Chapter 17
Plastic Pollution During COVID-19 Pandemic: A Disaster in the Making

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Abstract The COVID-19 pandemic has impacted all spheres of human life and the global environmental parameters to a large extent. Research studies by scientists across the globe pointed out that COVID-19 is both a boon and a bane for the environment. While safety restrictions imposed because of this global pandemic led to a substantial reduction in air and water pollution due to the lowering of anthropogenic activities and other associated human interferences, there has been an increasing dependence on plastics in people's lives all over the world. The astronomical increase in online shopping of groceries and associated home supplies, disposable plastic utensils, packaged food containers, and protective gears while under lockdown or in self-isolation have led to plastic pollution being out of control. The solid waste management system in the Indian cities already has its inherent shortcomings

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due to the lack of human resources, machinery, funds, awareness, etc. Excessive use of plastics has further augmented this problem, thereby jeopardizing the ambient environment. Moreover, the utilization of sealed bags in a clinical setting for the safe disposal of contaminated plastic wastes that need further sterilization adds to the existing burden of plastic wastes. The disposable masks on getting submerged in water result in the leaching of ecotoxic chemicals and nanoplastics into the environment, thereby impacting aquatic life in the long run. Exorbitant use and careless disposal of personal protective equipment (PPE) kits, face shields, gloves, disposable surgical/other masks, and shower caps have been a perennial problem during the ongoing pandemic in all cities (big or small) across the globe. Therefore, the need of the hour is to mitigate this uncontrolled rise in plastic pollution and the introduction of alternatives to conventional plastics for daily medicinal use. The focus should be on sustainable plastic waste management and moving toward eco-friendly materials such as jute, hemp, and bioplastics, etc., along with creating awareness among the public about scientific management and disposal as well as advocating the principle of 4 Rs, i.e., reduce, reuse, recycle, and refuse/recover.

Keywords COVID-19 pandemic · Single-use plastic (SUP) overuse · Plastic pollution · Sustainable waste management · Bioplastics · Biodegradation · Recycling

1 Introduction

The SARS-CoV-2, the causative agent of the novel coronavirus disease 2019 (COVID-19), reigns over the entire global community since the first outbreak of this virus in Wuhan, China, in December 2019. The World Health Organization (WHO) declared COVID-19 a pandemic on March 11, 2020, owing to more than 3 million cases and 207,973 deaths in 213 countries and territories (WHO, 2020). This infectious virus has thrown the entire world's machinery out of gear with unanticipated fear and anxiety despite the slowly emerging vaccination drives in most countries around December 2020. Needless to say, the pandemic has created unparalleled catastrophic distress in people's lives, physically, mentally, and financially (Agarwal et al., 2020; Pak et al., 2020; Alghamdi, 2021). To control the rapid spread of SARS-CoV-2, local/regional/nationwide lockdown measures had been announced worldwide during early 2020 and continued in 2021 in many countries with the emergence of new viral variants; this has left an indelible mark on the environment as well (Table 17.1). Initially, during the lockdown period in 2020, some researchers had observed an improvement in environmental parameters across the world, such as the air (Mitra et al., 2020; Wang et al., 2020) and water quality (Chakraborty et al., 2020; Dhar et al., 2020) with imposed travel restrictions and as several thousands of people were all stranded at home for months, thereby reducing the anthropogenic and/or carbon dioxide (CO_2) footprints.

Table 17.1 Environmental impacts of COVID-19 pandemic and subsequent lockdown measures

Environmental impacts	
Positive	Negative
• Improved outdoor quality of air (Bashir et al., 2020; Dutheil et al., 2020; Muhammad et al., 2020; Tobías et al., 2020)	• Deteriorated indoor quality of air (Dutheil et al., 2020)
• Decreased noise pollution	• Increased biomedical wastes, including plastic wastes (Wang et al., 2020; Kalantary et al., 2021)
• Decreased household and commercial food wastes (Jribi et al., 2020)	• Decreased recycling of wastes and increased use of landfilling and incineration as methods of solid waste disposal (Torkashvand et al., 2021)
• Decreased energy consumption and greenhouse gas (GHG) emissions (Ficetola & Rubolini, 2020; Wang & Su, 2020)	• Increased disinfection regime using toxic chemicals, including sodium hypochlorite (NaClO) (1%) and ethanol-based products (at least 70%) in both indoor and outdoor (domestic and commercial) environments https://www.mohfw.gov.in/pdf/Guidelinesondisinfectionofcommonpublicplacesincludingoffices.pdf)

On the other hand, solid waste generation has taken a gigantic leap. COVID-19 is scientifically and medically proved to be a highly contagious disease with multiple entry routes via abiotic and biotic contacts through surfaces, wastes, airborne aerosols or respiratory droplets, and oral-fecal transmission (Dietz et al., 2020; Heller et al., 2020; Kitajima et al., 2020). Owing to the persistence of the virus on inert surfaces from 3 h to 9 days (Kampf et al., 2020a; van Doremalen et al., 2020; Wang et al., 2020) and because of human-to-human transmission primarily through respiratory droplets (Chan et al., 2020; Jayaweera et al., 2020), there has been a rapid spread of infection within the community. Irrespective of nations, the central government/governing bodies in compliance with the guidelines recommended by WHO issued various safety protocols related to COVID-19, which included but were not limited to maintenance of social distancing, frequent washing/sanitizing of hands, use of face shields, face masks, and gloves along with the practice of quarantine measures upon accidental contact with COVID-19 suspects to prevent and control the rapid transmission of SARS-CoV-2 infection. However, many of these containment measures taken by public and healthcare workers have resulted in an increase in the plastic wastes by leaps and bounds, mainly in the form of disposable protective gears such as personal protective equipment (PPE) kits, face shields, surgical/other types of masks, gloves, shower caps along with packaging materials, and disposable plastic cutlery for hospitalized/home quarantined patients and/or isolated individuals suspected of COVID-19 (Adyel, 2020).

Plastics are affordable, accessible, durable, and water-resistant; thereby, they have a wide application in innovation related to modern science and technology (North & Halden, 2013). The plastics and their use are not harmful, but their mismanagement and underutilization of these multipurpose resources are causing hazards to the environment (Borg, 2020). Moreover, the announcement of lockdown measures and subsequent restriction on traffic movements and imposed curfews had resulted in panic buying of medicines as well as accelerated online and/or offline shopping for essential daily needs, including groceries, etc., leading to overuse of single-use plastic (SUP) carry bags of various shapes and sizes in a short span than never before. It is noteworthy that in order to cater to the millions of bachelors, frontline workers, working couples, and older people who did not have the time or scope to cook their meals, the online/offline home delivery services were kept accessible (some of which were even made specially available) during the lockdown period. This has created a huge demand and supply of packed or packaged food, thereby stimulating the usage of plastic food containers and accompanying cutlery along with SUP packaging materials. During the pandemic, with shops and restaurants closed due to the imposed lockdown together with the government slogan *Stay safe stay home* has changed people's consumption and living habits creating ambiguity in waste generation patterns for convenience (e.g., online shopping and food delivery) and assurance (e.g., contactless delivery) (Bengali, 2020). Figure 17.1 shows the increasing trend in e-shopping and food takeaways on a global scale during the COVID-19 pandemic. This humongous plastic waste generation during the pandemic is adding to the existing solid wastes, thereby aggravating the challenges of the overburdened solid waste management system, eventually leading to

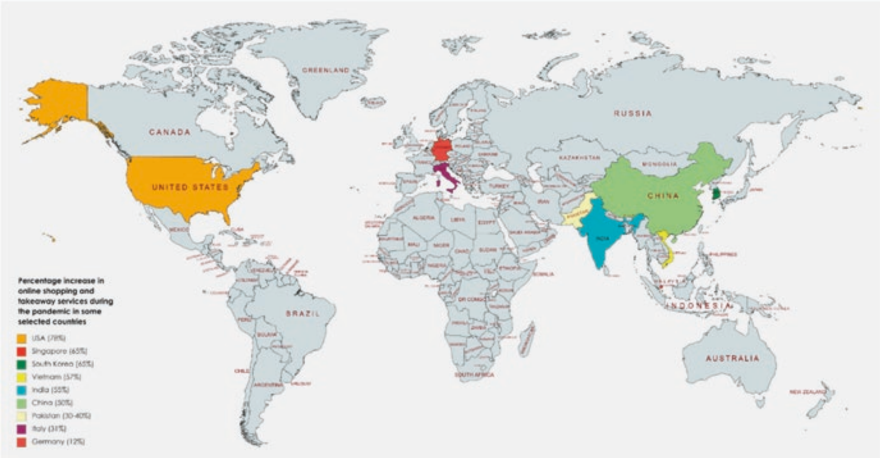


Fig. 17.1 Global map showing an increase in the percentage of e-shopping and takeaway services in a few selected nations during the COVID-19 pandemic. (Reprinted from Parashar and Hait (2021). Copyright (2021), with permission from Elsevier CC-BY-NC-ND license no. 173901166796)

deterioration in the overall health of the environment and ecosystem toxicity. Many shortcomings and discrepancies in the waste management system have been observed during the pandemic due to many reasons, which included capacity constraints of facilities, a shortfall in the workforce due to nationwide lockdown, disturbances in mechanical recycling facilities (like compactors), absence of doorstep waste collection systems daily, stigma against COVID-19 patients resulting in non-collection of their regular domestic wastes, etc. (B.I.R., 2020; Das et al., 2021). All these constraints would eventually lead to inappropriate waste disposal and massive mismanagement of municipal solid wastes in almost all big cities of the world, especially in the developing countries, causing massive deterioration of environmental health.

As is evident from both Figs. 17.2 and 17.3, the biomedical plastic wastes consisting of personal protective equipment (PPE) kits, glucose bottles, syringes, gloves, disposable face masks, etc., have been on the rise due to the global pandemic. The average daily generation of biomedical plastic wastes during the SARS-CoV-2 viral outbreak in India is represented in Fig. 17.3.

Figure 17.4 shows the various plastic types, uses, and recyclability during the pandemic.

Prior to the pandemic, the key attention was to beat the use of plastics and make crowded places such as temples, churches, mosques, markets, shopping malls, and multiplexes plastic-free. The cumulative action worldwide was to reduce plastic consumption and change customers' behavior toward plastic use by levy charges for getting access to a plastic bag(s) after every purchase of groceries/goods. However, the pandemic has dramatically augmented the complexities of plastic waste management across the globe. Researchers from Swansea University (UK) have found

Fig. 17.2 The map illustrates the average daily generation of biomedical wastes comprising discarded synthetic plastics in some selected Asian nations or their important cities during the COVID-19 pandemic. (Reprinted from Parashar and Hait (2021). Copyright (2021), with permission from Elsevier CC-BY-NC-ND license no. 173901166796)

that the disposable masks leach toxic chemicals (like heavy metals/metalloids) and nanoplastics into the ambient environment on becoming submerged in water. The levels of heavy metals such as antimony, copper, and lead were found in the range of parts per million (ppm) or parts per billion (ppb) (https://www.swansea.ac.uk/press-office/news-events/news/2021/05/nanoplastics-and-other-harmful-pollutants--found-within-disposable-face-masks.php). Although the levels are low, in the larger picture, the amount of production, usage, and disposal of these protective face masks have been increasing and would continue for quite some time in future till this pandemic is ongoing. The impact on the aquatic environment might not appear to be a big issue at present as the focus is arresting the pandemic and saving human lives. These heavy metals can bioaccumulate in the tissues of edible fish, as has been studied by Dutta et al. (2021), and they are not removed from the fish body but instead build up over time as recalcitrant xenobiotic substances that interact with socio-ecological systems, causing havoc damage to the fragile ecology of the ecosystems in consideration. As per the report of the WWF (World Wide Fund for Nature), if people only dispose of 1% of the face masks inappropriately and they are dispersed in nature, it would amount to almost 10 million masks (0.33 million

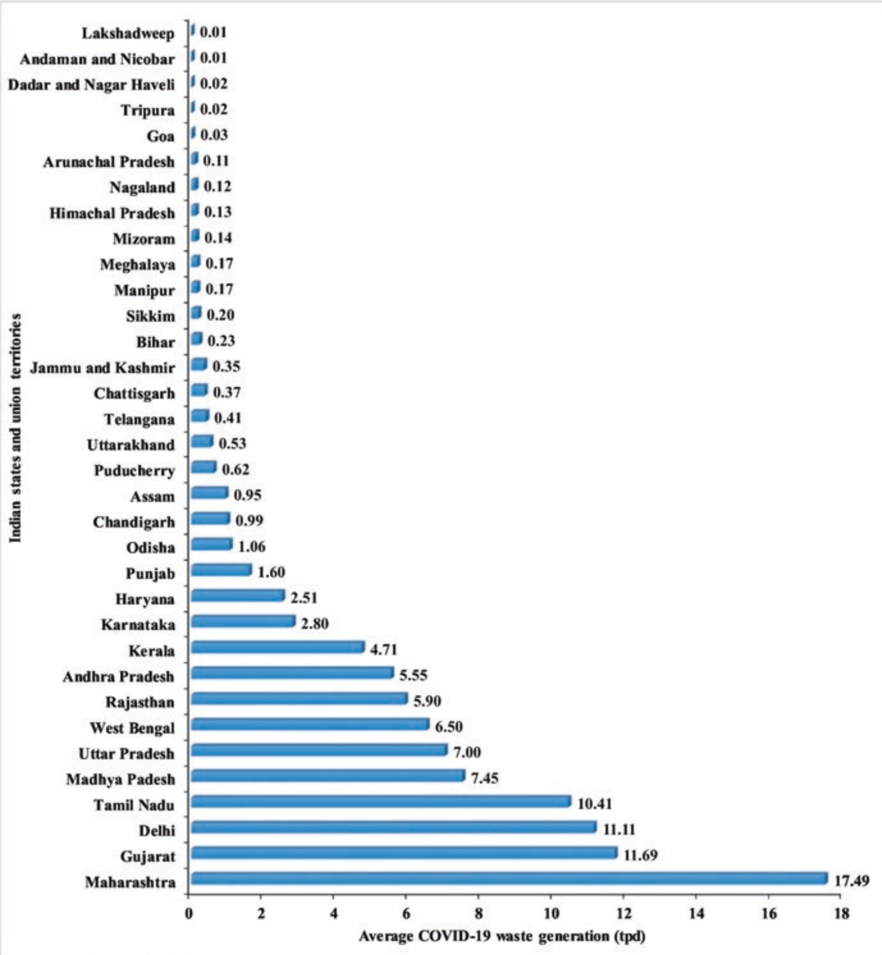


Fig. 17.3 Daily average of generated biomedical wastes comprising disposed plastics in India. (Reprinted from Parashar and Hait (2021). Copyright (2021), with permission from Elsevier CC-BY-NC-ND license no. 173901166796)

masks per day) that would be contaminating all trophic levels of the ecosystem (Italy WWF, 2020). The multilayered masks with various polymers are difficult to recycle, especially those imported from China (Monella, 2020).

The fear of the contagious disease and the protective measures used by the commoners and frontline workers following the medical/WHO guidelines resulted in the enormous use of protective gears, which have become a tremendous challenge for environmental scientists and researchers across the globe. The present pandemic needs to mitigate plastic pollution by promoting alternative biodegradable plastics (or bioplastics) and advocating and practicing the principle of 4 Rs, namely, reduce, reuse, recycle, and refuse/recover.

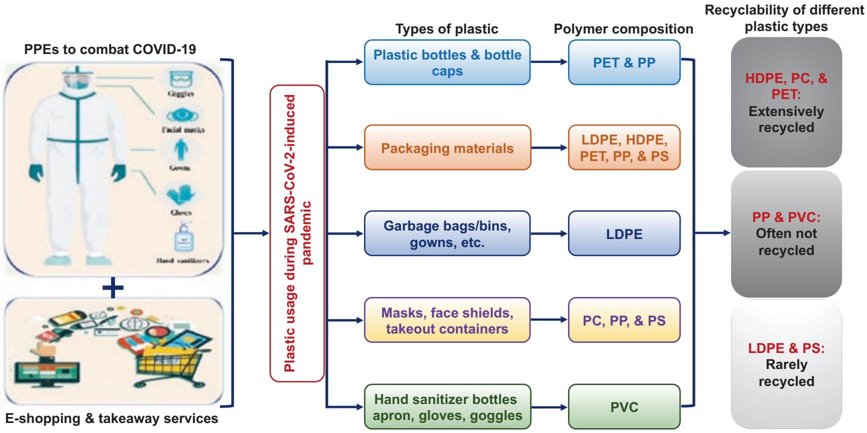


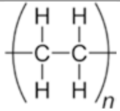
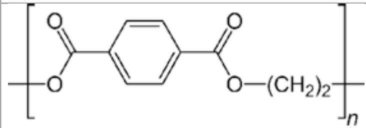
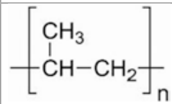
Fig. 17.4 Various categories of plastic-based biomedical and domestic/commercial wastes generated during the global SARS-CoV-2 outbreak and subsequent COVID-19 pandemic phase with their utilization and recyclability

2 Diversity of Commonly Used Synthetic Plastics

Based on the degradation pathways (associated with bonding patterns in the polymer backbone), the synthetic plastics are categorized as (1) plastics having carbon-carbon (C-C) backbone (i.e., backbone made of carbon atoms) and (2) plastics having heteroatoms in their main polymeric chain. Polythene/polyethylene (PE), polypropylene (PP), polystyrene (PS), and polyvinyl chloride (PVC) plastics with C-C backbones comprise the first group. In contrast, polyethylene terephthalate (PET) and polyurethane (PU) with heteroatoms in their main polymeric chains fall under the second group (Table 17.2).

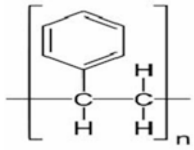
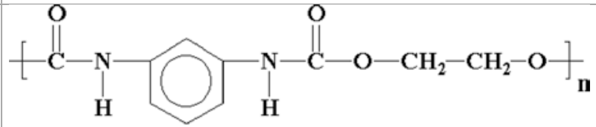
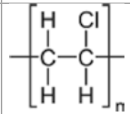
The polymeric chain is linear in PE with hydrogen-bonded carbon atoms, and its structure is semicrystalline. Based on the differences in densities, PE polymers are further classified as low-density polyethylene (LDPE), linear low-density polyethylene (LLDPE), low-molecular-weight polyethylene (LMWPE), and high-density polyethylene (HDPE). Out of all these four types of PE, the LDPE is found to be discarded mostly in landfills as plastic bags (69.13%) (Mohanan et al., 2020). However, the most abundantly used plastic is PS, owing to its low cost and good mechanical property. Based on application, PS are generally grouped as general purpose polystyrene (GPPS) or oriented polystyrene (OPS), high impact polystyrene (HIPS) (also referred to as PS), PS foam, and expanded polystyrene (EPS) foam (Ho et al., 2018). PP is a linear polymer, which is widely used among synthesized polymers. The properties of PP are quite similar to PE, but some differences exist, for instance, in hardness, heat, and chemical resistance, the former being more hard, more resistant toward heat and chemicals. PVC has been in use for many years owing to its rigidity and plasticized form. PET and PU plastics are more thermally stable in comparison to PE, PP, PS, and PVC because of the presence of heteroatoms in their main polymeric chain (Venkatachalam et al., 2012).

Table 17.2 Characteristic features, molecular formula, IUPAC nomenclature, structure, and uses of major commercial synthetic polymers

Sl. no.	Name	Highlight(s)	Formula	IUPAC name/ID	Structure	Uses/used in/used as
1.	Polythene/ polyethylene (PE)	• Most common plastic in use today	$(C_2H_4)_n$	Polyethene or poly(ethylene		Films, tubes, plastic parts, laminates, etc., in packaging, automotive, electrical appliances/ parts, etc.
2.	Polyethylene terephthalate (PET)	• Most common thermo- plastic polymer resin belonging to the polyester family	$(C_{10}H_8O_4)_n$	Poly(ethyl benzene-1,4- dicarboxylate)		Manufacturing bottles, liquid and food containers, textile fibers, and films Also, thermoforming for manufacturing and engineering resins (in combination with glass fibers)
3.	Polypropylene/ polypropene (PP)	• A thermoplastic polymer with wide-spectrum applications • Produced via chain- growth polymerization from the monomer known as propylene • Belongs to the group of polyolefins • Partially crystalline and nonpolar	$(C_3H_6)_n$	Poly(propene)		Food packaging, textiles, laboratory equipment, and automotive components

(continued)

Table 17.2 (continued)

Sl. no.	Name	Highlight(s)	Formula	IUPAC name/ID	Structure	Uses/used in/used as
4.	Polystyrene (PS)	• A synthetic aromatic hydrocarbon polymer that is made from the monomer called styrene • Can be solid or foamed	$(C_8H_8)_n$	Poly(1-phenylethene-1,2-diyl)		Packaging foam, food containers, construction materials (insulation), cassette boxes, compact disks, disposable cups, plates, and cutleries
5.	Polyurethane (PU/PUR)	• A commonly found polymer, which is composed of organic units that are joined by carbamate (urethane) links	$C_3H_8N_2O$	Ethylurea		Catheters for medical application, as foams, domestic consumables, in industrial products, adhesives, insulation, coats, tires, sponges, paints, and fibers
6.	Polyvinyl chloride (PVC)	• World's third-most widely generated synthetic plastic polymer (after PE and PP)	$(C_2H_3Cl)_n$	Poly(1-chloroethylene)		Building, transport, packaging, electrical/ electronic, and healthcare applications

3 Causes and Effects of Plastic Pollution on the Different Ecosystems: A Global Perspective

Representative examples highlighting the current global plastic pollution crisis across various geographically distinct locations and ecosystems derived from the review of recent literature with particular emphasis on the SARS-CoV-2-induced COVID-19 pandemic have been tabulated below (Table 17.3).

From Table 17.3, it can be further concluded that mushrooming of plastic waste accumulation has turned out to be a public menace and poses a severe socio-environmental challenge. Hence, the need of the hour is to develop innovative techniques or utilize existing ones for the disposal and/or degradation of plastic wastes in a sustainable manner.

4 Generation of Biomedical and Domestic/Commercial Plastic Wastes During COVID-19 Pandemic

During the period of the COVID-19 pandemic, plastic-based products have played essential roles in providing protection to people against viral infection. The extensive use of PPE during the pandemic caused significant disruption in the supply chain as well as waste disposal systems. Millions of discarded SUPs, including aprons, hand sanitizer bottles, gloves, and face masks, have been incorporated into the land ecosystems, which might eventually result in plastic surges along the sea/ocean coastlines and littering of the seabeds. Benson et al. (2021) assessed the potential environmental impacts of the synthetic plastic wastes generated globally during the pandemic. The study estimated that 1.6 million tons of plastic wastes per day had been generated worldwide since the viral outbreak. Further estimation revealed that around 3.4 billion single-use face masks or face shields are disposed of daily due to the pandemic throughout the world.

Biomedical waste (BMW) is a tricky business; it has become even more so in the wake of COVID-19. Not only has the number of biomedical wastes produced increased but also with people being quarantined at home, infectious wastes need to be collected and processed from residential complexes. Based on the State of India's Environment in Figs. 2021 (a CSE publication), there has been a 46 percent jump in the generation of biomedical wastes in India in just 2 months of April and May 2021 (https://www.cseindia.org/ state-of-india-s-environment-2021-in-figures-e-book%2D%2D10831). The report further adds that the BMW generation in India has grown from 559 tons per day to 619 tons per day between 2017 and 2019, whereas the percentage of treated BMW has dropped from 92.8 percent to 88 percent. The states of Bihar and Karnataka have been listed as the worst offenders, with 69 and 47 percent untreated BMW, respectively. At the same time, although the number of authorized healthcare units across the country almost increased twofold (i.e., from 84,805 to 153,885), the number of unauthorized healthcare units also hiked up (i.e., from 57,010 to 66,713).

Table 17.3 A comprehensive review on the causes and impacts of plastic pollution across a variety of selective global ecosystems

Sl. no.	Notable examples of plastics found	Key findings	Geographical location/ ecosystem(s)	Reference(s)
1.	• PE, PP, PPE, and PS	• The highest abundance of microplastics ranging from 37,440 to 38,790 particles per kg dry weight of sediment was detected in Jakarta Bay (Indonesia) • By far, polymers like polythene or polyethylene (PE), polypropylene (PP), and polystyrene (PS) are the most extensively used plastic categories. The PE, PP, and PS were dominant in the area under study, and their sizes ranged from 300 μm to 1000 μm; this suggests the condition of microplastic particles, which have resisted deterioration for an extended period • Data on released riverine debris collected during the first wave of the COVID-19 pandemic (i.e., March and April 2020) have shown a 5% increment in debris abundance and a 23–28% decline in debris weight relative to March and April 2016 • Plastics dominated the composition of river debris at an abundance of 46%. Personal protective equipment (PPE) (face shields, gloves, hazard suits, medical masks, raincoats, etc.) accounted for around 16% of the daily collected river debris with 780 ± 138 items or 0.13 ± 0.02 tons in terms of abundance or weight, respectively • Notably, microplastics were found in the fish intestines from Jakarta Bay and mussels from Semarang Bay	Tropical coastal and marine (aquatic) ecosystems; Indonesia	Adyasari et al. (2021), Cordova et al. (2021)

2.	• PE, PET, PP, PS, and nylon	• Continental distribution of microplastics in sediments has been reported to range between 5 and 18,000 particles per kg dry weight. The highest microplastic abundance (mainly comprising fragments and fibers) was recorded in the Tunisian lagoon sediments, Northwest Africa; this is among the highest reported microplastic sediment concentration worldwide • Microplastic concentration in collected mussels from Tunisia was also high (1031 ± 355.69 particles/kg). Most of the recovered Tunisian mussel microplastics were fibers (97%) • Microplastics in the range of 7000 particles/fish were recorded from the Mediterranean coast on the Egyptian side; this accounts for one of the highest quantities of microplastics ever salvaged from any aquatic organisms globally • The order of plastic pollutants appearing in the reviewed studies is PE > PP > PS > polyethylene terephthalate (PET) > nylon. This order is representative of the global plastic demand patterns and may also represent the plastic demand patterns of the African continent • Freshwater systems act as vital channels for microplastic contamination from terrestrial sources as they ultimately drain into the estuarine and marine environments. River Niger and River Nile, the two principal African rivers are among the top ten global sea polluters • Reports suggest that African nations are among the leading air-polluting countries globally. However, no reported studies have examined the abundance of atmospheric microplastics in Africa	Marine ecosystems; Africa	Alimi et al. (2021), Choudhury et al. (2022)

(continued)

Table 17.3 (continued)

Sl. no.	Notable examples of plastics found	Key findings	Geographical location/ ecosystem(s)	Reference(s)
3.	• CE, PE, PL, PP, and RY	• A study aiming to characterize the microplastic distribution in the estuarine surface sediments of the Kayamkulam Estuary found that maximum microplastic distribution occurs at a station located in the estuarine mouth. The average abundance of microplastics in the estuarine arms was 438.8 particles/kg (left arm) and 421.5 particles/kg (right arm). Most of the particles at the site were under 1000 μm, followed by those between 1000 μm and 2000 μm. The estuarine sediments were dominated by polyester (PL) (42.98%) and PP (34.38%), followed by PE (22.62%). Fiber-shaped microplastics were most dominant, followed by the film-shaped ones • The mean abundance of microplastics was measured to be 40.7 ± 33.2 particles/m^2 (beach sediments) and 1.25 ± 0.88 particles/m^3 (coastal waters) • The abundance of microplastics in the beach sediments and coastal waters was influenced highly by the river runoffs and anthropogenic actions. PE and PP polymers were found to be predominant in marine environments • Interestingly, the digestive tracts of 21.43% commercially important fish showed the presence of microplastic particles with microplastic composition in the order 38.46% PE > 23.08% cellulose (CE) > 15.38% rayon (RY) > 15.38% PL > 7.69% PP • In addition, a wide spectrum of heavy metals, metalloids, and several other toxic chemicals was tested positive in the collected microplastic samples from the Kerala beaches	Coastal waters; Southwest India (Kerala)	Robin et al. (2020), Radhakrishnan et al. (2021)

4.	• PPE	• During a 12-week sampling span, 138 different PPE items were detected in 11 beaches at a density ranging from 0 to 7.44×10^{-4} PPE m^{-2} • The PPE items found were in the sequence: Face masks (87.7%) > face shields (6.5%) > gloves (4.3%) > others (1.5%). Among masks, 54.5% were regular surgical masks, 12.4% were KN95, and the remaining were cloth masks or unidentified mask types. • The polluted sites were in the order: recreational beaches > surfing areas > fishing sites. It was found that rather than being washed ashore, most of the PPE was discarded by the beachgoers • Both sessile and mobile aquatic species were found to be entrapped in or associated with marine plastic litter (including synthetic textiles).	City coastline; Lima City, Peru	(De-la-Torre et al., 2021, 2021a, b)
5.	• PE, PPE	• PPE wastes were sampled four times in 40 days across nine stations across the Bushehr port coastline in the Persian Gulf • Notably, 1578 face masks (including ordinary cloth masks, N95, and surgical masks) and 804 gloves (including latex gloves, nitrile gloves, plastic gloves, and vinyl gloves) were detected across a cumulative stretch of 43,577 m^2. The presence of PE gloves and surgical masks was higher than the other PPE found in the area under study. However, alcohol sanitizer spray bottles and face shields were not found in the study site • The PPE density recorded at stations closer to crowded areas was higher than the values recorded at more distant stations • Interestingly, 10% of the PPE samples collected per sampling day from the coastal areas of Bushehr port were damaged, highlighting the risk of microfiber and secondary microplastic generation, their release into the marine ecosystems, and their consequent uptake by the marine organisms	Port coastline; Bushehr, Persian Gulf (Iran)	Akhbarizadeh et al. (2021)
6.	• PE, PP	• Sediment and seawater collected from eight sandy beaches (across the Qatar coastline) and four sea surface stations (on the eastern coast) during a survey carried out between December 2014 and March 2015 revealed the presence of microplastics in these samples. The microplastics were predominantly low-density PE and PP. The microplastic concentration in the intertidal sediments ranged from 36 particles m^{-2} to 228 particles m^{-2}, with no notable differences between the eight sandy beaches investigated	Sandy beaches; Arabian Gulf	Abayomi et al. (2017)

(continued)

Table 17.3 (continued)

Sl. no.	Notable examples of plastics found	Key findings	Geographical location/ ecosystem(s)	Reference(s)
7.	• PE, PET, PP, PS, and PVC	• A review covering 98 lakes globally (78 urban +20 rural) found evidence suggesting the presence of microplastics in one or more locations (surface waters, sediments, snow and/or ice, aquatic fauna, and tributaries) of all the lakes. The predominantly studied microplastic size range was 300 microns to 1000 microns • The most common varieties of polymers found in the surface water and sediments of the 98 lakes were PE and PP, which can be associated with the global demand for polymers in 2018 • Another study covering a different set of lakes reported the most common microplastic categories in lake systems across the world to be PE, PET, PP, and polyvinyl chloride (PVC) • Effects of microplastic biomagnification in lake ecosystems have also been observed. For instance, an examination of microplastics in lake Taihu (China) revealed that the microplastic concentration in sampled fish (16.7%) was higher than the concentration of the same in the sampled water (1.8%) and sediments (9.3%) • Analysis of the microplastic content in the two representative estuaries of North China, namely, the Haihe Estuary and the Yondingxinhe Estuary of Bohai Bay, revealed that human activities were the primary driver of microplastic pollution. This finding is consistent with other reports as well. PP was the most predominant microplastic as it is commonly used in making fishing tools and other general items. Interestingly, denser microplastics like PET, PS, and PVC were present in the surface water, whereas lighter microplastics like PE, PP, and PE–PP were found in the sediments	Lake ecosystems; global	Wu et al. (2019), Dusaucy et al. (2021), Yang et al. (2022)
8.	• PE	• In a recent study, microplastics were found at all 15 sampling sites of North German farmlands, and their composition was uniform across all the sites sampled • The mean abundance of microplastics was 3.7 ± 11.9 microplastic particles per kg dry weight • Black films made of PE were the most abundant among the microplastic particles, and the microplastic contamination was noted to decrease with increasing soil depths, despite regular plowing • There is evidence suggesting that microplastic pollution in agricultural soils can negatively impact earthworms, which might lead to a decrease in agricultural productivity	Agricultural land; Northern Germany	Harms et al. (2021)

9.	• HDPE, LDPE, PE, PET, PP, and PS	• Plastics like high-density polyethylene (HDPE), low-density polyethylene (LDPE), PET, and PS have been shown to pollute sea salt in India • PE and PP have been noted to be the most prevalent microplastics across the Coromandel Coast • Microplastics have also been noticed in the marine biodiversity hotspots such as the Gulf of Mannar • Evidence suggestive of the detrimental effects of microplastics on the coral reef found along the coastline, such as the Tamil Nadu coast, has been documented • A study aiming to estimate the microplastic contamination levels in the coral reef ecosystems of the Tuticorin (or Thoothukudi) and Vembar groups of islands (Gulf of Mannar, southeast India) documented an average abundance of 60 ± 54 to 126.6 ± 97 items/l and 50 ± 29 to 103.8 ± 87 items/kg in the water and sediments of the coral reef, respectively. PE was the most abundant polymer, with fibers (1–3 mm) being the most common form in water and fragments (3–5 mm) being the most abundant form in sediment • Benthic and littoral species and fish have been documented to be at risk of microplastic consumption and accumulation • Avian fauna is also at considerable risk of microplastic poisoning. Typically, microplastic accumulation in birds occurs by accidental ingestion during their feeding and via dietary sources • For example, on the basis of their selection of food and closeness to microplastic-impacted areas in the coast of Tamil Nadu, the brahminy kite (*Haliastur indus*), white-bellied sea eagle (*Haliaeetus leucogaster*), and osprey (*Pandion haliaetus*) are most vulnerable to microplastic contamination	Indian coastal ecosystems	Patterson et al. (2020), Vikas Madhav et al. (2020), Choudhury et al. (2022)
10.	• Microplastics	• The abundance of microplastics in the seawaters of Chinese coastal seas was found to range between 0.13 and 545 items/m^3. In contrast, the abundance of microplastics in the estuarine sediments has been documented to range between 20 and 7900 items/kg • High microplastic contamination was found in the estuarine waters, especially during the monsoon season. For example, Pearl River Estuary exhibited maximum microplastic abundance (851 ± 177 items/kg) • Microplastic levels in Chinese seas were moderate or lower compared to other countries	Coastal and marginal seas; China	Jiang et al. (2022)

(continued)

Table 17.3 (continued)

Sl. no.	Notable examples of plastics found	Key findings	Geographical location/ ecosystem(s)	Reference(s)
11.	• Microplastics (synthetic fibers)	• Microplastics were found to contaminate aquaculture installations. For example, 16.4/m^3 microplastics were detected in the region in Jurujuba cove, where mussel farming is practiced • In contrast, the overall mean abundance of microplastics in the Xiangshan Bay was 8.9 ± 4.7 items/m^3 (seawater) and 1739 ± 2153 items/kg (sediment) • The presence of microplastics has also been documented in the freshwater aquaculture environments like the fishponds in the Carpathian Basin (13.79 ± 9.26 particles/m^3), rice-fish co-culture systems in Shanghai (0.4 ± 0.1 items/l), eel culture stations in Shanghai (1.0 ± 0.4 items/l), and scallop aquaculture sites in Shandong • Microplastics have been detected in several aquatic species, namely, commercially edible species like fish, shrimp, crabs, and mussels. For instance, shrimp from coastal waters of the southern North Sea and channel area have shown the presence of synthetic fibers ranging from 200 to 1000 mm (average = 1.23 ± 0.99 items/individual)	Aquaculture ecosystems; China	Chen et al. (2021)
12.	• Microplastics and synthetic fibers	• Microplastic particles (26–51 particles/m^3) have been found in the surface water of the River Ganges, India, which is equivalent to 91% plastic fibers and 9% fragments of plastics • Based on the study findings, it is estimated that 1–3 billion microplastics finally get released into the bay of Bengal based on the flow rates at different sites	Freshwater ecosystem, River Ganges, South Asia (India)	Napper et al. (2021)
13.	• Microplastics	• Microplastics averaging 288 pieces/m^3 found in the river Netravathi, Karnataka, India, 96 pieces/kg in sediment and 84.45 pieces/kg in soil. This river finally debouches in the Arabian Sea. The categories of microplastics obtained are fibers, fragments, and films	River Netravathi, Karnataka, India	Amrutha and Warrier (2020)

On the contrary, it is noteworthy that the number of units generating hazardous wastes across the nation increased by 3.5 percent, but the generation of hazardous wastes has reduced by around 7 percent. In April 2021, India generated 139 tons per day of COVID-19-related BMW, as the world's second populous nation was battling the second wave of COVID-19. In the following month (i.e., May 2021), the figure rose to 203 tons per day (with an increment of 46 percent), which is extremely distressing. The increase in BMW has directly contributed to the astronomical increase in the plastic wastes throughout the pandemic era.

5 The Sustainable Road Ahead

5.1 Microbial Degradation of Plastics

Microbes play a pivotal role in the biological degradation or decomposition of substances, such as synthetic polymers present in the ambient natural environments; this process is known as biodegradation. Petroleum-based polymers or petro-polymers like PE, PET, PP, PS, PU, and PVC are tough to degrade naturally. HDPE and LDPE are among the most frequently utilized synthetic plastics. However, they pose serious environmental threats because of their slow degradability in natural environments. Therefore, there is an increasing interest in the biodegradation of nondegradable/recalcitrant synthetic plastics with the use of effective and selective microbes (Lee et al., 1991; Boonchan et al., 2000; Bonhomme et al., 2003; Gu, 2003; Mohanan et al., 2020).

A few microbes capable of degrading these petro-polymers (i.e., synthetic polymers) under laboratory (in vitro) conditions have been isolated, identified genetically, and characterized. The microbial enzymes involved in petro-polymer biodegradation have been successfully cloned and sequenced in a few instances. Notably, the biodegradation rate of synthetic polymers relies on multiple factors, such as molecular weights, chemical structures, and their degree of crystallinity. Generally, polymers are bulky molecules containing both irregular groups (i.e., amorphous region) and regular crystals (i.e., crystalline region) where the former imparts flexibility to the polymer molecules. Polymers with high crystallinity, such as PE (95%), are usually rigid and have a low capacity for impact resistance. PET-based plastics are also highly crystalline (30–50%), which is one of the main reasons for their low biodegradation rates. Such a slow microbial degradation of PET is predicted to take >50 years for complete degradation under natural environmental conditions and over hundreds of years if disposed into the oceans, primarily because of the low temperature and availability of oxygen (Mohanan et al., 2020).

The enzymatic degradation of plastics takes place in two distinct stages, (1) surface adsorption of microbial enzymes on the polymers, which is followed by (2) hydroperoxidation or hydrolysis of polymeric bonds. Plastic-degrading or petro-polymer-degrading enzymes can be found in microbes from a variety of environments and in the digestive tracts of a few invertebrates. Microbial and/or enzymatic degradation of petroleum-based plastic wastes is undoubtedly a promising strategy

(a) for the depolymerization of these waste petro-plastics into their respective monomeric units, which is useful for plastic recycling purposes or (b) for the bioconversion of these petro-plastic wastes into value-added bioproducts, including biodegradable polymers (or biopolymers) through mineralization (Mohanan et al., 2020).

Numerous studies have been put forward, discussing the role of several microorganisms and microbial enzymes in degrading synthetic plastics. Microbes degrade biodegradable polymers quickly, owing to their inherent ability to degrade most inorganic and organic materials, such as celluloses, hemicelluloses, lignin, and starch. Although a number of reviews and research perspectives have been published on this pertinent topic of plastic biodegradation, these articles have mostly focused on the microbial/enzymatic degradation of a single category of plastic, namely, PE (Restrepo-Flórez et al., 2014), PET (Wei and Zimmermann, 2017; Kawai et al., 2019; Taniguchi et al., 2019), PS (Ho et al., 2018), PP (Arutchelvi et al. 2008), and PU (Cregut et al., 2013; Magnin et al., 2019). Biodegradation of almost all kinds of plastic has been comprehensively reviewed by (Wei and Zimmermann; 2017; Mohanan et al. 2020). The development of biofilms (which are multicellular microbial communities) on synthetic plastic waste surfaces has been proved to be effective degrading agents with enhanced resistance toward antimicrobials.

Moreover, in the majority of natural and artificial habitats, most microbial (bacterial and fungal) populations form biofilms on the solid substratum (Atkinson & Fowler, 1974), and interestingly the metabolic activity of such biofilms was found to be higher than that of individual microorganisms (Kirchman & Mitchell, 1982). Hence, there is a tremendous opportunity for developing a biofilm-based technology for increased plastic biodegradation (Seneviratne, 2003). In order to enhance the biodegradation process, chemicals or photoinitiators (molecules that generate reactive species like free radicals, anions/cations upon exposure to UV/visible radiation) or both are often added to the PE; these modified PE are then referred to as degradable PE (DPE) (Lee et al., 1991). In one such study by Seneviratne et al. (2006), microbes associated with different disposed PE (e.g., carry bags) lying and degrading in the soils were isolated and identified for developing a fungal-bacterial (*Penicillium frequentans* and *Bacillus mycoides*) biofilm for enhanced DPE biodegradation.

Notably, biological upcycling (also referred to as bio-upcycling) of plastic wastes is comparatively a newer and innovative sustainable strategy that requires further attention (Fig. 17.5) (Wierckx et al., 2015; Salvador et al., 2019; Blank et al., 2020). Jaiswal et al. (2020) has reviewed recent state-of-the-art biotechnological approaches, including applying synthetic bacterial/microbial consortia, systems biology, and genetic engineering tools/techniques that can pave the way for bioremediation of plastics through their biodegradation in the future.

5.2 *Biodegradable Plastics or Bioplastics*

Bioplastics are a suggested alternative to conventional plastics derived from mineral oil. Bioplastics are environment-friendly because of their biodegradability. Conventional nondegradable plastics are threats to the environment, and replacing

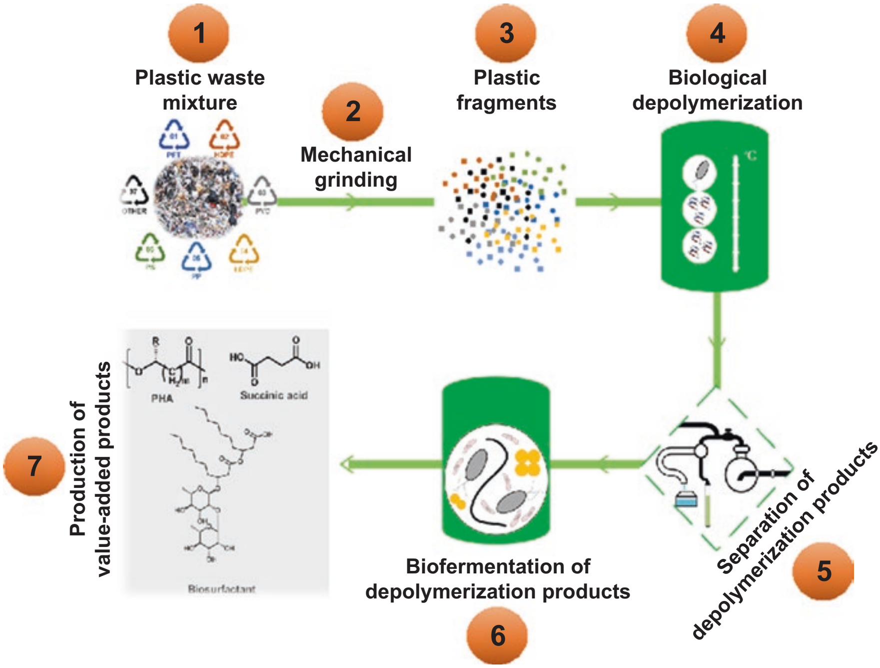


Fig. 17.5 The generalized concept of biological upcycling of plastic wastes. A mixture of various plastic wastes is first mechanically ground and biologically depolymerized using plastic-degrading microbes and microbial enzymes. The depolymerization products are then separated from the start-up culture and used as feedstock for microbial fermentation to produce chemicals/substances with high commercial value like biosurfactant, polyhydroxyalkanoate (PHA), and succinic acid. (Source: Adapted from Ru et al. (2020) with modifications)

these petroleum-based plastics with bioplastics can help overcome environmental plastic pollution; this can be a sustainable global solution. Bioplastics are made from biomass or fossils. The common raw materials that are used to produce biodegradable plastics and compostable biopolymers are maize, wheat, sunflower, wood, rice, sugarcane, etc. (Ilyas et al., 2016). Cellulose and sugar are not plastic but are converted to plastic through various innovations in polymer or fermentation technology (Misra et al., 2011). The following techniques such as extrusion (Wang, 2007), internal mixing (Mhumak & Pechyen, 2017), injection molding (Salleh et al., 2012), and casting (Yudianti & Karina, 2012) could be used for the sustainable development of bioplastics.

Polyhydroxybutyrate (PHB), a polymer utilized for bioplastic production, is utilized by microorganisms as carbon and energy sources. The enzyme that is secreted by the microbes is polyhydroxyalkanoate depolymerase to degrade the bioplastics (Mukherjee & Chatterjee, 2014). Several types of bioplastics are synthesized using various biodegradable polymers, but the biodegradability varies, and only the ones based on the polymer PHB are 100% biodegradable. The polyhydroxyalkanoates (PHA), which have been most characterized, are PHB and its copolymers, poly(3-hydroxybutyrate) [P(3HB)] and poly(3-hydroxybutyrate-co-3-hydroxyvalerate)

[P(3HB-co-3 HV)]. The polymers, PHBs, are synthesized by bacteria and are accumulated as reserve materials during their growth phase under conditions of stress (Galia, 2010), i.e., when certain nutrients become limiting like carbon (as in the case of Hyphomicrobacterium spp. and *Spirillum* spp.), nitrogen (as in the case of *Ralstonia eutropha*, *Pseudomonas oleovorans*, and *Alcaligenes latus*) and phosphates (as in the case of *Caulobacter crescentus* and *Rhodobacter rubrum*) (Kim & Lenz, 2001). More than 250 microorganisms have been identified so far, which can biosynthesize PHB naturally. However, a few are viable commercially, namely, *Alcaligenes latus*, *Bacillus megaterium*, *Cupriavidus necator*, and *Pseudomonas oleovorans*, as a low-cost and easily usable substrate having high sugar that can be utilized as a carbon source. Although greater than 300 variety of microorganisms are known to synthesize PHA, only some of these are best suited to produce high-yielding PHA (e.g., *Alcaligenes latus*, *Azotobacter vinelandii*, *Ralstonia eutropha*, recombinant *Escherichia coli*, and several strains of methylotrophs) (Lee, 1996; Lee & Chang, 1995). Bioplastics can be derived from various sources, and some common bioplastics produced from these sources are given in Table 17.4.

5.2.1 Toxicological Impact of Biodegradable Plastics

The toxic effects of pure plastics on living organisms are less because of their relative chemical inertness and water insolubility. For altering the tensile strength of plastics, plasticizers like adipates and phthalates are mixed with various plastic products, including PVC as an additive, which percolates from the plastic products in trace amounts. It has been predicted that PS present in the food containers leached and entered the body tissues of humans, causing hormonal imbalance; PS is highly carcinogenic and may have adverse impacts on living organisms. Notably, the parent polymer products are not toxic, but the monomers used during the production process are highly toxic (Venkatesh et al., 2021). Aswale (2010) investigated the impact of biodegraded PE on the germination of seeds in plants such as groundnut, safflower, sesame, soybean, and sunflower. A reduction in seed germination percentage was observed in the case of pre-treated seeds during the study. Other groups of researchers studied the microbial degradation of LDPE/PE, using both bacteria (*Pseudomonas aeruginosa*, *Staphylococcus aureus*, *Streptomyces* sp.), fungi (*Alternaria alternata*, *Aspergillus* spp., etc.), and bacterial-fungal biofilm (*Bacillus mycoides* and *Penicillium frequentans*) along with the level of biodegraded PE toxicity (Seneviratne et al., 2006; Pramila & Ramesh, 2011; Ameen et al., 2015). It is to be noted that the main product produced during PE degradation is CO_2.

Moreover, the granules produced from the bio-treated PE negatively impacted the plant roots, resulting in abnormalities in polysaccharide and protein production and uptake of nutrients (Abrusci et al., 2011). According to the report of Bonhomme et al. (2003), the only degradation products of environmentally degradable commercial PE, produced in the presence of the selected bacteria (*Nocardia asteroides* GK 911 and *Rhodococcus rhodochrous* ATCC 29672) and fungus (*Cladosporium cladosporioides* ATCC 20251) after two (abiotic and biotic) stages of OXO-biodegradation [i.e., "degradation resulting from oxidative and cell-mediated

Table 17.4 List of bioplastics, their compositions, and microbes used for their biodegradation

Sl. no.	Types of available bioplastics	Substrate(s)/source(s)	Composition	Microorganism(s) used for degradation	Reference(s)
1.	Cellulose-based bioplastics	Pomegranate (*Punica granatum*) peel	Pectin, celluloses, hemicelluloses, and lignin	*Bacillus subtilis*, *Pseudomonas aeruginosa*	Gumienna et al. (2016), Ko et al. (2021)
		Orange (*Citrus sinensis*) peel	Pectin, starch, lignin, celluloses, and hemicelluloses	*Bacillus subtilis*	Bátori et al. (2017), Umesh et al. (2018)
		Water hyacinth (*Eichhornia crassipes*)	Celluloses, lignin, and hemicelluloses	*Bacillus subtilis*, *Pseudomonas aeruginosa*	Preethi and Vineetha (2015)
		Rice (*Oryza sativa* L.) straw	Celluloses, hemicelluloses, and lignin	*Pseudomonas aeruginosa*	Bilo et al. (2018), Suardi et al. (2018)
2.	Starch-based bioplastics	Banana (*Musa balbisiana*) peel	Starch, celluloses, hemicelluloses, protein, and pectin	–	Mehta et al. (2014)
		Potato (*Solanum tuberosum* L.) peel	Starch, non-starch polysaccharides, lignin, polyphenols, protein, and lipids	*Alcaligenes latus*, *Bacillus subtilis*, *Micrococcus*	Wang et al. (2013), Trivedi et al. (2016), Priedniece et al. (2017))
		Cassava (*Manihot esculenta*)	Starch, soluble sugar, uronic acid, lignin, and ash	*Acetobacter xylinum*	Adhani et al. (2019)
3.	Protein-based bioplastics	Wheat (*Triticum aestivum*) gluten	Glutenins and gliadins	–	Jiménez-Rosado et al. (2019)
4.	Oil-based bioplastics	Soybean (*Glycine max*) oil	Protein, fat, and carbohydrate	–	Park and Kim (2011)
		Cotton (*Gossypium hirsutum*) seed oil	Fatty acids and triacylglycerols	*Ralstonia* spp.	Magar et al. (2015)

(continued)

Table 17.4 (continued)

Sl. no.	Types of available bioplastics	Substrate(s)/source(s)	Composition	Microorganism(s) used for degradation	Reference(s)
5.	Polylactic acid (PLA) bioplastics	Starch, lignocellulosic biomass, agro-industrial wastes, and glycerol	Starch, lignin, and celluloses	*Lactobacillus amylophilus, Lactobacillus bulgaricus, Lactobacillus delbrueckii, and Lactobacillus leichmannii*	Jiménez et al. (2019)
6.	Polyhydroxyalkanoates (PHA) bioplastics	Corn (*Zea mays*) starch, glucose	Starch and glucose	*Azotobacter* sp., *Bacillus* sp., *Bacillus subtilis*, *Burkholderia* sp., *Cupriavidus* sp., *Pseudomonas* sp., and recombinant *E. coli*	Singh et al. (2009), Gupta et al. (2020)

phenomena, either simultaneously or successively" as defined by the European Committee for Standardization (CEN) in CEN/TR 1535–2006 (Hann et al., 2016)], were protein and polysaccharides. Kannahi and Sudha (2013) noticed the production of aldehyde, carboxylic acids, and ketones in the smoke of LDPE film extrusion.

5.3 Advocating the Principle of 4 Rs

As per the data on global urbanization released by United Nations, 55% of the world's population urbanized in 2018, compared to 30% in the year 1950 (United Nations, 2018). With a projected rate of urbanization to be 68% in 2050, the concept of sustainable living becomes more and more crucial and of paramount importance. The vision of a sustainable city is based on a closed system of manufacturing and utilization. Rural employment is reducing as agriculture is getting modernized with less mechanization; the charm and enchantment of city life allure the rural population to move to the adjoining cities. As the population of cities is sprawling, the resources need to be shared, recycled, and reused effectively for sustenance. One of the most challenging tasks ahead is managing the flow of materials in the increasing urban population. In the present *era*, the management of solid wastes, especially persistent plastic components, is vital for sustainable growth and development.

The burden of plastic wastes can be minimized by changing people's traditional thinking and practicing the principle of 4 Rs, i.e., reduce, reuse, recycle, and refuse/recover (Fig. 17.6).

1. Reduce: The foremost principle in managing wastes is reducing and avoiding waste accumulation. It emphasizes discontinuing those processes that produce hazardous wastes and replacing them with environmentally friendly activities; this leads to less waste generation, and the related overheads on treatment, disposal, and environmental effect are also reduced. The substitute or replacement of synthetic plastics would imply using eco-friendly alternatives like jute, cotton, or hemp, as they are made from plant materials.
2. Reuse: The following principle favors the concept of reutilizing materials or things that could be discarded or trashed, and this is primarily applicable to the end users. At times, reuse might require repairing the item or making it suitable for at least short-term if not long-term usage. This principle can help in reducing the generation of plastic wastes.
3. Recycle: The following principle in the waste management hierarchy is recycling, which involves electrical or mechanical processes to convert waste materials into valuable items for use afresh. Although recycling is eco-friendly, it is labor- and cost-intensive. Hence, waste reduction, avoidance, and reuse are recommended before recycling.
4. Refuse/Recover: Above all these, it facilitates minimizing waste generation if the end users refuse. Recovery of useful plastic monomers/components from plastic wastes is a futuristic concept and would be extremely expensive and would require a massive setup and enormous workforce unless robotics are

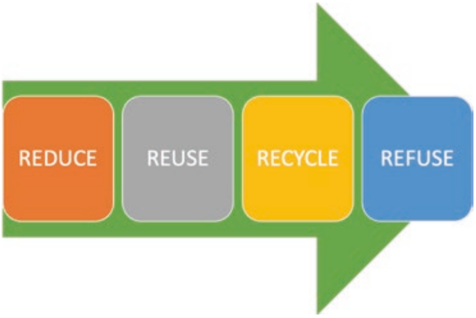


Fig. 17.6 Illustration of the principle of 4 Rs

introduced. If the concept sees the light of the day, then it will revolutionize the entire plastic waste management system.

5.4 Circular Economy

The concept of zero waste is part of a circular economy where all the wastes move from a linear model to a circular one wherein the wastes from consumption become the raw material for the new product (Fig. 17.7).

The concept of circular economy has various benefits, some of which are listed below.

- It helps in reducing the environmental plastic footprints.
- It helps in minimizing wastes.
- It helps in increasing income, eventually, the economy of the whole nation.
- It helps in reducing the dependencies on resources.

6 Conclusions and Way Forward

Synthetic polymers/plastics are indispensable in our current lifestyle. Consequently, daily use of synthetic plastics results in plastic pollution, which is among the most alarming issues of recent times from the environmental, organismal, and human health perspective. This current trend of uncontrolled synthetic polymer or SUP use coupled with improper plastic waste management, leading to plastic accumulation, is undoubtedly a wake-up call for global citizens, environmentalists, law, and policymakers. Although many will argue that plastic pollution is the problem of the underdeveloped or developing nations, the fact that plastic waste generation and disposal of the Asian, North, and South American nations can accumulate as a gigantic floating gyre of marine debris (the Great Pacific garbage patch) in the central North Pacific Ocean near Hawaii-California-Japan refute that argument. Moreover, from Antarctica (South Pole) to the tip of the Himalayas (the Mt. Everest, Nepal), from the tropical rainforest of Amazon, Brazil to the mangrove forest of

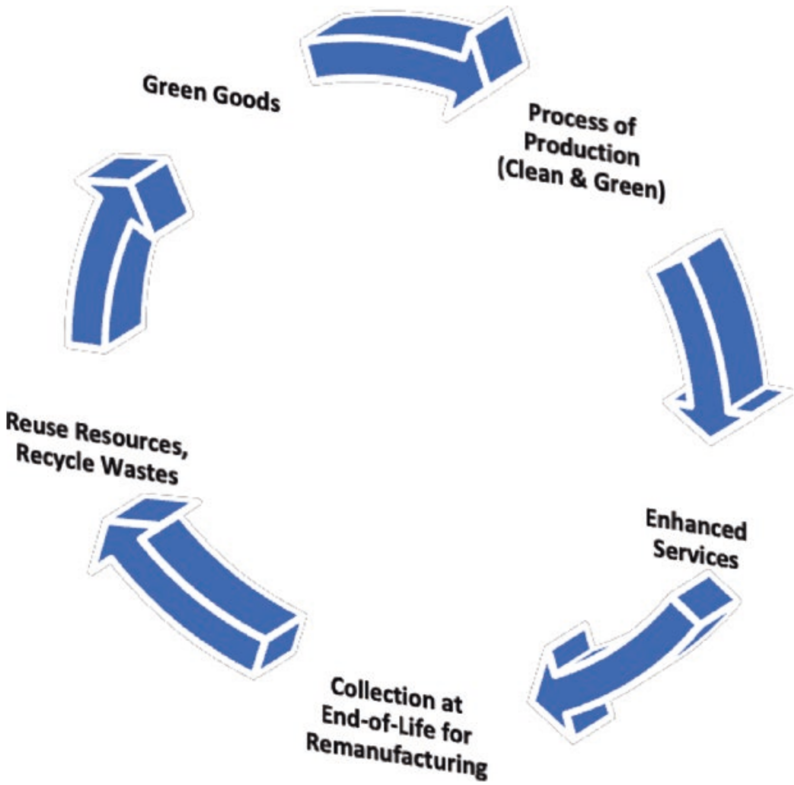


Fig. 17.7 Representative flow diagram of circular economy

Sundarbans, India, and Bangladesh, from the Sahara desert, Africa to the Pacific Ocean, there is hardly any place on earth where plastics have not left their footprints.

In addition to the existing problem of plastic overuse, the COVID-19 pandemic came as a bane for the global environment. While safety restrictions imposed because of the pandemic led to a substantial reduction in air and water pollution due to the lowering of human activities, there has been an exorbitant increase in plastics' use worldwide. The astronomical hike in online shopping for groceries and associated essential home supplies and use of disposable plastic utensils and packaged food and protective gears while under lockdown or in self-quarantine have led plastic pollution out of control. The solid waste management system in developing countries like India already has its inherent lacunae because of a shortage of human resources, machinery, funds, policies, public awareness, etc. Excessive use of plastics has further augmented this problem, polluting the ambient environment.

Moreover, the biomedical plastic waste generated in overloaded hospitals is adding to the existing plastic waste burden. Upon getting submerged in water, the disposable masks cause the leaching of toxic chemicals like heavy metals and nanoplastics into the environment, thereby impacting aquatic life in the long term. Massive use and casual disposal of PPE suits, disposable surgical/other masks, face shields, gloves, and shower caps has been a perennial nuisance during the ongoing pandemic worldwide. Therefore, there is a crucial need to mitigate this uncontrolled rise in plastic pollution by introducing eco-friendly alternatives to conventional synthetic plastics for daily household or medical use.

Petro-polymers, including PE, PET, PP, PS, PU, and PVC, are highly recalcitrant to normal biodegradation pathways. Natural degradation of synthetic plastic with the action of microbes and microbial enzymes is prolonged and can take several hundred to thousand years, even though total degradation is never possible. The plastic biodegradation rate depends on many factors like the type of plastic used or their chemical structures, molecular weights, and degrees of crystallinity. For optimal microbial biodegradation of plastics, it is highly recommended to select appropriate microbial strains, adapt suitable in situ and ex situ bioremediation techniques, continuously monitor bioremediation sites, and adequately maintain such sites by providing adequate aeration, necessary nutrients for optimum microbial growth, and appropriate physicochemical conditions. Additionally, improvement and acceleration of bioremediation of plastic wastes and their disposal can be made through high-throughput genetic identification and molecular analyses of microbial genes expressing plastic-degrading enzymes in conjunction with recombinant DNA technology (for creating synthetic polymer-degrading genes). The focus should be centered on sustainable plastic waste management and shift toward plant-based green materials like jute, hemp, bamboo, coir, and bioplastics; thus, an immediate solution to this problem is the manufacture and commercialization/use of biodegradable plastics, which can undergo up to around 60% decay based on current innovations. Other options for sustainable plastic waste management are highlighted here.

1. Creating public awareness about plastic pollution and its ill effects on living organisms (through area-wise mass-level monthly campaigns on plastic pollution).
2. Scientific management and proper disposal of plastics; dissemination of appropriate plastic disposal methods among people must be done using all available media platforms. Moreover, awareness on plastic disposal should start at the primary school level by guiding students and their parents about proper segregation of biodegradable and nonbiodegradable plastic wastes before their disposal.
3. Encouraging people to use bio-based products.
4. Building strict laws and policies.
5. Advocating the principle of 4 Rs, i.e., reduce, reuse, recycle, and refuse/recover within the global community in the present and in the post-pandemic *era*.

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