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# Impacts of Plastic Pollution on Ecosystem Services, Sustainable Development Goals, and Need to Focus on Circular Economy and Policy Interventions

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**Abstract:** Plastic pollution is ubiquitous in terrestrial and aquatic ecosystems. Plastic waste exposed to the environment creates problems and is of significant concern for all life forms. Plastic production and accumulation in the natural environment are occurring at an unprecedented rate due to indiscriminate use, inadequate recycling, and deposits in landfills. In 2019, the global production of plastic was at 370 million tons, with only 9% of it being recycled, 12% being incinerated, and the remaining left in the environment or landfills. The leakage of plastic wastes into terrestrial and aquatic ecosystems is occurring at an unprecedented rate. The management of plastic waste is a challenging problem for researchers, policymakers, citizens, and other stakeholders. Therefore, here, we summarize the current understanding and concerns of plastics pollution (microplastics or nanoplastics) on natural ecosystems. The overall goal of this review is to provide background assessment on the adverse effects of plastic pollution on natural ecosystems; interlink the management of plastic pollution with sustainable development goals; address the policy initiatives under transdisciplinary approaches through life cycle assessment, circular economy, and sustainability; identify the knowledge gaps; and provide current policy recommendations. Plastic waste management through community involvement and socio-economic inputs in different countries are presented and discussed. Plastic ban policies and public awareness are likely the major mitigation interventions. The need for life cycle assessment and circularity to assess the potential environmental impacts and resources used throughout a plastic product's life span is emphasized. Innovations are needed to reduce, reuse, recycle, and recover plastics and find eco-friendly replacements for plastics. Empowering and educating communities and citizens to act collectively to minimize plastic pollution and use alternative options for plastics must be promoted and enforced. Plastic pollution is a global concern that must be addressed collectively with the utmost priority.

**Keywords:** plastics; climate change; ecosystem service; policy; sustainable development goals; life cycle assessment; circular economy

## 1. Introduction

Plastics are a geological indicator for the Anthropocene era that have recently become an environmental hazard due to their resistance to degradation and long-term persistence in the environment. Plastic is a wonderful material and a driver of economic growth and synthetic modernity; however, the irresponsible and unethical disposal of plastic waste in any habitat is recognized as plastic litter. The modern lifestyle is embedded in the complexity of economic and toxic interdependency of plastic use. In the 20th century, researchers have invested their efforts in identifying the physicochemical structures and functionalities of plastics to make them suitable for various applications. However, injudicious use and the unethical disposal of plastics cause environmental pollution. With a growing concern of environmental stewardship, plastic pollution gained increasing attention in the scientific community, governments, media, and the public due to its negative impact on the environment and human health. Although plastics serve as valuable resources and provide many benefits to society, such as comfort, hygiene, and safety, leading to the well-being of society, its single-use nature and disposal outweigh the benefits unless it is used and disposed of appropriately [1]. Plastic materials have made significant contributions to food packaging [2–4], drug delivery [5,6], refused fuel [7,8], safety from communicable diseases [2,9–11], roads, and pavements [12,13]. Looking at the plastics market, the packaging sector had the largest share in 2019, followed by building and construction, textiles, automotive and transportation, infrastructure and construction, and consumer goods, among other sectors [1,14–16]. Advanced nano-sized polymers are innovatively suggested as a vector for drug delivery against deadly diseases, such as cancers, etc., to improve the efficacy of medicines [17]. Particularly, condoms have played a significant role in preventing HIV, other sexually transmitted infectious diseases, and birth control [18]. Apart from these, polymers scaffolds are engineered for artificial bone and cartilage implants [19]. Similarly, clean meat or eco-friendly meat are being developed through tissue engineering to reduce the ecological footprints from meat industries [20].

Plastics become waste due to irrational production, inappropriate disposal at landfills, and inadequate recycling management. The leakage of plastic wastes into the environment, including terrestrial and aquatic ecosystems, is occurring at an unprecedented rate, and poses significant challenges to the waste management for growing populations, mainly in developing countries [15,21]. In 1950, global plastic production was 1.5 million tons, which grew to around 370 million tons in 2019, with Asia as the largest contributor (51%), followed by the North American Free Trade Agreement (NAFTA) countries (Canada, Mexico, and the United States; 19%), Europe (16%), the Middle East and Africa (7%), Latin America (4%), and the Commonwealth of Independent States (Azerbaijan, Armenia, Belarus, Georgia, and other; 3%) [14,22]. Geyer et al. [16] estimated that plastics litter in landfills and natural ecosystems will reach 12 billion tons by 2050 in the business-as-usual scenario of current waste management and if there are no targeted improvements made through technological innovations and other interventions. According to Geyer et al. [16], plastics wastes are recycled (9%), incinerated (12%), dumped in the environment, or landfilled (79%) after the end of their lifespan. There are huge opportunities for using principles of circularity (with reuse, recycle, and rethink) in plastic waste management.

Schmidt et al. [23] reported that plastics get transported from land to oceans via rivers; the Yangtze River carries 1,469,481 tons of plastics, followed by the Indus River (164,332 tons), Yellow River (124,249 tons), Hai He (91,858 tons), Nile (84,792 tons), Meghna, Ganga, and Brahmaputra (72,845 tons), Pearl (52,958 tons), Amur (38,267 tons), Niger (35,196 tons), and Mekong (33,431 tons). Plastics waste cause severe problems if leaked into the environment, such as the blockage of waterways, leading to standing water that serves as a breeding niche (to mosquitoes, pests, vector-borne diseases transmission), becomes a vector for toxic chemicals, and ultimately disturbs the natural cycles (biogeochemical cycle in terrestrial ecosystems) [24,25]. Plastics also create major challenges for aquatic ecosystems, where small-sized plastic particles are easily ingested by organisms, get into their system, and are eventually transferred to the broader food chain. The transfer of plastic into the food chain is dangerous to animals and human beings [15,24–39]. In addition, plastic ingestion by aquatic organisms (e.g., dolphins, turtles, seabirds, and others) blocks their breathing pathways, leading to death. Jambeck et al. [40] projected that marine litter may harm almost 600 species by 2050; 90% of seabirds will be under threat due to plastics ingestion, and approximately 15% of the marine species come under endangered categories because of the ingestion and entanglement of plastics.

Large plastics undergo degradation via interaction with the natural environment because of physical, chemical, and biological processes, such as mechanical degradation, biodegradation, thermal actions, UV degradation, photodegradation, mechanical forces (e.g., friction), turbulence, and other processes [35,41–44]. Lambert et al. [45] categorized macroplastics as less than 5 mm, mesoplastics in the range of 1–5 mm, microplastic (MPs) as less than 1 mm and greater than 0.1 µm, and nanoplastics (NPs) as less than 0.1 µm. Small-sized plastic particles—macroplastics, MPs, and NPs, either originated from primary or secondary sources that come into the environment directly from personal care products (e.g., shampoo, detergents, cosmetic products, paints) or degraded from larger plastic particles, respectively [44,46–48]—are inevitably present in natural ecosystems. Due to its versatility and wide-scale uses, plastic litter and even small-sized particles, MPs, and NPs are present in soil [49–52], sub-surface systems [48,53–55], groundwater [50,56–58], atmosphere [59–63], wetlands [48,64–68], rivers [35,50,69–73], and marine environments [53,59,74–78], among others, and they are also accessible in high-altitude ecosystems, for example, snow, mountains, and glaciers [79–82].

Intrinsic characteristics, i.e., the density, shapes, and polymeric chemical composition, of micro- and nano-sized plastic particles govern the fate of MPs and NPs in the environment [83–85]. Fibers, films, filaments, foams, fragments, granules, pellets, and microbeads are common irregular and heterogeneous shapes of MPs observed in different ecosystems, which originated subsequently through degradation and mechanical abrasion from construction work, fishing nets, garbage, household effluents, washing clothes, or greenhouse poly bags [28,86–92]. Additionally, MPs and NPs particles are heterogeneous in nature, retain intrinsic characteristics, have various densities from 0.85 to 1.41 g $cm^{-3}$ [93–95], and have unique physical properties in terms of shape and size [96,97]. Large-sized MPs and NPs particles, having high density, can easily be deposited in the aquatic environment as compared to low-density plastic particles [97]. Degradation and fragmentation can modify the diameter, density, and shape of the particles [98–100]. Although virgin plastics have densities in the range of 0.01–2.3 g $cm^{-3}$, these can change due to aggregation, biofilm growth, degradation, and flocculation in the environment [95,101–103]. MPs and NPs ingestion make them an ecological hazard to aquatic as well as terrestrial organisms, and adsorbed toxic contaminants have long persistence in the respective environment [27,30–32,104–117]. Several studies reported small-sized plastics as vectors for the transport of heavy metals and other toxic chemicals in different natural ecosystems because of the large surface-to-volume ratio and because of modifications in plastics properties. These modifications include increases in the surface area, adherence, flakes, fractures, avulsions, etc., which ultimately encouraged the adsorption and attachment of toxic chemicals onto their surfaces [112,118–129].

According to the United Nations Environment Program (UNEP) [15], single-use plastics (e.g., plastic bottles, caps, cigarette butts, grocery bags, lids, stirrers, straws, food wrappers, etc.) are evidence of poor waste management systems and our attitude toward natural ecosystems. These plastics have severe health and social impacts; for example, plastic particles possess toxic chemicals that can be carcinogenic and can also impact the nervous, reproductive, and respiratory systems. In developing (or low-income) countries, plastics are burnt for cooking and heating purposes, resulting in prolonged exposure of toxic emissions to women and children. In addition, plastic litter causes visual disamenity to garden/locality, which indirectly increases social costs due to plastic contamination and pollution [15,130]. Plastic litter causes economic losses to the tourism, fishing, and shipping sectors globally [15,131,132]. Therefore, the future cost for the remediation of all plastics from the different ecosystems would be financially unviable and expensive [15].

Small-sized plastics, for example, MPs and NPs, are considered as physical, chemical, and biological stressors that impact the key ecosystem services and valuable resources as well as induce global climatic stress to marine ecosystems [77,133,134]. Prata et al. [135]

provide insights on the transdisciplinary approaches of direct impacts on animal and human health and indirect impacts on ecosystem services due to MPs. Plastic pollution and climate change are interlinked; for example, photodegradation and de(nitrification) promote climate change and thus intensify MPs, which leads to eutrophication in aquatic settings [136]. Hu et al. [137] highlighted knowledge gaps related to the consequences of MPs and NPs on global biodiversity and impacts on ecosystem services. MPs pollution promotes greenhouse gas emissions (GHGs) and interferes with carbon fixation in marine ecosystems [138,139]. In addition, Sridharan et al. [140] investigated how MPs and NPs destabilize the global ecosystem services as well as influence the functioning of aquatic and terrestrial biota. Therefore, several nations worldwide implemented ban policies against single-use plastics and encourage the recycling process and life cycle assessment of plastic materials. For example, government agencies implemented bans on single-use grocery bags, shopping bags, and plastic bottles in California (USA), plastics packaging materials in Massachusetts (USA), non-biodegradable tableware in France [141], and cosmetic products consisting of plastics in Canada [142,143]. In addition, Sweden adopted household wastes and achieved zero waste and sustainable energy by recycling 99% of the household wastes [144].

Syberg et al. [145] overviewed policy initiatives for plastics mitigation and a value chain for analyzing the circular plastics economy. For better understanding, Rochman et al. [146] suggested integrating science and policy to solve global plastic waste management with the help of scientific evidence for MPs and NPs mitigation. The strong association among the interconnected plastics value chain and stakeholders at the regional or global scale requires advanced approaches with innovative and sustainable solutions, which are mainly focused on developing frameworks through plastics blueprints and boosting the circular economy for a sustainable future [14]. Plastics have been disposed in the environment on a large scale, and only a small percentage of plastics are being recycled or reused. It is projected that the quantities of plastics in the environment will be huge if citizens are not aware of the negative impacts of plastics and if there is no appropriate infrastructure to manage waste or recycle. In addition, there is also a need for policies and laws for the use, management, and disposal of plastics.

To date, limited information is available related to MPs and NPs regarding both short-term and long-term multi-stress impacts on climate change, ecosystem services, greenhouse gas emissions, and biogeochemical cycling. The linkages between plastic pollution and key sustainable development goals are not well articulated. In addition, policy initiatives for plastic pollution mitigation are lacking, including life cycle assessment and plastic production mitigation for the circular economy framework. Although there have been a few reviews published, most of them focused on individual components of either highlighting plastic pollution management, recycling approaches, existing policies, or links to sustainable development goals. They do not provide a complete picture and interconnections and linkages among the various components. There is a need for such a comprehensive review that provides all the necessary information together and discusses plastic pollution, impacts, policies, management approaches, and the need for systems approaches to address such a complex problem.

The goal of this review is to provide a background assessment of adverse effects on natural ecosystems, identify knowledge gaps, and address policy initiatives under transdisciplinary approaches through life cycle assessment, circular economy, and sustainability. The main objectives of this review are to (a) highlight potential impacts of plastics on ecosystem services and climate change, (b) emphasize the importance of plastic waste management, socio-economic impacts, and the role of community, (c) offer interlinkages between plastic pollution, waste management, and sustainable development goals, (d) summarize policy interventions to minimize plastic pollution and plastic waste management, (e) discuss life cycle assessment and circular economy with plastics pollution, and (f) provide current knowledge on plastic pollution, plastic waste management, and policy initiatives and recommendations.

## 2. Impact of Micro and Nano Plastics on Ecosystem Services and Climate Change

Every minute, a million plastic bottles are bought around the world, which is expected to further increase in the coming years, resulting in an environmental crisis that may contribute to global climate change. MPs in sea-ice were shown to be positively associated with chlorophyll, indicating that living biomass can contribute to the deposition of MPs and NPs into the sea-ice. Significantly, sea-ice in the Southern Ocean has the potential to contribute as the depository for MPs. Due to this reason, rather than being transported to deep oceans, MPs and NPs are likely being trapped in and released from the sea-ice seasonally in accordance with sea-ice development and ice melting process. As a result, these MPs and NPs particles would be more accessible to aquatic biota and are being ingested. Plastics are assimilated through physical or biological mechanisms, or a combination of both factors, based on the time-span and regions [147]. So, MPs affecting ecosystem services are mostly propagating through three mediums: terrestrial, aquatic, and atmospheric ecosystems (Figure 1). Current knowledge gaps are highlighted due to the impact of MPs and NPs pollution on ecosystem services, which are directly concerned with ecosystems and their functionality.

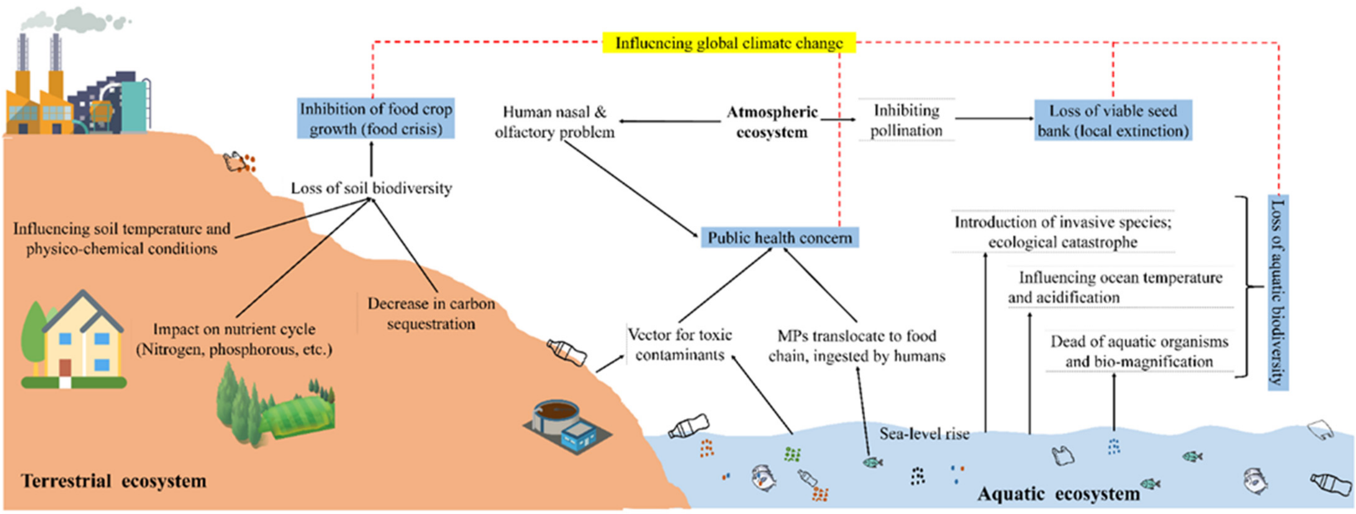


**Figure 1.** Illustration of MPs and NPs affecting various ecosystem services and climate change on terrestrial, aquatic, and atmospheric ecosystems.

A comprehensive approach requires balancing human well-being with nature's services; although it is one of the basic essences behind the development of ecosystem services, it has yet to be investigated despite being emphasized in the late 1990s [140,148–151]. In this section, emphasis is given to connect the dots among the micro or nano plastics, ecosystem services, and human well-being; we do not delve into the fundamentals of the functionality of the natural systems, which is already available in various literature [44,48,152,153]. Ecosystem services as an established concept connect ecological science with the economics and social sciences. MPs or NPs do not only pose ecological threats; rather, their impact can be understood in human society as well both economically and socially [154]. Determining the impact of MPs on ecosystem services and subsequently on human well-being is beneficial to highlight the real-world problem for the various stakeholders in the society [137,155].

MPs and NPs in terrestrial ecosystems reduce the ability to sequester carbon, which is one of the major ecosystem services provided by the soil ecosystem to maintain the carbon cycle [152,153,156]. As MPs are an organic carbon (around ~80%), no significant methods have been developed yet to distinguish soil organic carbon and MPs carbon, and as MPs come in contact with the soil matrix, it forms the MPs cycle (i.e., slow MPs/NPs decomposition). Current experimental studies are still determining the detrimental influence of MPs/NPs on the terrestrial ecosystem with soil carbon storage, which has often been seen to be linked with global change [157]. Other nutrient's cycles, such as nitrogen and phosphorous, are also vividly influenced due to MPs and NPs in the soil ecosystem. Soil productivity is impacted due to the nutrient imbalance followed by oxidative stress and leading to the poor growth of food crops, which is already a well-established phenomenon in the case of wheat production [44,137,158]. As stated earlier for the health issues, the impact on the food production in this context will severely undermine agricultural production and might lead to food crisis at the local and global level. MPs and their suspended solids also hasten climate change and eutrophication. MPs accumulation can promote mineralization, nitrification, and denitrification in aquatic ecosystems, therefore releasing $CO_2$, $CH_4$, and $N_2O$. Eutrophication worsens as a result of both resuspension and algae growth, adding more contaminants to the food chain supply and primarily creating organic contamination [136]. The huge production of plastics in the petrochemical and plastic sectors may destabilize the global climate, making it difficult to limit global temperature rise to 1.5 °C or even 2 °C [138], which is the goal set by the Paris Climate Agreement. MPs and NPs in aquatic environments have the potential to influence phytoplankton's photosynthesis and proliferation, zooplankton growth and overall development, the marine carbon pump, and the ocean carbon pool. Consequently, marine carbon sinks are critical in analyzing the global climate change and are potentially affected by MPs and NPs pollution on phytoplankton-sequestered $CO_2$ and their transmission to the deep ocean via zooplankton [77].

In terrestrial ecosystems, various soil parameters are also affected by MPs, which dynamically cause $N_2O$ and $CO_2$ emissions. MPs also reduce $N_2O$ emissions during extensive nitrogen fertilization. The effects of MPs on GHGs emissions should be considered in future impact evaluations, and the soil structure should be examined to better understand such impacts [159,160]. Furthermore, chemically changing processes will not eliminate the enormous amount of emissions produced, despite the possibility that the development of renewable energy-based polymeric materials could reduce GHG emissions from production units [138]. Plastics-induced variations in solar radiation in the water column can alter physical processes at the ocean's surface and near-surface layers as well as trigger climate feedback mechanisms [161].

Plastisphere contribution to surface layer GHGs stock is adding a new unreflective effect to the reported adverse effects of plastic pollution in the oceans. This output is influenced by the biogeochemical aspects of the surrounding waters, but it is sustained by active microbial processes that consume and produce $CO_2$ and $N_2O$. The degree to which the types of MPs and NPs influence nutrient concentrations and are correlated to plastisphere microbial diversity needs to be understood. Similarly, how these changes would affect the plastisphere's significant benefit to surface biogeochemical cycles, including climatically active GHGs, needs to be understood as well [139]. MPs and NPs are known to cause a dynamic shift in the soil temperature as is commonly practiced in agriculture sectors with extreme climatic conditions. Topsoil temperature fluxes and the subsoil environment have impacts on soil ecosystems and subsequent ecosystem services. Soil temperature flux alters soil decomposition rates, which can have massive impacts on soil ecosystem services [157,162,163]. The subsequent alteration of physicochemical parameters is also known to have a significant impact on the forested land; especially, it can lead to soil erosion, forest fire, and desertification of unprecedented levels, causing immense loss of biodiversity and subsequent ecosystem services [164]. Soil temperature and physico-chemical parameters are known to play a pivotal role in the survival of micro- and macro-fauna in the soil ecosystem; for example, they directly affect fauna regarding their feeding (arthropods) and reproduction (reptiles). Soil temperature plays a deterministic role in eggs hatching and even sex determination of the hatchlings. Therefore, MPs and NPs in the soil ecosystem are known to have a strong impact on the population structure and survival of these faunas [135,137,154,158]. It is important to conduct further studies in this context to add to the existing knowledge base.

The existing knowledge on the effects of MPs and NPs on aquatic ecosystems is relatively better in comparison to other ecosystems. MPs are entering into the marine ecosystems at an unprecedented level; a decade ago, estimation revealed 4.8–12.7 metric tons of MPs every year, which can have detrimental impacts on marine ecosystems [154]. Small-sized plastics act as stressors, altering the ocean level and temperature and influencing the acidification. The rise in ocean temperature is highly crucial, since its effects on glaciers, tropical cyclones, ocean currents more or less, and the global climate change will, directly and indirectly, be influenced by the MPs influx in the marine environs [164,165]. Thus, MPs and NPs can play a crucial role in climate change. High amounts of MPs and NPs are more substantially found in pelagic species than in deep-water species. The most prevalent plastic shapes recovered are fragments, and substantial differences are observed throughout the polymers comparing pelagic and deep-water species. Findings show that pelagic and benthic species have different frequencies and amounts of plastic items in their stomach, with open-ocean pelagic species consuming many more plastics in different forms of polymer over the benthic species [134]. Limited evidence implies that in addition to genetic changes, phenotypic plasticity and the evolution of plasticity will contribute significantly to apparent phenotypic changes in aquatic invertebrates because of global warming. Therefore, photoperiodic modifications to global warming are ubiquitous and may even lead to phenological alterations in addition to thermal adjustments [166]. MPs may have amplified the effect of multi-stressors with climate-induced stress, potentially compromising the health and resilience of populations and ecosystems. Effects on ocean salinity and volume, as well as air and water circulation on climate change, are projected to significantly alter the existing distribution patterns. Major concerns over projecting the future patterns of plastic aggregation and accumulation in response to global circulation are currently uncertain about the consequences of global warming on the oceans [167]. MPs concentration, accumulation, fate, and their ingestion may all be assessed through field surveys and time-series monitoring [133].

Economic impacts due to the MPs pollution in the aquatic ecosystem are also unparalleled. The negative impact of MPs is estimated to result in a loss or reduction of approximately 1–5% in the provided ecosystem services, amounting to approximately US$2.5 trillion [154]. MPs and NPs act as vectors for toxic chemicals and microbes and can breach any ecosystem. Thus, these invasive microorganisms lead to change in the community structure, loss of local biodiversity, and other ecological catastrophes [149,168]. Since MPs and NPs are already established to act as a vector and breach through any system (organisms) and even via trophic transfer (one trophic level to another via food chain), therefore, it can be hypothesized that MPs in the future can play a pivotal role in the spill over of infectious diseases, leading to an epidemic or pandemic of unknown scale [44,148,152,169]. Aquatic ecosystems are highly impacted by MPs and NPs, at times more than terrestrial ecosystems. Especially bottom feeders have a high intake of MPs, which leads to blockage of their feeding system, resulting in death. Polystyrene can get into blood cells and into the brains of feeders, resulting in death [137]. MPs and NPs are known to travel up through the food chain, leading to biomagnification. It has already been studied that the perceived risk of consumption of MPs can be detrimental at times since more than 1.4 billion people are dependent on seafood, which is essential to highlight among the public health concern [154]. Therein, MPs consumption has also been known to hamper the reproduction of few genera of fishes, leading to lower egg-laying capacity or infertility at times [170]. It can be said that the marine system is influenced by a triage: climate change, overfishing, and MPs and NPs pollution. Each one of the above factors is convergently working toward the loss of human well-being.

MPs and NPs in the atmosphere also lead to the obstruction and lowering of pollination. Few species of pollens have a similar size to that of MPs and NPs. Therefore, MPs and NPs can mimic the pollens and thus obstruct the pollen grains; subsequently, the process of pollination gets inhibited [163,170]. On a larger scale, hindering pollination will lead to a decrease in seed banks; the worst affected species might be endemic or rare ones with limited viable seed banks, because, to a large extent, pollination is more prone to local extinction [170]. Since MPs and NPs are abundant in the tropical region, which is coincidentally the most diverse region with a high number of endemic and rare plant species, therefore, hypothetically, MPs and NPs pose a serious threat to the plant diversity in the tropics [48,137,149]. Similar to other pollutants, humans inhale MPs; therefore, the continuous inhalation of MPs leads to serious health concerns including lung congestion, cancer, ulcers, and several other nasal and olfactory infections [164]. There are significant knowledge gaps, ecological concerns, and serious public health concerns regarding the toxicity of MPs and NPs, as they will lead to a burden for the health system infrastructure in society, especially in the third world nations, whose current medical infrastructure is already overwhelmed. The public health concern will directly lead to lowering the HDI (Human Development Index) and simultaneously will be a major hurdle for achieving the SDGs targets [171,172].

## 3. Plastic Waste Management: Socio-Economic Impacts and Community Involvement

Marine biota-ingested plastics reduce the efficiency and productivity of commercial fisheries and aquaculture through physical entanglement and damage [173], and they are a direct risk to fish stocks, which has direct and indirect effects on the entire food chain [25,174,175]. Seafood is the main source of animal protein and accounts for more than 20% of the food intake by weight for 1.4 billion people, which is 19% of the global population [176]. According to Mouat et al. [173], recreational activities are directly affected by marine plastics; for example, marine litter and debris float on the surface of the ocean and land on the shoreline, which creates heavy pollution along the coastline. This is a reason why tourists avoid visiting beaches, resulting in major socio-economic problems. The economic development of the country requires a developed tourism industry and lounges in the coastal areas; however, shorelines are being polluted by plastic litter, which automatically reduces the recreational values, thereby threatening the social, human, and mental stability. The economic cost of plastic pollution will not only damage tourism but also cause health risks. As plastics and plastic-based products are spread around the world, there is an ever-increasing exposure to disposable plastics in the environment that have complex chemical compositions. As a result of unprecedented urbanization, cities face difficulty in managing waste in a socially and environmentally responsible manner. Locally generated waste behavior varies with cultural, environmental, and socio-economic elements, including institutional capabilities, which also influence the effective waste management and efficient alternative solutions. Waste governance is becoming more regional and codified around the world. Waste management is formally done on a municipal or regional basis in developed countries, where citizens generate significantly more waste than other residents, while people in the developing world are generally creating less waste because of using biogenic products. There is a critical need for integrating the informal waste sector in developing cities, reducing the consumption in developed cities, increasing and standardizing solid waste data collection and analysis, and effectively managing the increasingly complex waste while protecting the people and environment [177].

Different countries have different perceptions of waste management. For example, in South Africa, about 85% of waste goes into proper dump sites, whereas 15% of waste goes into improper landfills [178]. Thailand is one of the main producers and exporters of plastic products, generates twice the global average of plastics, which accounts for 29 kg per capita per year, almost 4% in 2018. The living standard in Thailand is reduced by the presence of plastics and its waste management [179]. Cyprus is managing its waste well, and it has only 7% mismanagement of waste, while about 93% of waste is collected within the state. The perception on handling, managing, disposing, and recycling the waste is overall good in the country [180]. Waste management in Mozambique is in a critical situation where most of the waste is untreated and mismanaged (at about a 99% rate). In Mozambique, there is no indigenous plastic manufacturing; all plastic products are being imported. The country's estimated generation of plastic is 6.1 kg per capita per year, which is considerably less than the global average; therefore, it has a very poor collection rate, and the recycling rate is only 1%. Around 17 kilotons of plastic trash are poured into the river and the ocean. It means that 10% of all plastic debris finds its way into the ocean [181]. Menorca is the best in managing and handling plastic waste. In 2018, the country created 10,220 tons of plastic garbage, out of which 2476 tons (24%) were created by the tourism sector alone. Tourism is the most responsible sector for generating waste in Menorca. The generation of plastics per capita is 111 kg per inhabitant per year, including tourism, but the average collection rate is 90%, which is relatively good. Meanwhile, 10% of plastics trash is unmanaged in Menorca, and they are uncollected and littered [182]. Vietnam is currently importing the majority of plastic product consumption. Due to the increase in industrial growth in Vietnam, more than half of the total plastics go into the stockpile. The increase in plastic waste indicated that the country is failing to manage the waste. The burning of plastic in an open environment causes severe human health (due to the release of noxious chemical substances such as dioxins and particulate matter) and it is directly contributing to climate change [183]. Kenya is consuming 98% of its plastics, which are being imported from another country, in both production form and as primary virgin plastic. Kenya is also high on the list of not collecting plastic waste properly because of the absence of sanitary landfills and incineration facilities [184].

Community participation, according to the WHO (2003), involves members of the community actively and genuinely getting involved in defining issues that concern them, making decisions about factors that affect their lives, formulating and implementing policies, planning, developing, and delivering services, and acting to effect change. According to Kolk and Pinkse [185], the community and stakeholders should take initiatives to reduce the use of plastic-based products such as mineral water bottles, encourage tourists to carry reusable water bottles, and store food in non-disposable containers. The lack of participation of stakeholders and the community in environmental protection leads to the irresponsible dumping of large amounts of waste in the developing world. Therefore, both tourists and operators should take responsibility for encouraging everyone to respect the environment by helping the local communities protect the beaches and coastal shorelines [186]. For instance, community participation in Nigeria shows that community members realized the value of the intervention of the people in managing the waste through demonstrating capacity-building impact in terms of turning waste into wealth, as their willingness to segregate the waste at the source for recycling is dependent on their ability to benefit economically from such an operation. Environmental protection, financial benefits, and personal interests were among the incentives to participate [187].

During the coronavirus disease 2019 (COVID-19) pandemic, single-use plastics, such as PPE kits, masks, etc. are helping in preventing infections; however, there has been a significant rise in plastic pollution due to excessive disposal and poor waste management [188]. Several studies have already warned of the COVID-19 pandemic causing ecological disasters [9,189]. The spread of COVID-19 causes health crises globally as protective gear (masks and gloves) exposed to the environment not only harm people's health and economy but also threaten ecosystem services and environmental sustainability [190]. During the pandemic crisis, high demand for plastic materials resulted in up to 40% consumption of non-biodegradable packaging materials [191]. Guidelines and actions for management, treatment processes, and the disposal of the generated plastic wastes are crucial during the COVID-19 crisis. Planned waste management via on-site waste collection, sorting, and then the disposal of hospital waste eventually ended in waste treatment [192]. Despite the Biomedical Waste Management Rules 2016, specific guidelines are required to ensure the scientific disposal of COVID-19 wastes. According to Aldaco et al. [193], many countries have different types of research and development institutions to solve different types of problems, but there are no regulatory authorities to oversee them. By reducing waste generation and finding alternative disposal methods, the circular economy can help reduce the impact of plastic pollution. Therefore, there is a need to again think of a more resilient, circular, and low-carbon economic model [194]. It is likely to resolve the traditional conflict between socio-economic and environmental objectives; however, as the government implements this economy in the private sector, the economy will regenerate on its own, resulting in better social outcomes for the country and improved climate ambition.

## 4. Interlinkages between Plastic Pollution, Waste Management, and Sustainable Development Goals

After the millennium development goals, the United Nations launched the sustainable development goals (SDGs) in September 2015, which have been widely implemented by various nations to achieve sustainability [195]. The objectives of the SDGs are to take the collective decision against the most critical multi-dimensional socio-economic-environmental global threats. There are 17 SDGs and 169 targets; out of them, only one goal is directly related to plastic pollution, i.e., SDG 14: *Life Below Water* with its target 14.1.b, as an indicator, focuses on reducing marine (micro)plastic debris loads particularly from the land activities by 2025 [196]. SDG indicators depict challenges for each country at national, sub-national, or supra-national levels to pursue the nature and behavior of plastics in the environment, including MPs pollution monitoring and management [196,197]. Therefore, the interlinkages between plastics pollution and waste management with each of the SDGs are discussed in the following subsections and are highlighted in Figure 2.


**Figure 2.** Perspectives on interlinkages and relationships between plastics pollution, management, and each SDG.

### 4.1. SDG 1 (End Poverty in All Its Forms Everywhere)

Natural ecosystems are vulnerable to plastic wastes, and they also negatively affect ecosystem services and livelihoods, especially in coastal communities in less developed countries due to their inability to handle plastic pollution [154]. Poor people are critically vulnerable to climate events and disasters. Therefore, actions to call for resilient environments with reduced plastic pollution and exposure concerning economic, social, and environmental development are needed. These communities are already poor, and the majority of the population are under the poverty line. The negative impacts of plastic pollution on the productivity of their value chains (agriculture or aquaculture) and income generation opportunities may create new problems. Global trade between developed and developing countries for plastic waste as well as an informal waste management sector is required for improving livelihoods [198].

### 4.2. SDG 2 (End Hunger, Achieve Food Security and Improved Nutrition and Promote Sustainable Agriculture)

Millions of people still grapple with the hunger, malnutrition, stunting, and waste issues prevalent in the global south [199,200]. Plastics (particularly MPs) in the agricultural soil [201,202], vegetables and fruits [203], and seafood [204,205] are a potential threat to sustainable food production system and food security. Zhang et al. [206] reported that the accumulation of plastic film residues in the field negatively impacts the physicochemical properties linked to soil health and negatively impacts food production. They showed that crop yield decreased at the mean rate of 3% for an additional 100 kg/ha of film residue and there were also negative impacts on plant height, root growth, and soil properties such as soil water infiltration rates, soil organic matter, and soil available phosphorus. China is the largest user of plastic mulch in agricultural systems; it was estimated that 550,800 tons of plastic residue had been accumulated in the soils, which has caused an estimated reduction of 6–10% in cotton yield in some of the polluted sites due to the plastic residue [205]. Detailed meta-analysis of the effect of plastic mulching and plastic residue on agricultural production showed that there are benefits of plastic mulching on increasing crop production, but the residual plastic film would seriously affect crops yield over time [207]. The decreased yield on long-term and environmental degradation would have negative impacts on food security and sustainable agricultural production. Therefore, plastic pollution in soils is not only a threat to soil health, soil fertility, and crop production, but also food security and human health.

### 4.3. SDG 3 (Ensure Healthy Lives and Promote Well-Being for All at All Ages)

There are several studies in the literature on the ingestion of MPs in humans through air, seafood, packaged water, salts, personal care products, etc. [208–213]. However, the potential health concerns posed by MPs in humans have no specific health problems primarily because such studies are scarce. It has been reported that plastic particulate matters have been observed in the human gut and stool [214–217]. However, plastics at nano-levels in higher concentrations may cause local inflammations, and direct contact with RBCs (red blood cells) might cause hemolysis [218]. Dioxin, furans, and other pollutants released during the open burning for disposal may cause respiratory issues [219,220]. Not only is there a direct negative impact of plastics but also trace elements may be adsorbed to plastic surfaces that can also be dangerous to human health. The review of Bradney et al. [216] highlighted that once the plastic is in the gut, it can affect the digestive and immune system of humans, but the effects of exposure of trace-elements-sorbed particulate plastics on humans are not known.

### 4.4. SDG 4 (Ensure Inclusive and Equitable Quality Education and Promote Lifelong Learning Opportunities for All)

Education, either formal or informal, including training and public awareness, are vital to promoting sustainable development and improving people's potential. Addressing the environmental and developmental concerns, the SDG 4 (target 4.7) links to the environment as "*By 2030, ensure that all learners acquire the knowledge and skills needed to promote sustainable development, including, among others, through education for sustainable development and sustainable lifestyles, human rights, gender equality, promotion of a culture of peace and non-violence, global citizenship and appreciation of cultural diversity and of culture's contribution to sustainable development*". In addition to science-based solutions, it is critical to use educational and awareness programs to limit excessive plastic use and its improper disposal into the environment.

*4.5. SDG 5 (Achieve Gender Equality and Empower All Women and Girls)*

Promoting gender equality in society is crucial to restoring ecosystem services and protecting our planet's oceans. Women who are engaged in interacting, exploring, and protecting oceans can be instrumental in making decisions that ensure diversity and gender inclusion at all levels [221]. According to the UN reports, women engagement is generally limited; however, empowering women and girls to achieve SDGs will concert action toward gender equality [195]. A circular brief by the United Nations Environmental Program (UNEP) (2019) provides an overview of the linkage between gender equality and marine pollution and highlighted the effective interventions to empower women. Both men and women are equal consumers of plastics products. Men associated with fishing in oceans, rivers, etc. are also a crucial source for plastics pollution to marine ecosystems; however, in household waste management, women are the key in making decisions and are the authorities related to plastics management and the reduction of packaging waste. Women are the largest consumers of personal care and cosmetic products, which contain MPs and microbeads that ultimately end up in the water bodies. Therefore, gender-based roles and attitudes toward plastics management in household activities, as well as public spaces, need to be recognized and addressed for effective interventions and to strengthen the accountability mechanisms through various public awareness and training programs [221].

*4.6. SDG 6 (Ensure Availability and Sustainable Management of Water and Sanitation for All)*

As mentioned above, there is a growing body of literature reporting the evidence of MPs in drinking water supply and bottled water [210,222–224]. The concentration of MPs depends upon the source of treatment facilities and the frequency of bottles used. Therefore, the World Health Organization recognizes MPs in drinking water as potential hazards [225]. A survey of both tap water and bottled water found that 80% of samples taken across 14 countries contained 4.34 plastic particles per liter of water [226]. Another study just focused on bottled water found that 90% of samples had plastic pollutants [227]. The MPs can enter the aquatic system directly through effluent release and indirectly to agricultural soils through the leaching and application of soil amendments. The government of India has launched *Swachh Bharat Abhiyan*, multi-stakeholder interventions, including government bodies, private sectors, and society to segregate solid waste (including plastics waste as well) and clean up cities for providing clean water and sanitation to each citizen [228]. Providing clean and safe water is likely to minimize the use of bottled water and ultimately the plastic pollution. The appropriate disposal of plastic waste also minimizes the pollution and contamination of freshwater bodies that are being used as drinking sources for several living organisms, including animals and humans. In addition, water purification and cleaning units that use inland water can provide safe and clean water to communities.

*4.7. SDG 7 (Ensure Access to Affordable, Reliable, Sustainable, and Modern Energy for All)*

Energy production from plastic waste has been a preferred option compared to landfills due to potential leakage into the environment. However, the incineration of plastic waste generates large emissions of GHGs [229] and other air pollutants. It has been estimated that GHG emissions from plastics globally will reach 1.34 gigatons per year by 2030 and 2.8 gigatons by 2050 [138]. GHGs and air pollutants emissions contradict SDG 13 and SDG 15, respectively. The chemical recycling of plastic waste to fuels through pyrolysis has been getting attention [230,231]. In the pyrolysis process, the plastic waste is heated in an oxygen-free environment to convert the polymers into monomers [232]. This chemical recycling has the potential to reduce GHG emissions and other pollutants to a large extent as compared to incineration for waste-to-energy conversion [230].

*4.8. SDG 8 (Promote Sustained, Inclusive, and Sustainable Economic Growth, Full and Productive Employment, and Decent Work for All)*

Economic losses caused by marine plastic can be high in developing economies due to direct environmental damages and costs associated with their clean-up. It is estimated that Asia-Pacific regions will lose about US$1.2 billion every year due to damage caused by marine litter [233]. Jambeck et al. [40] suggested that unless waste management practices are improved, the flux of plastics into the oceans will significantly increase. They calculated that 275 million tons of plastic were generated in 192 coastal countries in 2010, with about 4.8 to 12.7 million tons entering the ocean. The cost associated with their clean-up will be high, and if they do not invest in cleaning their coastline, the economic loss caused due to loss of tourism will be large. These countries need significant infrastructure for appropriate waste management, which could be seen as an economic growth opportunity. The management of plastic waste through physical or chemical recycling might help to achieve a circular economy [234,235]. There is great scope for job creation in a circular economy for material management while managing the issue of plastic waste physically [235,236]. The informal recycling sector (IRS) manages a significant proportion of plastic wastes; however, their workspace is very unhygienic, hazardous, and associated with related health and social issues [237]. The integration of the IRS in public and private waste management agencies was found to be synergistically beneficial in terms of environmental and economic improvement and also provides decent and respectable livelihood [238]. With better plastic management, the water bodies will be cleaner, which will help in the tourism sector [239] as well as entrepreneurship [240].

### *4.9. SDG 9 (Build Resilient Infrastructure, Promote Inclusive and Sustainable Industrialization, and Foster Innovation)*

Great efforts would be required to innovate better ways to manage plastic wastes and to develop sustainable alternatives, such as biodegradable plastics [241]. At present, bio-based plastics only account for about 2% of the total plastic production, and there are huge opportunities for innovations and use in replacing regular plastics. There is increasing research on pyrolysis oil extraction along with various innovative side products such as multi-walled carbon nanotubes [242], plastic wax [243,244], and other high-value chemicals [245]. The incorporation of plastic waste in concrete [246] for making tiles [247], bricks [248], paving roads [249], etc. is also becoming popular. Innovative enterprises and start-ups with informal waste pickers in waste clean-up businesses were reported to be symbiotically beneficial [240]. Research and innovation in plastic waste reuse, as well as physical and chemical recycling, will be a great boon as plastic is ubiquitous, and its replacement with alternatives would be difficult and would take a long time.

### *4.10. SDG 10 (Reduce Inequality within and among Countries)*

The global trade of plastic waste has been the model for plastic waste management for decades [235]. Such practices have been widely criticized for dumping the burden of plastic pollution from developed countries to developing countries [199,250,251]. Recently, China banned the import of plastic wastes, and now, its new destinations are Southeast Asian countries that lack recycling facilities and are reported to be dumped in landfills and burned or leaked into the environment [250–252]. These highly unsustainable practices create unavoidable plastic pollution and huge inequalities in terms of environmental costs. The practice of dumping plastics produced in the developed economies to the poor and vulnerable countries will further create inequalities between the two and cause more serious environmental damage to vulnerable populations or the world who are currently facing issues with food security. Furthermore, some of these economies depend upon tourism, which will be negatively impacted as plastic waste will destroy their natural ecosystems that preserve biodiversity. This will lead to conflict between the local economies and further widen the inequalities.

### *4.11. SDG 11 (Make Cities Inclusive, Safe, Resilient, and Sustainable)*

The improper disposal of plastic wastes is clogging the urban infrastructures such as stormwater drainage and sewer systems, leading to widespread plastic pollution [253,254] and waterlogging [255]. Building appropriate infrastructure in both developed and developing countries will be required to handle waste on both land and water. If waste management on land is not improved, then the cumulative quantity of plastic waste in the marine environment will continue to increase, as it was predicted to increase at least ten times by 2025. With continued migration, the population of cities will continue to increase, and about half of the total world population will be living in cities or urban areas by 2030. SDG 11.6 specifically mentioned that waste management can "*reduce the adverse per capita environmental impact of cities including by paying special attention to air quality and municipal and other waste management*". Therefore, it will be critical to improve the infrastructure in the cities for the appropriate handling and recycling of waste, including plastic. If this is not handled properly, the risks associated with plastic pollution will continue to rise and will impact the lives and livelihood of people in both urban and rural areas.

### *4.12. SDG 12 (Ensure Sustainable Consumption and Production Patterns)*

A very large number of studies show unsustainable plastic production and consumption as well as a lack of proper management of plastic wastes [16,251,253]. Plastic consumption has reached over 320 million tons per year. Less than 10% gets recycled, 12% goes for incineration, and the remaining 78% goes to landfills or leaks into the natural environment [16]. About 11% of the global plastic waste reaches oceans and impacts marine ecosystems [253]. Under business-as-usual conditions, the situation of plastic looks very bleak. Plastic pollution is a multi-dimensional problem that requires a holistic approach. There is a need to rethink how to tackle this issue and drive economic growth via first minimizing plastics production and second increasing the sustainable production and consumption of plastics, especially single-use, low-value, disposable plastics. Therefore, SDG 12.4 target is to "*achieve the environmentally sound management of chemicals and all wastes throughout their life cycle, in accordance with agreed international frameworks, and significantly reduce their release to air, water and soil in order to minimize their adverse impacts on human health and the environment*". Similarly, the SDG 12.5 states that "*by 2030 overall waste generation must be significantly reduced through prevention, reduction, recycling, and reuse*". In the shorter term, focusing on improvement of the waste collection and management can help; however, in the longer term, a more sustainable solution will be moving toward a circular economy to remove waste and single-use plastic out of the production cycle and focus on building the producer's responsibility models with new product design that would enable reuse, recycling, and minimizing plastic packages. It was estimated that about 50% of plastic is produced for single-use, and the majority of them are being used for food packaging [2–4]. Stefanini et al. [256] reported that glass packaging, which is eco-friendly and easier to recycle, is a potential alternative for reducing marine litter; however, the use of glass is not increasing due to high energy demand. Therefore, the focus should be on both sustainable production and consumption practices for efficient use and recycling.

### *4.13. SDG 13 (Take Urgent Action to Combat Climate Change and Its Impacts)*

GHGs are emitted in most of the parts of plastic's life cycle. For example, plastics are derived from polymers obtained through fossil fuels; therefore, a significant concentration of GHGs are emitted during its production, transportation, incineration, open burning, or degradation under sunlight at the end of product's life [229,257,258]. It is estimated that currently, around 400 million tons of GHGs are emitted during its life cycle per year globally, and it is projected to increase by 1.34 gigatons per year by 2030 and 2.8 gigatons per year by 2050 [138]. As climate change is an urgent issue to be solved, there is a need for the promotion of mandatory reuse and more environmentally sound recycling technologies and energy conversion than incineration for waste to energy [258].

### *4.14. SDG 14 (Conserve and Sustainably Use the Oceans, Seas, and Marine Resources for Sustainable Development)*

Due to improper management, plastic wastes reach the aquatic ecosystems in both fresh and marine water by getting loaded with all kinds of plastics [259,260]. Plastics in micro and nano sizes are affecting the aquatic organisms severely [47,261,262]. Due to the ubiquitous presence of micro and nano plastics in oceans, it is now considered to be a planetary threat [253,263]. According to SDG 14 to reduce marine plastics pollution on a global scale, the UN explains "*Conserve and sustainably use the oceans, seas and marine resources for sustainable development*". In detail, the UN also defined a target (SDG 14.1) that "*By 2025, prevent and significantly reduce marine pollution of all kinds, in particular from land-based activities, including marine debris and nutrient pollution*". SDG 14 is the single goal among all SDGs that directly addresses the plastics pollution via an indicator, as 14.1.1b, i.e., plastic debris density, but it does not address the MPs (plastic <5 mm), even though MPs are a major source of pollution and threat for the marine and aquatic systems. As stated above, ample quantities of plastics reach marine ecosystems; therefore, urgent efforts are needed to protect oceans for better marine health, which are critical for achieving several other SDGs, including food security and hunger.

### *4.15. SDG 15 (Protect, Restore and Promote Sustainable Use of Terrestrial Ecosystems, Sustainably Manage Forests, Combat Desertification, Halt and Reverse Land Degradation, and Halt Biodiversity Loss)*

Plastic waste mismanagement is affecting the terrestrial ecosystems [47,264]; however, a large number of research studies are reported for aquatic ecosystems [44,48,118]. About 80% of the MPs pollution is derived from land-based sources, and it is estimated that there will be a significant increase in use of MPs in the terrestrial ecosystems [47,265]. Terrestrial mammals consume plastics in a similar manner to marine animals, but very few recent studies are available [266]. There is more microplastic litter in terrestrial ecosystems: four to 23 times that found in marine ecosystems [265]. Therefore, there is a much-needed requirement to study the impacts of macro, micro, and nano plastics on terrestrial ecosystems alongside aquatic ecosystems to restore and preserve the biodiversity in terrestrial ecosystems.

### *4.16. SDG 16 (Peace, Justice, and Strong Institutions)*

By nature, the global trade of plastic waste is an injustice to poorer nations by the rich countries [235,250,251]. Developed countries need to be held responsible for their management of plastic wastes rather than just dumping them on other countries. There is a need for a global body that looks after this issue and the culture or norms of sustainable reuse-recycling should be practiced by all countries. Most of the vulnerable economies of developing countries depend upon tourism due to their natural ecosystems, wildlife, and biodiversity. Furthermore, these countries are poor and looking for revenues. The dumping and payments for taking the plastic waste by developed nations are causing conflict [267,268]. Sometimes, the poor nations take the waste to please the developed countries for future opportunities with regard to loans or aid for economic development and food security [269]. This often creates a conflict between the government and citizens, as the income or aid is not shared or trickled down to the citizens. In addition, it also leads to conflict between the local economies and further widens the inequalities. Strengthening the government, non-government organizations, and private sectors to support the implementation of equitable and just environmental solutions not only at the local levels but also at regional and international levels is going to be critical to address the pollution caused by plastic waste. In addition, identification of the issues that cause conflict, development of policies to prevent conflict, promote peaceful resolution to conflicts, and manage post-conflict reconstruction and the promotion of equitable solutions through dialogue and inclusive policies will be critical. This will require strong institutional building of social capital focused on co-creating and enforcing policies that are just and equitable to all parties.

### *4.17. SDG 17 (Partnerships for the Goals)*

Developed countries that have greater resources and facilities for research and development should take the lead in conducting research and innovation for the sustainable management of plastics and develop better alternatives at low cost. In addition, the transfer of environmentally sound technologies, related capacity building, and financial investments will help to eradicate the issues of plastic pollution in both developed and developing nations while achieving the SDGs [270]. As plastic pollution is a global problem, it can only be resolved by global partnerships that will bring the government, national, and international organizations, private sector, and civil societies together. Collective action is required to solve this global problem, and all governments should come together to mobilize and commit appropriate resources to minimize plastic pollution. The innovations that can further minimize the negative impacts of plastics should be scaled up through partnerships so that they are equitable to developing countries.

## 5. Policy Interventions to Minimize Plastic Pollution and Plastic Waste Management

This section discusses plastics management strategies, challenges, and policy interventions to mitigate micro- and nano-sized plastic pollution. Each year, nearly 320 million tons of plastic waste are generated, and the number is expected to be tripled by 2050. Jiang [143] has discussed the initiatives taken to mitigate microplastic pollution by-laws, levies, policies, and the role of government, non-governmental organizations (NGOs), and international institutions to control the detrimental impacts and to protect the ecosystem. Several government agencies, research organizations, and institutions have concerted mitigation and management strategies to protect the ecosystem by plastics exposure and monitoring harmful impacts on aquatic animals and humans [143]. In Germany, the Netherlands, Switzerland, Sweden, and Norway, the supermarket charges for the use of plastic bags [271], and a tax on plastic bags was imposed in Portugal in 2015, and from that time, plastic consumption has reduced to 74% [272]. Studies reported the presence of microbeads in a number of cosmetics, which constitute a low part of MPs; therefore, a few countries have imposed a ban on the usage of microbeads in cosmetic products. For instance, California banned the use of microbeads in personal care products in 2020 [273]. Five states of the USA—Minnesota, Maine, Illinois, California, and New York—have banned plastic bags and products that contain microbeads [274–276]. The ban on microbeads has been continued by the other countries also; the Dutch government and trade organization pressured the industries to cease the manufacture of microbeads and issued a statement regarding the ban of microbeads, "Beat the Microbeads, 2016" [275]. Similarly, the UK also banned the production of a cosmetic product that contained microplastic in January 2018 [277]. In Australia, some states such as Tasmania, the Northern Territory, and South Australia have banned plastic bags [275]. Many countries have implemented laws, bans, and also charges to reduce the usage of plastic; for example, Bangladesh banned LDPE (Low-Density Polyethylene) bags [278], Kenya announced punishments of 4 years in jail [279], as did South Africa [280], but all these strategies failed in some aspect to address the exposure to plastic that results in the hazardous effects of plastic and microplastic in the environment. As of now, 127 countries regulate the use of plastics, while 115 countries have implemented various laws and policies to combat plastic waste both nationally and locally. Many countries have completely banned plastic use or there are restrictions and a fee to pay for the use of plastic. Approximately 30 countries in Africa, Asia, North America, or Europe have completely banned plastic bags; these countries have banned single-use plastics, and in some parts, there are restrictions on single-use plastic (as listed in Table 1). Some countries have imposed user fees from the sales so that the use of plastic can be reduced as well as plastic pollution can be decreased [280,281].

**Table 1.** Plastic ban in different countries.

| S.No. | Country | Year | Ban Policy | References |
|---|---|---|---|---|
| 1 | Rwanda | 2008 | Ban on the sale and import of synthetic microbeads | [282] |
| 2 | US | 2015 | Ban on cosmetic products containing plastic microbeads | [283] |
| 3 | France | 2016 | Ban on the distribution of light weight plastic bags in supermarkets | [284] |
| 4 | Canada | 2015 | Microbeads regulation to prohibit the manufacture, sale, and import of personal care products containing microbeads | [142] |
| 5 | Denmark | 2016 | Ban on products containing microbeads | [285] |
| 6 | Bangladesh | 2002 | Ban on LDPE bags | [278] |
| 7 | China | 2008 | Total plastic bags ban (<25 µm) | [275] |
| 8 | India | 2002 | Ban on ultra-thin plastics bags (<50 µm) | [275] |
| 9 | Canada | 2019 | Ban on natural health products and non-prescription drugs containing microbeads | [286] |
| 10 | UK | 2016 | Ban on cosmetic products containing microbeads | [287] |
| 11 | California | 2015 | Ban on the use of plastic and microbeads in personal care products by 2020 | [273] |
| 12 | Italy | 2020 | Ban on the marketing products such as cosmetics containing microbeads | [288] |
| 13 | India | 2017 | Ban on disposable plastics in Delhi and NCR | [289] |
| 14 | Australia | 2009 | Ban on distribution and sale of plastic shopping bags of less than 35 micron | [290] |

In addition to bans and imposing fees, other activities such as recycling and eco-labeling have also been practised. Recycling has been practiced in many countries, and the recycling rate varies in different countries: it is 50% in the Netherlands, Sweden, Slovenia, the Czech Republic, and Germany, 20% in France [286], and 7% in India [291]. To ease the process of recycling, the governments of many countries have adopted strategies by introducing a color-code system for the collection of plastic waste. For this process, yellow bins have been set up at the designated places for plastic waste collection [286]. According to Singh and Sharma [292], for the identification and separation of plastic waste, the American Society for Testing and Material (ASTM) has introduced a new seven-scale solid equilateral triangle system for the resin identification of triangles 01, 03, 05, 06, and 07 for the origins of the plastic. Eco-labeling is a tool that is used to reduce marine plastic pollution [142,274]. Eco-labeling has been adopted by many developed countries and also succeeded; for example, the UK and the European Union (EU) have adapted eco-labeling to reduce the plastic pollution in the ocean [286]. Many Nordic regions such as Iceland, Norway, Sweden, Denmark, and Finland have adopted eco-labeling, and it is widely used in those countries [293]. The European Commission in January 2018 embraced a strategy that proposed reusing and recycling all the plastic packaging and also to reduce single-use plastic and microplastic consumption [288].

To reduce or control plastic and microplastic pollution from the sea and land-based sources, several agreements and international conventions have been adopted [294]. The first convention addressing the regulation of plastic can be traced back to the International Convention for the Prevention of Pollution from Ships (MARPOL) of 1973. Annex V of the convention deals with the complete ban on the disposal of any forms of plastic wastes; it came into force on 31 December 1988 [295]. One of the main agreements that was adopted to reduce plastic waste in the marine environment is the Action Plan on Marine Litter (OSPAR Convention, 2014), which came into force on 22 September 1992 and was signed by Denmark, Finland, Germany, France, Belgium, the EU, Ireland, Norway, Spain, the UK, Portugal, Sweden, Northern Ireland, Switzerland, and Luxembourg. The main proposal of this convention was to reduce marine litter in the Northeast Atlantic and not to harm the ecosystem by 2020, which included the prevention and elimination of pollution from offshore sources, land-based sources, dumping or incineration, quality assessment of the environment, protection of the ecosystem, and biological diversity of the maritime area (https://www.ospar.org/convention; accessed on 25 June 2021) [286].

Another convention that was adopted to protect the Baltic Sea and its catchment area from both sea and land-based plastic and microplastic pollution was the HELCOM Baltic Sea Action Plan, which covered four major priority areas: hazardous substances, maritime activities, eutrophication, and biodiversity conservation [296]. In 2007, the main concern of adopting this convention was to reduce pollution, which was increasing rapidly (https://helcom.fi/about-us/convention/; accessed on 25 June 2021). In addition to these two agreements, other strategies were also adopted to reduce plastic and microplastic pollution such as the strategy of either cleaning up or removing wastes from the sources [296].

Several countries have initiated national approaches to reduce marine debris by implementing laws, action plans, and policies. For instance, the United States implemented the Marine Debris Research, Prevention and Reduction Act (2006), which was later on modified in 2012, Australia also enacted the Environment Protection and Biodiversity Conservation (EPBC) Act in 1999 and listed the aquatic species that were threatened [297]. In addition, in Canada, the Environmental Protection Act was adopted to prevent the manufacture, sale, and import of microbeads, especially in cosmetic products [142,143]; likewise, the US Federal Government also introduced an act, i.e., the Microbeads-Free Water Act, 2015, which imposes the prevention of sale and manufacture of those products containing microbeads [298]. To control the marine litter and mitigate the pollution in the Mediterranean, the EU Marine Strategy Framework Directive was proposed. In 2016, it was revised with the facts regarding the amount of litter ingested by the aquatic animals, its effect on their health and the proviso to look after the number of species affected by the litter and their impact on health, mortality, and also injury of aquatic animals [299]. Another plan for plastic pollution management was made, which was called the Barcelona Convention Regional Plan, in December 2013, a first regional sea programme to look after the adverse impact on the coastal and marine environment due to the marine litter, and it contains measures, policies, and a technical nature as well as regulatory measures [299]. Oman, Bahrain, Iraq, Iran, Kuwait, Qatar, the United Arab Emirates, and Saudi Arabia have adopted a regulatory body to look after the marine environment and to reduce pollution, this regulatory body is known as the Regional Organization for the Protection of the Marine Environment (ROPME); commonly known as the Kuwait Action Plan, this regulatory body contains legal binding signatories [300]. There are also other similar plans, agreements, and projects that have been adopted by the East Asian Region such as the Sustainable Development Strategy for the Seas of East Asia, the East Asian Seas Action Plan, UN's Global Environment Facility (GEF), and the Association of Southeast Asia Nations (ASEAN) [198].

Many strategies have been adopted for the protection of the ecosystem from the detrimental impact of microplastic; for example, according to the UNEP and NOAA (National Oceanic and Atmospheric Administration) report of 2015, Honolulu has adopted strategies to protect the aquatic life as well as manage marine litter. Honolulu's strategies have been adopted globally to mitigate plastic pollution; in the USA and Canada, they have been adapted to reduce plastic use or completely ban plastic [142,286]. This is a type of framework that can be implemented anywhere in the world and for a different programme to mitigate the issues related to the environment [301]. The USA has introduced many legal regulations that emphasize marine litter and marine environment protection. These regulations are called the Marine Plastic Pollution Research and Control Act (MPPRCA), the Beaches Environmental Assessment and Coastal Health and Shore Protection Acts, and the National Marine Debris Monitoring Program (NMDMP) [302]. In the year 1973, 134 countries signed the first global legislation, the International Convention on Plastic Pollution from ships (MARPOL 73/78). However, it failed to implement and reduce the plastic pollution in the aquatic system due to the conflicts of economic interest across the country [303].

Recently, the G7 and the EU communities committed to practising sustainable plastic waste management by increasing its reusability and the strategy of recycling [303]. UNEP has also established guidelines to increase the awareness of plastic pollution and recycling and plastic waste management at the global level [303] through the project of the Marine Waste Action Act approved by the European Commission under NOAA. The project was expected to run an awareness program on plastic particle pollution through the public education program by 2020, enact an absolute ban through legislation (partial ban to those who are under the phase of progress), and provide incentives to those who are using reusable bags [186,303]. The Basel Convention on Transboundary Hazardous Waste Control has 188 parties, which means that practically all nations are bound by revisions (which took effect on 1 January 2021) to tighten the transboundary plastic waste movement [304]. The UNEP initiative in Asia presented scientific knowledge regarding microplastic pollution in the Ganges, Mekong, and other Asian rivers. As a result, the Mekong River Commission and its member states are focusing on a way to address and monitor plastic trash in the Mekong River basin by 2022 [305]. UNEP observed substantial progress by dozens of major companies in putting recycled content into plastic packaging and phasing out single-use plastic bags and straws, in collaboration with the Ellen McArthur Foundation and UNEP's New Plastics Economy Global Commitment [305].

NGOs and other institutions play an important role in plastic reduction. NGOs also play an important role in encouraging the reduction of plastic waste productions [142]. Pettipas et al. [142] have also discussed the current policies and management frameworks for microplastic mitigation, which are high-performing, eco-friendly, and cost-effective; their study focused on the laws and policies implemented in Canada. NGOs acts as an important pillar to create awareness with different aims and strategies to tackle the problem of marine litter. NGOs mainly focus on the issue-specific strategies, such as the ban of microbeads. All these resulted in a positive impact on the policies and changes in regulations such as bans or taxes [297]. NGOs along with stakeholders of different categories can help to reduce plastic pollution and create awareness by organizing volunteers, launching projects, hosting events, and showing the success stories [306]. Social media helps the NGOs create awareness among the people, who awake against microplastic and plastic pollution through community engagement and scientific research [143]. Some international NGOs, such as the World Conservation Union, Greenpeace, the World Wildlife Fund, etc. have been working to reduce microplastic pollution [297]. Another conventional approach that is also useful in reducing plastic pollution from the environment is 'Biotechnology' by producing 'bioplastics', which can be degraded using a microorganism and an eco-friendly material [307–309]. Bioplastics have similar functions and properties, and they are believed to less hazardous for the environment as compared to synthetic plastics [310]. A variety of materials have been used to develop bioplastics, such as chitosan material, crustacean shell, polysaccharides, and insect cuticles, which are believed to be degraded in the environment within 2 weeks [311]. Correspondingly, the provision of incentives has also been adopted in many developed countries to reduce marine pollution by collection, recycling, and disposal. These include several states in the USA, such as California, New York, Arizona, and Maine [312,313]. The Extended Producer Responsibility (EPR), a waste management policy, has been recognized as one of the best policies globally in Canada, South Korea, Europe, and Japan [314].

## 6. Role of Circular Economy and Life Cycle Assessment on Plastic Products

Circular economy (CE) is an economic system that replaces the 'end-of-life' concept with reducing, alternatively reusing, recycling, and recovering materials in production/distribution and consumption processes (Figure 3).

Life Cycle Assessment (LCA) is a tool to assess the potential environmental impacts and resources used throughout a product's life cycle [315]. The LCA of plastic products is categorized into five stages, namely, *raw materials for plastic pellets*, *manufacturing of plastic products*, *use/reuse of plastic products*, *end of life*, and *discharge to the environment*. Each stage has been analyzed from the point of view of the generation of plastic waste, including both macro and microplastic wastes. The overall goal of LCA is to analyze the life cycle of plastic products from cradle to grave and their impact on the environment. The circular economy of plastic products is also being studied to understand the environmental impact of plastic products. Thus, operating CE at the micro-level (i.e., products, companies, and consumers), meso-level (i.e., eco-industrial parks), and macro-level (i.e., city, region, nation, and global) accomplishes sustainable development, considering environmental quality, economic prosperity, and social equity [316]. In other words, the CE concept addresses the value lost at the 'end-of-life' or grave of a product. At the 'end-of-life' of plastics, waste has loss of value; here, waste can be viewed in four different forms, namely wasted resource, wasted life cycle, wasted capacity, and waste embedded value. These wastes create an economic opportunity for businesses and also prevent plastic from reaching the end of its life and being exposed to the natural ecosystem, as the most substantial source of MPs and NPs [317,318].

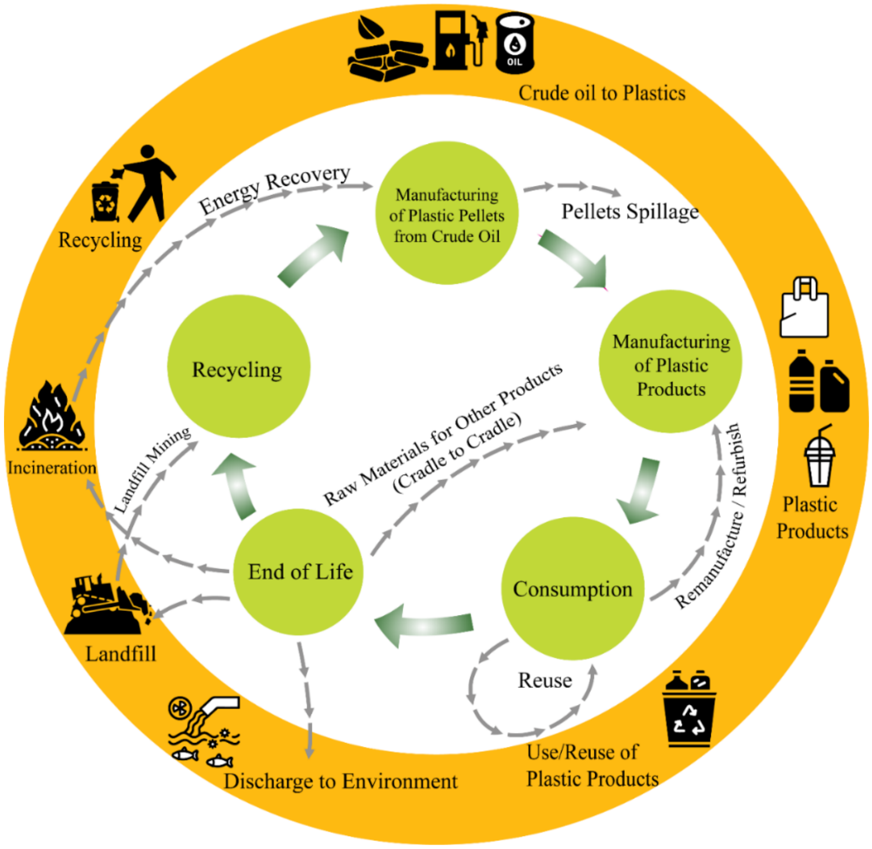


**Figure 3.** Highlights for the life cycle assessment and circular economy of plastic products.

A typical plastic goes through the following stages in LCA: manufacturing and use/reuse of plastic products, end of life, and exposure to the environment [319]. Therefore, LCA and CE can be facilitated together at each of the following stages, such as manufacturing plastics from raw materials, the production of plastic products, consumption, end-of-life, and recycling.

### 6.1. *Manufacturing of Plastics from Raw Materials*

In the first stage, plastic pellets are produced from petrol, which is obtained from crude oil. Monomers are converted into polymers via polymerization, and various other types of pellets are also produced, which are transported off to various vendors for the manufacturing of plastic products. Crude oil as a major raw material used for production depends on the type of plastic being produced. To produce 1 liter of petrol, 0.9 kg of crude oil is required, which in turn can produce either 0.57–0.72 kg of PE, 0.75–1.65 kg of PVC, 0.54–0.68 kg of PP, 0.50–0.72 kg of PS, or 0.47–1.28 kg of PET [320,321]. For plastic products production, plastic pellets and various additives are used in various plastic production industries. In the UK, 17.5% of plastic production is of low-density polyethylene (LDPE), while 12.1% is of high-density polyethylene (HDPE) [322]. PET pellets are used for manufacturing soft drink bottles, hard plastic bottles, and hard plastic containers, whereas HDPE is mostly used to produce milk jugs, cleaner bottles, shampoo bottles, other stiff bottles, jugs, and containers. Plastic pellets along with various additives are used to produce plastic products such as bags, bottles, pipes, etc. [323]. For functionality, aging, and performance, several additives in the forms of chemical compounds are being added to the polymer during the shaping phase [324].

### *6.2. Production of Plastic Products*

At the production stage, the design of a product decides its longevity; therefore, the principles of circular design are to last long as well as be easy to repair and maintain, easy to disassemble and reassemble, and easy to upgrade [325]. This stage is the primary source of MPs and NPs, and CE can be facilitated here by designing products that reduce or eliminate the need for plastic microbeads in personal care products containing scrubs and abrasives as well as from synthetic textiles and cloth manufacturing [326]. For example, in the case of plastic packaging, anti-static agents and colorants are added to HDPE, while slip promoters, colorants, and anti-static agents are added to LDPE [322]. Common additives used in plastic products are categorized into functional additives, colorants, fillers, and reinforcements, which include plasticizers, antioxidants, acid scavengers, flame retardants, light and heat stabilizers, lubricants, pigments, anti-static agents, slip compounds, and thermal stabilizers [324]. During the process of producing various types of plastics, huge amounts of pellets are lost accidentally due to spillage and find ways into the environment [322]. About 5–53 billion plastic pellets each year in the UK alone, i.e., approximately 0.001–0.01% of total plastics production, are lost to the environment through accidental spillage from the plastics manufacturing industry [327]. Sundt et al. [328]) reported that a Norwegian polystyrene (PS) plant loses around 0.4 g/kg of PS produced, i.e., 0.04% of PS exposed to natural ecosystems. Small-sized plastics are emitted to the environment along their value chain from synthesis to processing [329]. The pathways of pellets' exposure to the environment are complex to understand; however, pellets exposed during the pre-production phase of plastic production were the largest sources of microplastic pollution [330]. Packaging is the major use of plastic in Europe, amounting to 40% of plastic demand and about 42% of demand in the United States. Consumer and institutional products such as appliances, toys, cutlery, and furniture account for the next most used products (20–25%), followed by building and construction products, such as roofing, sliding, pipes, window frames, and door frames (19–20%), the transportation sector (5–9%), electrical products and electronics (4–5%), and others (4–5%) [331]. The finished products are being purchased and, in many cases, depending on the reusability of the products, are being reused. As plastic products complete their lifespan, they are being discarded to waste collection points, where waste management institutions (either a local municipality or private waste management units) collect the waste to sort, compact, and reprocess. After that, the waste is either landfilled, incinerated, recycled, organically recycled, or used for energy production. Unfortunately, the rest of the non-collected wastes gets released into the environment, mostly into the aquatic ecosystems [322]. Considering the environmental impacts of plastic wastes, recycling should be the preferred method of waste management as it creates jobs, reduces emissions, reduces the depletion of natural resources, prevents loss of value, and recovers valuable petrochemicals, and hence, perpetuates CE [332]. However, recycled plastics come with challenges; for example, recycled plastic is not as good as virgin plastic, huge emissions can be created from its transportation, and the use of non-renewable energy may be required for its production. Hence, the benefits from recycling must be considered.

With the amount of plastic produced every year, it is also important to investigate the reusability of these products in advance to minimize waste generation and environmental degradation. Due to limited investigations on plastic products worldwide, this review paper focuses more on the plastic waste status in the EU and the United States. Most plastic waste is created from single-use plastics. According to Geyer et al. [16], 47% of plastic waste globally amounted from single-use plastic packaging, out of which 50% came from Asia. About 30% of plastics ever produced is currently in use, suggesting that the remaining 70% of the plastic products are either single-use in nature or simply not reused or recycled and exposed to the environment [16]. To minimize the waste, the 5R principles (refuse, reduce, reuse, recycle, raise awareness) must be employed. The CE can be facilitated by reducing plastic consumption, which can be done by substituting plastics for other materials; for instance, avoiding unnecessary packaging or using alternatives and green logistics in global supply chains [333]. At the current rate of resource consumption in the linear economy, CE provides an alternative logical solid case, especially for plastics, where the discarded waste in the linear economy is kept in closed loops for as long as possible using the 5Rs to extract the maximum value and to prevent it from disintegrating in the form of MPs or NPs.

### *6.3. Consumption*

In the consumption phase, most of the plastic items can be reused, and they can even have alternative implications; for example, air-filled plastic bottles, which are commonly used in masonry blocks as construction materials, may be replaced with plastics-based model rooms that have better thermal insulation than traditional block construction, etc. [334]. Recyclable plastic materials can be sorted and separated from contaminants as a waste of high quality; in addition to reducing costs; it can even substitute the original material in a 1:1 ratio. For example, one kg of recycled polyethylene (PE) substitutes 1 kg of virgin PE [332,335]. LCA study also shows that the recycling and reuse of plastic-based packaging not only reduces the quantity of waste to landfills but also reduces its environmental impact [336]. In the current scenario, pressure on the healthcare system has also led to an unprecedented rise in the use of plastics to combat the COVID-19 pandemic, causing plastic and plastic-related problems to take a back seat, but as the world recovers, it also presents an opportunity to shift toward a more sustainable trajectory [337]. In the EU, the reusability of the plastic bags varies significantly within different countries. Countries such as Estonia, Hungary, and Latvia rely heavily on LDPE plastic bags with an estimated 450 bags per citizen per year, while in countries such as Denmark and Finland, multi-use HDPE plastic bags are most common, with only 100 bags per citizen per year [322]. During the life of a plastic product, MPs are produced due to the wear and tear of the product and environmental conditions such as wind, waves, temperature, and ultraviolet light [152]. A recent study found that 30,000 to 465,000 microfibers per $m^2$ are detached from textile garments, and about 0.81 kg/year per capita are emitted from the abrasion of tyres on the road worldwide [152].

For the efficient processing of use and reuse of plastic products, all plastic products come with an SPI (Society of Plastic Industry) Resin Identification Coding system that is inscribed within the recycling symbol. These code numbers are assigned according to the plastic pellet used, and they indicate the reusability and recycling capability of the product. For example, PET (polyethylene terephthalate, code 1), HDPE (code 2), and PS (polystyrene, code 6) are commonly recycled, while PVC (polyvinyl chloride, code 3) and LDPE (code 4) are recycled depending on the local context. PP (polypropylene, code 5) is recycled occasionally, but it is not as recyclable as PET and HDPE, and all other plastics are designated with code 7. These other types (code 7) of products are usually made of a mixture of various plastic resins, which makes them non-recyclable [338]. Plastic wastes, due to the multipurpose applications of plastics and plastic-based products, in both developing and developed countries, are increasing exponentially. India generates about 5.6 million metric tons of plastic waste every year with the majority of them finding their way to water bodies [339].

### *6.4. End of Life*

At the end of their lifetime, plastic products are mostly landfilled, incinerated, or recycled. Most (65%) of the plastic waste in India generally ends up in landfills [340], while about 24.9% of plastics collected by the EU find their way to landfills [14]. Plastic waste landfills in the United States since 2000 have had marginal growth, from 20 million in 2000 to 27 million in 2018 [323]. Globally, 22–43% of plastics are disposed of in landfills [331], which is a result of the linear economy. Landfills should always be chosen as the last option as they require land and pose the threat of contamination to the local groundwater and soil in addition to the loss of resources [14].

Landfill mining is a practice at landfills that re-introduces the wastes into the economy. Most plastics that end up in a landfill are contaminated and degraded and are not fit for recycling. Plastics in landfills do not degrade for thousands of years, resulting in environmental degradation such as the decline in soil fertility, accidental burning, resulting in gaseous pollutants, and indigestion by terrestrial animals [339]. For incineration, Sarker [340] estimated about 25% of plastic wastes are burnt in the landfill to overcome landfill issues such as land occupancy and soil fertility. The biggest challenge in this process is its environmental impact. This can be addressed by incineration plants (the most expensive waste management technique) that can be used to convert plastic waste into an energy-generating alternative [341]. For example, medical wastes have seen an unprecedented rise in the current COVID-19 pandemic situation; these can be incinerated to use as an energy source in furnaces, which are commonly used in industries. After incineration, the resultant ash can also be used for road pavements, ceramics as fine aggregate, or landfilling [342]. Several countries in Europe such as Switzerland, Austria, Belgium, and Denmark, to name a few, have banned landfilling. In these countries, landfills receive only 5% of plastic waste, and the remainder is sent for either material recovery via recycling or energy recovery via incineration [322].

### *6.5. Recycling*

With the growth of plastic production, recycling in recent years has gained much-needed attention. The recyclability of plastic products depends on various factors such as additives and the presence of impurities [343]. Gourmelon [331]) reported that only 9% of plastics were recycled in the United States in 2012, and it stands at 8.7% as of 2018, inferring difficulty in recycling despite development in management techniques [323]. Globally, only 10% of plastic wastes are recycled, whereas in India, 60% of the plastics recovered from wastes are recyclable [340,344]. In order to tackle the issue of plastic waste recycling, the United States is shifting its focus to recycling PET and HDPE bottles and jars, which are considered more significant than the other types due to their demand and recyclability [323]. The recycling of PET and HDPE bottles and jars stands at 29.1% and 29.3% respectively in 2018 [323]. Plastics Europe reports that around 75.1% of plastic wastes collected from the waste collection points in Europe were recovered through recycling (accounting for 42.6%) and energy (accounting for the remaining 32.5%) [14]. Sources of MPs and NPs, such as tires, are difficult to recycle due to the diverse composition of raw materials and highly complex structures. CE can present solutions, as tires can be reused by retreating. After grinding, particles can become a raw material source for valuable polymer composites or can be used as a filler for mortar in construction activities. It can be used as a fuel at its end of life and has a comparable calorific value to that of coal [14,318].

For bio-based plastics, composting and anaerobic digestion are the most common waste management techniques. Bio-polymers plastics are produced from renewable materials such as sugarcane, corn, hemp, and soy. Some bio-polymer plastics are produced using petrol, making them non-biodegradable or compostable. For such bio-based plastics, chemical recycling, waste-to-energy (WTE/incineration), biological and thermochemical conversion for fuel, and chemical production are the most common waste management techniques [345]. Bio-based plastics have low environmental impacts, as they can save emissions equivalent to 241–316 million tons of carbon dioxide annually; however, further life cycle assessment is required for analyzing the positive and negative impacts [346–348]. Blanc et al. [349] estimated the LCA of bioplastics and observed that bioplastics have less global warming potential and non-renewable energy use, 12% and 30%, respectively than conventional plastics. In life-cycle costing, the cradle-to-grave cost for bioplastics is slightly more than (nearly 11%) traditional plastics. Therefore, the cost for bio-polymeric plastics, i.e., bio-based plastics, is higher than that of traditional ones.

Recent works have reported the degradation of polymeric plastics using the microbial approach [350–353]. Sourkouni et al. [354] proposed that the activated oxidation process and biotechnology can boost the circular economy for plastics, in which bacteria and enzymes can digest plastics. During the process of end-of-life waste management, plastic wastes are discharged into the environment accidentally due to human error, transportation, and runoff. The ocean usually is the most common point of accidental discharge. According to Steensgaard et al. [322], 23,150 tons of plastic debris was found in the Mediterranean Sea. According to a study by Sundt et al. [331] in the EU, 8% of plastic bags are accidentally discharged into the ocean, with PE found to be a major (79%) plastic in the marine litter [355]. Therefore, in circular economy, Sheldon and Norton [346] proposed calls for reformation in CE from linear economy to a greener circular model to reduce carbon dioxide emissions and their leakage into the environment. Green chemistry can redesign the plastics value chain in plastics production to recycling and end-of-life via widening rules and incentives intervention. Nikolaivits et al. [356] summarized mechano-biocatalytic perspectives for the valorization of plastic wastes. The depolymerization of plastics can produce new products, instead of waste disposal, with high product value, having effectively combined interdisciplinary approaches for the end-of-life in circular economy. As global plastic production increases gradually, LCA and CE can be implemented to reduce plastics ending up in landfills or for that matter reaching the 'end-of-life'. The linear economy model continued from the industrial revolution, where products become waste at the end of life is unsustainable and poses challenges such as depleting resources and increasing emissions [357]. Therefore, CE is seen as an alternative to the linear economy model and is already promoted by several nations such as Japan, China, UK, France, Canada, the Netherlands, Sweden, and Finland. China is also the first country to adopt circular economy in 2008 to save energy, reduce emissions, and contribute to the three dimensions of sustainable development. Therefore, CE can be seen as a win-win solution [358]. For plastics, CE can be used as a solution to minimize the MPs and NPs exposure, as it replaces the 'end-of-life' situations of plastic by using the 5R principles of waste management; therefore, it reduces MPs and NPs, due to the degradation of larger plastic items [318]. The green economy approach should provide eco-friendly alternatives and substitutions for single-use plastics to reduce carbon dioxide emissions and leakage in the environment. Green chemistry eliminates wastes and toxic chemicals from plastics and stimulates the transition from linear plastic disposal economy to sustainable circular economy [346].

## 7. Knowledge Gaps, Future Scope, and Recommendations

A drastic increase in the presence of MPs across the globe will create a problem for overall ecosystems including animal and human health. MPs can harm the habitat of microbes and environmental processes in an aquatic environment [359]. Methods for the identification or monitoring of MPs in the environment, water, food, and cosmetics should be carried out, which would help in the policy making of rules and regulations [360]. Most fish intentionally and unintentionally ingest MPs that also ultimately reach the human body, which raises food security concerns globally and will lead to food shortages and the degradation of aquatic ecosystems [304,361]. Other important aspects are environmental degradation and climate change. The presence of plastics and the small degraded particles in the environment encourages droughts that induce global warming due to carbon emission [362]. Limited studies have been conducted on all types of plastics and plastic products. PET and HDPE have received most of the attention; among them, plastic bags and bottles are the most studied products. The unavailability of detailed information and data on each component of LCA, such as plastic production, use, waste, recycling, and energy recovery, for countries other than the EU and the United States is a concern. Considering that all plastics ever produced are either in use or in waste form, it is important to pay great attention to material and energy recovery. In 2018, the United States was able to recycle only 29.1% of PET bottles and 29.3% of HDPE natural bottles [323]. Being one of the leading plastic manufacturing nations, it is important to invest in the recovery of material.

Plastic microbeads in personal care products and single-use plastics should be banned completely with exceptions for medical use and perishable food items [14,345]. Therefore, the paradigm shift in concept product design must change from "cradle to grave" to "cradle to cradle" [363]. Corporations should be made accountable for the waste produced through EPR (Extended Producers' Responsibility) taxations, which shall be used to subsidize products made from high recycled waste [317].

At present, there is a need for strict laws and policies as well as a greater focus on the implementation of levies, taxes, laws, and policies to minimize the use of plastics at the local, national, and international levels. Strict laws and rules must be made and implemented. For the management of marine debris, effective development in policy is needed through the intervention of international conventions, and decision makers should emphasize the mitigation of marine debris [364]. The following policy recommendations may be considered to prevent MPs and NPs pollution: (a) continuous monitoring and regulations for fish and inspection should be implemented for human health risk analysis; (b) the need to reduce cleaning costs and depredating environmental health and biodegradation, and (c) the need for further research on data collection of ecological damage and impacts on micro and nano plastics exposure.

There are many existing recommendations that are at different stages for the effective management and mitigation of plastic pollution. Some of the selected key recommendations include the following:

- Major challenges emerged for hazardous medical waste management during pandemics, such as regulation, technology, financial, and awareness related to plastics waste [337]. There is a need to develop agreements among stakeholders to ensure responsibilities, duties, and benefits in collaboration [365].
- Efforts should be put into limiting the landfilling and deposition of plastics debris in marine ecosystems. Heavy reliance on landfilling leads to the burning of waste to make room for more waste, which leads to environmental degradation [339]. Following the EU countries' initiatives [322], developing nations such as India should focus on material and energy recovery instead of landfilling.
- To achieve sustainability and action to combat climate change, the UN aims to minimize and address the impacts of ocean acidification, sustainably manage and protect marine and coastal ecosystems, and avoid significant adverse impacts by strengthening their resilience. Therefore, it is necessary to take initiatives for conserving ocean, sea, and marine resources around the globe.
- In the wake of plastic pollution and waste management challenges posed by plastic, more than 60 countries have imposed bans and levies to limit single-use plastic waste [345]. In the current situation, it is difficult to impose a complete ban on plastic products [341]; however, it is possible and important to ban single-use plastics and encourage alternatives to plastics. All countries need to pay attention to the bio-based biodegradable polymer as an alternative to plastic and impose bans and levies on other forms of plastics. The development and use of biodegradable plastic will reduce the plastic pollution in the aquatic ecosystem [366]. It is also important to promote the use of eco-packaging, which will reduce the use of plastics to a great extent [367].
- Landfill tax is profitable for all the landfill operators, as it incentivizes landfill operators and controllers to enact better diversion habits [368,369]. Therefore, an alternative could be EPR, which has emerged through the Green Dots program in Germany [360–372]. EPR helps encourage the producers to confront and handle the

cost of "end of life" disposal of the plastic products produced; hence, it provides incentives for producers to take account of these costs in designing their products [373–375].

- An implicit solution to solve the plastics pollution problem is through improved waste management systems and encouragement for low-income countries to adopt environmentally sound technologies from developed countries via the Clean Development Mechanism (CDM) of the Kyoto Protocol.
- Climate variables play an important role in determining whether households consume bottled water. Limited access to drinking water or untrustworthy water quality in different areas accelerates the consumption of bottled water and leads to plastic pollution, which has a strong link with climate change [376]. There is insufficient data regarding different types of plastic polymer and their ability to pollute or damage marine ecosystems. Legal consideration of handling plastic waste in terms of production and consumption requires comprehensive investigations at an international scale, which is also an important aspect that must be considered [377].
- Public awareness can be an alternative approach to avoid single-use plastics, and thereby, formal and informal training may largely impact the recycling and life cycle assessment of non-biodegradable and biodegradable plastics. Engaging citizens and using citizen sciences and social awareness programs to fight against plastic pollution will be critical to minimize plastic use and recycling.
- The distribution and concentration of micro and nano plastics need regular monitoring, which can be justified by the potential socio-economic causes/losses/costs resulting from the risks that plastics pose [378].

## 8. Summary and Conclusions

Plastic pollution has become inevitable for human civilization in the Anthropocene era. Plastics production is increasing dramatically, and the negative impacts on our ecosystem are also increasing mainly via micro- and nano-sized plastics. Both types of plastics are having significant negative impacts on the ecological functions of natural habitats. Plastic pollution is interlinked with the SDGs and climate change. Despite the existing knowledge about the impacts of plastic pollution, plastic waste management is at a dismal level, especially in developing countries. For example, open burning, unscientific landfilling, and disposal in the natural environment, including incineration, are largely prevalent, which is a health hazard to several lifeforms. Our review provides a comprehensive overview of the ecological, environmental, socio-economic costs, including linkages to climate change and SDGs, in the context of plastic pollution and plastic waste management. Although, plastics waste management and subsequent policy interventions exist in major countries and cities around the world, they are yet to be strictly enforced or implemented. Therefore, a summary of various policy recommendations is provided based on current knowledge gaps, use of circular economy, LCA, and sustainability approaches. There is an urgent need to use the principles of circularity in plastic waste management and change from the current linear model to a circular model with chemical or physical recycling. Since plastic pollution is ubiquitous, it needs to be treated as a global threat similar to climate change, COVID-19, and other pandemics. The SDGs were developed to deal collectively with key global issues; therefore, they provide a global platform and they should properly address plastics pollution and its management to support other top priorities such as food security, human health, and sustainable economic growth promotion. Issues related to plastics are directly or indirectly linked and affecting global goals to achieve SDGs targets. There is need to develop clear mechanisms to address plastic issues for better monitoring, innovations, technology transfer, and collaboration between organizations and citizen science to take collective action. Research and innovation should be encouraged to reduce, reuse, recycle, and recover plastics and find eco-friendly replacements for plastics, and alternative solutions must be emphasized. In addition, empowering and educating communities and citizens to act collectively to minimize plastic pollution and use alternatives options for plastics must be proactively promoted and enforced.

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