Are microplastics destabilizing the global network of terrestrial and aquatic ecosystem services?

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Abstract

Plastic has created a new man-made ecosystem called plastisphere. The plastic pieces including microplastics (MPs) and nanoplastics (NPs) have emerged as a global concern due to their omnipresence in ecosystems and their ability to interact with the biological systems. Nevertheless, the long-term impacts of MPs on biotic and abiotic resources are not completely understood, and existing evidence suggests that MPs are hazardous to various keystones species of the global biomes. MP-contaminated ecosystems show reduced floral and faunal biomass, productivity, nitrogen cycling, oxygen-generation and carbon sequestration, suggesting that MPs have already started affecting ecological biomes. However, not much is known about the influence of MPs towards the ecosystem services (ESs) cascade and its correlation with the biodiversity loss. MPs are perceived as a menace to the global ecosystems, but their possible impacts on the provisional, regulatory, and socio-economic ESs have not been extensively studied. This review investigates not only the potentiality of MPs to perturb the functioning of terrestrial and aquatic biomes, but also the associated social, ecological and economic repercussions. The possible long-term fluxes in the ES network of terrestrial and aquatic niches are also discussed.

Keywords: Microplastics; Plastisphere; Ecosystem Services; Green/Blue Economy; Biodiversity

Abbreviation

Bis(2-Ethylhexyl) Phthalate	DEHP
Bisphenol A	BPA
Contaminants of emerging Arctic concern	CEACs
Dichloro-Diphenyl-Trichloroethane	DDT
Ecosystem services	ESs
Ecosystem services value	ESV
Green gross domestic product	gGDP
High-density polyethylene	HDPE
Low-density polyethylene	LDPE
Micro-Fourier Transform Infrared spectroscopy	μ-FTIR
Microplastics	MPs
Nanoplastics	NPs
PerFluoro-Octanoic Acid	PFOA
Persistent Organic Pollutants	POPs
Polybutadiene	PBD
Polycarbonate	PC
Polyethylene	PE
Polyethylene terephthalate	PET
Polylactic acid	PLA
Polymethyl methacrylate	PMMA
Polypropylene	PP
Polysiloxane	PSX
Polystyrene	PS
Polyurethane	PU
Polyvinyl chloride	PVC

Visible near Infrared	Vis-NIR

1. Introduction

Plastics find applications in all industries and could remain in the environment for centuries as the most prevalent type of debris in the land and oceans (Brahney et al. 2020; Henry et al., 2019). The magnitude of contamination in the oceans is increasing drastically with wide socio-economic and environmental impacts, making the scientific communities refer to this current period as "Plasticene", where the ocean has become a plastic soup (Reed, 2015). MPs (<5 mm), either formed by the breakdown of macro/meso-plastics (i.e., secondary MPs) or designed as such (primary microbeads), pose a serious threat to the environment (Camins et al., 2020). These MPs are not fixed entities, but undergo further disintegration and change over time, which make them dynamic in size, contribution, prevalence, and distribution. Gradually humans have created a plastic ecosystem (plastisphere) along the coasts (Amaral-Zettler et al., 2020; Pietrelli et al., 2017), where polyethylene terephthalate (PET), polypropylene (PP), polyethylene (PE), and microfibers are the most commonly recognized (Iñiguez et al., 2018). The continuous rise in the utility of plastics has led to a steady increase in the loading of MPs in marine (Huang et al. 2020b; Barboza et al. 2018), lentic (Pippo et al. 2020; Lechner et al. 2014), lotic (Crew et al., 2020; He et al. 2020), terrestrial (Rillig and Lehmann, 2020; Boots et al. 2019), and anthropogenic (Malizia and Monmany-Garzia, 2019) ecosystems. The omnipresence of MPs has emerged as an issue of global concern due to their long-term persistence in ecosystems (Ma et al., 2020; Zhang et al., 2018b). MPs have been recognized as a common contaminant in water bodies (Camins et al., 2020; Kumar et al., 2020a) and terrestrial ecosystems (Rillig and Lehmann, 2020; Kumar et al., 2020b). Also, MPs pollution have been recently found in the pristine polar ecosystems (González-Pleiter et al., 2020; Ostle et al., 2019; Routti et al., 2019). The alarming levels of MPs (16-766 particles m^{-2}) in the Antarctic marine sediments are comparable with the global marine estimates (Reed et al., 2018). MPs are considered as the contaminants of emerging Arctic concern (CEACs) along with mercury and other persistent organic pollutants (POPs) (Routti et al., 2019). MPs can be hazardous to the prevailing environment either directly (e.g., via ingestion, food chain, and biomagnification) or indirectly (e.g., additives and adsorption/release of co-pollutants) (Kumar et al., 2020a).

The fate and existence of MPs in natural ecosystems have been reviewed extensively (Kumar et al., 2020a; Kumar et al., 2020b; Xu et al., 2020; Wu et al., 2019b) and abundance and distribution of MPs in marine/costal environment were also widely explored (Aslam et al., 2020; Gallo et al. 2018; Kane and Clark, 2019; Wu et al. 2019). Highly polluted beaches have been shown to contain 3.3% of the sediments (0-25cm depth) by weight as MPs (Lee et al., 2013; Carson et al., 2011). The fresh water ecosystem is also considered as possible sink of MPs (Wagner and Lambert, 2018; Strungaru et al., 2019; Prokić et al., 2019). Sources, types, sizes, and concentrations of MPs in an environment are associated with local human activities. For instance, the distribution patterns of MPs along the Gulf of Mannar coast, India (Vidyasakar et al., 2018), Huatulco Bay, Mexico (Retama et al., 2016), and the Bohai Sea, China (Yu et al., 2016) were inferred to be majorly influenced by tourism and local fishing.

The existing studies on MPs dealt with sources (He et al., 2019), fate and distribution (He et al., 2020; Wu et al., 2019b), impacts (Li et al., 2020a), human health concerns (Barboza et al., 2018, 2020), ecotoxicity (Ma et al., 2020), and degradation (Veerasingam et al., 2016b). Early research on environmental implications (from 2010) focused on bioaccumulation, biomagnification, and other ecotoxicological effects of MPs, but their deleterious impacts are becoming more apparent only through recent research (Ma et al., 2020; Long et al., 2015). Earlier studies focused mainly on the fate and effects of MPs in the aquatic environment whereas their occurrence in the terrestrial environment received comparatively limited attention (Malizia and Monmany-Garzia, 2019; Zhang et al., 2018b). However, MPs in aquatic ecosystems often have a terrestrial origin (Kumar et al., 2020b). Land-based sources include overland run-off, sediment transfer, and soil erosion (Cole et al., 2016). The increase in MPs abundance in ecosystems leads to an increase in their bioavailability for ingestion by aquatic, terrestrial, and avian species, thus increasing their potential to become part of the food chain (Jin et al., 2018). For instance, zooplanktons, which are a crucial food source for a wide range of secondary consumers (from small fish/crustaceans to huge whales), can readily ingest MPs (Almeda et al., 2020; Cole et al., 2016). Various studies reveal that ingestion of MPs can reduce the feeding and energy reserves of the organisms due to their long gut residence times, resulting in inflammation and physiological damage (Jin et al., 2018) (**Table 1**).

MPs, due to their hydrophobic surface, may adsorb or absorb various co-pollutants from environments (Bradney et al., 2019). PE, PP, and polystyrene (PS) adsorb environmental contaminants through generally hydrophobic and bond interactions (Li et al., 2020b; Wu et al., 2019a). Also, the high surface area of MPs, which can be improved via weathering, not only assists adsorption of pollutants but also helps in its chemical transportation via leaching (Bradney et al., 2019). However, despite the large number of studies exploring the adsorption/absorption mechanisms (Lee et al., 2021), the knowledge about the effectiveness and overall implications remain limited. In addition to containing other chemicals (e.g., additives and plasticizers) (Wu et al., 2019a) introduced during polymerization, extrusion, moulding, and spooling from process industries (Gallo et al., 2018), MPs also absorb and desorb high concentrations of organic/inorganic pollutants from the surrounding environment, causing their bioaccumulation in ecosystems (Yu et al., 2020; Godoy et al., 2019; Rodríguez-Seijo et al., 2018). For instance, polyvinyl chloride (PVC) and PE MPs (200-250µm) can accumulate persistent organic pollutants (POPs) like Dichloro-Diphenyl-Trichloroethane (DDT), Bis(2-Ethylhexyl) Phthalate (DEHP), PerFluoro-Octanoic Acid (PFOA) and Phenanthrene (Kumar et al., 2020a; Bakir et al., 2013). PE (virgin, water/soil/air-exposed) MPs (75-140µm) can adsorb and desorb antibiotics (tetracycline) along with copper (Cu(II)) (Wang et al., 2021). Sheng et al. (2021) observed enhanced accumulation of triclosan in the tissues of *Danio rerio* (zebrafish) in presence of PE, PP, and PVC (Polyvinyl chloride) MPs (≤15μm), leading to upregulation of vital metabolic pathways. Many studies explored the ecotoxicological impacts associated with MPs polymers/additives (**Table 1**) and advocated their effects on the functioning of biomes (Huang et al., 2021; Nava and Leoni, 2021), but more long-term impact assessment studies at large spatial scales are needed to link MPs with the global biodiversity loss.

On account of the alarming levels, regardless of the environmental risk, efforts must be taken globally to manage plastic waste, for they can easily hinder ecological functioning (Green et al., 2017). As the available literature suggests that MPs impair the normal growth, reproduction, and survival of various species, it can be inferred the service functions of the species, niche, and subsequently ecosystem are also adversely affected, impacting the global biodiversity (Hu et al., 2019a). However, much more implications remain unknown. There is still a long way to go and understand the impacts of MPs at the habitat level and correlate the possible links between the global ecosystem degradation and biodiversity.

The fluxes induced by MPs in the ecosystem functioning need to be quantified. All the effectively functioning ecosystems across the world (global ecosystem) contribute innumerable direct or indirect socio-economic and environmental benefits to humans (Ziter et al., 2017; Costanza et al., 2014), collectively termed as ESs. The global habitats and biodiversity are essential capital assets for providing food, water and air, livelihood, environmental sustainability, recreation, cultural, social and spiritual values, etc (Sylla et al. 2020). Understanding the importance of ESs and the possible impacts from the contaminants of emerging concern is crucial to bridge the gap between environmental conservation and sustainable development.

No review to date exists to critically examine whether MPs can independently impact the flow, and delivery of the aquatic and terrestrial ESs. Cauwenberghe et al. (2015) focused on the sediments and highlighted the uptake and impacts on the marine organisms like demersal fish, echinoderms, bivalves, crustaceans, and polychaetes. Anbumani and Kakkar (2018) focused on the ecotoxicity on the marine and freshwater biota and discussed the associated implications at producer (autotrophs) and consumer (heterotrophs) levels. Yao et al. (2019) explored the biological implications for the sediment dwellers and highlighted the lack of studies (lab/field) using realistic experimental concentrations. Recently, Prata et al. (2021) gave a perspective related to MPs pollution and their impacts on organisms, populations, and processes, and highlighted the need for transdisciplinary research. Hu et al. (2019a) focused on the biodiversity and concluded that MPs and NPs cannot significantly influence global biodiversity change, but would lead to an obvious reduction in the ecological services. However, none of them addresses the impacts of MPs on the ESs. Oliveira et al. (2019) was the first to highlight the implications of MPs with respect to the ESs by insects, where they briefly discussed the behavior of different groups of insect populations in response to MPs/NPs. The review did not address the possibility of impacts on the overall ESs and economy as they only discussed the biological impacts on a very limited number of insect species. The present work critically reviews whether the existing levels of MP pollution can destabilize the global network of ESs (terrestrial and aquatic) and the associated economic and social benefits. To estimate the magnitude of impacts caused by MPs in the ESs network, their accumulation, and transportation in the environment need to be understood, which are critically emphasized in this work. The present paper systematically reviews the available literature on the occurrence, distribution, and qualitative/quantitative impacts on various species of ecological significance, and critically infers them in terms of the associated ESs.

2. MPs in terrestrial ecosystems and its impacts

Soil ecosystems play an important role in the natural nutrient cycles, and form the basis for human food production, and thus, the management of productive terrestrial ES and natural capital becomes obligatory. Soils receive high loads of plastics from diverse sources including soil compost, biosolids, effluent irrigation, and plastic mulching (Zang et al., 2020; Ziajahromi et al., 2020). A case study in Chile proposed that successive biosolids applications were an important source for soil MP (mainly fibers) accumulation, with possible plastic remobilization away from fields (Corrradini et al., 2019a). Generally, plastics accumulate in the zones of high anthropogenic influence in the continental environments (agricultural, urban/peri-urban regions), especially in the developing countries with inefficient waste management practices (Malizia and Monmany-Garzia, 2019).

MP contamination on land could be 4-23 fold higher than that in the ocean, and hence, agricultural soils alone might contain more MPs than oceanic basins (Machado et al., 2017). The ubiquity of MPs in the terrestrial ecosystems, and the possible implications for soil organisms, make them a relevant, albeit unexplored factor in soil ecology (Bigalke and Filella, 2019). MPs in the soil can influence the structure, metabolism, and functioning of the soil microbiota, which may cause serious impacts on plant productivity (Zang et al., 2020). Regardless of the remark by Rillig (2012) that plastic pollution could be an important driver of global change during the 21st century, research in the terrestrial ecology paid limited attention to the inland plastic pollution until recent times. Research on soil plastics was relatively few in comparison with that on MPs in the aquatic ecosystems (Chae and An, 2018), mainly because of the analysis methods for soil MPs being tedious and unstandardized previously (Corradini et al., 2019b). More studies emerged after the development of reliable extraction methods (Zhang et al. 2018) and instrumentation tools like micro-Fourier Transform Infrared spectroscopy (μ-FTIR) and Visible- Near Infrared (Vis-NIR) spectroscopy for characterization (Corradini et al., 2019b).

Although MPs in the terrestrial environments have gained increasing attention in recent years, there is still plenty of knowledge gaps to be bridged (He et al., 2018; Zhang and Liu, 2018; Zhang et al., 2018b). It is uncertain if MPs/NPs are a potential carrier of pollutants in remote ecosystems. For instance, MPs that enter the polar (marine/snow) sediments by oceanic or atmospheric transport enter the polar terrestrial food chain. Routti et al. (2019) reviewed the fate and exposure of pollutants to the polar bears (*Ursus maritimus*), the terrestrial predators in the circumpolar Arctic region, and concluded that some known persistent organic compounds were the major pollutants, while MPs occurred only in traces; but it is still unclear whether these chemicals have been absorbed and carried through MPs/NPs. The difference in the distribution of MPs/NPs regarding various soil conditions and environments has not been systematically addressed. For instance, the occurrence of mesoplastics (5mm - 10mm) or MPs (mainly PE and PP) was reported in farmland soils of Shanghai (China), wherein the topsoil had higher concentrations and larger sizes of MPs than the deep soil (Liu et al., 2018). The study suggested plastic mulching and ploughing are important causes for the abundance and vertical transfer of MPs/NPs in agricultural soils, but the possible migration mechanisms were not elucidated. Lv et al. (2019) extracted MPs from water, soil, and aquatic animals of a rice-fish co-culture system in China, where the MP level was higher in the rice-planting soils than that in the aquaculture soils, suggesting the influence of bioturbation (reworking of aquatic sediments through burrowing, defecation, and ingestion by sediment dwellers) by aquaculture species (e.g., eel, crayfish, and loach) on transporting the MPs to the terrestrial agroecosystem. The study suggests predation as a potential reason for the secondary accumulation of MPs in rice-fish co-culture systems. Moreover, MP levels vary in different soils regarding different land-use systems, which needs to be explored further. For instance, Scheurer and Bigalke (2018) reported the presence of MPs in 90% of the floodplain catchment soils in Switzerland with the highest concentration as high as 0.5 mg kg^{-1}. The study emphasized the need to understand the plastic exchange with the atmosphere and hydrosphere, and the possible transfer mechanisms. Although recent studies focus on the bioaccumulation and impacts of terrestrial MPs, there are limited systematic studies on the existence of MPs in various conserved terrestrial systems (forests and nature reserves) distant from sources (microfibers in the air), particularly in correlation with the soil type (Malizia and Monmany-Garzia, 2019).

Unlike aquatic ecosystems, the role of MPs as vectors for bioaccumulating organic micropollutants has not been much studied in terrestrial ecosystems (Rillig, 2018). Yu et al. (2019) found that the red wriggler earthworm (*Eisenia fetida*) avoided pesticide-contaminated MPs in the media, while it was not clear whether the MPs can be pesticide carriers to the worms. Wang et al. (2019) claimed that *E. fetida* could ingest and excrete MPs (PE and PS) from agricultural soil, and oxidative stress occurred only at high concentrations (1% w/w). A study suggested that long-term exposure to nano-PS, at environmentally relevant concentrations (1 μg L^{-1}), could cause oxidative stress, and further, enhance the toxicity of TiO_2-nanoparticles (widely used as additives/pigments) on the terrestrial nematode *Caenorhabditis elegans* (Dong et al., 2018). Song et al. (2019) found that the terrestrial snails (*Achatina fulica*) consumed substantial concentrations of MP fibers (PET) from the soil, and prolonged MP exposure inhibited feeding and excretion, elevated oxidative stress, and damaged their gastrointestinal tracts. This suggested that MPs could adversely impact the health of soil organisms. A recent demonstration on the adsorption and phytotoxicity of NPs (≤1μm) and MPs on terrestrial vascular plant *Lepidium sativum*, suggested that plastic particulates got accumulated on the pores in seed capsule, and got adsorbed to the root hairs, and affected the germination rate and root growth of the plant (Bosker et al., 2019). Lahive et al. (2019) observed that, at high concentrations of nylon fibers (10.8%) in soils, there were reduced reproductive outputs in the terrestrial worm *Enchytraeus crypticus*, indicating a possible alteration in population dynamics upon prolonged exposure. MPs can also influence the sorption properties of soil for nutrients and contaminants. For instance, the presence of PE in soils may reduce their nutrient retention capacity and upsurge the mobility of organic contaminants in the vicinity (Hüffer et al., 2019). MPs in the soil surface can migrate to the deep soil, and further reach the ground water through alluvial aquifers (Goeppert and Goldscheider, 2021).

Soil fauna can also influence the migration and fate of MPs/NPs. A commonly found anecic earthworm, *Lumbricus terrestris*, can facilitate the biogenic transport of MPs from the soil surface into their burrows, and further increase the possibility of groundwater pollution and consequent uptake by other organisms (Yu et al., 2019; Lwanga et al., 2017), which leads to their migration into the deep soil (**Figure 1**). *Lobella sokamensis*, a noted springtail species, showed slower mobility in plastic-contaminated soils, while MP particles showed certain mobility patterns in soil pores, which were associated with the insect's behaviour and movement (Kim and An, 2019). The soil biota may enhance the movement of MPs down the soil profile through bio-pores or vertical and horizontal movement (Rillig et al., 2017). Current soil management practices (tillage) can transport MPs to greater depths, even when epigenic earthworms avoid plastic debris (Rodríguez-Seijo et al., 2018). A study on the MP accumulation in agricultural soils in a Chinese river valley suggested that the levels of MPs fluctuated with respect to the land use patterns, irrigation sources, and locations (Zhang et al., 2018b).

The plastics entering the soils, may either get transferred to aquatic systems through surface runoff or get retained in the terrestrial ecosystems (Lahive et al., 2019). Landfills and croplands filled with plastic mulches may become long-term sinks for MPs in the terrestrial environment (Lahive et al., 2019). Moreover, terrestrial MPs potentially pose higher risks to the global ecosystems and biogeochemical cycles than the aquatic MPs as they become a part of the soil carbon (90% of PE and PP is carbon) (Rillig, 2018). To accurately model the transport and fate of MPs in terrestrial environments, research must focus on the physical and chemical mechanisms governing their transportation and retention in soil vadose zones (O'Connor et al., 2019). The evolutionary implications concerning microbial adaptions in the dynamic soil environment should also be addressed (Rillig et al., 2018). For example, the impacts of MPs on the physical properties of different types of soil, and the consequent implications on the soil productivity, as well as the possible effects on the soil microbial communities and their bioremediation potential, remain unclarified (Rillig et al., 2019).

3. Transportation of MPs from terrestrial to the aquatic environment

The routes of MPs in the terrestrial ecosystem entering the aquatic ecosystem is shown in **Figure 1**. Municipalities in many developing countries do not follow appropriate methods for the treatment of plastic litter. Simple incineration of plastics releases carbon dioxide and other volatile organic compounds while dumping them in anaerobic landfills can leading to the leaching of Bisphenol A (BPA) and other toxic compounds into the groundwater (Barboza et al., 2020). MPs have been found in the leachates of active and closed landfills in China, suggesting that municipal landfills (He et al., 2019), which store 21 to 42% of the global plastic waste, are an important source of MPs (Murphy et al., 2016). Most MPs do not get filtered in the wastewater treatment plants, but the treatment processes affect their redistribution in biosolids and effluents (Jiang et al., 2020). Hu et al. (2019b) claimed that the conventional wastewater treatment processes might be effective in the removal of microbeads from cosmetics, but could not treat synthetic microfibres. Primary treatments (skimming and sludge settling) are the only major processes to retain plastic particles (Mason et al., 2016) in municipal wastewater treatment plants, which become a channel for the entry of MPs to waterways (Raju et al., 2018). The contaminated waterways can transport high loads of MPs to the ocean (Pan et al., 2020; Li et al., 2017).

Lebreton et al. (2017) developed a global model of annual plastic load (tons year^{-1}) getting emitted from rivers into oceans, calibrated against the measured plastic concentrations in the major rivers of Europe, Asia, North America, and South America. It indicated alarming input levels (1.15-2.41 Million tons year^{-1}) from the major rivers of the world and the twenty major rivers of Asia alone contributed to 67% of the global input. Boucher et al. (2019) estimated the mean annual loading of plastics input into Lake Geneva (Switzerland) through model and field studies as 49 tons year^{-1} and 59 tons year^{-1} respectively. Documentation of MPs accumulation in freshwater lakes started in 2013 when the surface litter of Laurentian Great Lakes (United State of America) (**Table 2**) showed striking resemblances to the microbeads found in selected personal care products, suggesting that those were primary MPs (Eriksen et al., 2013). River Danube in Europe was found to have plastic debris in high concentrations (mean abundance: 316.8 ± 4664.6 particles per 1000 m^{-3}), outnumbering the native fish larvae (Lechner et al. 2014). However, Steer et al. (2017) identified microfibers from fish larvae in the western English Channel (United Kingdom) and observed an ingestion in 2.9% of the sampled population. To date, there are fewer studies on the MPs occurrence in freshwater as compared to the marine ecosystem (Li et al., 2020c; Mendoza and Balcer, 2019), leading to poor knowledge on their prevalence, concentrations, and fate in the fresh water ecosystems (Li et al., 2017; Dris et al., 2015). The occurrence and impacts of MPs in lakes/estuaries that serve as the water and food source are critical issues, which are yet to be addressed, particularly in developing countries (Sruthy and Ramasamy, 2017).

The discharged MPs that eventually get into the oceans either float (density <1g cc^{-1}) or sink (density >1g cc^{-1}). Ultimately the oceanic currents and other abiotic factors act upon and accumulate the floating MPs in gyres (Lebreton et al., 2019). The polar coasts become the dead ends for such floating plastics, making them abundant and widespread in the northernmost and southernmost regions (Cózar et al., 2017). The MP particles in the global beach sediments have been found to occur in a wide range of sizes (<20 µm to 5mm), whereas MPs in the water surface are generally smaller (0.35 mm to 2 mm). Their sizes further decrease in the subsurface (average depth: 6m) and deep-sea environments (**Figure 2**) due to further disintegration by surface transport and ocean currents (Lusher et al., 2015). It was estimated that globally around 93 to 268 kilotons of MPs are floating on the ocean surface (Everaert et al., 2020). Findings have perceived that the concentrations of MPs on the ocean surface could be lower than expected, suggesting the existence of potential sinks such as sediments (Beaumont et al., 2019). The shores become another sink for these floating polymers (low density), that accumulate in remote locations, as a result of the long-range global ocean transport (Imhof et al., 2017). The sinking polymers (high density) get transported by the benthic fauna to the sediments (Coppock et al., 2021), larvaceans (Katija et al., 2017), planktons and bivalves (Bonello et al., 2021), etc., and accumulate on the ocean floor, therefore the deep sea becomes their major sink (Kvale et al. 2020). They further get ingested by the benthic invertebrates (Iliff et al., 2020; Seltenrich, 2015) or get transported by adherence to the filter-feeders (Gonçalves et al., 2019; Nelms et al., 2019) and ultimately enter the food web. The availability and impacts of MPs on benthic ecosystems need to be explored in near future (Iliff et al., 2020; Coppock et al., 2017).

The major materials of MPs identified in previous studies (Patchaiyappan et al. 2020; Schmidt et al. 2018; Imhof et al. 2017; Bouwman et al. 2016; Veerasingam et al. 2016a; Veerasingam et al. 2016b) were PE, PP, PS, microfibers, polyurethane (PU), polysiloxane (PSX), polybutadiene (PBD), and polymethyl methacrylate (PMMA). The issues of MPs accumulation in water bodies, and the corresponding implications for ocean sustainability have been studied for over a decade (Rillig, 2018), but understanding the fate, accumulation, and impacts of MPs in terrestrial ecosystems is the key to address their routes of transfer to aquatic ecosystem.

4. MPs accumulation and its impact on aquatic ecosystems

MPs have been detected in species living in the aquatic biomes, in the surface, sediments, and pelagic zones. MP distribution in the aquatic ecosystem is influenced by various abiotic/physical forces like water currents, wind, etc (Iwasaki et al., 2017). Generally, the floating plastics appear unevenly distributed. Large amounts of MPs may be assimilated by aquatic organisms, making the inherent and absorbed toxic chemicals pass into the food chain (Beaumont et al., 2019; Seltenrich, 2015). The ingested particles reduce the appetite and actual food intake of aquatic organisms, making them either starve to death or egest the plastics through faeces (Banaee et al., 2020). MPs get excreted in the form of feeders' faecal pellets which have different density and sinking rates, affecting their transfer to coprophagous biota (Cole et al., 2016). MPs could be further consumed by suspension feeders and detritivores. A mangrove polychaete worm, *Perinereis aibuhitensis*, showed a reduced posterior-segment regeneration rate in the presence of MPs in its feeding medium, and the effect increased with increasing concentration and decreasing size of MPs (Leung and chan, 2018). Even phytoplankton aggregates become a potential MP sink (Shiu et al., 2020; Long et al., 2015). High-density polyethylene (HDPE) and PVC leachates could vitiate the in-vitro growth and photosynthesis of two different strains of *Prochlorococcus*, the primary producers that play important role in the marine carbon cycle (Tetu et al., 2019). It is worth exploring the possible overlap between the previously known hazardous organic pollutants, to which *Prochlorococcus* is sensitive, and the chemicals found in the MP leachates.

MPs can potentially interfere with the growth and photosynthesis of microalgae (Wu et al., 2020; Sjollema et al., 2016). Filter feeders, such as the endangered Baleen whales are readily being exposed to macro-litter (>10mm) ingestion, which makes them potential indicators of the abundance of MPs in the pelagic environment (Zantis et al., 2020; Fossi et al., 2012). Interaction of MPs with aquatic biota makes them a potential pollutant in seafood (Saha et al., 2021; Smith et al., 2018). MPs have been found in aquafarms, where fishes and molluscs are cultured for human consumption (Zhang et al., 2020b; Rochman et al., 2015). This not just of health concerns, but implies its potential influence on the service of food provision by the marine ecosystems. Though there is a lack of robust evidence for MP-induced health effects on humans, existence of MPs/NPs in commercially important fauna needs in-depth investigation. It should also be noted that the ingestion and impacts are exposure- and species-specific, and some studies do not observe any significant impact of MPs on biota (Suckling, 2021). Therefore, it is important to evaluate the impacts on different taxa, at various degrees of exposure, to understand the realistic implications on biomagnification through the food chain.

Besides accumulating in the food chain, MPs also help in transporting invasive epifauna/microbes to new regions. Floating marine debris becomes a mobile home to various colonizing fauna like hydroids, bryozoans, barnacles, molluscs, and polychaete worms, which creates a huge ecological imbalance (Yang et al., 2020). Pickett et al. (2019) observed that filamentous fungi can attach and grow on the environmentally exposed (6-12 months) weathering plastic surfaces (e.g., PS, polycarbonate (PC), and polyester) more firmly than to the automotive paint (where firm growth appeared only after 12-18 months). MPs floating on the ocean surface may support the growth of alien invasive microflora, faunal, and microbes.

When washed ashore, MPs can alter the temperature and composition of beach sand. When exposed to sunlight, MPs (especially the dark pigmented ones) can retain large amounts of heat, even in a moderate climate, leading to the warming of the beach environment. Carson et al. (2011) reported an increase in the beach sand permeability, and thermal insulation of shore sediments caused by PE fragments, suggesting non-negligible changes in the heat transfer through sand. The heat transfer study was conducted under controlled conditions, and no datum is available at varied environmental/field conditions. Anyway, this potential warming effect may make MPs a persistent menace to the beach fauna, particularly the nesting sea turtles

(Nelms et al., 2016). High concentrations of MPs get accumulated in dunes, where most of the marine turtles tend to nest (Beckwith and Fuentes, 2018). The heat retained in the nesting grounds (only at very high concentrations) can significantly influence their life-cycle parameters by altering sensitive incubation environments, thus reducing the hatching success rates of their eggs (Duncan et al., 2018). Moreover, the sex determination of turtle eggs is temperature dependent, i.e. eggs incubated at lower temperatures (~24-29.5 ºC) become males and higher temperatures (~29.5-34 ºC) become females (Carter et al., 2018). The heat retained by these MPs may bias the sex ratio, as most of the incubating eggs may develop into females, jeopardizing the future reproductive success, e.g., the endangered olive ridleys along the Bay of Bengal coasts. However, the fact that there is limited in situ evidence of MPs impacting the temperature and heat transfer in the prevailing microhabitat must not be neglected. Though MPs/NPs tend to sink fast in sands, high concentrations of MPs (mainly polymers of low relative density) have been reported in the top sediment cores (Lee et al., 2013). For instance, Carson et al. (2011) observed that 95% of the plastic particulates (mainly PE) in the Kamilo beach (Hawaii) sand accumulated in the top 15 cm of the sediment cores, suggesting a significant exposure to beach fauna. Though MPs are perceived to be impacting the marine ecosystems, not much is known about their possible impacts on the ESs offered (Pauna et al., 2019). The ocean is an essential sink for about 24% of anthropogenic carbon emissions (Macovei et al., 2020). If aquatic ecosystems degrade, the major carbon sinks of this planet will malfunction, and thus, crucial stages of biogeochemical cycles will get perturbed. It is well known that MPs impact the functioning of the habitats, but the extent to which they impact the services provided by the ecosystems is still unknown.

5. MPs in the ESs Chain

Quantification and mapping of ESs are obligatory to assess the associated impacts, risks, and trade-offs in the network due to environmental degradation and climate change (Redhead et al., 2018). The conventional methodologies for ES assessment do not address the complex, multi-scale dynamics integrated with ES provision, flow, and delivery (Liu et al., 2020). Empirical field studies in rural Indonesian forests on the complex interactions and the mediating mechanisms of ESs suggested that their flow and delivery are influenced by multiple crucial elements (e.g., human interactions, accessibility, infrastructure, policy), highlighting the necessity of interdisciplinary assessment (Fedele et al., 2017). This conclusion was supported by Potschin-Young et al. (2018), who suggested the need to build a conceptual framework to better understand the complications concerning ES. Therefore, human interventions play a pivotal role in the delivery of ESs and benefits (Culhane et al., 2019).

Marine (>97% of aquatic biome) and freshwater (<3% of aquatic biome) ecosystems provide an array of services, which are crucial for the Earth's sustenance (**Table 3**). A small imbalance in the aquatic nutrient flow can pave the way to a serious perturbation in the global biogeochemical cycles. By persisting and interfering in the functioning of aquatic ecosystems, MPs destabilize the provisional, regulatory, supportive as well as cultural services of the aquatic ecosystem network, which make up more than 70% of Earth's ecosystems. Coastal shelves, one of the most economically and ecologically productive ecosystems on Earth, observe high loads of MPs (271 ± 230 MPs/kg DW) (Carretero et al., 2020), which suggests a high probability of them interacting with the biota (Steer et al., 2017). It is crucial to explore such complex interactions to understand the impacts on the ES network.

MPs debris, which has already become part of the food chain and biological systems, is a potential but overlooked mediator in the ES cascade (**Figure 3**). The cyclic flow of energy and matter is mandatory for the functioning of any ecosystem. An ecosystem functions only when the food chains and natural biogeochemical cycles are balanced (Martino et al., 2019). As MPs can cause an imbalance in the natural nutrient flow cycles, they can also destabilize the ES flow and delivery (**Figure 3**). It is evident that MPs pervade aquatic food webs, and hence inferred as a potential threat facing the aquatic flora and fauna (Hu et al., 2019a), and plastic pollution is acknowledged as a factor in the global biodiversity loss (Barnes, 2019). Mesoplastics (PE and PET) can intervene in the inter-specific chemical communications which are crucial in the natural predator-prey interactions (Trotter et al., 2019), but whether MPs adsorb chemical messengers (like kairomones) needs to be explored. MPs are linked to general plastic (macro/meso-plastic) pollution, but the same effects observed in macroplastics cannot be directly attributed to MPs/NPs. Some studies recommend that MPs are hazardous to the terrestrial and aquatic fauna (e.g., **Table 1** and **Table 4**). In the terrestrial environment, research on MPs has been rapidly expanding from species to mesocosm studies but has not focused at the ecosystem level yet (Rillig and Lehmann, 2020). It is not evaluated whether MPs alone could disturb the overall global biodiversity to a significant extent, but these particles have already become pervasive enough to lessen the efficiency of ecological functions and services (Hu et al., 2019a; Hu et al., 2019b). The services offered by any ecosystem can be classified into provisioning, regulating, supporting, and cultural benefits (Sylla et al., 2020) (**Table 3**).

5.1 Provisional Services

Provisioning services of an ecosystem mainly include the production of food, products, and biomass (Sylla et al., 2020). MPs occur in all the natural consumable goods including potable water (Koelmans et al., 2019), vegetables and fruits (Conti et al., 2020), edible animals (Huang et al., 2020a; Kedzierski et al., 2020; Lv et al., 2019), seafood (Smith et al., 2018), salt (Selvam et al., 2020) and honey (Oliveira et al., 2019). As MPs are abundantly found in the coastal shelves (Carretero et al., 2020), they can potentially impact aquaculture, fisheries, seaweed farming, oyster/pearl, and coral farming. Synthetic ghost fishing nets/gears (made of PP, PE, nylon) (Deshpande et al., 2020) and other plastic particles in water bodies accumulate in fishing nets and influence the catch. For instance, 86% of fishing vessels in Scotland were littered with small plastic debris, incurring an average loss of 12.8–14.2 million USD per year

(Arabi and Nahman, 2020). The study inferred the abandoned synthetic fishing gears/nets as a potential source of MPs pollution. MPs have been found in the natural freshwater and marine water (Mediterranean region) of Ebro delta in Spain (Simon-Sánchez et al., 2019). Even though the levels were in ppt (parts per trillion), their significance cannot be underestimated as the area of study (Ebro delta) was an important agricultural zone (Schirinzi et al., 2019). There are many studies that document the presence of MPs/NPs from the species used for human consumption. Collard et al. (2018) established the presence of anthropogenic particles in the stomachs and livers of 60 members of the edible freshwater fish *Squalius cephalus* from the Marne and Seine Rivers in France. In the Southern Wales catchment (a commercial fishing zone in the United Kingdom), all the macroinvertebrates analyzed so far (Heptageniidae, Baetidae, Hydropsychidae) have been found to contain MPs within them (Windsor et al., 2019), which indirectly suggests MP ingestion by species of commercial importance. Parker et al. (2021) reviewed the occurrence of MPs in the freshwater fishes (*Tilapia sparrmanii,* Cichlidae, shrimps, minnows, Cyprinidae, etc.) and highlighted the evidence of active (feeding, gills, epidermis) and passive (swimming, respiration) uptake. Thiele et al. (2021) identified high concentrations (123.9 ± 16.5 items kg^{-1}) of MPs (<1 mm) from commercial processed fish-meal which are extensively used for marine aquaculture, and the commercial (edible) fish tissues (assessed nearly 56 species), highlighting an interesting source of direct exposure for human consumption. The study highlights the potential consequences on the fisheries and seafood, with direct impacts on the quality of provisional ESs. Moreover, MPs (<100 μm) have been separated from commercial sea salt farms in Tuticorin, India (Selvam et al., 2020), suggesting a direct human exposure, with implications for the provisional ESs. It is inferred that humans already ingest plastic (mainly MPs, additives) in their everyday life (Senathirajah et al., 2021), but there is a gap in understanding how much this truly affects human health. Nevertheless, plastic particulates (MPs/NPs) are known to have deleterious impacts on various keystone species of flora and fauna (**Table 1**), and hence, may have many indirect, but hazardous consequences on not only aquatic but also terrestrial ecosystems and biodiversity (Machado et al., 2019), which remains to be better understood though. The presence of MPs (HDPE) can alter the soil's natural structure and pH (Boots et al., 2019), which can affect the crop productivity. Boots et al. (2019) demonstrated that MPs in soil could reduce the biomass and productivity of a common perennial grass (*Lolium perenne*) and an endogeic soil earthworm (*Aporrectodea rosea*). As synthetic/biodegradable MPs/NPs could impair the biomass, productivity, and growth of various commercially important crop species like common bean: *Phaseolus vulgaris* L. (Meng et al., 2021), garden cress: *Lepidium sativum* (Pignattelli et al., 2021), barley: *Hordeum vulgare* (Li et al., 2021), cucumber: *Cucumis sativus* L. (Li et al., 2020d), rice: *Oryza sativa* L. (Zhou et al., 2021), there is a good chance of reduction in the crop yield. Therefore, research needs to further explore (possibly through modelling) if MPs may interfere in the productivity of global agricultural ecosystems. The uptake and effects of MPs in drinking water under environmentally relevant exposures in animal models have not been elucidated yet (WHO report, 2019). The decline in ecosystem productivity solely caused by particulate plastics has not been modelled or quantified to date.

5.2 Regulating and Supporting Services

The regulation and maintenance of environmental conditions and quality are important for the functioning and sustainability of an ecosystem (Leverkus et al., 2020). The major regulatory services include climate regulation through carbon sequestration (soil and plant biomass), nutrient and water cycles (ecological sustainability or restoration), disaster mitigation (soil erosion regulation through water infiltration) (Grimaldi et al., 2014). Supporting ES refers to the services including primary production (soil quality and water storage), nutrient balance, habitat provision, etc., that enable the delivery of other services (Hasan et al., 2020). Primary producers and consumers play a pivotal role in the provision and delivery of these services

(**Table 3**). For instance, in freshwater ecosystems, zooplankton (mainly Ostracoda, Otifera, Copepoda, and Cladocera) plays a major role in trophic transfer, preventing eutrophication, bioindication, providing fatty acids to secondary consumers, thus maintaining the overall ecological balance, structure, and function of the ecosystem (Bakhtiyar et al., 2020). MPs in the polar marine ecosystem (20 particles L^{-1}) induce feeding suppression along with other behavioural stresses in Arctic zooplankton toward crude oil pollution (Almeda et al., 2021). The available literature establishes that MPs are harmful to the planktons (Almeda et al., 2021), earthworms (Wang et al., 2019), snails (Song et al., 2019), insects/pollinators (Oliveira et al., 2019), and plants (Bosker et al., 2019). Ecosystem "engineers" are species that significantly influence and modify the habitat and/or other communities thriving in the environment. They play a crucial role in the flow and delivery of regulatory and supporting services of an ecosystem, like forest litter, soil layer, soil turnover, etc. (Maisey et al., 2020). If MPs/NPs are consumed by ecosystem (terrestrial/aquatic) engineers, the isotopic composition of their gut microflora can change (Zhu et al., 2018), leading to serious physiological (metabolism, enzyme activity, and reproduction) and ecological (bioremediation and nutrient flow) implications. Moreover, soil ecosystem "engineers" like earthworms, other invertebrates, termites, and ants transport plastic particles down the soil profile (Rillig et al., 2017), which exposes MPs/NPs to the deep soil, suggesting non-negligible implications in the soil-based regulatory ESs like carbon and nutrient cycles (Rillig, 2018).

MPs also interfere with the key regulatory services provided by insects including decomposition (impact microbial community structure and bioremediation), nutrient cycling (alter litter composition, nutrient ratio), pollination (MPs can get translocated to the ovary of plants), pest control (impact hormonal regulations linked with biocontrol), prey-predator balance (change feeding behavior, and promote invasive predators) (Oliveira et al., 2019). PVC, HDPE, and polylactic acid (PLA) (biodegradable) alters the metabolism and burrowing activity of a marine keystone species (*Arenicola marina*), which in turn impairs the sedimental microalgal biomass and nutrient cycling (Green et al., 2016), and also alter the infauna assemblage (1.8 times less ammonia in the spiked sediments) and biomass production (7.5 times increased filtration in the spiked samples) of microalgae and cyanobacteria (Green et al., 2017). At high concentrations, MPs, as they favour biofilm formations, can alter the natural microbial community structure in the pelagic environment (Eckert et al., 2018). The presence of MPs at high concentrations changes the microbial community structure in waterbodies/wastewater treatment plants (reducing the secondary treatment efficiency) (Eckert et al., 2018), and enhance the risk of spreading biohazardous (horizontal transfer of antibiotic-resistant genes) microbes from the plastisphere to the natural environment (Fei et al., 2020), which imply significant impacts on bioremediation, a notable regulatory service.

Plastic debris is usually mistaken by hermit crabs and other molluscs for shelter (de Carvalho-Souza et al., 2018), which may act as a vector of invasive microbiota and microfauna across the seas. When these macro(meso)-plastics are disintegrated, the fragmented MPs can harbor and transfer invasive, virulent, resistant, pathogenic microbes (Liu et al., 2021) that are harmful not only to humans, but also to economically, ecologically or culturally important fauna. For instance, the marine plastic debris (including macro(meso)-plastics) of the Norwegian West Coast harbored virulent, antibiotic-resistant strains of microbial communities that are potential fish pathogens (Radisic et al. 2020). MPs can disrupt the native microbiome by transmitting resistant strains to peculiar environment (Liu et al., 2021). MPs (PE) impact the health of different reef-building corals (*Acropora*, *Pocillopora*, and *Porites*) by interfering with their mucus production and feeding behaviour (Reichert et al., 2018), and these stony polyps serve as a primary habitat for the reef ecosystem. Few more studies demonstrate the interactions of the marine anthropogenic litter with hard corals (Huang et al., 2020b; de Carvalho-Souza et al., 2018), but such studies fail to identify or quantify those ecological interactions. An in-situ study in the reef ecosystem of South China Sea (Hainan Island) showed significant ingestion of MPs by the scleractinian corals and other reef-dwellers, where they observed significant physiological impacts on small-polyps, while the large-polyps were mostly tolerant (Tang et al., 2021).

Jung et al. (2021) conducted an in-situ observation of the MPs (20-300 µm, fibers and fragments) in the South Korean surface and subsurface seawaters in the coastal, continental shelf, and deep-sea. It was found that the current detected MPs concentrations are unlikely to pose a significant risk to the marine ecosystem. Windsor et al. (2019) demonstrated that the occurrence and interactions of MPs in macroinvertebrates and riverine food chains were independent of their ecological niches. Both the grazers and filter-feeders showed similar MP ingestion irrespective of the feeding behavior, suggesting bioaccumulation throughout the habitat. The corresponding changes in the ecological interactions may impact the prey-predator relationship and energy-flow across the trophic levels. As MPs impair the functional traits (survival, feeding, growth, development, health, behaviour, fecundity, and hatching) of fishes (Salerno et al., 2021), the changes in the prey-predator relationship may influence the ecological sustainability. Moreover, plastic particles have been identified on mayflies, mosquito larvae, and caddisflies (Oliveira et al., 2019), which are the chief food sources for predators like birds, bats, lizards, and spiders, leading to ontogenic transference (Al-Jabaichi et al., 2018), and these interactions could influence the aerial prey-predator populations. MPs can change the biotic and abiotic interactions in soil ecosystems (Machado et al., 2019). As ecosystem structure, functioning and processes are interlinked with the ESs (Fu et al., 2013), it is important to understand if MPs could impact ecological niches. For instance, MPs can disrupt the natural microbial communities (Radisic et al., 2020), their succession (Hou et al., 2021), and the natural genetic resources of an ecosystem by inducing plasmid transfer and gene exchange in phylogenetically diverse microbial communities thriving in the contaminated environment (Arias-Andres et al., 2018), which have direct implications on the supporting services provided by the associated ecological niches.

MPs impact the biotic biomass (retarded germination, growth, and photosynthesis of plants, reduced body mass of invertebrates), and thus reduce the carbon sequestration rate (35-45% increased root/shoot ratio) of the degrading ecosystems (Boots et al., 2019). Moreover, chemically being carbon compounds, researchers can misestimate soil MPs as a part of soil organic carbon in the contaminated terrestrial ecosystems, thus overestimating the natural carbon sequestration processes (Rillig, 2018). MPs may affect soil water content, which may in turn impair litter decomposition, nutrient cycling, soil aggregation, and drought prevention. For instance, Lozano et al. (2021) designed a microcosm experiment using grassland communities (7 native plant species in sandy loam soil), where the negative impacts of MPs (fibers) on the ecosystem functions were analogous to those of drought, highlighting deleterious impacts on the soil aggregation, water and nutrient retention, pH, respiration, and enzyme production. MPs can also interfere with the natural biogeochemical cycles. For instance, in salt marsh sediments, PVC MPs can inhibit the microbial nitrification and denitrification processes, while PU and PLA can accelerate them, implying significant deviations in the natural sedimentary nitrogen cycle (Seeley et al., 2020). The leachates from PVC and HDPE are found to significantly impair the growth, metabolism, and photosynthesis of an important marine autotrophic bacteria: *Prochlorococcus* (Tetu et al., 2019), which in turn destabilize the natural carbon sinks and the oxygen production processes, but it is still unclear whether MPs can influence microclimate and favour extreme events. As MPs retain heat (Duncan et al., 2018), it is necessary to understand if MPs increase microclimatic temperatures to a non-negligible extent. Though it can be inferred that MPs impair the ESs and primary production of an ecosystem (Tetu et al., 2019), most of the impact assessment studies remain at laboratorial scale or were conducted under non-controlled conditions (e.g., Redondo-

Hasselerharm et al., 2020). Further research is needed to understand the possible links of MPs with extreme events.

5.3 Cultural Services

Cultural ES compromise all the non-material benefits of an ecosystem that influence the physical and mental wellbeing of the public (Oliveira et al., 2019) (**Table 3**). Though the knowledge on the key variables (spatial, socio-demographic, and environmental) associated with cultural ES is limited, cultural services of an ecosystem may be majorly grouped into nature interactions (visual aesthetics of a forest, bioindication, healthy flora and fauna) and social interactions (exercise, relaxation, education) (Dade et al., 2020).

5.3.1 Nature interactions

Bioindication provides scientific knowledge and key insights on the extent of pollution, degradation, and disturbances in the environment (Heckwolf et al., 2021; Gül and Griffen, 2020). MPs impact the growth and reproduction of soil invertebrates (e.g., earthworms, nematodes, termites, and springtails), which are regarded as important bioindicators of heavy metal pollution and overall environmental quality (Oliveira et al., 2019).

5.3.2 Social interactions (exercise and relaxation)

Nature/heritage/educational tourism and wildlife observatories are important for building the cultural aesthetics (cultural/spiritual trees, animals) and socio-economy (urban parks, cultural tourism) of a nation (Ghermandi et al., 2020; Zhang et al., 2020a). Native biodiversity (aquatic/terrestrial flora and fauna) is deeply rooted in the culture and traditions (culinary, art, etc.) of a region (Zhang et al., 2020a). For instance, fauna like Asiatic elephants, whales, seals, cattle, tigers, polar bears, monkeys, and flora like bamboo, neem, rice, banyan, peepal, etc. hold cultural, religious, and spiritual significance in the traditions of the locals. Endangered flora/fauna are the major attractions for nature tourism. MPs have been found in the faeces of rare and vulnerable marine birds in the protected breeding areas of the Bay of Biscay, Europe (Masiá et al., 2019). MPs are found in various endangered species including the Indo-Pacific humpback dolphins: *Sousa chinensis* (Zhang et al., 2021), baleen whales: *Balaenoptera physalus* (Fossi et al., 2012), loggerhead turtles: *Caretta caretta* (Di Renzo et al., 2021). MPs are being ingested through the natural diet by Asiatic elephants (a flagship megaherbivore) of the Indian (Uttarakhand) jungles (Katlam et al., 2020) (**Table 4**). However, knowledge remains limited about how this could qualitatively or quantitatively impact animal reserve and ecotourism. The wellbeing promoted by ecological conservation is an important cultural service, but the degree to which it is directly or indirectly affected is still unclear. As MPs are known to be prevalent in various marine and freshwater fishes (Parker et al., 2021), it may have implications for the recreational activities like game fishing, which also needs to be explored. MPs can also impact domestic animals and pets. For instance, MPs (PET, PC) have been identified from the commercial pet food (mainly for dogs and cats) and the domestic cat/dog feces (Zhang et al., 2019a), which may have direct implications for their health and behavior and need to be better understood.

Plastic pollution is widely recognized to affect tourism and the associated economy. For instance, the plastic pollution along the coastlines causes tourists to avoid or shorten their visits to a particular beach (Arabi and Nahman, 2020). The macroplastic (not MPs) pollution could significantly cause a visual distress and lessen the scenic beauty. There is no evidenced effect of MPs on the biodiversity and the associated tourism. MPs may also be a factor for coral reef degradation as they are known to reduce the stress tolerance of various keystone (reef-building ecosystem “engineers”) coral species (Huang et al., 2020b; Reichert et al., 2018). The decline of coral diversity in Australia’s Great barrier reef, where there was reduce domestic tourism, has raised protective sentiments among tourists and environmentalists in recent years (Curnock et al., 2019). Therefore, the increasing awareness on the omnipresence and impacts of MPs may influence (positively or negatively) not only the non-material services of nature tourism but also the associated economy. Many studies evaluate the ecotoxicological impacts of MPs/NPs on various keystone species (**Table 4**), but there is limited understanding of the possible impacts of MPs/NPs on the cultural services of an ecosystem. The impacts of MPs on the ESs can in turn have an implication for the associated economy.

6. Green and Blue Economy

Natural capital sets the ecological limits for the socio-economic systems and cannot be safely replaced with other forms of capital (Cohen et al., 2019). However, the problem wherein the value of natural capital is not being reflected in policy trade-offs occurs in decision-making at all scales. Major societal benefits from ESs can be perceived, if the ES values (marketed as well as non-marketed), through economic analyses, are embodied into real-world environmental decision-making, as insisted by the Millennium Ecosystem Assessment (Liu et al., 2020; Bateman et al., 2013). The concepts like the green gross domestic product (gGDP) and ecosystem services value (ESV) aim to assess the net economic value of all the available ecosystem (natural/artificial) products and services, to facilitate sustainable management (Li and Fang, 2014). Natural capital and ESV play a crucial role in the sustainable use of land (green economy) and water (blue economy) resources for socio-economic development (Silver et al., 2015). The terms 'blue economy' (sustainable ocean economy) and 'green economy' (sustainable land economy) were first used in 2012 in the United Nations Conference on Sustainable Development (Rio de Janeiro) (Lee et al., 2020; Loiseau et al., 2016).

Every year, global marine ES provide approximately 49.7 trillion USD (as of 2011) to the global society (Arabi and Nahman, 2020). To promote the "blue/green economy" approaches, sustainable waste management practices are needed, which is a challenge for small developing states (Phelan et al., 2020). For instance, MPs are found in the market-bought (Mwanza Harbor, Tanzania) samples of Nile Tilapia (35% of the samples) and Nile Perch (55% of the samples), two of the most economically and culturally important freshwater fishes in the North Africa (Biginagwa et al., 2016), suggesting that the Lake Victoria: a potential source of the blue economy for small developing states (Several states around Uganda, Tanzania, and Kenya) is prone to the plastic contamination. There are multiple studies finding MPs in tissues and stomachs of economically relevant species (Parker et al., 2021). As fisheries are a very important source of income and livelihood for local populations across the globe, it is important to study the implications of MPs for the economic development. Nevertheless, evaluating the impact of MPs in the economy of fishes is very difficult due to the lack of datum on population-level effects. Managing plastic waste has been a major global challenge for harnessing the blue or green economy (He et al., 2019). Plastic waste accumulated in the environment is estimated to incur a loss of 1-5% per annum in the ocean economy, a global loss of 0.5-2.5 trillion USD every year (Arabi and Nahman, 2020). Moreover, cleaning the mismanaged plastic waste from the environment costs money (Oosterhuis et al., 2014). For instance, the collection of floating plastic debris in Puerto de Barcelona (Barcelona Port Authority), Spain, has been costing over 330, 000 USD per 117 tons of litter (Werner et al., 2016). In the terrestrial environment, industries (59%) have been the major contributor to global plastic waste, while the contribution of agriculture remains only at 5% (Pazienza et al., 2020). International efforts (United Nations Sustainable Development Goals) and policy emphasis (European Union Plastics Strategy) of the sustainable land economy led to the popularization of biodegradable or green plastics (Watkins et al., 2017). However, biodegradable plastics also impact the environment, similar to conventional ones (Green et al., 2016). Therefore, European Union proposed the concepts of recycling, reuse, and circular economy as powerful strategies to economically manage plastic waste, proposing ambitious targets of 65% recycling of municipal waste and 75% recycling of packaging waste by 2030 (Watkins et al., 2017). The circular economy has been proposed as an effective scheme to curtail the accumulation of plastics in the environment and boost the green economy. However, there is limited information to date about the direct impacts of plastic particulates on the green economy.

As the building up of MPs in terrestrial and aquatic ecosystems is known to have implications for ecosystem degradation, the socio-economic benefits acquired from those poorly functioning ecosystems shall also be intervened by this emerging macro-threat. Even though it can be inferred that MPs impact the productivity of ecosystems, the economic impacts and losses caused by MPs in the ESs cascade and delivery have not been introspected yet. The quantification of the economic impacts of marine litter is an intractable task (Li et al., 2020a; Critchell et al., 2015), but still the blue/green economic losses need to be considered in decision-making. Future studies need to disclose the pathways through which MPs influence the productivity of ecosystems and quantify those impacts in terms of green/blue economy, with more focus on aquatic (freshwater and marine), mangrove covers (estuarine), and terrestrial (soil) ecosystems, which are increasingly being susceptible to MP pollution.

7. Conclusion and Recommendations

MPs in terrestrial ecosystems provide a major source of contamination to aquatic ecosystems. Recently, more studies have been exploring the implications of MPs in the terrestrial environment. MPs have already emerged as a potential hazard to various aquatic and terrestrial threatened species, communities, and habitats. The available studies suggest that MP-contaminated ecosystems show reduced floral and faunal biomass, productivity, and carbon sequestration. As MPs could reduce the photosynthesis of oxygen-producing bacteria, it is necessary to analyse whether MPs impact the overall oxygen production of the contaminated ecosystems. MPs induce fluxes in global ecosystems as they can affect keystone species in the prevailing environment. Dedicated modelling or ground assessment (field evaluation) of long-term impacts caused by MPs on ESs are yet to be explored. The impacts of MPs on ESs delivery and green/blue economy have not been elucidated and quantified yet. As it is acknowledged that MPs are ubiquitous in various terrestrial and aquatic ecosystems, there is a need to correlate their abundance with the increasing biotic and abiotic disturbances (including microclimate) in the degrading ecosystems, to understand the probability of MPs to accelerate ecological disturbances. Also, the residential time of different MP particles in different biological systems should be estimated to understand their fate and migration in a habitat. Irresponsible tourism has been widely proposed as a major reason for increased anthropogenic litter in fragile ecosystems. Therefore, the ongoing/forthcoming global ecotourism projects (public-private partnership) in fragile and pristine habitats should strictly bear the responsibilities of sustainable tourism. The future research, ES assessment strategies/models, and legislative frameworks concerning particulate plastics should address the following:

- Documentation studies of MPs in the open oceans report the abundance of PE, PP, PE, PS, PET, etc., but very low levels (PVC, polycarbonate) or no traces of other widely produced and used polymers. It is important to examine their fate in the environment.
- Developing more reliable and trained environmental models to understand the fate of floating and sinking aquatic litter.
- Developing a generalized modelling approach to understand the migration and disintegration patterns of individual types of MPs and NPs.
- Examination of the long-range atmospheric or ocean transport, current long-term exposure, and the associated ecotoxicological effects of micro/nano-plastic particles on the polar flagship species, including walrus and polar bears.

- Correlation studies relating global concentrations of MPs in beach dunes to changes in life-history parameters and sex ratio of the sea turtles to understand the reason for the population decline in the beach fauna.
- Examination of the effect of MPs microclimate influencing coral bleaching and ocean acidification.
- Leaching of MPs or associated chemicals in wastewater used for irrigating croplands, thereby reaching the food chain, need extensive investigation.
- Modelling the effect of MPs on the global biodiversity changes, especially in the sensitive/fragile ecosystems and biodiversity hotspots.
- Effect of MPs on biofilms formation and the spread of pathogenic microorganisms, particularly with freshwater/potable water sources need to explored.
- The environmental behaviour and ecosystem effect of NPs, and their ready integration with ecological and biological systems are required.
- Microcosmic or field studies on the ecological impacts of MPs currently remain mainly at the species-level, which calls for research at the ecosystem-level.
- Last but not least, more studies are needed to explore the direct impacts of MPs on ESs flow and delivery. It is desirable to connect and correlate existing fragmented studies to develop accurate knowledge about such areas as the impacts of MPs on nutrient cycling processes, carbon sequestration, etc.

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