons; hydrological factors including scale of water system, water level and flow rate [184]. Drainage tiles, plastic mulch, fertilizer and pesticide microbeads are additional sources of MP contamination in freshwater used in agriculture and food production [13]. Horton et al. [197] summarized results from sampling studies of freshwater environments, including water and benthic and shore sediments of lakes and rivers, which ranged from 0.00005 particles/L to 616 particles/kg. Koelmans et al. [106] reviewed fifty studies that evaluated MPs presence and concentrations in drinking water and freshwater sources including lake water, groundwater, tap water, and bottled drinking water. Microplastics were frequently detected in various freshwater sources and ranged in concentrations from 1×10^{-2} to $10^8/m^3$, with PE and PP particle types being most abundant followed by PS, PVC, and PET. Mason et al. [198] sampled 11 globally sourced brands of bottled water from 19 locations in 9 countries and reported that 93% of samples had detectable concentrations of MPs with an average of 10.4 particles > 100 µm/L. However, some samples contained more than 10,000 particles/L, some particles showed presence of industrial lubricants, and 95% of the particles were between 6.5 and 100 µm in size.

Microplastics in wastewater originate from urban centers, air particulates, manufacturing and textile industries, personal care and cleaning products in domestic sewage, and effluent from wastewater treatment facilities [184]. Sewage sludge from wastewater treatment facilities contains high concentrations of MPs and is commonly applied to agriculture soils, causing MP accumulation over time with continual applications [199,200]. This represents a direct recycling link between wastewater sources and soil. Furthermore, because wastewater contains relatively high concentrations of nutrients, it serves as an optimal environment for microbial growth, and MPs can create habitats for bacteria to be transported downstream and potential colonization of pathogenic bacteria [201,202].

6.3. Soil

Microplastics from the atmosphere can be directly deposited in soil from dry and wet atmospheric fallout via wind, rain, snow, and runoff from flooding. Several types of microplastic fragments and films have been detected in agricultural soils, including PE, PS, PP, and LDPE [203]. Soil can become contaminated with MPs from application of human sewage sludge and vermicompost; plastic mulching; irrigation, flooding, and run-off; plastic waste disposal and littering; industrial wastes; contaminated animal manure [204]. Plastic sheets are commonly used to cover soil in seed beds, greenhouses, and landscaping areas to provide warmth and prevent weed growth, in vertical farming applications, and mulching [203]. Sewage sludge application and plastic film mulching are the primary reasons for MP accumulation in agricultural soils [204–208]. Furthermore, application of organic or inorganic fertilizer to soils increased MP concentrations between 1966 and 2022, indicating that agriculture fertilizers are a significant contributor to MP contamination in soil over time [209].

Once MPs and NPs have entered soil, they agglomerate with organic matter and microbial secretions and become embedded in the soil microstructure [115]. As a result, MPs and NPs alter the soil physicochemical properties by increasing porosity and water-holding capacity; reducing bulk density and moisture permeability; destroying its structural integrity and changing its structure; disrupting carbon, nitrogen, and phosphorus ratios and cycling; increasing or decreasing pH; and inhibiting or inactivating enzyme activities, all of which can alter the soil microbial community and cause oxidative stress in plants and microbes [204,210]. In addition, there are multiple toxicity effects of MPs in soil resulting from various additives (plasticizers, flame retardants, antioxidants, light and heat stabilizers, lubricants, pigments) that they release during degradation; hydrophobic organic pollutants (polychlorinated biphenyls, polycyclic aromatic hydrocarbons, petroleum hydrocarbons, organochlorine pesticides) that they adsorb; adsorbed heavy metals that affect migration, transformation; and other changes in environmental pollutants that result in toxic effects on soil organisms [210].

Very little is known about the responses of various types of organisms to MP and NP pollution in soil. Toxicological studies and risk assessments for estimating population and ecosystem responses are crucial for policy making and potential mitigation strategies [211]. Earthworms have been the most studied, with variable responses depending on type and concentration of MP exposure. No studies have evaluated responses from nematodes, rotifers, and ciliates when exposed to MP and NP pollution. Similarly, little is known about the effects of MP and NP contamination on soil microbiome because variables are difficult to control in field studies, but some evidence from a controlled laboratory experiment showed that soil microbial biomass, enzyme activities, and functional diversity tended to decrease with increasing plastic mulch residue [212]. Limited studies have shown that MPs inactivate or inhibit microbial activities, microbial diversity, and community structures [213–216].

6.4. Plants

Although the effects of MPs and NPs on physical properties and microbiota of soil are becoming apparent, there is limited information on the consequences of these changes on plant growth. Beginning with germination, MPs accumulate on the pores of seed capsules and delay germination and root growth [217]. Plants can absorb MPs and NPs from soil through root hairs [218]. Although MP particles cannot directly enter plant tissue because their large size prevents entry through plant cell walls [219], NP particle sizes between 20 nm and 40 nm can be absorbed [220]. Plant uptake of MPs and NPs occurs via transpiration pull, where particles enter the epidermal tissue of primary and secondary roots and are stimulated through the pericycle and moved into the xylem [218]. Once NPs are inside the central cylinder via the xylem, they can move to the aerial part of the plant and potentially be transported to grain [218]. Studies have shown that MPs can accumulate in leaves and stems of specific plants and may accumulate in flowers and fruits [217,221]. Adeel et al. [222] suggested that plastic particles could also enter leaves through the stomata via foliar application. Rillig et al. [122] proposed several mechanistic pathways of how MPs may affect plant growth, including altered soil structure, nutrient and microbial immobilization, contaminant transport and adsorption, direct toxicity, altered soil microbial communities and root symbionts, and plant community level effects.

Very little is known regarding the physiological effects of MP and NP exposure in plants. In addition to direct uptake of MPs by roots, direct toxicity can also occur by adversely affecting root growth, movement, and water and nutrient absorption efficiency [204]. Root growth is reduced presumably through changes in root length, diameter, and biomass that vary between species [218]. Plant photosynthesis and chlorophyll content appear to be positively and negatively affected in a dose-dependent manner by MPs and NPs, and changes in biochemical enzyme are different between plant species [218]. However, MPs and NPs consistently induce oxidative stress in plants regardless of species. Therefore, despite limited studies, there is substantial evidence indicating that MPs and NPs are taken up by various agricultural and food plant species which makes them sources of MP and NP accumulation in food-producing animals and humans that consume them.

6.5. Animal Feed

Livestock and poultry are exposed to MPs and NPs through contaminated feed, water, inhalation, and environment, which leads to bioaccumulation of these particles in meat, milk, and eggs which becomes a direct route of human exposure [223]. Low-density polyethylene (LDPE) and polyamide copolymer LDPE films are used extensively to store and cover horizontal silos of fermented forages and to wrap and tie hay and straw bales as feed sources for ruminants. These materials undergo fragmentation due to exposure to ultraviolet light and mechanical abrasion, which is common on farms. Glorio Patrucco et al. [224] sampled total mixed rations on a dairy farm in northern Italy and found an average of 17 MPs/g with lengths ranging from 0.20 mm to 3.73 mm.

In another study, Maganti and Akkina [225] collected 36 livestock and poultry feed samples from 12 farms in India and reported that all samples contained significant concentrations of PET, PP, and PVC particles that ranged in size from 2.0 to 10.7 µm. Likewise, Wang et al. [226] assessed the occurrence of bisphenol compounds in feed packaging and

https://doi.org/10.3390/su18147361

transfer to animal feed and observed that bisphenol A was most commonly found in a wide range of concentrations in PP- and PE-based packaging, with six different bisphenols found in PP-based woven bags and two types of bisphenols found in PE-based packaging. These results show that bisphenols in plastic packaging materials can migrate to feed and the extent of feed contamination is determined by initial bisphenol concentration and contact time with packaging materials.

Analytical methods to identify and quantify MPs in animal feed have many challenges. Masoero et al. [227] evaluated the use of near-infrared spectroscopy (NIRS) to detect MPs in four types of ruminant feeds (corn silage, rye grass silage, mixed hay, and soybean meal) and a total mixed ration by adding LDPE and PS at different concentrations to each matrix. They found that using a short wavelength range (714 to 1070 nm) or a smart NIRS instrument provided acceptable measurements of concentrations of MPs, with an accuracy of 0.8 mg/g and a detection limit of about 1 mg/g. These results are promising for use as a field application to screen sources of feed ingredients for MP contamination before feeding.

Plastic contamination in animal feed is prohibited in the EU, which is a significant barrier for using some types of organic waste streams in animal feed [228]. The use of insect meal is an emerging technology that uses waste substrates such as food waste and animal manure to produce insects, such as black soldier fly larvae (BSFL), as a sustainable source of high protein animal feed. Therefore, Dam et al. [228] developed a method to determine the potential transfer of MPs from waste stream substrates to the BSFL biomass produced. Although there was no effect of dietary exposure of PET and three sizes of LDPE particles on larval yield and survival, PET was recovered, not LDPE from larvae. These results suggest that it may be possible to use BSFL as a means of producing a sustainable animal feed ingredient from certain types of waste streams contaminated with some types of plastics.

6.6. Food-Producing Animals

The amount of plastic contamination in the terrestrial environment is 4 to 23 times greater than the amount of contamination in the marine environment [197]. However, the transfer of MPs across both aquatic and terrestrial organisms and impacts on health are poorly understood. Terrestrial food-producing animals, including cattle, sheep, goats, swine, and poultry, are directly exposed to plastic- and MP-contaminated air, freshwater, soil, and plants, which can lead to potential adverse health and welfare effects, losses in productivity, and significant bioaccumulation and contamination in meat, milk, and eggs consumed by humans. Therefore, there is significant potential to reduce MP and NP exposure to humans by minimizing exposure and accumulation in farm animals. Unfortunately, only a limited number of studies have evaluated the health impacts of MPs and NPs on livestock and poultry (Table 2). As a result, most of our current understanding of the health effects on animals and humans is derived from mouse and rat models.

Farm animals can be exposed to MPs and NPs from contaminated air, freshwater [104], and terrestrial environments [229]. The major routes of MP and NP exposure in grazing-based and mixed livestock systems are from plastic mulching, fragmentation of plastic waste, and runoff into streams [229]. Plastics have been found in digestive systems of sheep [230] and cattle [231]. Interestingly, the combined action of bacteria, archaea, and eukaryotes in rumen fluid was effective in hydrolyzing three types of synthetic polyesters [232], suggesting that ruminants may be capable of degrading plastics. Microplastics have been shown to transfer from soil to earthworms to chickens [233].

Microplastics have been found in chicken meat [234] and cow's milk [235]. Milne et al. [236] sampled and analyzed the microplastic concentrations in 16 different types of unprocessed, minimally processed, and highly processed seafood, terrestrial meat, and plant-based protein products in the U.S. to estimate the average U.S. adult microplastic exposure per year across all products at three contamination levels. The average concentration of MPs per serving was 74 particles and ranged from 2 particles per serving in chicken breast to 370 particles per serving in breaded shrimp. Average microplastic particles per serving of pork loin chop, top sirloin steak, and chicken nugget were 4, 25, and 62, respectively, compared with 7, 10, 46, and 73 microplastic particles per serving in plant-based tofu, ground beef, fish stick, and nugget, respectively. Using U.S. protein consumption data, average annual adult consumption of these protein sources was 11,000 particles per person per year with a maximum estimated consumption of 3.8 million exposure per person per year.

Table 2. Summary of physiological effects from plastic, MP, and NP ingestion by ruminants, poultry, and swine.

Species	Physiological Effects	References
Ruminants (dairy cattle, beef cattle; sheep, goats)	Ingestion of large plastics causes rumen impaction, abdominal pain, constipation; Reduced growth rate; Increased concentration of heavy metals in rumen, blood, liver, kidneys, muscle; Liver and kidney dysfunction; Absorption of MPs and NPs from the digestive system cause digestive dysfunction and ruminitis; Alterations in relative abundance of selected rumen microbes; Reduction in rumen ammonia; Reduced dry matter, fiber, and lipid digestibility and nutrient absorption; Reduced meat quality and nutritional value; Abnormal blood physiology and metabolism; Mitochondrial dysfunction, oxidative stress, reduced cell viability, damaged organelle integrity, changes in morphology of goat mammary epithelial cells; Endoplasmic reticulum stress and apoptosis; Decrease in number of mature oocytes; reduced cleavage rate and embryo development at blastocyst stage along with modifications to gene expression; MP particles were found in edible cow and sheep tissues (liver, meat, tripe) in Iranian butcher shops.	[237–248]
Poultry (broiler chickens, layer chickens, ducks	Macroplastics transformed to MPs during digestion; Ingestion decreased feed consumption and body weight gain; Increased gizzard volume; Altered intestinal morphology, microbiome composition and decreased microbiome richness; Body weight loss; Increased leg and breast muscles; Disruption of skeletal muscle function; Liver inflammation and disruption of function; Underdevelopment of kidneys; Kidney tissue damage; Impaired mitochondria; Altered blood-urinary barrier; Oxidative stress; Inflammation of heart muscle; Myocardial dysplasia; Dysfunctional energy metabolism; Inflammation and impairment of testicular tissue; Significant liver damage through gut barrier disruption, microbial translocation, and tissue necrosis; Impaired growth, alters gut microbiota composition and structure resulting in an imbalance; Greater number of MP particles found in egg yolk than in egg white with about 12 particles per egg; MP particles found in intestinal tracts of domestic ducks.	[233,249–260]
Swine	Reduced feed intake; Altered gut microbiome composition; NPs disrupt cell proliferation, steroidogenesis, and redox status of cultured granulosa cells; NPs reduced viability, increased oxidative stress and altered inflammatory markers in adipose stromal cells; Consumption of PET microparticles results in histological changes in the jejunum with potentially neurotoxic and proinflammatory effects; Altered oocyte maturation, caused cytoskeletal disruption, changed mRNA levels and cumulus expansion; NPs caused oxidative stress in kidney cells which leads to aging and inflammation in kidney cells; Consumption of MP-PET caused significant changes in the composition of fecal microbiome; Increased ROS levels in oocyte and decreased blastomere number per blastocyst that interfered with oocyte maturation; A dose of 1 g PET/day/animal caused changes in the enteric nervous system and in the histological structure of duodenum; PS particles adversely affect meat quality and is detrimental to skeletal muscle angiogenesis; MPs detected in fetal pig lungs in natural environment.	[261–272]

6.7. Food Contamination

Plastic use in agriculture, food production, processing, storage, packaging, and consumption has become a dominant use of global plastic production. Various plastics are used extensively in agriculture for optimizing seed germination; reducing water demand; increasing crop yield; making ropes and nets for support structures and crop protection; extending growing seasons and protecting plants; maintaining quality of fresh products; reducing food losses; and reducing herbicide use [35]. Likewise, various plastics are used in the food industry for packaging to provide effective barriers against moisture, gases, and potential contaminants to maintain quality and extend shelf life, ensure food hygiene and safety, allow for efficient distribution at low cost, and provide transparency for visual inspection of food products, and are lightweight, strong, stable, durable, and versatile [35]. Therefore, because of all of these positive attributes, removing fossil-fuel-derived plastics from agriculture and food production is realistically impossible and requires replacing them with viable, biodegradable alternatives that are derived from renewable resources. Although some biodegradable and renewable-resource-based polymers such as PLA, PHA, and PHE are being used in agriculture and the food industry, more research and development of biobased alternatives to traditional plastics is needed.

Microplastic contamination in wild and farmed fish and shellfish is the most widely studied of all food types. Several reviews have been conducted to summarize these findings [273–277]. More than 400 original research papers (62% for marine species and 38% for freshwater species) were summarized by Galafassi et al. [274], where plastic ingestion (0 to 30 particles per fish) was detected in up to 90% of samples from 257 species from more than 32 countries. The most common types of plastics detected were PE, PS, PP, rayon, PA, cellophane, and acrylonitrile. Similarly, Markic et al. [275] reviewed 93 studies published between 1972 to 2019 which showed that plastics were found in two-thirds (323 of a total of 494) of wild marine fish species. Sequeira et al. [276] reported that a median of 60% of fish from 198 wild species in 24 countries contained MPs in their organs, with carnivorous species containing greater concentrations of particles than omnivores, and PE, PP, PET, and PA were the most common polymers detected. Kwon et al. [277] reviewed more than 30 papers that reported concentrations of MPs in various types of shellfish, with the majority of studies focused on blue mussels, which detected <1 particle per gram, but greater concentrations were reported for other shellfish species.

Beyond fish and seafood, very little information is available regarding MP contamination in meat, eggs, fruit, vegetables, grains, milk, honey, and sugar, which comprise the majority of food consumed worldwide (Table 3). Milne et al. [236] conducted a study to determine the MP concentrations in 16 different types of protein foods in the U.S. which included fresh, minimally processed, and processed seafood (shrimp, pollock fillets), terrestrial meat (chicken nugget, beef sirloin steak, pork loin chop, chicken breast), and plant-based protein (nugget, "fish stick", "ground beef", tofu). They detected MPs in all 16 protein products, but concentrations did not differ between brands and store types, and highly processed products contained the greatest MP concentrations. Interestingly, numerous sources of table salt from Africa [278], Spain [279], Italy and Croatia [280], Turkey [281], India [282], Sri Lanka [283], Australia [284], China [285], Taiwan [286], and globally [287–289] have been shown to contain MPs.

Table 3. Summary of studies that have evaluated the presence and concentrations of microplastics in foods, beverages, and packaging materials associated with foods.

Foods	References	Beverages	References	Packaged Foods	References
Fish and seafood	[273–277]	Groundwater	[290]	Canned fish and seafood	[291,292]
Seaweed nori	[293]	Treated water	[294]	Packaged beef	[295]
Chicken	[256,296]	Tap water	[161,289,294, 297,298]	Packaged chicken and turkey	[295,299,300]
Eggs	[253]	Plastic bottled water	[161,198,301]	Cured meats (bacon, mortadella, salami)	[302]
Milk	[303–305]	Bottled mineral water	[306–309]	Take-out food containers	[310]
Honey	[303,311–313]	Soft drinks	[303,314,315]		
Fruit (apple, European pear)	[316]	Cold tea and ready-to-drink teas	[314,315]		
Vegetables (broccoli, lettuce, carrot, potato)	[316–318]	Sports and energy drinks	[314,315]		
Grains (uncooked and instant rice, wheat)	[317–319]	Juice drinks	[315]		
Sugar	[311]	Soda waters	[315]		
Table salt	[278–288]	Beer	[289,303,306, 320]		
Vinegar	[321]	White wine	[322]		

Water is the most significant contributor to our daily consumption of MPs because it is consumed directly or as part of various beverages and alcoholic drinks, is a major component of foods we consume, and it is used in the primary production of food, cleaning and sanitation of food processing facilities. According to the World Health Organization [323], about 90% of MPs can be removed from wastewater when using conventional and optimized water treatment. Several studies have evaluated the presence and concentration of various sources of water from groundwater, treatment plants, tap water, and plastic bottles. Microplastics have been found in other beverages including soft drinks, cold tea, energy drinks, beer and wine (Table 3).

Microplastic contamination in foods can occur from exposure to airborne particles, food processing and distribution equipment, other ingredients, packaging, and various types of food contact materials. However, only a few studies have evaluated the presence and concentration of MPs and NPs in packaged food (Table 3). Microplastics in bottled water come from PET and PP used to manufacture returnable plastic bottles and caps, while PE and biofilms which are commonly used as coating materials and lubricants are found in beverage cartons and glass bottles [306]. Millions of PP particles can be shed by infant feeding bottles [324]; PS food trays can be a source of MP contamination (4 to 19 particles/kg) in meat [299]; and take-out containers shed 3 to 29 particles/container into food [310]. In fact, opening a food package by cutting or tearing a sealing tape and twisting a cap to open a bottle to drink a beverage can release 0.46 to 250 microplastic particles/cm [325]. There are at least 10,259 known chemicals related to plastic packaging, and many of the chemicals including plasticizers, antioxidants, slip additives, and light stabilizers have been shown to migrate from food plastic packaging under different contact times and temperature conditions [326].

6.8. Circularity of Microplastics in Animal Manure and Waste Streams

Microplastics and NPs in the atmosphere can serve as carriers for microorganisms, including bacteria and viruses, which may facilitate the spread of diseases and antibiotic-resistant bacteria in the environment [143–145]. There is emerging evidence that MPs and NPs enhance the mobility and transfer of antimicrobial-resistant (AMR) genes in ecosystems [327–329]. Antibiotic resistance caused by extensive use and misuse in human medicine and food animal production has created a One Health crisis, which is now further compounded by the presence of MPs and NPs promoting circularity of AMR genes in the environment [330]. Liu et al. [331] showed that the combination of MPs and chlortetracycline is more harmful for increasing antibiotic resistance genes in the gut microbiome of Muscovy ducks than the independent effects.

As previously described in Section 5 of this review, recent evidence indicates that MPs actively facilitate the evolution and spread of antimicrobial resistance [150]. Horizontal transfer of antibiotic-resistant genes appears to be highly dependent on MP and NP particle size and increases with UV aging in *E. coli* [75]. Nanoplastics have been shown to promote antibiotic resistance gene propagation in a biological phosphorus removal system [332] and enrich intracellular and extracellular AMR genes to selectively inhibit ammonia-oxidizing bacteria and enhance nitrate-oxidizing bacteria, affecting the aerobic oxidation performance of granular sludge nitrification [333]. Additional studies have shown that MPs can enhance the propagation of AMR genes in various environments [334,335]. This evidence should create additional concern for global public health because our current regulatory and health management systems have not been effective in curbing the antibiotic use and misuse that have led to antimicrobial-resistant bacteria affecting human and animal health worldwide.

Microplastics adsorb antibiotics [336], and AMR genes are spread through highly polluted air [337]. Microplastics interact with minerals and form aggregates in soil, which facilitates vertical and horizontal spread of MP and adsorbed pollutants, such as AMR genes through the agricultural ecosystems [338,339]. Microplastics combined with tetracycline in soil facilitate the development of AMR in annelids (*Enchytraeus crypticus*) that live in soil [340]. Microplastics and AMR genes present in soil can be absorbed by plant roots and transported to edible parts of the plant to be consumed by livestock [341].

Livestock and manure are considered reservoirs of AMR genes [342]. Qian et al. [343] detected 109 AMR genes in animal manure, with greater diversity and abundance in swine and poultry manure than in cattle manure, but composting was effective in reducing AMR genes in poultry manure. Application of animal manure, biosolids, and irrigation with reclaimed wastewater enables the recycling of MPs and AMR genes in soil and agricultural systems.

Heavy metals adsorbed on the surface of plastic particles can enter or be recycled in the food chain. Abbasi et al. [344] showed that Pb and Cd were adsorbed on the surface of plastic particles, transported, and desorbed in the rhizosphere of wheat (*Triticum aestivum*). Microplastics have been shown to release Cd and Hg during *in vitro* digestion studies in ruminants [345]. This suggests that if heavy metals and MPs are present in feed ingredients and grazing systems, MPs may facilitate the consumption of heavy metals, which could lead to health and food safety concerns.

7. Effects of Micro- and Nanoplastics on Human Health

7.1. Routes of Human Exposure

Humans are exposed to MPs and NPs primarily through ingestion and inhalation, and, to a lesser extent, dermal penetration, but this varies based on lifestyle and living conditions [346]. Human exposure to these MP and NP particles occurs at the gastric, respiratory and skin levels where they enter the body and subsequently interact with numerous target cells that are associated with numerous adverse metabolic and health effects [347,348]. Furthermore, particles inhaled can be swallowed with nasal mucus, and particles in air can settle on food before consumption [349].

Plastic fragments from synthetic textiles used in clothing, furniture, and building materials along with dust in urban environments are major sources of inhalable MPs [346]. Less is known about dermal penetration of MPs because only particles less than 100 nm in size appear capable of being transported through sublayers of epidermis before entering the circulatory system [350,351]. Personal care products, such as hand cleaners, shampoos, and facial and body scrubs, contain nanoplastic particles and plasticizers such as phthalates and bisphenols that can be dermally absorbed [352,353]. In fact, results from one study that analyzed 8000 samples of face rinse, hand rinse, hair rinse, and mouth rinse from 2000 participants in Iran found that head hair had the most MPs, with >3.5 MPs per individual per day, and men had about twice the number of MPs as women [354]. Plasticizers are endocrine disruptors and induce immunosuppression by acting on nuclear receptors, such as estrogen receptors, and disrupt the antioxidant system of erythrocytes [353].

Limited studies have been conducted to determine concentrations in food and beverages and subsequent exposure through ingestion [298]. Microplastic and NP exposure from ingestion of contaminated food has been shown to occur primarily from seafood [355], along with drinking water and manufactured beverages [315,320]. Barboza et al. [356] summarized the results from numerous studies showing that MPs have been found in a wide variety of shellfish and many species of commercially important fish, along with other foods and beverages, including honey, sugar, salt, canned sardines, beer, mineral water, bottled water, and tap water. The high prevalence, concentrations, and wide range in types of MPs in seafood is a result of the many types of microplastic debris found in marine environments including high-density polyethylene used in milk and juice containers, and low-density PE found in plastic bags, six pack rings, bottles, and drinking straws reported in 79% of 42 studies, followed by PP (64% of studies), PS (33% of studies), PA, PE, PVC, and PET [357]. Chemical plasticizers and plastic used in food packaging and containers such as water bottles, take-out containers, and plastic wrap is directly shed into food as a result of mechanical stress, physical abrasion, freezing and thawing, and washing and reuse, which also contribute to human microplastic exposure [320,358,359].

Epidemiological studies that determine the threshold exposure levels from different types and amounts of MP inhalation and ingestion that cause adverse health effects on humans in different demographics are needed. Although data on MP and NP prevalence and concentrations in food and beverages is extremely limited, several exposure assessment studies have been conducted to estimate annual MP consumption for humans [298,355,360–364].

Danopoulos et al. [360] conducted a review of 50 studies that included 19 studies in the meta-analysis and reported the range in MP particle content in mollusks (0 to 10.5 particles/g), crustaceans (0.1 to 8.6 particles/g), fish (0 to 2.9 particles/g), and echinoder-mata (1 particle/g), with a maximum annual human intake of about 55,000 MP particles, indicating that action should be considered to reduce human consumption of MP-contaminated seafood. Domenech and Marcos [355] conducted a systematic review of studies conducted from recent studies and provided estimates of annual human intake of MPs and NPs from fruit and vegetables (19.38 $\times$ 109 particles/year), seafood (22.04 $\times$ 103 particles/year), salt (260.61 particles/year), bottled water (9.89 $\times$ 109 particles/year), and alcohol (25.92 particles/year) compared with inhalation of 2.16 $\times$ 103 particles/year. Using U.S. protein consumption data, and MP concentrations in 16 different types of protein foods (seafood, terrestrial meats, plant-based proteins), Milne et al. [236] estimated the average adult exposure consuming these proteins was >11,000 MP particle/year, with a maximum exposure of about 3.9 million particles/year. In another systematic review and meta-analysis of studies that evaluated MP contamination in salt intended for human consumption, the majority of samples contained MPs with variable concentrations in sea salt (0 to 1674 MPs/kg), lake salt (8 to 462 MPs/kg), and rock and well salt (0 to 204 MPs/kg), resulting in estimated potential human exposure of 0 to 6110 MP particles per year [361].

Cox et al. [362] estimated that average annual MP consumption based on U.S. diets is between 39,000 and 52,000 particles/person depending on age and sex and may be as much as 74,000 to 121,000 particles/person when inhalation exposure is considered. An additional 90,000 MP particles may be ingested annually by individuals who meet their daily water intake only by consuming bottled water. However, these authors indicated that these exposure estimates are likely underestimated. Danopoulos et al. [298] conducted a systematic review of MP contamination in drinking water and estimated annual human consumption. They summarized results from six studies involving tap water and six studies involving bottled water which showed that PET and PP were the main polymers present, particle size varied from 1 to 100 μm, and maximum reported concentrations were 628 MPs/L for tap water and 4889 MPs/L for bottled water. Using typical consumption data, maximum annual adult human intake of MPs from tap water was estimated to be 458,000 MPs for tap water and 3,569,000 MPs for bottled water [289]. Senathirajah et al. [363] estimated that the average global ingestion of MPs is between 0.5 and 5 g weekly, mainly from tap and bottled water. However, many of these estimates have been questioned based on limited data and assumptions used.

Danopoulos et al. [364] conducted a systematic review involving 17 studies and a meta-regression to estimate dose–response thresholds of dose–response relationships of MP exposure in humans based on cytotoxicity, immune response, oxidative stress, and barrier attributes. Results showed that irregular shape, duration, and concentration of MP exposure predicted cell death; cell cytotoxic sensitivity varied, but low MP concentrations had adverse effects on cell viability and cytokine release. Mohamed Nor et al. [365] developed a probabilistic lifetime exposure model for children and adults that accounted for MP intake of eight food types and inhalation, intestinal absorption, biliary excretion, and plastic-associated chemical exposure through a physiologically based pharmacokinetic submodel. Median MP intake rates were 553 and 883 particles/capita/day for children and adults, respectively, corresponding to irreversible accumulation on 8.32×10^3 particles/capita for children until age 18, and up to 5.01×10^4 particles/capita for adults in body tissue ranging in size from 1 to 10 μm. Based on the assumptions used, these results indicate that the accumulation of MPs in body tissues of children and adults during many years of exposure to contaminated food and air is relatively small.

7.2. Effects on Human Health

About 39,000 to 52,000 microplastic particles are ingested by an average adult annually, with greater amounts ingested in people living in plastic-polluted areas and consuming high-meat diets [298]. There are multiple sources of plastic-derived fragments and chemicals that can enter the human body through multiple routes and elicit numerous adverse health effects. However, to date, there are no definitive threshold values or risk assessments associated with microplastic exposure. This is primarily due to the vast heterogeneity of micro- and nanoplastic particles (size, shape, chemical composition, abundance, chemical additives, age, and weathering). Because these contaminant particles do not represent a single toxic entity, it is difficult to definitively determine the amount or duration of exposure that will most likely yield a negative health outcome. Studying the extent of MP and NP exposure needed to increase the likelihood of a negative health outcome in human populations would require control of many variables and creates many logistical and ethical challenges [346]. For this reason, most studies involve relatively small sample sizes and non-invasive sampling such as feces, saliva, hair, and skin, compared with more invasive sampling of organs and internal tissues except for those obtained for medical biopsies.

Several studies have reported the presence of MPs and NPs in various tissues, organs, fluids, secretions, and excretions in humans, indicating the potential widespread distribution in the human body (Table 4). Lusher et al. [273] summarized the fate of MP and NP particles in mammalian bodies as particles of ≤0.1 μm capable of penetrating all organs and translocation of the blood–brain and placental barriers, ≤20 μm able to enter organs, 100 μm absorption in the portal vein, <150 μm absorption in lymph, with no absorption if particles are >150 μm. As a result, MPs and NPs have been found in 63 human biological compartments, are retained in biological tissues for decades, have organized distribution and interactions across biological compartments, and are actively involved in many biological activities [366]. Guan et al. [367] conducted a non-targeted microparticle analysis of 13 types of body fluids (cerebrospinal fluid, whole blood, thyroid cyst fluid, hepatic cyst fluid, renal cyst fluid, gallbladder cyst fluid, pelvis cyst fluid, pericardial effusion, pleural effusion, peritoneal effusion, testicular effusion, intrauterine effusion, and joint effusion) representing 8 physiological systems obtained from 104 patients ranging in age from 24 to 96 years. A total of 23 MPs were detected and grouped into nine types, including polypropylene (PP), polystyrene (PS), polytetrafluoroethylene (PTFE), polyvinyl butyral (PVB), polyamide 6 (PA), low density polyethylene (LDPE), polyethylene-co-acrylic acid (PEAA), polystyrene-co-acrylonitrile (PSAN), polyvinyl alcohol (PVA), which were distributed as follows: whole blood (PA, LDPE, PEAA, PSAN, PVA), thyroid cyst fluid, hepatic cyst fluid, renal cyst fluid, gallbladder cyst fluid, pelvis cyst fluid (PS), pericardial effusion (PP, PS, PTFE, PVB), pleural effusion, peritoneal effusion, testicular effusion (PP, PS, PA), intrauterine effusion (PP, PS), and joint effusion (PS).

Microplastic particles have been found in human feces, with infants having greater abundance than adults, suggesting that exposure is heavily dependent on diet, immediate surroundings (clothing, indoor furnishing), locomotion (walking versus crawling), and habits (putting dirty hands/teething rings into mouth) [368,369]. It also suggests that our most vulnerable populations may face higher levels of exposure. The microbiome fermentation in the gastrointestinal tracts of animals and humans facilitates the degradation of MPs, affects particle size distribution, and enables penetration of the intestinal barrier to enter systemic circulation and various organs and tissues in the body [370]. The gastrointestinal microbiome may play an important role in facilitating the transfer of plastic particles across the intestinal barrier through fermentation activity that may affect the breakdown and particle size distribution of some plastic materials and the permeability of the intestinal barrier [371]. Therefore, it is useful to know which bacterial taxa are altered during MP exposure in different animal species to develop predictive models for determining the potential for accumulating plastic particles in feed, animal-derived food products, and the human body. Eichinger et al. [371] reviewed studies that evaluated the interactions between MPs and the gastrointestinal microbiome in humans, mice, chickens, and aquatic animals. They concluded that interpreting the overall effects of MP on the gastrointestinal microbiome is difficult because of several limitations in experimental designs (e.g., lack of homogeneity of MP particles, unknown intake, lack of replication, and evaluation at the phylum level for selected number of genera. Furthermore, exposure to different MP types, doses, and particles sizes, location of sampling (i.e., feces, gut, larvae, cecum, small intestine), and host species affected changes in microbiome taxa.

Anatomical and physiological barriers can keep MPs out of deep lung tissues, but a very small proportion of these particles (<1%) may be absorbed [372]. Because of their suspected inherent toxicity and ability to adsorb other toxic compounds, MPs and NPs are carcinogens of increasing concern because of long-term exposure and their accumulation in organs and tissues [163]. Interestingly, MP and NP impacts on the human body deviate from our current understanding of conventional toxicology because although they follow certain biological rules, they violate others, and exposure results in a measurable, transgenerational burden that increases health risks with increasing plastic production, use and contamination [366]. However, eight paradoxes have been identified that must be addressed for advancing MP and NP science from detection and description to mechanistically based effects on human health to provide much needed guidance for mitigation actions and regulatory policies. These paradoxes involve analytical (exposure, detection, fate of fibers and fragment), biological (size, penetration, accumulation, excretion, pharmacokinetics, persistence, and threshold for toxicity), and chronological (temporal exposure, inheritance and familial characteristics) factors that limit our understanding of exposure, accumulation, and risk [366]. Therefore, standardized detection protocols, polymer-specific safety thresholds, and source-targeted policy interventions are urgently needed [366].

Table 4. Microplastic detection in human fluids, feces, organs and systems.

Biological Matrix	Effects	References
Brain	NPs and MPs can cross the blood–brain barrier and affect secretion of neuroinflammatory cytokines and chemokines, transporters, and receptor markers; PE NPs in the form of shards or flakes was found in greater concentrations in decedent brains than other polymers, brain samples contained 7 to 30 times greater concentrations than in livers and kidneys, and brain samples from dementia cases had greater concentration of NPs especially in cerebrovascular walls and immune cells.	[373,374]
Nervous system	MPs and NPs caused cytotoxicity in cerebral and epithelial human cells.	[375]
Saliva	About 4% of samples contained MPs; Polyethylene-PET and PP fibers < 100 µm were the most abundant type.	[354]
Digestive system	The number of MP particles consumed in the American diet to be 39,000 to 52,000 particles per year depending on age and sex, and individuals who meet their recommended daily water intake through only bottled sources may consume as additional 90,000 particles per year compared with an additional 4000 MPs per year for those consuming only tap water; Nine types of MPs (50 to 500 µm) have been found in human feces with PP and PET being most abundant; PS NPs have been shown to enter adenocarcinoma gastric cells by an energy dependent mechanism depending on size, time, and dose, and subsequently alter cell morphology, viability and small particles alter gene expression involving inflammation; Positively charged PS NPs strongly interact and aggregate mucin, affecting cell viability and inducing apoptosis in all types of cells independent of their ability to produce mucin; NPs are detrimental to intestinal membranes due to the destruction of their barrier protection over time; MPs serve as a potential vector for Cr in an *in vitro* human digestive model; Cellular uptake of minor amounts of orally ingested microparticles; MPs were detected in all colectomy samples with 28 particles/g of tissue and the predominant types were polycarbonate, polyamide, and polypropylene; Despite the preferential accumulation of NPs in the Peyer's patches it is unclear whether absorption of particles is via the lymphatic route.	[298,356,370,371, 376–381]

Table 4. *Cont.*

Biological Matrix	Effects	References
Feces	One study found more than 15 types of MP fragments, fibers, and films in >95% of fecal samples analyzed and range in size from 20 to 4800 µm; Another study found nine types of MPs (50 to 500 µm) in human feces, with PP and PET being most abundant.	[382–385]
Kidney	Polystyrene NPs (44 nm) are capable of entering human primary renal epithelial cells by energy dependent endocytosis or energy independent mechanisms; Toxic effects on kidney are increased by the presence of heavy metals and other environmental contaminants; Patients with kidney failure are at risk of increased exposure to plastic particles during dialysis; Short-term exposure can induce oxidative stress, endoplasmic reticulum stress, inflammatory responses, and disorders in lipid metabolism with long-term exposure resulting in renal fibrosis caused by ferroptosis; A specific range in particle size causes the greatest toxicity.	[386–388]
Urine	Polyethylene vinyl acetate, PVC, PP, and PE fragments between 5 to 15 µm were detected in urine in men and women indicating that MPs can pass through the gastrointestinal tract and kidneys and be excreted in urine.	[389]
Liver	Concentrations of 6 different MP polymers (4 to 30 µm) were detected at greater concentrations in cirrhotic liver tissues than samples without disease.	[390]
Immune system	Plasticizers are endocrine disruptors that act directly on immune cells via nuclear receptors, disrupt the antioxidant system of erythrocytes, induce immunosuppression via mitochondrial dysfunction, and cause three times greater immune cell death rate than when exposed to several xenobiotics.	[353]
Lung	Lung samples from patients with cancer or lung volume reduction contained 39 MPs in 85% of samples in all lung regions, 12 polymer types were identified with PP, PET, and resin as the most abundant, and indicated that inhalation is a route of MP exposure; Polymeric particles and fibers were detected in 65% of lung tissue samples obtained at autopsies and polymeric particles were <5.5 µm while fibers ranged from 8.1 to 16.8 µm, with PE and PP being most prevalent.	[391,392]
Respiratory system	Airborne MPs are commonly present in indoor living spaces and can be inhaled or ingested, and cause airway and interstitial lung diseases through dust overload, oxidative stress, translocation and gene mutation; Most inhaled MP particles are likely subjected to mucociliary clearance while some may persist in lungs causing localized inflammation; Co-contaminants like polycyclic aromatic hydrocarbons may desorb and cause genotoxicity; PS NPs are rapidly internalized in human lung epithelial cells and disturb gene transcription and protein expression while also affecting viability apoptosis, and cell cycles but effects are size, exposure time, and concentration dependent; Exposure to MPs from street dust in outdoor urban areas was estimated to average 3223 and 1063 particles per year for children and adults, respectively; MP fiber ingestion was greater from household dust than fibers from mussel consumption; All NPs were partially adsorbed and internalized on pulmonary epithelial cells and macrophages and were cytotoxic and genotoxic.	[349,393–398]
Bronchoalveolar lavage fluid	Microfibers were the dominant form of MPs detected in samples with <6% as particulate MPs with an average size of 1.7 mm in lower airways of adult humans; 65 microfibers and 24 MP particles (>20 µm) were detected in 100 lung tissue samples and were more prevalent in tumors than normal tissue.	[399,400]

Table 4. *Cont.*

Biological Matrix	Effects	References
Sputum	Sputum samples from 22 patients with respiratory diseases contained 21 different types of MPs (most <500 µm) with polyurethane as the most prevalent followed by polyester, chlorinated polyethylene, and alkyd varnish the greatest.	[401]
Heart	Nine types of MP particles < 469 µm in diameter were detected in pericardia, epicardial and pericardial adipose tissue, myocardia, and left atrial appendages.	[402]
Cardiovascular system	MP and NP particles have been found in cardiovascular cells and toxicity is increased by the presence of other environmental contaminants.	[387]
Blood	Whole blood from healthy volunteers contained PET, PE, and several polymers of styrene with lesser amounts of methyl methacrylate with average concentrations of 1.6 µg/mL; Nine types of MPs with average diameter of 184 µm were detected in pre- and post-operative blood samples from cardiac surgery patients.	[402,403]
Spleen	Deceased male donors had microplastic particles detected in seven major organs including spleen samples which had the lowest abundance.	[404]
Semen	MP fragments measuring 2 to 6 µm with spherical or irregular shapes were detected in 6 of 10 semen samples consisting of PP, PET, PS, PVC, polycarbonate, polyoxymethylene, and acrylic suggesting that MPs were ingested or inhaled and passed through the epididymis and seminal vesicles which are most susceptible to inflammation.	[405]
Placenta and meconium	Maternal, fetal, and amniochorial membranes of placentas contained microplastic fragments from 5 to 10 µm of spheric or irregular shapes; MPs (>50 µm) were detected in placenta and meconium samples obtained from cesarean delivery and PE, PP, PS were the dominant types; Transport of PS particles was greater from fetal to maternal than the maternal to fetal direction likely via an active, energy-dependent transport pathway resulting in all particles accumulating in the syncytiotrophoblast of placental tissue; Sixteen types of MPs were found in placenta and meconium ranging in size of 20 to 50 µm and were predominantly polyamide and PU; Localization of MP fragments in cellular compartment of human placentas may be associated with ultrastructural alterations of the mitochondria and endoplasmic reticulum which may be a result of physiological attempts to destroy plastic particles in placenta tissue and consequently contribute to activation of pathological traits and metabolic disorders; MP particles per g of tissue ranged from 0.28 to 9.55 particles/g and 11 polymer types were identified with PVC, PP, polybutylene succinate being the predominant forms with 80% being less than 100 µm.	[406–410]
Breast milk	MPs were detected in 76% of breastmilk samples ranging in size from 2 to 12 µm and PE, PVC, and PP were most abundant.	[411]
Skin	NPs $\leq$ 4 nm can penetrate and permeate intact skin, NPs size between 4 and 20 nm can potentially permeate intact and damaged skin, NPs size between 21 and 45 nm can penetrate and permeate only damaged skin, NPs size > 45 nm cannot penetrate nor permeate the skin; MP and NP particles are translocated to other organs through skin exposure.	[350,412]
Hands, Hair	Polyethylene-PET and PP fibers < 100 µm were the most abundant type in hair and on hands found in 44% of samples; Less quantities found in residents living in remote and less populated areas than in urban regions; Prevalence 2 times greater in males compared with females.	[354]

7.3. Use of Mouse Models to Study Micro- and Nanoplastic Effects on Animal and Human Health

Due to the many logistical and ethical challenges of conducting controlled studies in food-producing animals and humans, bioaccumulation and physiological effects of MPs and NPs have been more extensively studied in mouse and rat models. Murine models can serve as useful proxies to achieve greater understanding of the physiological and toxicological effects of MP and NP ingestion in food-producing animals and humans on various organs, tissues and systems. As shown in Table 5, ingestion and bioaccumulation of MPs and NPs have been shown to affect every organ, tissue, and physiological system. Although both MPs and NPs are harmful, MPs mainly cause physical stress while NPs exert stronger and more systemic effects because of their greater bioavailability, cellular uptake and molecular activity [413]. Furthermore, NPs disrupt cellular homeostasis at lower exposure concentrations, often act on a subcellular level, and exert greater toxic effects due to smaller size, surface chemistry, and functional properties [413].

Table 5. Summary of studies evaluating the bioaccumulation and physiological effects of micro- and nanoplastics in mice.

Organ or Tissue	Physiological Effects	References
Bone	Impacted cell viability, induced oxidative stress and apoptosis, and altered gene expression related to inflammation and bone formation.	[414]
Digestive system	Disrupted gut microbiota and accumulation in gastrointestinal tract; Gut microbiota imbalance, intestinal barrier dysfunction, and metabolic disorders; Gut microbial changes, increased inflammation, and intestinal dysbiosis in mice.; Increased blood glucose and lipid concentrations, NAFLD activity, intestinal inflammation, and altered nutrient absorption.; Induced gut macrophage activation and IL-1 signaling; Decreased colon mucin production, altered immune responses, and increased amino acid metabolism by changing colon microflora composition; Decreased body weight gain, mucin secretion, and major changes in composition of intestinal microbiota; Caused acute colitis; Caused damage to gastrointestinal tract, reduction in expression of tight junction proteins in intestine epithelium, and significant alterations in intestinal microbiota; Altered composition of intestinal microbiota and increased inflammation in intestinal tract; Altered gut microbiota and mucus-related genes; No inflammation or oxidative stress in major organs after 30 days oral exposure of 10 mg/kg; Accumulated in intestine > kidneys > liver; Increased iNOS, COX-2, cytokines, reactive oxygen species, superoxide dismutase activity, Nrf2 expression; Detected in stomach, intestines, liver; Entered cells via endocytosis; Induced apoptosis, autophagy, lysosomal disruption; Crohn's-like ileitis; Intestinal epithelial necroptosis (RIPK3/MLKL); Impaired mitophagy (lysosomal dysfunction); Intestinal barrier damage (decreased tight junctions); Villus erosion; Oxidative stress; Immune disruption (increased B cells, decreased $CD8^+$ T cells); Constipation; Decreased stool weight and moisture content; Colon structure changes; Decreased AQP3/8, CFTR; MAPK/NF-κB pathway activation.	[415–429]
Various organs including heart, spleen, lung, liver, kidney	Impaired hematopoietic stem cell function and accumulation in multiple organs including liver, and bone marrow; Hematotoxicity and altered gene expression related to immune and metabolic processes; Hematopoietic toxicity by disrupting bone marrow function, gut microbiota, metabolism, and inflammation; Reduced body weight gain, altered immune responses, and negatively impacted reproductive and developmental outcomes in mice; Lipid metabolism abnormalities in liver; Altered immune function including increased proportion of neutrophils and IgA in blood and altered composition of lymphocytes in spleen; MPs containing phthalates accumulate in the liver and intestines; Accumulated in liver, kidneys, pancreas; Disrupted lipid metabolism, insulin resistance; Increased reactive oxygen species, glucose; Altered liver and kidney markers; Disrupted energy metabolism; Stress-related biochemical changes; Accumulated in multiple organs; Inflammation, apoptosis, lipid metabolism disruption; Functionalized PS was more toxic; Kidney damage (renal corpuscles/tubules degeneration); Increased blood urea nitrogen, creatinine, malondialdehyde; Decreased glutathione; Immune disruption.	[239,415,430–438]

Table 5. *Cont.*

Organ or Tissue	Physiological Effects	References
Reproductive system	Increased inflammation and oxidative stress in ovaries, reduced oocyte quality, and impaired reproductive outcomes; Reduced sperm count and motility, increased deformity, decreased enzyme activity and testosterone levels, and induced oxidative stress; Reproductive dysfunction, including decreased sperm quality, testosterone levels, testicular inflammation, and disruption of the blood–testis barrier; Impaired sperm quality, disrupted testicular structures, and affected acrosome biogenesis in mice, with autophagy; Reduction in percentage of live births; MPs reduced quantity and motility of spermatozoa, increased percentage of malformed spermatozoa, decreased activity of succinate dehydrogenase and lactate dehydrogenase, reduced testosterone levels, and caused oxidative stress; MPs can penetrate mouse testes, and MPs containing phthalates accumulate in the testes and increase reproductive toxicity; Testes toxicity, decreased testosterone, abnormal sperm; Decreased luteinizing hormone, follicle-stimulating hormone; Sperm DNA damage; Abnormal sperm morphology; Disrupted hypothalamic-pituitary axis; Reduced body and testis weight; Poor sperm quality; Leydig cell hyperplasia.	[430,431,437–446]
Brain and neurological system	Brain inflammation and cognitive decline in mice; MPs caused cognitive deficits, disrupted redox balance, and reduction in acetylcholinesterase activity in brain; can cross blood—brain barrier; Reduced locomotor activity; Suppressed acetylcholinesterase activity (neurotoxicity); Parkinson's-like neurodegeneration; Mitochondrial dysfunction; Excitatory neurons most vulnerable; Astrocyte and microglia inflammation; Microglial activation; Neuronal damage; Increased ROS, NF-κB activation, TNF-α release, necroptosis; Cognitive decline; DNA damage; Altered expression of mRNAs, miRNAs, circRNAs; synaptic dysfunction; Anxiety-like behavior.	[427,437,447–451]
Muscle and adipose tissue	Delayed skeletal muscle regeneration, inhibiting myogenic differentiation, and promoting adipogenic differentiation; Regeneration of skeletal muscle was delayed and negatively correlated with microplastic particle size, Increased intracellular ROS generation and oxidative stress, inhibited myogenic differentiation, and promoted adipogenic differentiation.	[452]
Transgenerational	Reduced offspring body weight; male offspring liver damage, oxidative stress; impaired testis development and sperm count; Impaired neural stem cell function; Altered brain structure in offspring; Sex-specific neurocognitive deficits.	[453,454]

Nanoplastics are found in bone, intestinal, pancreatic, liver, kidney, spleen, lungs, testis, ovaries, muscle, adipose tissue, and blood, causing numerous adverse effects on growth, gut microbiome, immunity, metabolism, and reproduction. They can also cross the blood–brain barrier and contribute to oxidative stress, neuroinflammation, mitochondrial dysfunction, and synaptic disruption, which can lead to cognitive impairment and neurodegeneration [413]. A few studies have also provided evidence for transgenerational toxicity and heritable defects [413]. Despite the extensive body of evidence that clearly shows the many adverse health consequences in animals, more information is needed to relate these findings to human health and other animal species, and assess long-term multigenerational effects and transfer within ecosystems.

Extrapolating this evidence to farm animals would indicate that MPs and NPs would induce oxidative stress, endocrine disruption, inflammatory responses, genetic alterations, direct cellular damage, mitochondrial dysfunction, immune system dysfunction, and accumulation in reproductive tissues; reduce male and female fertility and impair reproduction; disrupt gut microbiota; impair nutrient digestion and absorption; cause brain inflammation and neurological damage; and bioaccumulate in various organs. Because most of these results were obtained from short-term studies, it is likely that even more extensive and detrimental effects can occur from long-term exposure in reproducing farm animals. However, there is a substantial body of evidence, indirectly through mouse models and directly from farm animal studies, indicating that MP and NP exposure not only reduces growth, reproduction, productivity, and animal health, but it compromises meat, milk, and egg quality and safety due to bioaccumulation of plastic particles.

Ali et al. [455] proposed an animal health assessment index for MP and NP exposure using an interdisciplinary approach that integrates exposure science, toxicokinetics, toxicodynamics, and environmental detection, that would include the following:

- Multiroute exposure quantification—combine exposure doses from water, feed, soil, and air with species-specific hazard thresholds.
- Species-targeted toxicokinetics and toxicodynamics—uptake and systemic effects should include absorption, distribution, metabolism, and excretion involving gut morphology, respiratory and dermal barrier integrity.
- Effect-based biomarkers—molecular markers to assess oxidative damage, inflammatory cascades, immune dysfunction, reproductive dysfunction, metabolic disruptions including gene expression of stress responses and detoxification pathways should be used to enhance sensitivity and specificity of hazard detection and analysis.
- Bioaccumulation and trophic transfer—determine bioaccumulation and linked chemicals in animal tissues and the potential for increasing concentrations in food webs.
- Chemical additives and adsorbed pollutants—assess cumulative toxicity of hazards associated with plastics including additives (e.g., bisphenols, phthalates) and adsorbed contaminants (heavy metals, pathogens).
- Composite hazard scoring system—weighted hazard score that includes exposure dose, toxicological endpoints, and species sensitivity.
- Probabilistic risk assessment—enhance reliability and robustness of the index by using probabilistic models that include variability, uncertainty of exposure, and response.
- Chronic and cumulative effects—include long-term, low-dose exposures and cumulative impacts with other environmental stressors to optimize reliability and robustness of hazard assessments.

7.4. Limitations of Current Toxicological Studies

The scientific community and the general public are keenly interested in determining and understanding the potential health consequences that can be attributed to MP exposure. Although conducting large-scale, randomized clinical trials would be an ideal approach to characterize the adverse health effects caused by MPs and NPs, it would be extremely challenging and unethical. As a result, there are only three viable routes of investigation available for exploration: human cell lines (*in vitro*), animal models (*in vivo*), and observational epidemiological studies. Each approach offers insights into human health outcomes, but each of them also has limitations that must be acknowledged.

First, both *in vitro* and *in vivo* studies involve exposing human cells, human tissues, or experimental animals to a known concentration of MP and NP particles. However, the wide range of plastic polymer types, morphologies, chemical additives, extent of weathering, abundance, and size that are known to exist in environmental media are difficult to completely account for in study designs. To avoid complexity, most researchers focus on a single type of plastic polymer, and due to availability, this tends to be virgin (non-weathered) PS spheres [456]. This is a problem because PE and PP are more frequently found in water [106], and PET is most common plastic variety found in air [457]. Furthermore, morphologies that are more prevalent in water and air are different, with fragments, fibers, films, and foams more commonly found in water [106], and fibers are more prominently found in air [457]. In addition, because most studies involve using pristine MP particles that have not undergone mechanical stress or degradation through weathering, the results likely underestimate the harmful health effects caused by an altered surface chemistry, which exacerbates the leaching of endogenous chemicals and the hosting environmental contaminants [458]. Finally, particle size is an extremely important factor that affects experimental outcomes, with smaller NPs correlated with greater toxicity, but this association is more ambiguous in the MP size range [456]. For this reason, a wide range of environmentally relevant MP and NP particle sizes should be considered when designing toxicology studies.

The MP and NP doses evaluated in toxicology studies represents another important shortcoming in both *in vitro* and *in vivo* studies. Studies that involve exposing animals and cell cultures to MPs tend to use unrealistic concentrations that do not reflect relevant contamination concentrations in environmental matrices. In some studies, MP and NP doses were as much as 102 to 107 times greater than concentrations found in the environmental media [459]. Furthermore, most of the previous studies involved short-term MP and NP exposure, with very few involving chronic, low-level plastic particle exposure. Given the ubiquity of this contaminant in various environmental matrices, it is vitally important that long-term, cumulative exposure be the focus of future toxicology studies because it best reflects real-life experiences. In addition, there are no studies that have examined the potential synergistic and antagonistic effects of the myriad chemical additives and environmental pollutants associated with MP and NP contamination. It is extremely important to know if the interactions of two or more chemicals associated with MPs and NPs amplify or diminish adverse health effects. It is difficult to design studies that control for chemicals that may leach out of plastic particles and quantify their effects. All of these factors determine the environmental relevance of experimental results obtained [459]. There is a tremendous need to standardize experimental methodologies across studies so that reporting metrics for toxic doses is consistent among experiments in order to make results comparable [456].

Many of the epidemiological studies that have examined the uptake of microplastics in humans involved the exploration and quantification of particles in organs, tissues, and body fluids. In these studies, sample collection tended to focus on a single location in the body, and the results were frequently extrapolated to represent the overall burden for a particular organ such as the brain, placenta, or testes. Because these studies were primarily focused on the mere presence or absence of MPs or NPs in the area of interest, the sample sizes tended to be small. Even the number of samples collected in studies involving less invasive human excretions such as feces ($n = 8$; [378]), urine ($n = 6$; [383]), and blood ($n = 22$; [397]) were small. Some types of observational epidemiological studies involve separating research subjects into two cohorts, one with a known disease status and one without, and then testing for contaminant load for making comparisons. This has been done for human populations suffering from inflammatory bowel disease (IBD) [381], colorectal cancer [460], and respiratory disease [461] to assess associations between MP and NP exposure and disease incidence. However, it is important to note that none of these studies can point to a causal relationship between exposure and disease. For example, in the case of IBD, it is possible that exposure to microplastics caused the disease, but it is also possible that the disease makes the population more vulnerable to the uptake and retention of MPs. As a result, more research is needed to determine if the many correlations between MP exposure and disease reported in previous studies indicate causal relationships, and, if so, the mechanisms that cause these adverse health effects.

8. Can We Fix This One Health Problem?

8.1. Challenges

8.1.1. Micro- and Nanoplastic Research, Analysis, and Interpretation of Results

There are numerous challenges associated with MP and NP research. Many of these challenges are a result of the heterogeneous nature of plastic as a material category. Although 10 distinct plastic categories comprised 86.8% of plastics produced in 2019, the remaining 6.5 Mt of plastics that are classified as "other" represented thousands of specialized synthetic polymers, including coatings, sealants, and adhesives [106]. Certain polymer types, such as high- and low-density PE, PP, PVC, and PET, are produced in large amounts. For example, the global production of PP alone in 2024 was 82 Mt, representing 19% of all plastics produced that year. Aside from the limited number of high-demand plastics, more than 1000 synthetic polymers exist, some of which are polymers made in small batches and designed for very specific applications. In addition, there are more than 16,000 chemical additives used to make plastics. Some of these chemicals are residues remaining after the manufacturing process is complete and were not originally intended to be in the final product, while others are integral components of the polymer matrix. This heterogeneity in plastic polymer chemistry requires the development of a vast polymer library. In addition, the weathering of MPs captured in the environment can change the surface chemistry of these particles, which further complicates identification.

Another factor challenging MP research is the increasingly small sizes that are being discovered in environmental matrices. For example, plastics were first found in Arctic Sea ice samples by a team of scientists that were searching for diatomaceous life. The research team noticed brightly colored particles embedded in the samples, which prompted an investigation. Samples were filtered through a 22 µm pore membrane and the density of these contaminant particles ranged from 38 to 234 particles/m^3 [96]. Arctic Ocean waters were tested by another team of scientists four years later, and the filter that was used allowed the researchers to capture particles as small as 11 µm. A range of 1,100,000–12,000,000 particles/m^3 was reported, with more than half (67%) of the particles found in the smallest size fraction [462]. These findings indicate that smaller particles were likely missed in early MP research and also in other matrices sampled and tested, such as bottled water [198,289,462].

Current MP and NP research is trending toward the examination of smaller, NP particle size fractions, but there are technical barriers that make capturing, counting, and characterizing these smaller particles more difficult [463]. One of these challenges is that smaller NP particles must be captured with finer sieves and filters. Extremely small pore sizes of sieves and filters can make processing more difficult, especially when media with copious amounts of non-plastic debris clog them. In addition, very small plastic particles are more prone to adherence to glassware, non-plastic debris, and even other larger pieces of plastic; therefore, they can be lost and reduce the representativeness of the MP sample. Finally, when analysis is focused on smaller particle size fractions, it is possible for NP contaminants from laboratory sources, such as NP particles shed from nitrile gloves or polycarbonate filters, to be included in samples being analyzed for MPs and go undetected because they would be under the assay detection limits. It is also more difficult to sort plastic and non-plastic debris and confirm the chemical properties of suspected plastic particles using analytical instruments [464]. Up to 70% of particles identified as plastic with a stereomicroscope were found to include natural particles when confirmed using Fourier-transform infrared spectroscopy (FTIR) analysis [465]. However, even the most widely accepted methods and standards for chemical characterization in microplastics research have size limits greater than the NP threshold, which is about 20 µm for FTIR and 1 µm for Raman spectroscopy [466].

Some efforts have been made to standardize MP analysis methods. For example, the first ISO for microplastic sample processing was published in 2023 [467]. In addition, an interlaboratory study involving spiked samples sent to 22 laboratories in 6 nations revealed relative harmony in particle recovery and identification [468]. However, analytical methodologies and techniques in this discipline are dynamic, with innovations regularly emerging and adoption based on accuracy, precision, and feasibility. This has led to a lack of methodological standardization in MP research which may create inconsistencies in reported findings. Some differences occur due to the use of low volumes of environmental media and filters that are structurally different (lattice versus membrane), made from different materials (polycarbonate, glass microfiber, cellulose), or have different pore sizes [469]. Differences in results can also occur from the use of wide variety of processing reagents available. For example, strong acids (such as nitric acid or hydrochloric acid) or strong bases (such as potassium hydroxide) can be used, but there is evidence that they can damage the plastic particles of interest [470]. Enzymes can also aid in MP digestion, especially for biota media. Examples of these include Proteinase K, chitinase, pepsin, or cellulase enzymes. These alternatives are safer than strong acids and bases because they are not caustic and they tend to cause less damage to the MP and NP particles of interest, but they tend to require long exposure times, and they can be more expensive [471]. A final method for digestion of organics involves a wet peroxide oxidation treatment with an iron (II) catalyst, known as Fenton's reagent [472]. This method is neither expensive nor time consuming, and it tends to be less abrasive on MPs than other methods. However, the use of this method may result in incomplete sample digestion.

The method used for counting MP particles can also vary. Some MP particle concentrations are so rarefied that they can be manually counted, while other samples may contain so many MP particles that only a small fraction of the filter is counted, and the results are then extrapolated to the entire sample. This approach has been used in water studies [308], as well as in studies involving human tissues, excretions, and body fluids [408]. However, it must be assumed that MP particles are evenly distributed across the surface of the filter, which may not always be the case.

The different types of controls incorporated into study design to maintain quality assurance and quality control standards is another important factor that influences MP experimental outcomes. Because MPs are ubiquitous, they can be found in wash and rinse water, on and around laboratory equipment and analytical instruments, and settling out of laboratory air. For this reason, positive and negative control treatments account for the proportion of particles lost during sample processing (positive controls), and the unintentional accumulation of particles during sample processing (negative controls). Failing to use positive controls may result in undercounting particles, while a lack of negative controls may result in overcounting MPs. The result of both circumstances threatens the accuracy and applicability of study findings. A critical review that examined over 50 microplastic publications that involved water found that only 48% of the studies incorporated negative controls into their study design while 6% incorporated adequate positive controls into their study [106]. It is also important to monitor plastic particle loss by using particle standards throughout the analytical procedures, developing and following standard operating procedures (SOPs), and collecting and analyzing blanks during sampling and processing [473]. Dawson et al. [474] described the challenges of making corrections using blanks when reporting results from MP analysis. In some studies, MP particle blanks independent of size and morphology were averaged and subtracted from the total particles counted, while in other cases, they were only subtracted if they were of the same size, morphology, and composition. Furthermore, the concentration of MP particles recovered in blanks can also be summarily determined to be low enough to not warrant concern, but there is no standardized concentration threshold for this determination.

Sample processing can increase analytical error due to impurities of water used to wash glassware and rinsing MP particles through a filtering apparatus. Many researchers use filtered lab water for these tasks with the assumption that the sources are devoid of contaminants. These types of water include deionized water, NANOpure water, Milli-Q water, reverse osmosis water, or high-performance liquid chromatography-grade filtered water. However, many of these water purification systems have plastic tubing, membranes, structures, and coatings that render them possible sources of MP contamination [463,473]. Microplastic contamination in purified lab water was first reported by Kosuth et al. [473] and has since been corroborated in another study [463]. Despite its importance, this finding was not emphasized in the latter study, where it was mentioned in the supplemental information that the rinse water (Milli-Q) had the same level of polyamide contamination as the bottled waters being tested [463].

All of the previous factors related to sample processing and analysis can contribute to analytical error and variable outcomes in MP studies, but differences can also arise from the methods used during sample collection. For example, air samples can be captured through passive or active sampling. In active sampling, a pump is used to draw air through an apparatus for a predetermined amount of time, while in passive sampling, MP particles are allowed to fall out on their own, or they are driven out by precipitation [475]. Samples from an air pump provide MP concentrations in units of volume, typically particles/m^3, while passive collection of air samples results in measuring MP particle concentrations in terms of flux, or particles/m^2/day. As a result, using these two different units of measurement makes comparisons of MP concentrations between studies difficult. Similar challenges are also associated with water sampling in various environmental conditions. Some early studies used trawling as a method to collect samples from the water's surface, which involved a fine mesh net (neuston net) connected to a collection vessel (jar) pulled across the water surface for a known distance at a known velocity. Another method involves grab samples, which consist of a volume of water taken from the water surface or from the water column (1 to 30 L by a CTD rosette sampler), which would then require volume reduction through filtering. The former method provided concentrations as particles/km^2, while the latter method reported concentrations in volume (L or m^3). Once again, depending on the method used, it can be difficult to compare MP concentrations across studies.

A final MP analysis conundrum involves reporting of MP contaminants as quantities (which likely includes size and shape) versus overall mass. Particle size is crucial when considering potential interactions with biota, whereas surface-area-to-volume ratio is essential for quantifying chemical sorption and leaching. Particle morphology is necessary for studying and characterizing movement and transport of MPs, but combined with chemical composition, it may indicate both MP source and future pathways of contamination. Most MP studies have reported particle count per unit of volume, mass, area, or flux. Although overall particle enumeration is an important metric, plastics splinter into smaller pieces when subjected to mechanical, chemical, or photo degradation. Fragmentation is a dynamic process, and rates vary depending on chemical composition of the material and environmental conditions [476]. For this reason, MP particle count alone does not accurately indicate the total amount of contaminant in an environmental sample, which makes comparisons problematic between geographic regions and over points in time. However, the pyrolysis–GC/MS analysis method, used to determine mass or mass flux, represents total contamination independent of particle fragmentation. This measurement is not only a requirement for mass budget and mass balance calculations, but it is also commonly used in toxicology studies. In a rapid review of 17 publications investigating the potential toxicological impacts of MPs on human cells, all but one study reported concentrations on a mass basis [364]. In addition, the first and only findings of MPs in human blood were reported on a mass per unit of volume (µg/mL) basis [403]. Comparing the mass of particles inhaled or ingested with the mass of particles inside biological systems effectively circumvents the need for bulky and imprecise conversions based on plastic type (density), amount, and size. All of these metrics may be important, depending on the research question, but only some of these metrics have been measured and reported in published studies.

8.1.2. Lack of Regulations

Despite the increasing awareness and concern regarding the impact of plastic production, use, environmental pollution, and negative effects on One Health, there is no international agreement, long-term strategy, or universal set of government policies to address this critical topic. Some of the reasons that international agencies and governments have failed to address these challenges involve many of the difficulties in sampling and laboratory analysis of MPs and NPs for environmental assessments and monitoring, numerous challenges in interpreting the effects of MP exposure on adverse human health effects, and subsequent difficulties in risk assessment to establish hazardous exposure thresholds. These factors create uncertainty regarding the significance of plastic pollution on societies, ecosystems, and our global food system which contribute to inaction. Furthermore, the production and use of plastics are now so embedded in our daily lives, and there are no economic incentives for corporations and businesses to change behaviors, that curbing plastic production, use, and pollution has become an overwhelming challenge.

Plastic production has increased every year, except during the oil crisis from 1973 to 1974 and the global financial crisis in 2008, where it declined by 6% from the previous year [29]. Plastic production also declined by 0.3% in 2020 in response to the COVID-19 pandemic. Despite minor slumps in the market, plastic overall has proven to be a resilient commodity, and its production and use has surged steadily for the past 80 years. This growth of the plastics industry is forecasted to continue into the near future. According to the OECD (Organization for Economic Co-Operation and Development), projected growth in plastic manufacturing is expected to cause a tripling of plastic waste by 2060 [477,478]. In response to future growth, some governments [479,480], NGOs (Global Alliance for Incinerator Alternatives, https://www.no-burn.org/plastic/, (accessed on 8 March 2026)), and even corporate entities (Patagonia, Inc. (Ventura, CA, USA), https://eu.patagonia.com/no/en/why-plastics/, (accessed on 8 March 2026)) are involved in shaping and implementing policy around plastic reduction. However, comprehensive regulations to reduce MP and NP contamination do not currently exist.

The Global Plastic Treaty of 2022 is the most coordinated effort to manifest a legally binding instrument to curb plastic waste and production worldwide. This resolution was supported by 175 nations and was created by a committee appointed to draft language around regulation, but unfortunately a consensus was not reached and the work is ongoing. An important component of this treaty is the extended producer responsibility (EPR), which requires those producing plastic packaging to take responsibility and be accountable for the entire life cycle of their products. China and the United States are the greatest consumers of plastic. China's EPR ambitions are being phased in gradually [481]. In the United States, the Break Free from Plastic Pollution Act (S.3127) (https://www.congress.gov/bill/118th-congress/senate-bill/3127/titles; accessed 22 April 2026) was introduced in 2021 and reintroduced in 2023, and although it has not moved out of the legislative committee, seven states have enacted state-level EPR bills. Other nations that have implemented successful EPR bills include German's Green Dot Program, where bottle return rates are as high as 99%. France and Sweden also have robust EPR laws that are more focused on the development and use of improved and innovative package designs that were incentivized by reduced fees for companies. However, one of the drawbacks of Germany's program is the greater concentration of MPs found in reused PET bottles compared with single-use bottles [307,308]. Furthermore, sustainable packaging designed for reuse does not necessarily reduce upstream environmental and health risks associated with the manufacturing of the product. Finally, while some groups like the Business Coalition for a Global Plastics Treaty (https://www.businessforplasticstreaty.org/about#our-story, (accessed on 8 March 2026)) and the Consumer Goods Forum (https://www.theconsumergoodsforum.com/, (accessed on 8 March 2026)) are working to address the global plastic waste problem through corporate solutions, they tend to rely heavily on recycling as a solution and are ultimately constrained by the desire to increase economic growth.

8.2. Opportunities

8.2.1. Persuade Consumers to Adopt Lifestyle Changes to Minimize Daily Exposure

In the absence of an international treaty, citizens who are concerned about exposure can work on a local or individual level to protect themselves from undue exposure and prevent the spread of MPs and NPs in the environment and food system. There are many ways consumers can avoid purchasing plastic to reduce their daily exposure to MPs and NPs. One such health behavior is the avoidance of water and other beverages packaged in plastic bottles. According to the market analysis firm Euromonitor International, 481 billion plastic water bottles are used globally every year (https://www.reuters.com/graphics/ENVIRONMENT-PLASTIC/0100B275155/, (accessed on 9 March 2026)). Reducing consumption will not only reduce MP exposure because several studies have shown that tap water has lower concentrations of MPs than bottled water [482], but it will also reduce contribution to legacy plastics which will continue to accumulate and break down in the environment long after the product is consumed. Because reusable bottles made from glass have been shown to release fewer microplastics than reusable bottles made from plastic [307,308], this may also be true of metal bottles. However, these recommendations do not extend to areas where people are experiencing water insecurity or unsafe water quality in countries with inadequate potable water treatment of areas subjected to natural disasters such as flooding and hurricanes.

Single-use plastic bags are another plastic consumable that is produced in high amounts globally. The Worldwatch Institute estimated that 4 to 5 trillion of various types of plastic bags were produced in 2002, and if this amount has remained stable since then, 4 to 5 trillion plastic bags are used and disposed of globally every year (http://www.theworldcounts.com/counters/waste_pollution_facts/plastic_bags_used_per_year, (accessed on 9 March 2026)). On average, plastic bags are used for 12 min before they are discarded [483]. Because they cannot be collected and sent to a materials recovery facility for recycling, many are incinerated or landfilled. Furthermore, if these single-use bags are collected, the second life will most likely be used to make decks, park benches, and even playground equipment. According to UNEP, a cotton bag must be used 50 to 150 times before it is equivalent to the environmental footprint of producing and using one single-use plastic bag [484]. However, most life cycle analyses around plastic bags do not consider the end of the product's life and thus conclude that plastic, because it is lightweight, is superior [485–487]. The low density of plastic bags actually facilitates their ability to travel long distances, get caught in trees, and float in oceans, lakes, and rivers.

Plastic waste can also be significantly reduced when eating outside of homes. Takeaway containers, straws, single-use cutlery, and polystyrene and expanded polystyrene cups comprise a large amount of plastic litter [488]. Straws made from metal and glass work well as substitutes. Reusable cutlery made from metal or bamboo are also good alternatives. These and other efforts to reduce the creation of plastic waste and potential MPs and NPs should be used whenever possible. Many cooking implements are made from plastic or have plastic components, and although some of these spatulas, whisks, stirring implements and bowls are made from food-grade plastics, they can still release particles into food. Plastic containers can leach additives into foods, especially when they are heated by a microwave. Additionally, instead of buying liquid laundry detergents in high-density polyethylene bottles, several brands of solid sheet detergents can now be used as an alternative. In fact, many detergents, from dish washing liquid to hand soap, can be tablet-based and placed in reusable dispensers. Even shampoos and hair conditioners are available in solid form to avoid the proliferation of microplastics. Personal decisions may help create less demand for single-use plastics while signaling awareness about plastic waste and shifting cultural norms.

Another high-impact behavior is to engage in community-level conversations to encourage and implement actions to reduce plastic waste and exposure [489]. Much of this can be done by customers talking to local grocers and restaurant owners and expressing concerns about plastic waste, MP and NP contamination, and environmental and human health. Having these conversations to increase awareness at both the individual and community level can make a difference in shifting our consumption culture away from a convenience-oriented lifestyle to one where luxury and modernity is exemplified not by efficiency, but from the comfort of knowing that one's daily activities are not contributing to waste colonialism or linked to increased health risks for members of fenceline communities.

8.2.2. Invest in Research to Develop, Evaluate, and Implement Effective Mitigation and Bioremediation Strategies

Mitigating plastic pollution in the environment involves physical, chemical, and biological strategies [490], but they need further improvement to achieve more complete remediation [491]. Physical bioremediation strategies involve adsorption, flotation, or filtration techniques to separate plastic particles from the environment, whereas chemical and biological approaches are aimed at elimination of plastics through thermal, oxidative, and microbial degradation [492]. Physical removal strategies have low removal efficiency, are difficult to use in large-scale applications, and involve complicated on-site implementation [492]. In addition, physical methods involving chemicals can create health hazards if toxic byproducts leach into drinking water and agricultural soil [493]. Membrane filtration systems are often energy-intensive and can also produce secondary substances that may cause adverse health effects [494–496]. Chemical remediation strategies are costly, complicated processes that can only be applied to specific conditions and may create toxic secondary compounds that can cause serious health problems [497]. Biological strategies are generally considered to be safer for the environment and human exposure but may be inefficient and unable to be widely applied [492].

Bioremediation is a promising and sustainable approach for mitigating microplastic pollution that uses microorganisms and plants to break down or convert MPs to less toxic substances. Ngaba et al. [498] conducted a comprehensive review of microplastic bioremediation approaches and evaluated their strengths and weaknesses and impacts on the environment and human health, involving 827 studies across 84 countries. Strategies were evaluated based on technical aspects (effectiveness, remediation time, operability, scalability, implementation), social aspects (impacts on ecology, environment, and public acceptance), economic aspects (capital costs, detection and analysis costs, operation and maintenance costs), and human health risk levels (exposure pathways, duration, frequency of exposure, and toxicity of contaminants). Results from this review [498] showed that mycoremediation (use of fungi mycelia to degrade, sequester, and detoxify pollutants), phytoextraction (uses plants to absorb pollutants from soil and water), and soil microbial inoculants for enhanced biodegradation have been shown to be highly effective but pose high risk of toxicity to human health. Other strategies including plant-assisted remediation, rhizosphere degradation (plant roots and microbes break down pollutants), phytodegradation (plants and microbes degrade organic pollutants into simpler, non-toxic or less harmful compounds), and biodegradation (microorganisms break down organic substances into simpler compounds using metabolism or enzymes) are moderately effective (50 to 65%) with moderate risk of toxicity to human health. Phytofiltration (uses plant roots to filter, absorb, adsorb, or precipitate contaminants from polluted water, wastewater, and surface water) and floating wetlands are least effective but also pose the lowest risk of toxicity to human health. When the effectiveness, capital cost, remediation time, toxicity risk, and operational limitations were compared between bioremediation and traditional methods for microplastic mitigation, bioremediation technologies are a cost-effective, environmentally friendly, and minimally disruptive solution, but require a longer amount of time to achieve results and are less versatile than traditional methods, which can provide rapid results and are more versatile but costly and have significant negative effects on the environment [498].

Phytoremediation of microplastic contamination in air, soil, and water using suitable plant species is a promising strategy that needs further exploration [499] and will require collaboration among plant scientists, environmental scientists, engineers, policymakers, and regulatory organizations [500]. Remediation occurs by phytoaccumulation involving absorption and storage in tissues, phytostabilization of plastic particles in soil via root-mediated processes, and phytofiltration traps plastics in aqueous environments by filtering through roots or other aerial plant parts [492].

Specific types of plants, shrubs, and trees have been shown to help detoxify soil and water contaminated with MPs and NPs by adsorption (attach to surfaces of roots, leaves or stems), absorption (into tissues and remove from water or soil), trapping (dense root systems or vegetation trap in their structures), and remediation (degrade plastics). Strategic use of selected species can partially alleviate MP and NP contamination. For example, planting water hyacinth in wetlands can help capture and filter MPs. Strategically placing plants on river or stream banks can help filter MPs from water. Combining plants with other materials such as biochar can remove MPs from runoff and provide bioretention systems. Birch trees have been shown to be effective for soil remediation. Bioremediation strategies to remove MPs in soil include using biodegradable plastic mulching instead of conventional mulching, the addition of specific strains of bacteria (i.e., *Bacillus gottheilii*, *Bacillus cereus*, *Bacillus subtilis*, *Pseudomonas* spp., *Micrococcus* spp., *Ideonella sakaiensis*), fungi (i.e., *Aspergillus clavatus*, *Aspergillus fumigatus*, *Aspergillus niger*, *Aspergillus oryzae*), and microbial and de novo enzymes have been shown to be effective in degrading various types of plastic polymers in soil [204]. Examples of specific plant, shrub, and tree species with phytoremediation capabilities to remove MPs in contaminated soil and water are shown in Table 6. However, microplastic accumulation in several of these plant species (i.e., faba bean, fenugreek, garden cress, mustard, lettuce, okra, onions, and wheat) is a concern because they are commonly consumed as human foods, and this raises concerns about the practicality of this approach [501]. In addition, accumulation of MPs by plants causes physical damage and chemical stress that can lead to many adverse effects including growth inhibition, abnormal root structure and function, and plant health.

https://doi.org/10.3390/su18147361

Table 6. Examples of plants, shrubs, and trees with bioremediation capabilities to remove microplastics from contaminated soil and water.

Plant, Shrub, or Tree	Mode of Action	References
Aloe vera (*Aloe barbadensis miller*)	Composed of polysaccharides with adhesive properties.	[502]
Antler fern (*Ceratopteris pteridoides*)	Immobilization and removal of plastics from water due to high adsorption capability and tolerance to plastic exposure; MPs absorbed via roots and on spore surface.	[503]
Basket willow (*Salix viminalis*)	Effective in removing 73% of polycyclic aromatic hydrocarbons in contaminated industrial soil after 10 years treatment.	[504]
Birch trees (*Betula pendula* Roth)	Roots can absorb plastic particles of 5 to 50 µm in size from surrounding contaminated soil.	[505]
Bladderwort (*Utricularia vulgaris*)	Adsorption and accumulation of MPs in digestive organs.	[506]
Cattails (*Typha Latifolia*)	Hydrophobic fibers serve as bioadsorbants of MPs from wastewater.	[507]
Common reed (*Phragmites australis*)	Commonly used in constructed wetland globally for wastewater treatment and growth and functional traits were not affected by high concentrations of polyethylene or polystyrene; more than 50% of MPs can be removed by bioretention.	[508–510]
Duckweed (*Lemna minor*, *Spirodela polyrhiza*)	Floating plant with adhesion properties that can adsorb MPs and NPs in wetlands; effective in extracting microplastic from textile sludge.	[511–516]
Eurasian water milfoil (*Myriophyllum spicatum*)	A perennial submerged macrophyte found widely in aquatic ecosystems and plays an important role in ecological restoration in eutrophic aquatic environments and functional traits were not affected by high concentrations of polyethylene or polystyrene.	[509]
Faba bean (*Vicia faba*)	Adsorbs 100 nm NP particles on its roots within two days.	[517]
Fenugreek (*Trigonella foenum graecum*)	Polysaccharides were highly efficient as flocculants for removal of MPs from surface, ocean, and groundwater.	[518]
Garden cress (*Lepidium sativum*)	External microplastic adsorption blocking pores in seed capsule and delays germination and root growth; found on roots, leaves, and epidermis.	[217]
Indian mustard (*Brassica juncea*)	MPs in contaminated soil were transferred to plant roots and leaves.	[519]
Lettuce (*Lactuca sativa*)	Binds plastic particles to roots and absorb them in stems and leaves.	[520,521]
Mangroves (*Rhizophora*)	Effective in intercepting MPs from further distribution in ecosystems and sediment accumulates MPs to serve as a sink.	[522–526]
Mung bean (*Vigna radiata*)	NPs absorbed from soil to the body of the plant via plant vasculature.	[527]
Okra (*Hibiscus esculentus*)	Polysaccharides were highly efficient as flocculants for removal of MPs from surface, ocean, and groundwater.	[518]
Onions (*Allium cepa*)	NPs accumulate in cytoplasm and vacuoles of root cells.	[528]
Orange jasmine (*Murraya exotica*)	NPs accumulate in cell walls.	[529]

Table 6. *Cont.*

Plant, Shrub, or Tree	Mode of Action	References
Papyrus (*Cyperus papyrus* L.)	Capable of removing large amounts of MPs from water in sediments and retention in roots.	[530]
Penny grass (*Hydrocotyle vulgaris*)	Accumulates nanoscale polymer dots in stems and blades.	[531]
Seagrass (*Zostera marina*, *Cymodocea rotundata*, *Cymodocea serrulate*, *Thalassia hemprichii*, *Thalassia testudinum*)	Promotes formation of white floc to trap and sink MPs and MPs adsorb to blade surface.	[532,533]
Sea rush (*Juncus maritimus*)	Perennial macrophyte in saltmarshes and estuaries which facilitates MP accumulation in sediment to serve as a microplastic sink.	[534]
Seaweed (*Fucus vesiculosus*, *Cladophora* sp., *Padina* sp., *Pyropia yezoensis*, *Sargassum ilicifolium*, *Sargassum horneri*, *Ulva prolifera*, *Undaria innatifida*)	Hydrophobic attraction enables physical adsorption of polystyrene MPs; anionic polysaccharides may promote stabilization of plastics on plant surfaces.	[532,535]
Umbrella sedge (*Cyperus alternifolius* L.)	Effectively remove MPs from water.	[510,536]
Thale cress (*Arabidopsis thaliana*)	Small plant from mustard family that accumulates positively and negatively charged NPs.	[537]
Vetiver grass (*Chrysopogon zizaniodies*)	An economically and ecologically important plant with rhizospheric microbes that are highly tolerant to pollution stress which makes vetiver grass a good candidate for phytoremediation.	[538]
Water hyacinth (*Eichhornia crassipes*)	Adsorbs plastic particles.	[539]
Wheat (*Triticum aestivum*)	Binds plastic particles to roots and absorb them in stems and leaves.	[318,521,540]

8.2.3. Incentivize Development and Use of Biobased Alternatives to Plastic

Many biobased substrates and chemical matrices exhibit benefits as conventional plastic replacements when combined with other natural substrates, which potentially minimizes the use of petroleum-based chemicals (Table 7). However, not all bioplastics are biodegradable. In addition, decomposition may depend on aeration time, incubation time, moisture, and type of soil used [541]. Bioplastics include a wide range of materials that fall into three categories. The first category is made from biological feedstock, but it is non-biodegradable (such as biobased polyethylene or polypropylene). A second category is biodegradable, but it is derived from fossil fuel (such as polybutylene adipate terephthalate). A third category is made from biological feedstock and it is capable of biodegradation. This includes materials that biodegrade under composting conditions with water, heat, oxygen, and nutrients. These materials can be created from cassava starch, corn starch, sugar beet, or sugarcane, as well as plant oils waste [542]. In 2025, global manufacturing of biobased, non-biodegradable plastics was 1.23 Mt while biobased, biodegradable plastics was 1.08 Mt. Parity in these two categories is expected to extend into 2030, which means half of all bioplastics made are non-biodegradable [543]. Of all the types of bioplastics, PLA (polylactic acid) is produced in the greatest volume. These biopolymers are used in a wide variety of applications, including agriculture, medicine, packaging, and textiles, and account for nearly one-third of all bioplastics [544]. Another commercially important bioplastic is PHA (polyhydroxyalkanoates). Although it only makes up about 5% of all bioplastics today, it is the fastest growing bioplastic alternative and is expected to represent 17% of the market by 2030. These biodegradable polymers are produced by various strains of bacteria (e.g., *Bacillus* sp., *Brevundimonas* sp., *Burkholderia cepacian*, *E. coli*, *Enterococcus* sp., *Paraburkholderia* sp., *Pseudomonas aeruginosa*, *Pseudomonas putida*, *Staphylococcus aureus*) from carbon-rich sugars, starch, molasses, glycerol, mustard oil, and various types of food waste (waste frying oil, sorghum juice, orange and onion peels, rice bran), which makes it an environmentally sustainable circular solution to replace fossil-based plastics [545]. Polyhydroxybutyrates are the most promising PHA biopolymer, comprising short-chain PHAs synthesized by hydrolysis of mono- and disaccharides, which degrades to water and carbon dioxide in 20 to 45 days with optimal humidity, microbes, and oxygen exposure in the environment [545]. They have characteristics of flexibility, crystallinity, elasticity, and thermoplasticity comparable to petroleum-derived plastics but can be degraded by depolymerase enzymes found in common bacteria and fungi [545].

Table 7. Biobased substrates as potential alternatives to plastic.

Biobased Substrate	Description/Application	References
Bagasse	Bagasse is sugarcane waste rich in cellulose that can be reprocessed and used to produce and reinforce other materials.	[546–551]
Bamboo	Contain multiwalled fibers provide flexible deformation, high mechanical strength, low density, and degradability; plasticity can be enhanced by selectively removing parts of lignin and disrupting the chemical structure of cellulose.	[548,552–557]
Casein	Casein is a milk protein that has superior oxygen barrier properties compared with plastic, can be strengthened with natural fiber or cross-linking cellulose, nanoclay, or plant polyphenols to overcome brittleness and moisture sensitivity, and is used for biodegradable food packaging, coatings, and films to extend shelf life.	[558–563]
Coconut shells and husks	Lignin is partially removed from coconut fragments and subjected to hot-pressing; biocomposite films and high tensile strength.	[564–568]
Hemp	Lightweight, high density-to-weight ratio, high thermal, UV, flame resistance, and dimensional stability; up to 40% hemp fiber can be incorporated into biocomposites.	[569–571]
Mycelium	Fungal mycelium is comprised of an interconnected, self-expanding web of elongated cells that are highly stable, flexible, hydrophobic, non-flammatory, insulating, and biodegradable.	[568,572–578]
Paper-based composites	Cellulosic paper-based materials are light weight and biodegradable but mechanical strength and water resistance need to be improved through innovative chemistry and processing techniques.	[564,576,579–582]
Pineapple leaf fiber	High cellulose content provides excellent tensile and flexural mechanical qualities and is useful as reinforcement in biodegradable composites.	[583–587]
Polycaprolactone	Synthetic, biodegradable, biocompatible, and non-toxic polyester with high elasticity and low melting point that can be used as a sustainable alternative to conventional plastics in medical implants, drug delivery, and packaging.	[588–593]
Polyhydroxyalkanoates	Biodegradable and completely compostable polymers produced by bacteria that convert renewable carbon-rich plant sugars or food waste into plastic-like compounds stored within cells which is highly versatile to mimic stiffness and flexibility of plastics with superior barrier properties which makes it ideal for manufacturing single-use food service items, agricultural films, and medical devices; polyhydroxybutyrates are the most common and have significant potential to replace traditional plastics.	[545,594–598]
Polylactic acid	Biobased and biodegradable thermoplastic derived from corn starch or sugar from sugar cane commonly used for food packaging, disposable cutlery, medical devices, and films but is brittle, has low heat resistance, and high-water permeability that restricts its use or requires blending with other materials to improve performance and applications.	[544,588,593, 599–603]
Rice husks	Carbon, lignan, and silica in rice husks are used to produce durable products that can replace single-use plastics and using thermos-pressing techniques enable the production of durable, rigid, safe, and biodegradable food containers.	[546,604–608]
Seaweed	Seaweed is a sustainable, rapidly renewable natural resource rich in polysaccharides that can be used in food packaging, textiles, and biodegradable bags with good mechanical strength and UV resistance.	[609–617]
Wheat bran	Contains arabinoxylan which can be extracted and blended with polyvinyl alcohol to create biodegradable plastic films for food packaging and edible plates and tableware; various processing treatments are used to enhance structural and functional properties for it to serve as an eco-friendly filler for polymers to enhance mechanical performance.	[618–624]

Overall, production of bioplastics is expected to double in the next five years according to the trade association European Bioplastics [625]. However, despite these forecasts, it is important to remember that bioplastics currently contribute to 0.6% of the total global plastics market [30]. It is also important to consider that an increase in the bioplastics market may not necessarily result in a decreasing share of fossil-fuel-derived plastics, because these new synthetic polymers may simply be used to meet demand in new markets.

Some developments in current markets and applications include food packaging. For example, in 2024, the U.S. Food and Drug Administration approved PLA as a food contact substance [626]. Bioplastics are also being used to manufacture personal care products. In response to the federal Microbead Free Waters Act of 2015, there are now opportunities to bring biodegradable polymers to cosmetics and hygiene products, both in packaging as well as in the products for themselves (such as exfoliants). Another opportunity for bioplastics is pharmaceutical, medical laboratory, and medical supplies, especially in packaging for drugs and medical devices. Some examples of this already exist such as biomedical mats, pharmaceutical vials, and medical capsules [627]. Although current bioplastics may not perform the same as their fully synthetic counterparts, certain limitations of tensility, biodegradability, and mechanical strength can be overcome by mixing polymers with natural substrates [541]. The use of waste materials such as bagasse, casein, coconut shells and husks, mycelium, pineapple leaf fiber, rice husks, and wheat bran from the agri-food industry in the production of bioplastics not only contributes to a circular bioeconomy by repurposing food loss and waste, but it also reduces reliance on fossil fuels in the production of conventional plastics and enables biodegradation in the environment.

One obvious benefit associated with bioplastics made from plant feedstock is that they tend to have a smaller carbon footprint [628]. For example, a life cycle assessment of PLA showed that its carbon footprint is 85% less than a fossil-fuel-based equivalent [629]. Results from another study showed that PHA reduces emissions by 83% compared to conventional plastics [630]. Although the benefits reported in these studies focus on carbon emissions reductions, other considerations such as land use, biodiversity loss, and water footprint must also be considered. Another benefit of about half of all bioplastics is that they have the potential to biodegrade under the right environmental conditions. Complete degradation involves the transformation of organic matter via microorganisms into water, carbon dioxide, and inorganic nutrients. As of 2020, a total of 436 species of microorganisms and fungi have been recognized in various scientific studies for their ability to degrade specific plastics. For example, there are 24 fungal species and 55 bacterial species that can digest PE, although far fewer are able to break down polymers with high molecular weight, such as PP and PS. In comparison, PLA can be degraded by 31 fungal species and 63 bacterial species [631]. Despite these benefits, it is important to understand that even bioplastics can turn into microplastics, even if they do not last as long as their synthetic counterparts. For example, PLA may degrade faster into MPs than petroleum-based plastics, but they can still adversely affect ecosystem health. One study compared the biodegradable PBAT with non-biodegradable LDPE and found that PBAT released a greater quantity of MPs than the LDPE in various simulated aquatic environment [632]. Clearly, biodegradable plastics are not a panacea for eliminating environmental contamination of MPs because they may still fragment into MP particles under real-world conditions, and their production requires land, water, and energy resources. Furthermore, chemical additives used in both synthetic and biobased plastics may still leach from products. A study investigating chemical leaching from food packaging showed that of the 21 plastic additive compounds analyzed, 17 were found to leach from PLA while only 9 leached from PP when the particles were exposed to environmental conditions that mimic seawater [633]. Although there are certain similarities between biodegradable and non-biodegradable plastics, in their physical structure and ability to host chemical contaminants, they are potentially more complex and dynamic, which makes research regarding their toxicology especially important [459]. It is important to recognize that the environmental conditions used to conduct these types of evaluation are important because studies have shown that PLA is degradable *in vivo*, but it does not degrade completely in the aquatic and other natural environmental conditions [544].

8.2.4. Organize Transdisciplinary Teams to Address Knowledge Gaps

Microplastics research is a multidisciplinary field that can be approached from many angles and intersections including toxicology, ecology, biology, chemistry, material science, law, policy, engineering, social sciences, and economics. Presently, there are more questions than answers. This, coupled with the sense of urgency fueled by public awareness and concern, calls for the prioritization of the following research questions.

- How far can plastics travel in various media (soil, air, water, biota)?
- Can we identify "hot spot" sources to effectively shut down or "turn off" those taps?
- Are there MPs sinks or long-term sequestration sites?
- How long do MPs remain inside living systems—both human and other organisms?
- What is the mass balance of MPs inside the human body?
- What are the toxicokinetics of MPs inside the human body?
- What is the current equilibrium in environmental media, and how will that change if we continue to manufacture MP generating plastic products? What will that equilibrium look like in 50 and 100 years?
- What are the effects of chronic exposure to particulates and their chemical additives?
- What are the synergistic effects of these chemical additives?

9. Conclusions

Plastics provide many societal benefits and were originally created to improve our quality of life, but the lack of significant recycling and their extremely slow complete degradation in the environment have led to widespread MP and NP contamination throughout our global food production and ecosystems. The extensive MP and NP contamination in air, water, soil, plants, and food-producing animals has caused another global One Health crisis, and exporting plastic waste from high-income to low-income countries has created an environmental justice problem. Consumption of contaminated food and drinking water are the primary routes of human exposure to MPs and NPs, which have been found in every organ, tissue, and physiological system in the human body. Although several studies have shown that human and test animal exposure to plastic particulates and chemical additives are associated with negative health outcomes, more research is needed to determine if there is causal evidence between MP and NP exposure and disease. The types of polymers and additives in MPs and NPs not only have direct adverse health effects on soil, plant, animal, and human health, but they also adsorb and serve as carriers of heavy metals, persistent organic pollutants, antibiotics, and antimicrobial-resistant genes, and allow colonization of fungi, bacteria, and viruses in biofilms to further create unhealth environments and ecosystems. These secondary effects on One Health will be exacerbated as we transition to a more circular bioeconomy and food system. There are numerous challenges to begin addressing this complex problem, including overcoming numerous social, economic, and environmental sustainability obstacles largely driven by the ever-expanding plastics and fossil fuels industries that are subsidized and supported with favorable government policies, and by minimal, or lack of, regulations to discourage the continued production and use of plastics. In addition, there are many scientific challenges involving analytical methodology, environmental monitoring, and risk assessment of MPs and NPs in our food and drinking water supplies, and the subsequent long-term toxicological effects on plant, animal, and human health that need to be more extensively studied to develop meaningful action plans. The first step in reducing the escalation of this One Health problem is to reduce the production of plastics and subsequent plastic pollution by subsidizing the development and use of biodegradable alternatives. Simultaneous efforts must also be devoted to developing and implementing cost-effective remediation technologies to remove the MPs and NPs currently in the environment. To accomplish all of this, we need a coordinated global effort of cooperation, robust scientific research, and data sharing to develop standardized regulatory frameworks and safer alternatives to plastics if we are going to have a realistic chance of fixing this One Health problem.

Author Contributions: G.S. and M.K. contributed equally to the writing and editing of this manuscript and agreed to the published version. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: No new data were created or analyzed in this study. Data sharing is not applicable to this article.

Acknowledgments: We thank Claire Hartwig Alberg for reviewing this manuscript and providing valuable comments for improvement.

Conflicts of Interest: The authors declare no conflicts of interest.

Abbreviations

The following abbreviations are used in this manuscript:

ABS	Acrylonitrile-butadiene-styrene
AMR	Antimicrobial resistant
AQP3	Aquaporin 3
BP	British petroleum
BPA	Bisphenol A
BSFL	Black soldier fly larvae
CFTR	Cystic fibrosis transmembrane conductance regulator
circRNA	Circular RNAs
COX-2	Cyclooxygenase-2
CTD	Conductivity/salinity, temperature, depth
DNA	Deoxyribonucleic acid
EPR	Extended producer responsibility
EU	European Union
FTIR	Fourier-transform infrared spectroscopy
GC-MS	Gas chromatography–mass spectrometry
GHG	Greenhouse gas
HDPE	High-density polyethylene
iNOS	Inducible nitric oxide synthase
kWh	Kilowatt-hour
LDPE	Low-density polyethylene
LLDPE	Linear low-density polyethylene
MAPK	Mitogen-activated protein kinases
MLKL	Mixed lineage kinase domain like pseudokinase
MP	Microplastics
mRNA	Messenger ribonucleic acid

miRNA	MicroRNA
Mt	Million tonnes
NAFLD	Non-alcoholic fatty liver disease
NF-κB	Nuclear Factor kappa B
NGO	Non-government organization
NIRS	Near-infrared spectroscopy
NP	Nanoplastics
OECD	Organization for Economic Co-Operation and Development
PA	Polyamides
PAH	Polyaromatic hydrocarbons
PBAT	Polybutylene adipate terephthalate
PBDE	Polybrominated diphenyl ethers
PBS	Polybutylene succinate
PC	Polycarbonate
PCB	Polychlorinated biphenyls
PCL	Polycaprolactone
PE	Polyethylene
PEAA	Polyethylene-co-acrylic acid
PET	Polyethylene terephthalate
PFAS	Per- and polyfluorinated alkyl substances
PHA	Polyhydroxyalkanoates
PHE	Polyhydroxyester
PLA	Polylactic acid
PP	Polypropylene
PS	Polystyrene
PSAN	Polystyrene-co-acrylonitrile
PTFE	Polytetrafluoroethylene
PU	Polyurethane
PVA	Polyvinyl alcohol
PVB	Polyvinyl butyral
PVC	Polyvinyl chloride
RIPK3	Receptor-interacting serine/threonine-protein kinase 3
ROS	Reactive oxygen species
SOP	Standard operating procedure
TNF-α	Tumor Necrosis Factor-alpha
UNEP	United Nations Environmental Programme
USD	US dollar
UV	Ultraviolet

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