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Microbial strategies for degradation of microplastics generated from COVID-19 healthcare waste

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A R T I C L E I N F O

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A B S T R A C T

COVID-19 pandemic has led to the generation of massive plastic wastes, comprising of onetime useable gloves, masks, tissues, and other personal protective equipment (PPE). Recommendations for the employ of single-use disposable masks made up of various polymeric materials like polyethylene, polyurethane, polyacrylonitrile, and polypropylene, polystyrene, can have significant aftermath on environmental, human as well as animal health. Improper disposal and handling of healthcare wastes and lack of proper management practices are creating serious health hazards and an extra challenge for the local authorities designated for management of solid waste. Most of the COVID-19 medical wastes generated are now being treated by incineration which generates microplastic particles (MPs), dioxin, furans, and various toxic metals, such as cadmium and lead. Moreover, natural degradation and mechanical abrasion of these wastes can lead to the generation of MPs which cause a serious health risk to living beings. It is a major threat to aquatic lives and gets into foods subsequently jeopardizing global food safety. Moreover, the presence of plastic is also considered a threat owing to the increased carbon emission and poses a profound danger to the global food chain. Degradation of MPs by axenic and mixed culture microorganisms, such as bacteria, fungi, microalgae etc. can be considered an eco-sustainable technique for the mitigation of the microplastic menace. This review primarily deals with the increase in microplastic pollution due to increased use of PPE along with different disinfection methods using chemicals, steam, microwave, autoclave, and incineration which are presently being employed for the treatment of COVID-19 pandemic-related wastes. The biological treatment of the MPs by diverse groups of fungi and bacteria can be an alternative option for the mitigation of microplastic wastes generated from COVID-19 healthcare waste.

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1. Introduction

The COVID-19 pandemic has posed additional challenges in developed as well as developing countries by creating huge amounts of plastic waste. This pandemic had a profound impact worldwide (Anand et al., 2021), generating a huge amount of municipal wastes comprising one-time useable plastic wares, gloves, masks, tissues and other personal protective equipments (PPEs) which have been dumped (Anand et al., 2021b; Anand et al., 2022; De-la-Torre and Aragaw, 2021; Iyer et al., 2021; Zand and Heir, 2020). The recommendation of using face masks by the authorities is essential to control the transmission of infection, however, improper disposal of the masks is leading to the generation of a massive amount of waste worldwide. The usage of single-use disposable face masks has been estimated to be around 129 billion per month in the pandemic era (Prata et al., 2020). The different types of biomedical waste produced during the COVID-19 pandemic have been represented in Fig. 1. Most single-use masks and PPEs are made up of various polymeric substances such as polystyrene, polypropylene, polyethylene, polyurethane, and polyacrylonitrile which are persistent and can be emergent sources of microplastics (MPs) contamination in the aquatic, atmospheric, and terrestrial ecosystems (Anand et al., 2021c; Aragaw, 2020; Jung et al., 2021). Moreover, the imposition of lockdowns during the COVID-19 pandemic has led to the surge in the use of different plastic containers made up of low- and high-density polyethylene (LDPE and HDPE), polypropylene (PP) and polyethylene terephthalate (PET) for food packaging (Jribi et al., 2020). This addition of plastic waste material coupled with additional hazardous plastic wastes generated by the healthcare sector has increased the production of waste in addition to municipal solid wastes (MSW), construction, demolition wastes, and electronic wastes, resulting in lots of hurdles in their management. Improper disposal and handling of healthcare wastes and lack of proper healthcare and management practices are not only creating serious health hazards but also causing an extra challenge for the local authorities in proper management of solid waste. The government of different countries such as the USA, China and India are following several policies and legislative regulations for the management of the huge quantity of waste that is generated from hospitals and households (Singh et al., 2020; USEPA, 2020; Anand et al., 2021d). Several countries around the world have also taken action and followed the instruction and guidelines issued by different agencies, such as UN Environmental Programme (UNEP), UN-Habitat, World Health Organization (WHO), the World Bank, World Wildlife Fund (WWF), as well as other international organizations, such as Asian Development Bank (ADB) and International Solid Waste Association (ISWA) (UNEP and ILRI, 2020; United Nations Human Settlements Programme, 2020; WHO, 2020; World Bank, 2020; ISWA, 2020).

In the municipalities where there is no residential source separated organics program, the face mask, and other personal use protective equipment can mix up with the organic components in a landfill. Subsequently, the organic components of the landfill can be used for composting or anaerobic digestion leading to excessive pollution. If they are not recycled properly, they may add to the production of hazardous environmental pollutants *viz.* dioxins, polybrominated diphenyl ethers (PBDEs), phthalates, tetrabromobisphenol A (TBBPA), and toxic metals such as cadmium and lead. Presently, solid waste treatment is largely managed by landfilling and incineration practices, however, during the COVID-19 pandemic, the excessive production of waste has imposed significant pressure on the existing strategy (Iyer et al., 2021; Khoo et al., 2021). Many of these surgical wastes have been identified as a threat to the environment by various agencies like the world wildlife fund (WWF), Green-peace, and Marevivo (COVID-19, 2021) for being the source of MPs and nanoplastics (Aragaw, 2020; Khoo et al., 2021; Shen et al., 2021). It has been reported that these MPs may negatively impact the methanogenic communities occurring in anaerobic digestors and is also responsible for different types of health hazards including disruption of metabolic processes, cancer, and an increase in neurotoxicity in human being (Rahman et al., 2021).

These types of pollutants can undergo weathering and mechanical stresses such as mechanical abrasion and UV lighting resulting in the formation of MPs (De-la-Torre and Aragaw, 2021) and it has been estimated that each face mask releases a huge amount of MPs which poses serious environmental problems and health hazards (Wang et al., 2021). According to a study made by Peng et al. (2021) it was reported that globally around 8.4 ± 1.4 million tons of pandemic associated plastic

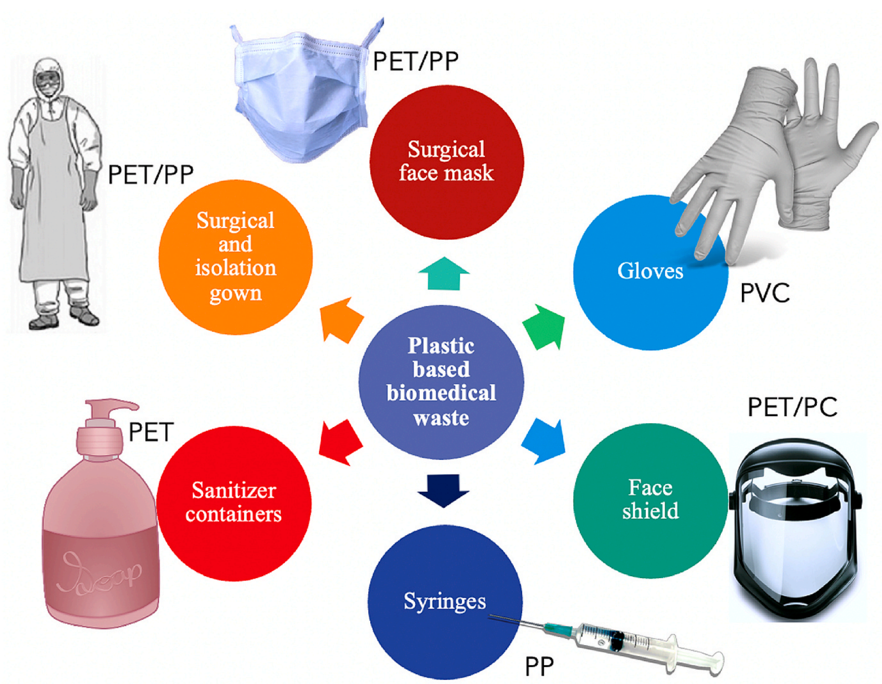

Fig. 1. Main typologies of plastic-based biomedical wastes originated during the COVID-19 pandemic. PP: polypropylene, PET: polyethylene, PVC: polyvinylchloride, PC: polycarbonate.

wastes were generated from 193 countries by August 23, 2021, of which 25.9 ± 3.8 thousand tons entered the global ocean. Most of these plastic wastes later were degraded to form microplastic particles causing environmental pollution. There have been several reports on the environmental impact of MP pollution by several research groups where they have emphasized the health hazards caused by MP particles on humans and aquatic flora and fauna (Anand et al., 2021c; Reid et al., 2019; Wang et al., 2021). In the present situation, MP pollution has increased many folds and resulted in a major threat to aquatic flora and fauna which forms the biggest share of the food web which is essential for human existence and raise a global concern on food safety (Fadare and Okoffo, 2020; Shen et al., 2020; Reid et al., 2019). MPs have been found in guts, tissues, and other parts of different animals in aquatic ecosystems (e.g., gills, intestine, and stomach of fishes) which jeopardises the aquatic fauna (Kale et al., 2015).

The present article aimed to discuss the impact of MP containing hazardous wastes generated during the COVID-19 pandemic period. The management of these plastic hazardous wastes was also discussed in detail along with the use of microbial and other biological strategies which are used for the removal of the MP.

2. Composition of COVID-19 medical waste and its fate in the environment

The COVID-19 medical waste largely comprises PPE kits, disposable masks, gloves and other associated protective wear containing plastics which were extensively used during the pandemic. These PPE kits and disposable masks are made up of high-density polyethylene and polypropylene which are mainly produced by non-woven fabrics (Chua et al., 2020). Apart from polypropylene, other polymers, such as polyester, polyethylene, polystyrene or polycarbonate are also used for making the masks (Akber Abbasi et al., 2020). N95 mask was highly approved by different agencies to prevent infection, mainly consisting of four different layers consisting of spun-bond polypropylene, cellulose/polyester, the inner layer of spun-bound polypropylene, and melt-blown polypropylene filter material (Barycka et al., 2020). The composition of different PPE is presented in detail in Table 1.

Sullivan et al. (2021) reported that most commercially used face masks showed the presence of heavy metals like lead and cadmium, plastic oligomers, surfactants, and dye-like molecules which pose long-term health risks. Similarly, nitrile, latex, and foil gloves also contribute plasticizers, emulsifiers, and heavy metals to the environment.

Most of these contents have low photooxidative stability and are extremely susceptible to oxidation of air and ultraviolet radiation ($\lambda_{315-400nm}$). Moreover, they may also interact with impurities, such as hydroperoxides, and carbonyls, which acts as a chromophore (Tocháček and Vrátníčková, 2014). The excited chromophores induced the polymer chains' photooxidative degradation, eventually causing damage to the material. The process generates free radicals which in turn can attack the backbones of different macromolecules causing chain cleavage (Mylläri et al., 2015). All these changes led to the loss of mechanical properties leading to materials degradation. They also form different types of oxygenated species having ketones and esters (Almond et al., 2020) which finally generate MPs (De-la-Torre and Aragaw, 2021; Saliu et al., 2021). Also, mechanical abrasion in presence of quartz sand can generate MP particles (Saliu et al., 2021). It was also confirmed in different studies that each face mask releases millions of MP particles made of polypropylene. Akber Abbasi et al. (2020) reported the presence of nearly 4.5 g and 9 g of polypropylene from surgical masks and N95 masks, respectively. Selvaranjan et al. (2021) reported the generation of a minimum of about 2.5 kt, 0.6 kt, and 0.04 kt polypropylene plastic from Australia, the USA, and India per week respectively.

Table 1
Composition of different personal protective equipment.

Components	Types of personal protective equipment	Materials used	Weight (%)
Mask	Tie-on surgical face mask	Polypropylene fabric rayon outer web	2
	Classical surgical mask, blue	Cellulose polypropylene, polyester	–
	Sofloop extra protection mask	Cellulosic fibers with polypropylene and polyester, ethylene methyl acrylate strip	–
	Aseptex fluid resistant	Polypropylene blend with an acrylic binder	–
	Surgical grade cone style mask	Molded polypropylene	–
Gloves	–	Nitrile butadiene rubber	4
Goggles	–	Polycarbonate	10
PPE kit	–	Polypropylene fabric	84

The material that comprises of these products were identified primarily based on manufacturer specification (PAHO, 2020).

3. Pollution caused by COVID-19 waste: the existing situation

The healthcare sectors are responsible for nearly 9% of air pollution, 10% of smog formation, 10% of the greenhouse gases, and 12% of the acid rain contributing to ozone depletion and release of carcinogenic and noncarcinogenic volatile toxic compounds all over the world (Manzoor and Sharma, 2019). However, the impact of the COVID-19 pandemic has worsened the situation to a great extent. Even if World Health Organization (WHO) has given a stringent protocol for the disposal of biomedical waste into the environment, the inappropriate disposal of solid waste in illegal dumping sites and the lack of infrastructure have compounded the problem of proper management of COVID-19 wastes (Akhbarizadeh et al., 2021; Thiel et al., 2003). Moreover, the ongoing Pandemic has led to extensive PPE pollution in coastal areas, rivers, and urban areas (Ardusso et al., 2021; De-la-Torre and Aragaw, 2021). Xiang et al. (2020) reported that the USA alone was estimated to use about 89 million medical masks due to the COVID-19 pandemic, whereas the estimated use of masks per year in the United Kingdom was around 24.37 billion. Both China and Japan were reported to use around 14.8 million face masks per day and 600 million face masks per month, respectively during the early phase of the pandemic (Fadare and Okoffo, 2020). The estimated face mask wastes generated worldwide due to the ongoing COVID-19 pandemic have been represented in Fig. 2.

Saliu et al. (2021) reported that in the year 2020 the global production of facial masks was estimated to be around 2.4 to 52 billion pieces which produced nearly 7200–312,000 tons of MP-containing waste. Out of which nearly 1–10% were released in the ocean which accounts to nearly 72 to 31,200 tonnes of MP wastes. Several pieces of research were conducted on the impact of this increasing pollution due to PPE kits on the environment (Akhbarizadeh et al., 2021; Kale et al., 2015; Wang et al., 2021). Kumar et al. (2021) recorded that they caused the highest Global Warming Potential (GWP) with 3816.06 kg of total CO_2 emission. The Acidification Potential (AP), Human Toxicity Potential (HTP) and Freshwater Aquatic Ecotoxicity Potential (FAETP) were noted to be significantly elevated because of PPE suits and masks.

In overpopulated countries like India, it has become very challenging for the Government to develop proper management of COVID-19 wastes. The Central Pollution Control Board (CPCB), Delhi, India declared several guidelines for the segregation and dumping of biomedical wastes (Central Pollution Control Board CPCB, 2020). Organizations, such as Common Biomedical Waste Treatment and Disposal Facilities (CBWTF), local bodies, and State Pollution Control Boards are designated to apply and carry out the rules. Moreover, the Ministry of Environment, Forest and Climate Change has released several guidelines for Biomedical Waste Management (Central Pollution Control Board CPCB, 2020) which included segregation of biomedical waste and fast delivery of

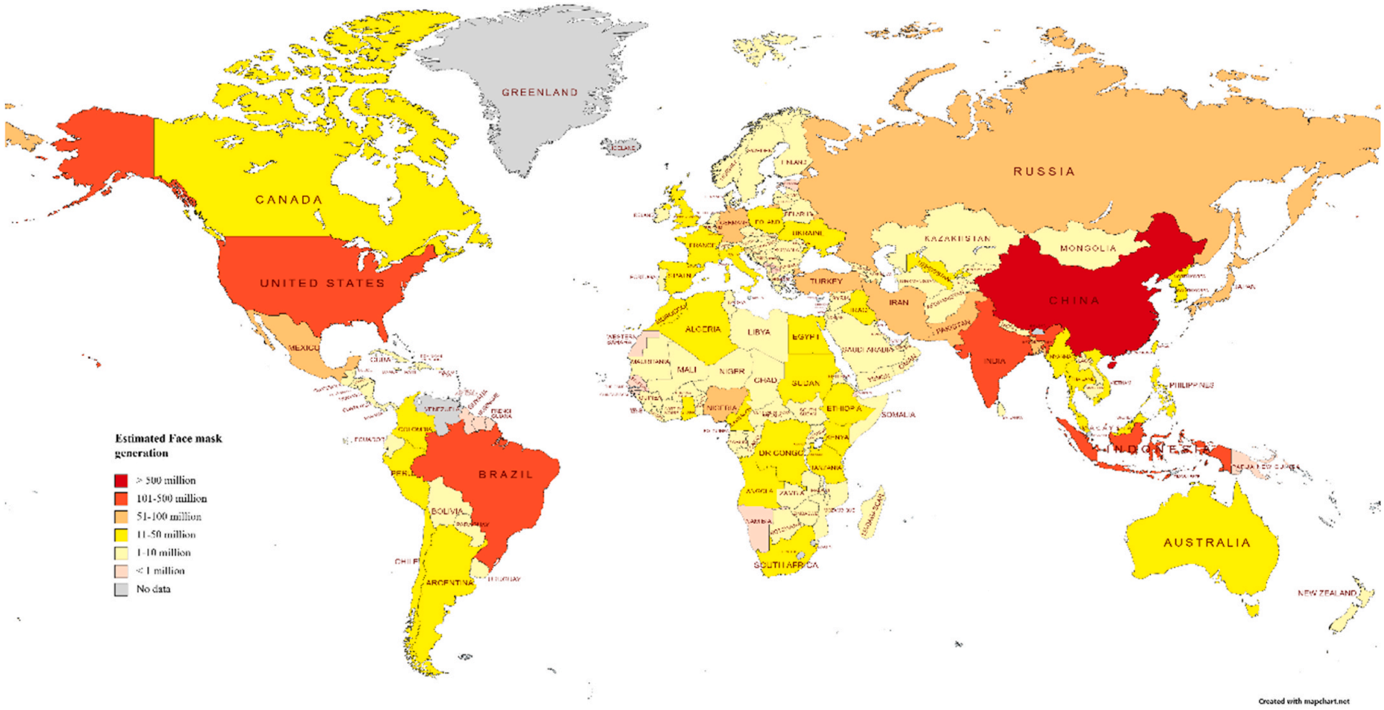

Fig. 2. Estimated face mask waste generated worldwide due to the ongoing COVID-19 pandemic (Map created by mapchart.net) (Benson et al., 2021).

waste to CBWTF. In developing and populous countries like India, the practical implementation of waste management guidelines including daily disinfection of containers and bins, use of double-layered bags, and regular sanitization become challenging (Aggarwal, 2020; Central Pollution Control Board CPCB, 2020).

4. Health associated with MP pollution in aquatic life and humans

MPs have a huge impact on the aquatic flora and fauna as it acts as a vector for the transport of heavy metals and persistent organic pollutants (Enders et al., 2015). Moreover, pandemic associated MP discharge has elevated potential ecological and health risks manyfold and even contributed to the indirectly spreading of the virus (Peng et al., 2021). PPE kits and single-used masks have been disposed of in water bodies can stick to the gill and fins of aquatic fauna causing its death. The fishing and aquaculture industry is most impacted as it is highly fragile, and its viability and productivity are affected by the presence of plastic waste in water bodies (Rochman et al., 2013). Moreover, these plastics may degrade and generate MPs which when ingested cause intestinal blockage subsequently reducing the absorption of nutrients and change in hormonal balance (Derraik, 2002). The improper absorption of the nutrients may result in a decrease in the ability of the organism to survive in adverse environmental conditions.

The impact of MPs on the growth and diversity of the microalgal and cyanobacterial population is usually varied. According to the study made by Khoironi and Anggoro (2019) it was reported that the growth of *Spirulina* sp. was severely impacted in the presence of a higher concentration of MPs which was largely affected due to shading effects and reduced light intensity. Li et al. (2018) reported that both PE and PP gradually degrade to microsized plastics and release potentially toxic additives including plasticizers, polychlorinated biphenyls, dichloro-diphenyl-trichloro-ethane, and heavy metals such as cadmium, chromium, bromium, copper, and titanium which cause cell membrane damage and growth inhibition (Campanale et al., 2020).

The effect of MPs on humans is not fully understood and requires further research. Humans usually uptakes MPs through three main pathways, such as ingestion, inhalation, and dermal contact. It is calculated that through inhalation a person can uptake 26 to 130 MP per day and impacts the respiratory system depending upon their size, hydrophobicity and absorption ability (Prata et al., 2020). The deposition of MP particles is largely dependent on the size and density of the particles. The less-dense smaller particles tend to be deposited deepest in the lungs which causes the release of chemotactic factors resulting in chronic inflammation (Gasperi et al., 2018; Prata et al., 2020). MPs also can cause an imbalance in the production of reactive oxygen species (ROS) and antioxidant capacity, and subsequently can cause oxidative damage (Kim et al., 2021).

5. Strategies for the management of COVID-19-related healthcare products

The Directives of WHO has given a mandate for incineration of PPEs and other COVID-19 healthcare product wastes (World Health Organization, 2020). The plastic materials present in the wastes are chemically stable and refractory to microbial degradation. For medical waste, treatments ranging from 900 °C to 1200 °C are generally made for safe destruction (Ilyas et al., 2020). However, there have been limitations in the widespread use of incineration as the enhancement in the quantity of biomedical waste has resulted in the generation of excessive pressure on the incineration facilities. In China alone, there has been a 370% and 600% rise in the quantity of biomedical waste in the Hubei and Wuhan provinces which largely exceeds the highest incineration capacity available in the country (Jiri et al., 2020; Klemes et al., 2020). Similarly, according to the Waste Agency of Catalonia, (ACR, 2020), there has been a 350% enhancement in COVID-19 medical waste with the formation of extra 925 tons of waste/month. Incomplete combustion generates products which get disintegrated after cooling and produces smaller MP particles which in turn leads to further pollution. The dioxin and furans, that may be generated during incineration, are released into the environment along with other toxicants. These toxicants are carcinogenic and can be stored in fat cells. Once entering the food chain, they activate aryl hydrocarbon receptors in humans which in turn induces hormonal imbalance, immunological disorders and also harms the immune system

(Ilyas et al., 2020; Bhar et al., 2022). Various disinfection processes, using steam, microwave, autoclave, chemicals as well as on-site incineration, are currently in use for managing harmful COVID-19 medical wastes in developing countries. In most developing countries like India, Pakistan, Bangladesh, Brazil, Argentina, and Peru, biomedical wastes are widely treated by incineration (Manzoor and Sharma, 2019). However, prior to incineration, the waste should be subjected to initial disinfection treatment. The ash produced in the process of incineration is analysed for toxicity before they are safely disposed of in a landfill (Makarichi et al., 2018).

Rotary kiln incineration is widely used all over China for the treatment of COVID-19 medical waste (Dharmaraj et al., 2021). It is considered an efficient method as it helps in the mixing of wastes along with a capacity of treatment of 0.5–3 tonnes of waste/hour. The incineration temperature is kept at 1200–1600 °C which is sufficient to kill the infectious particles present in COVID-19 medical wastes (Ma et al., 2011; Dharmaraj et al., 2021). However, the operation cost of a rotary kiln is high and during incineration produces corrosive by-products. Moreover, the life of this kind of rotary kiln is also short (Chen and Yang, 2016).

Plasma incineration is another technique for the treatment of COVID-19 medical wastes, and it uses a temperature of more than 2700 °C which enables a huge quantity of wastes to quickly degrade into finer particles. It does not form any intermediate by-product and gases are usually purified before release. This method is considered more efficient due to the production of a lower amount of ash (Sapuric et al., 2016; Messerle et al., 2018). Other feasible alternatives used for the treatment of COVID-19 medical waste can be high heat pyrolysis, low-heat autoclave, medium-heat microwaves, and plasma pyrolysis. Of these methods low-heat autoclave and medium heat microwave are widely used in hospitals as they are quite cost-effective, however, they are only efficient in treating a small amount of PPE waste (Dharmaraj et al., 2021).

High heat pyrolysis has been considered a better technique than incineration stated by Dharmaraj et al. (2021). It is functional at 540–8300 °C and a uniform temperature is applied during the entire process. Most of the organic wastes during high heat pyrolysis leads to vaporisation and leave only ashes. The process of plasma pyrolysis is carried on at a temperature of 9730 °C and shows a remarkable decline in the release of atmospheric toxins, such as pyrene, furans, and dioxins compounds (Chang-Ming et al., 2016; Dharmaraj et al., 2021). There is also a reduction in the formation of slag formation and residual ash showing a volume reduction of up to 95%. In medium heat microwave techniques, the COVID-19 medical wastes are treated at 177–540 °C and high energy destroying the various components of COVID-19 wastes (Dharmaraj et al., 2021). The main advantages of employing a microwave are its eco-friendliness, high-temperature attainment, low energy consumption, and lack of toxic emissions. This technique along with autoclave can be very effective in the management of COVID-19 wastes (Wang et al., 2020).

6. Alternative management options for MP generated from COVID-19 healthcare waste

As discussed in the previous section, improper disposal of COVID-19 healthcare waste or their insufficient incineration can subsequently lead to the generation of MPs which adds up to more pollution. Microbial degradation of MPs can be considered an environmentally friendly and sustainable treatment option without causing any adverse impact. (Brooks et al., 2011; Krueger et al., 2015). Microbial degradation of the plastic consists of steps like bio-deterioration, biofragmentation, assimilation, and mineralization as shown in Fig. 3.

Several microbes have the ability to remove MPs, however, a better understanding of the process is required to improve their metabolizing ability to acquire more efficient MP degradation. Although MPs are less susceptible to microbial degradation, they do provide a novel ecological niche for the growth and biofilm formation by the microbes. The microbes forming a biofilm on these surfaces can produce various microbial enzymes like esterases, lipases, oxygenases, and dehydrogenases which play a vital role in the oxidation-reduction-fragmentation of polymers (Prata et al., 2020). Apart from the enzymes, several proteins play important roles in MP degradation. For example, hydrophobins, a hydrophobic protein produced by fungal isolates primarily help in the attachment of hyphae to the hydrophobic surfaces of MPs (Wösten and Scholtmeijer, 2015). Fungal hydrophobins are known to be self-assembled into monolayers of amphipathic films due to hydrophobic-hydrophilic interfaces (Wu et al., 2017). The bacterial adhesion process is somewhat different from the fungi and is dependent on the physico-chemical nature of the cell surface (Urbanek et al., 2020). Moreover, different types of biosurfactants, such as glycolipids, glycolipoproteins, protein-lipid/polysaccharide complexes, and sophorolipids, improve mobility and bioavailability of MPs to microbes.

As stated earlier the COVID-19 medical waste mainly comprises HDPE, PE, PS or PC and PP. These polymers can be effectively degraded by different groups of microbes, using both pure cultures and consortiums. Although no direct studies on biological degradation of polymers generated from COVID-19 medical waste are available now, several MP degrading microbes have the potential to degrade MPs and can be used as an alternative strategy for removal of MPs generated in post-COVID-19 times.

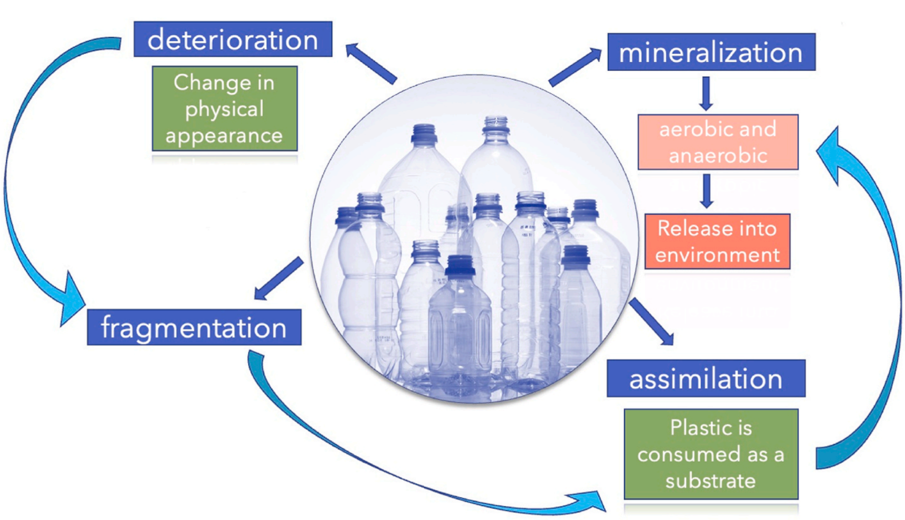

Fig. 3. Basic mechanisms of microbial degradation of plastics: bio-deterioration contributes to surface degradation of plastics changing their physical and chemical properties. Bio-fragmentation includes the break of plastic polymers. Assimilation and mineralization are the final steps of plastic polymer degradation due to microbial activities. Biodegradation of plastic needs their complete mineralization. The process of assimilation involves the integration of atoms into the microbial cell to complete the degradation.

6.1. Bacterial biodegradation of MPs

Numerous studies have been conducted around the globe on the degradation of MPs using bacteria. Both pure cultures, as well as a consortium, can be used for MP biodegradation (Habib et al., 2020; Jeon et al., 2021; Kimi Jain et al., 2021). Most of the MP degrading strains are isolated from contaminated sediments, mangroves, sludge, compost, cow dung, wastewater, and land contaminated with plastic wastes where there is an abundance of MPs. The process of biodegradation of MP starts with a reduction in the length and structure of polymers and changes the functional groups making them more prone to microbial degradative processes. Degradation and utilization of this hydrolysable and non-hydrolysable polymer further require a wide variety of metabolic pathways and associated enzymes. The main enzymes involved in the degradation of both hydrolysable and non-hydrolysable polymers are represented in Fig. 4.

Several studies reported biodegradation of PP by both axenic and by a mixed consortium of microbes isolated from polluted sites. Earlier studies conducted by Cacciari et al. (1993) reported a bacterial consortium comprising *Pseudomonas stutzeri, P. chlororaphis*, and *Vibrio* sp. which was able to degrade PP. The bacteria species *Pseudomonas stutzeri*, *B. subtilis*, and *Bacillus flexus* were able to utilize PP as a sole source of carbon (Arkatkar et al., 2010). Later, Fontanella et al. (2013) reported *Rhodococcus rhodochrous* which was capable of biodegradation of metal stearates containing PP films which acts as pro-oxidants. Kowalczyk et al. (2016) in a later study, reported *Achromobacter xylosoxidans* which

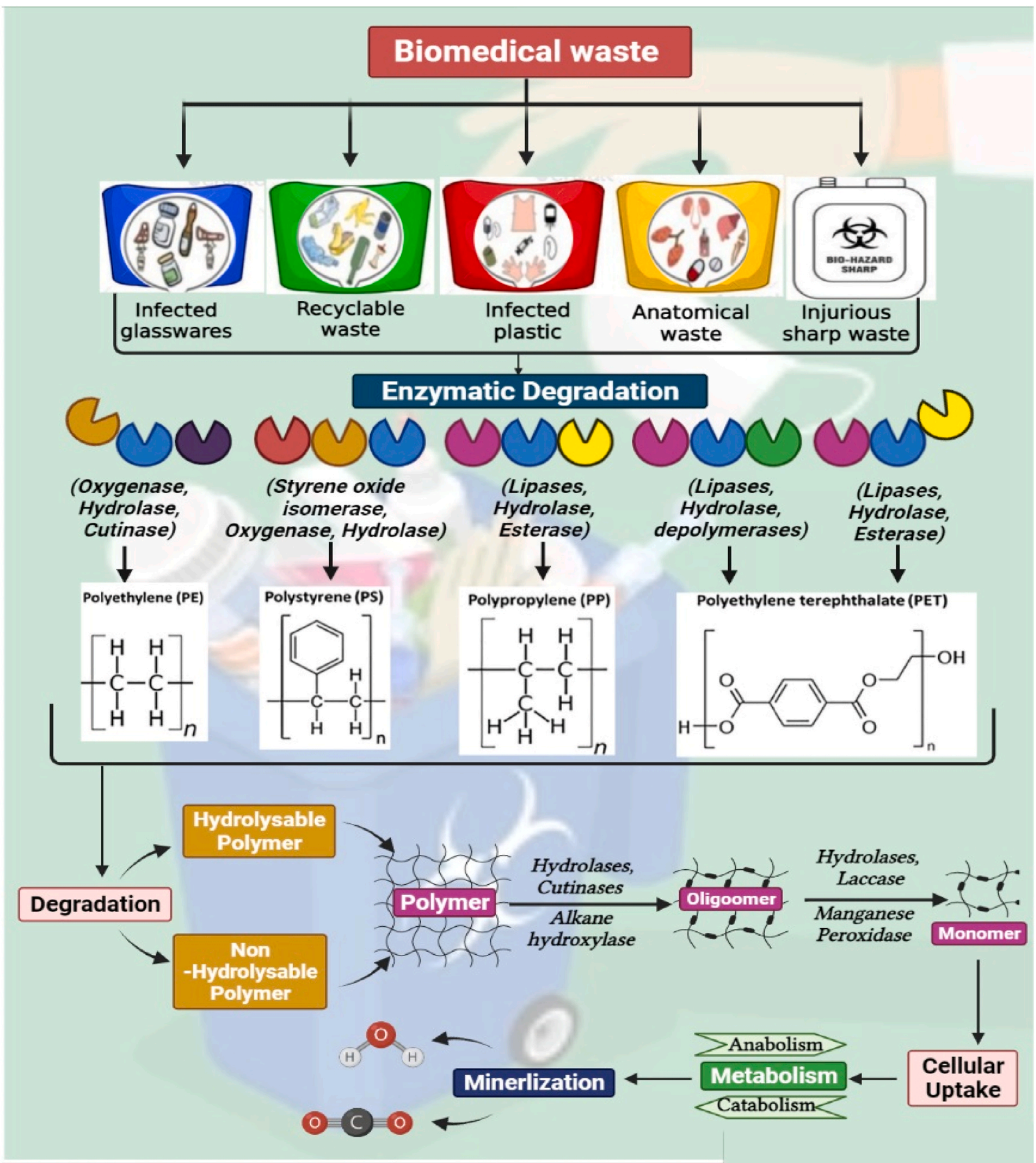

Fig. 4. Pathways and the enzyme play a vital role in the degradation of microplastics formed from COVID-19 health care waste. Biodegradation of MP starts with physico-chemical degradation, which disrupts the length and structure of polymers and changes the functional groups. Degradation and utilization of this hydrolysable and non-hydrolysable polymer further require a wide variety of metabolic pathways and associated enzymes.

not only formed a thin biofilm on high-density polyethylene but also degraded the polymer. In a recent study, by Auta et al. (2017) eight potential bacteria obtained from mangrove sediment have been identified to degrade UV-treated MPs like PP, PS, and PE.

In another study, the same authors isolated two bacterial genera, *Bacillus* and *Rhodococcus,* from mangrove sediments which showed MP degradation capacity of 4.0 and 6.4% after 40 days of incubation (Auta et al., 2018). Similar degrading ability was also seen in *Bacillus gottheilii,* which induced MP weight loss of 6.2, 3.0, 3.6, and 5.8% for PE, PET, PP, and PS respectively. Some other bacterial isolates that are involved in PP degradation include *Bacillus*, *Pseudomonas*, *Chelatococcus*, and *Lysinibacillus fusiformis*. It has been reported that diverse types of plastics are degraded in the arthropod guts including specifically insect larvae of mealworms (*Tenebrio molitor)* (Yang et al., 2015), Indian meal moth (*Plodia interpunctella*) (Yang et al., 2014), and wax moths (*Galleria mellonella)* (Kong et al., 2019) by nonspecific oxidative breakdown process (Brandon et al., 2018). However, more investigations are needed to understand the mechanistic details by which the insects and gut microbiome can degrade MPs (Yang et al., 2014, 2015; Kong et al., 2019) which can be beneficial for the development of enzyme-based strategies for plastic waste management in the future (Wierckx et al., 2018).

Although there are various advantages of using pure strains for the degradation of polymers where the impact of environmental factors viz. pH, substrate characteristics, temperature and surfactants can be monitored in an easier way (Janssen et al., 2002). However, it also has several drawbacks. As most of these polymers are extremely persistent and not easily biodegradable, thus, in most cases, bacterial-mediated degradation is very slow, and significant changes can only be visible after 2–3 months. Therefore, more innovative methods are required to optimize cultural conditions and shorten the degradation process. Several types of pre-treatments of PP are recommended to increase the degradation of plastic polymers including UV treatment and HNO_3 treatment. Apart from them, PP is blended with polymers like polyhydroxybutyrate (PHB), polycaprolactone (PCL), poly (3-hydroxybutyrate-*co*-3-hydroxyvalerate) (PHBV), starch derivatives, and cellulosic esters impart biodegradability to PP (Gironi and Piemonte, 2011; Morancho et al., 2006; Sadi et al., 2013; Ramis et al., 2004). *Microbacterium paraoxydans* and *Pseudomonas aeruginosa* showed nearly 61.0% and 50.5% polythene degradation in 2 months incubation period which was recorded using FTIR (Rajandas et al., 2012).

On the other hand, several studies have indicated that the use of bacterial consortium is a preferable option for the complete mineralization of toxic end products (Dobretsov et al., 2013; Kimi Jain et al., 2021; Muenmee et al., 2016; Skariyachan et al., 2018). Bacterial isolates present in the consortium have a symbiotic, synergistic, and mutualistic association which renders them better tolerance and activity during the treatment process (Singh and Wahid, 2015). Park and Kim (2019), reported a mesophilic bacterial consortium consisting of *Paenibacillus* sp. and *Bacillus* sp. that was capable of degradation of PE which resulted in the reduction of the dry weight of MP particles by 14.7% in 60 days.

6.2. Fungal biodegradation of plastics

The prominent fungal degraders of PE are *Aspergillus*, *Penicillium* and *Cladosporium* (Das and Kumar, 2014; de Oliveira et al., 2020). They use polyethylene (PE) as a main source of carbon and degrade these polymers using extracellular enzymes. These fungi promote the formation of different types of chemical bonds and decrease the hydrophobicity of plastic particles. Most of these fungi exhibit wide distribution, and efficient reproductive abilities (Chen et al., 2016) and play vital roles in the transformation and degradation of a wide range of MPs (Bryant et al., 2016; Danso et al., 2018). Moreover, the chemical treatment of MPs with sodium hydroxide (NaOH) and nitric acid (HNO_3) is also known to increase the biodegradation rate of PE by *Aspergillus niger* (Nwachukwu et al., 2010). Several reports have also identified the role of different fungal strains, including *Aspergillus fumigatus, Cladosporium pseudocladosporioides*, *Fusarium solani* and *Penicillium chrysogenum* in the biodegradation of Polyester polyurethane (PUR) (Espinosa et al., 2020; Muenmee et al., 2016). Two fungal strains, *Aspergillus tubingensis* VRKPT1 and *Aspergillus flavus* VRKPT2 obtained from PE waste piled upon marine coasts showed efficient HDPE degradation ability of 6.02 $\pm$ 0.2% and 8.51 $\pm$ 0.1%, respectively (Devi et al., 2015). Biodegradation of LDPE by *Aspergillus* spp. and *Fusarium* spp. was also reported by Kumar et al. (2013). Similarly, *Lysinibacillus* sp. and *Aspergillus* sp. showed 15.8% and 29.5% degradation of UV irradiated and non-UV irradiated films respectively (Esmaeili et al., 2013).

MP degradation is also done by different strains of fungi in different environmental conditions, which has emerged as an area of active investigation. The advent of omics technology and molecular tools, such as high-throughput sequencing, *in-situ* hybridization, *in-vitro* transcription, and PCR has immensely helped in the study of bacterial and fungal consortia being capable of degrading MPs. Future studies involving the use of omics toolkits like genomics, proteomics, and metabolomics methodologies will help to widen the knowledge on MP degradation by bacteria, fungi, and enzymes. Table 2 presents the detailed list of different bacterial and fungal strains which were reported to be the potential to degrade different types of MPs.

6.3. Enzymes involved in biodegradation of plastic

Microbial degradation of different polymers can be considered a safe, effective, and eco-friendly technique for the mitigation of MP wastes. However, several grades of plastic polymers exist in nature and each can be degraded with a heterogeneous group of enzymes which requires the activity of heterogeneous metabolic machinery. These included lipases, esterases, laccases, amidases, cutinases, hydrolases and carboxylesterases (Ashter, 2016; Gómez-Méndez et al., 2018; Anand et al., 2022b; Priya et al., 2021). All these enzymes were reported from a diverse range of microbiomes that can modify and degrade a wide range of synthetic polymers. It was also reported that most of these pathways become effective only under stressed conditions (Jaiswal et al., 2020a, b). Several oxygenase groups of enzymes including monooxygenases and dioxygenases were also reported to help in the oxidation of polymers. In a fungal system, the enzymatic system responsible for polymer degradation is mediated by cytochrome P450 family epoxidases (enzymes in Phase-I) and transferases (enzymes in Phase-II) that are mostly related to oxidation and conjugation reactions, respectively (Sánchez, 2020). Enzymes like monooxygenases are responsible for dealkylation, epoxidation, hydroxylation, dehalogenation, deamination, desulfuration, sulphoxidation, and N-oxide reduction reactions (Shin et al., 2018) and perform a crucial role in aliphatic, alicyclic, and aromatic hydrocarbon metabolism. Extracellular hydrolytic enzymes, such as hydrolases and other non-specific enzymes, such as class-II peroxidases, dye decolorizing peroxidases, laccases, versatile peroxidase, lignin peroxidase, manganese peroxidase, and unspecific peroxygenases also have the ability to degrade MPs which can be used in the biodegradation process. Apart from them, enzyme hydrolases are also known to degrade the polymer surface making it more prone to degradation by other enzymes (Kawai et al., 2019). Both alkane hydrolase and laccase enzymes from the *AlkB* family enzyme can be used for the degradation of PE (Ghatge et al., 2020; Montazer et al., 2020). HDPE which contributes almost 46% of total MP has a lower density compared to water and thus floats on the water surface (Lee and Chae, 2021). Enzyme laccase belonging to oxidase groups is also known to depolymerize polymer by oxidative cleavage (Devi et al., 2015, 2019; Matjašič et al., 2021) leading to the formation of pits and cracks on the MP surfaces (Kang et al., 2019). Copper binding laccase from *Aspergillus flavus* and *Rhodococcus ruber* was also reported to degrade PE oligomers (Santo et al., 2013; Zhang et al., 2020). A specialised carrier protein, such as ATP binding cassettes (ABC) or major facilitator superfamily (MFS) is also known to assimilate PE (Eyheraguibel et al., 2017).

Table 2
Bacterial and fungal strains able to degrade plastics. PP: polypropylene, PE: polyethylene, PLLA: poly-L-lactide, LDPE: low-density polyethylene, HDPE: High-density polyethylene, PS: polystyrene, PET: Polyethylene terephthalate, PBAT: Polybutylene adipate terephthalate.

Source of microbes	Isolate	Type of MP degraded	Incubation period	% of degradation	Enzymes	Reference
Bacterial isolates						
Polluted soil samples	*Lysinibacillus* sp.	PP and PE	26 days	4 and 9%		Jeon et al. (2021)
Compost	*Bacillus cereus*, *Bacillus thuringenesis*, *Bacillus licheniformis*	PP and PLLA	6 months			Kimi Jain et al., 2021
Cow dung sample	*Enterobacter* sp nov. bt DSCE01, *Enterobacter cloacae* nov. bt DSCE02, *Pseudomonas aeruginosa* nov. bt DSCE-CD03	LDPE and PP	160 days	64.25 ± 2% and 63.00 ± 2%		Skariyachan et al. (2021)
Antarctic soil	*Pseudomonas* sp. ADL15, *Rhodococcus* sp. ADL36	PP	40 days	17.3% and 7.3%		Habib et al. (2020)
Municipal landfill sediment	*Bacillus* sp., *Paenibacillus* sp.	PP	60 days	14.7%		Park and Kim (2019)
Earthworm gut	*Bacillus simplex*, *Bacillus* sp.	LDPE	21 days			Lwanga et al. (2018)
Mangrove sediments	*Bacillus*	PP	40 days	4.0		Auta et al. (2018)
Mangrove sediment	*Bacillus gottheilii*	PE, PET, PP, PS	40 days	6.2, 3.0, 3.6, 5.8		Auta et al. (2018)
Mangrove sediment	*Rhodococcus*	PP	40 days	6.4		Auta et al. (2018)
Compost	*Bacillus thuringiensis*	PP and PLLA	15 days	12%		Jain et al. (2018)
Compost	*Bacillus licheniformis*	PP and PLLA	15 days	10%		Jain et al. (2018)
Sewage treatment plants (STP)	Microbial consortia (including *Aneurinibacillus* sp., *Brevibacillus* sp.)	HDPE, LDPE and PP	140 days	47%, 58% and 56%		Skariyachan et al. (2018)
Mangrove sediments in Peninsular Malaysia	*Bacillus cereus*	PP	40 days	12		Helen et al. (2017)
Mangrove sediments in Peninsular Malaysia	*Sporosarcina Globispora*	PP	40 days	11		Helen et al. (2017)
Marine	Lysinibacillus sp. Salinibacterium sp.	PE	6 months	19%		Syranidou et al. (2017)
Municipal solid waste	*Stenotrophomonas panacihumi* PA3-2	PP	90 days	20.3 ± 1.39%		Jeon and Kim (2016)
	Nitrosomonas sp., *Nitrobacter* sp., *Burkholderia* sp., *Pseudomonas* sp.	HDPE, LDPE and PP	90 days	20%, 5% and 9%		Muenmee et al. (2016)
Plastic-eating mealworms	*Exiguobacterium* sp. strain YT2	PS	29 days	7.4%		Yang et al. (2015)
National Environmental Engineering Research Institute (NEERI), Nagpur India	*Bacillus flexus*, *Pseudomonas azotoformans*	UV treated polymers	12 months	22.7%		Aravinthan et al., 2016
Polypropylene waste	*Actinomycetes* sp., *Pseudomonas* sp	UV and HNO_3 polypropylene (PP)	15 and 45 days			Sepperumal and Markandan (2014)
Plastic-eating waxworms	*Bacillus* YP1	PE	28 days	10.7 ± 0.2		Yang et al. (2014)
Compost	*Chelatococcus* E1	PE	80 days			Jeon and Kim (2013)
Not reported	*Bacillus subtilis*, *Bacillus amylolyticus*, *Arthrobacter defluvii*	PE	30 days	30% and 20%		Thakur (2012)
Fungal isolates						
	Aspergillus sp., Penicillium sp.	PP/PBAT	30 days			deOliveira et al., 2020
Guts of wax moth *Galleria mellonella*	*Aspergillus flavus*	HDPE	28 days			Zhang et al. (2020)
Marine sediments	*Zalerion maritimum*	PE pellets	28 days			Paco et al. (2017)
	Bjerkandera adusta	Gamma irradiated polypropylene and biomass			Ligninase	Butnaru et al. (2016)
Marine coastal area	*Aspergillus flavus* VRKPT2	HDPE	30 days			Devi et al., 2015
Marine coastal area	*Aspergillus flavus* VRKPT2	HDPE	30 days			Devi et al., 2015
Endophytes of Humboldtia brunonis Psychotria flavida	Aspergillus sp. Paecilomyces lilacinus Lasiodiplodia theobromae	PP			Laccase	Sheik et al. (2015)
Municipal solid waste	*Aspergillus* spp. *Fusarium* spp.	LDPE film		10.3 and 9%		Das and Kumar (2014)
Plastic waste disposable site	*Fusarium* spp., *Penicillium* spp., *Mucor* spp., *Aspergillus niger*, *Aspergillus japonicas*, *Aspergillus flavus*	LDPE	4 weeks	36, 32 and 30%		Singh and Gupta (2014)
Dumpsite	*Penicillium simplicissimum*	UV-treated PE		38%	Laccase manganese peroxidase	Sowmya et al., 2015

Most of the PE MPs are degraded in two major steps. In the first stage, extracellular enzymes help in the depolymerization of the polymer into the shorter chain to form oligomers, dimers, and monomers. This stage facilitates the adsorption of polymers through permeable biomembrane lipid. In the second stage, mineralization is carried out to form end products such as CO_2, water, and methane for being used as a carbon source by the microorganisms for their growth and metabolism (Fig. 5) (Ganesh Kumar et al., 2020).

The metabolism of PE requires the involvement of succinyl-CoA and acetyl-CoA and produces NADH (Gravouil et al., 2017). This is followed

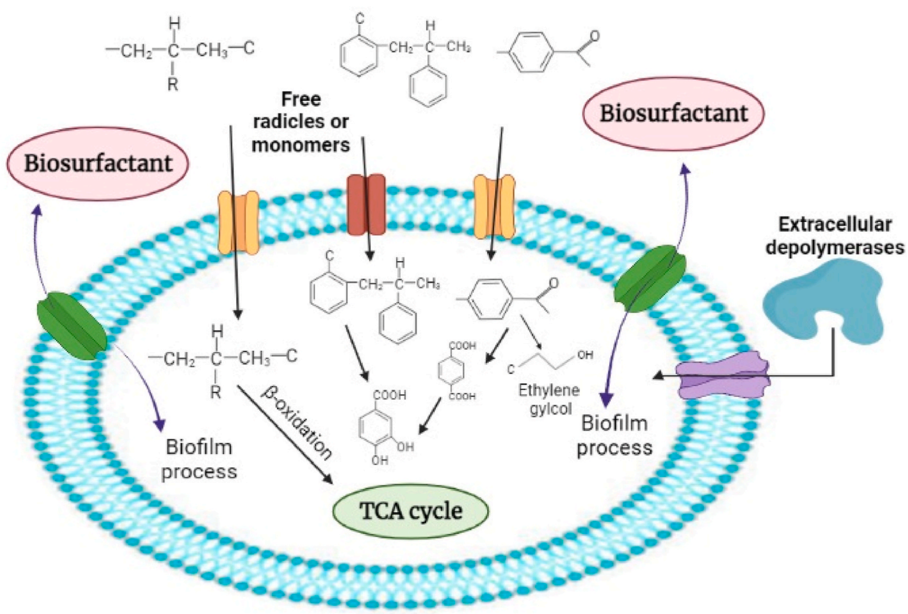

Fig. 5. Metabolic pathways for microplastic degradation by microbes. The mechanisms include intracellular and extracellular enzymatic systems, the ability of adsorption, and the production of natural biosurfactants. Microorganisms can catalyze the oxidation-reduction reactions with a consequent breakdown of the chemical bonds in the plastic polymers. Microbial biofilm formation contributes to the surface biodeterioration. Decomposition products with carbonyl groups can be metabolized intracellularly through the tricarboxylic acid cycle (TCA).

by energy production by ATP, CO_2, and H_2O and leads to the mineralization of PE. Polypropylene is hydrophobic which renders it recalcitrant nature (Khoironi et al., 2020). According to Ru et al. (2020), the degradation of PP occurs by attacking its backbone and also targets plasticizers on the surface of PP. Several microbes have been isolated having PP degrading ability, however, to date, no enzyme especially related to PP degradation or any metabolic pathway related to PP degradation has been identified (Chandra et al., 2020; Kumar et al., 2020). Information on PP degradation is still lacking mostly due to the resilient characteristics showed by the polypropylene and hence needs to be studied and investigated in detail.

Polystyrene (PS) is composed of styrene monomers which can be oxidized by enzymes styrene monooxygenase in presence of styrene epoxide. In the second step styrene epoxide further oxidises to phenylacetaldehyde, which is further converted to phenylacetic acid (PAA). In the styrene metabolism pathway, PAA is converted to phenylacetyl-CoA which subsequently enters the TCA cycle by forming succinyl-CoA and acetyl-CoA (Luu et al., 2013). A type of specialised pathway has been reported in *Pseudomonas putida* CA-3, which utilizes a catabolic operon which assists the growth of styrene, and plays a vital role in PS degradation to polyhydroxyalkanoates (O'Leary et al., 2005). The details of the enzymes related to the biodegradation of various kinds of plastics are presented in Table 3.

7. Safe disposal of COVID-19 waste

Guidelines have been provided by several international organizations (WHO, European Commission, UNEP, UNICEF, etc.) to safe manage plastic waste during the COVID-19 pandemic (Shams et al., 2021). The main recommendation concerns a safe waste separation, collection, transport, and storage of plastic waste, before the final treatment. Due to the high sanitary risk, all the medical wastes that may be contaminated by SARS-CoV-2 should not be recycled and must be addressed to incineration (in the temperature range of 900–1200 °C) or sanitary landfilling (Ducoli et al., 2021). Other possibilities concern subsequent treatments of plastic waste, including decontamination and/or treatment with suitable chemicals or electromagnetic radiation (Shams et al., 2021). The selection of the most suitable decontamination method, including chemical sanitization, depends on several influential factors, like the amount and type of COVID-19 generated plastic waste, operational maintenance, and transportation (Parashar and Hait, 2021).

A suitable way to reduce the MPs present in the environment can be obtained using different materials for example facemasks. In particular, fabric masks (made in tissues, such as cotton) can substitute for surgical masks in several activities (Cornelio et al., 2022). The mask washing possibility allows to guarantee their reuse and reduce their disposal.

However, the public contribution to a suitable and safe management strategy of plastic waste is mandatory: people must be empowered in the adoption of a zero-waste approach (Shams et al., 2021).

Table 3
Enzymes related to plastic polymer degradation. MP: microplastic particle.

Source	Microorganisms	Genes involved in MP degradation	Enzymes involved in MP degradation	References
Marine environment	*Alcanivorax* spp. 24	Cytochrome P450 genes, alkB1 and alkB2 genes, almA gene	Alkane monooxygenases AlkB and alkane hydroxylase almA	Zadjelovic et al. (2020)
Marine environment	*Pseudomonas* spp.		Esterase	Jaiswal et al. (2020)
Abandoned landfill site	*Moritella* spp. JT01	H39 Lipase Gene	Lipases	Puglisi et al. (2019)
	Alcaligenes faecalis AE122		Depolymerase	Sameshima-Yamashita et al. (2019)
	Desulfovibrio, Desulfobacteraceae, and Desulfobulbaceae		Depolymerases, adenylyl sulfate reductases (aprBA), and dissimilatory sulfite reductases (dsrAB)	Yoshida et al. (2016)
	Ideonella sakaiensis	cut1	Hydrolases, MHETase	Yoshida et al. (2016)

8. Conclusion

COVID-19 pandemic led to the generation of a huge amount of municipal wastes comprising of one-time useable plastic wares, gloves, masks, tissues, and other PPE. Most of these PPEs are made up of polymeric materials, such as polyethylene, polypropylene, polystyrene, polyurethane, and polyacrylonitrile which are persistent. Lack of proper disposal and improper management practices are creating serious health hazards and environmental pollution. Efforts should be made to reduce and manage this waste more cost-effective way. It is now the time to increase environmental awareness and impose stringent regulations to reduce the pollution caused by improper disposal of PPEs.

Now, most of the COVID-19 medical waste generated is treated by incineration. This may generate smaller MP particles, dioxin, furans, and toxic metals such as cadmium and lead, which cause serious environmental and health hazards. Biodegradation of these MP particles can serve as an eco-friendly approach for pollution mitigation. Different available research shows that microbes isolated from different sources impacted by MP pollution can produce a plethora of enzymes having the ability to degrade several polymers. However, there is a knowledge gap due to very little research, that has been done to explore the possibility of usage of these MP degrading microbes in the removal of MP pollution caused by the pandemic. Moreover, the employment of genomics and proteomics methodologies will help to widen the knowledge on MP degrading microbes and enzymes and enhance their efficiency for in situ application.

Credit author statement

Satarupa Dey: Conceptualization, Investigation, literature survey, Writing – original draft, Writing – review & editing, prepared tables and figures, revision, addressed referee's comments. Uttpal Anand: Review structure, Investigation, literature survey, Writing – original draft, Writing – review & editing, revised tables and figures, addressed referee's comments, final draft. Vineet Kumar: Writing – original draft, Investigation, Writing – review & editing, Resources, Validation, Visualization. Sunil Kumar: Conceptualization; Investigation, Writing – review & editing, Resources, Validation, Visualization. Mimosa Ghorai: Writing – review & editing; Investigation, revised tables and figures. Arabinda Ghosh: Writing – review & editing, Investigation, Validation, Visualization. Nishi Kant: Writing – review & editing, Investigation, Validation, Visualization. S. Suresh: Writing – review & editing, overall revision, suggestions. Sayan Bhattacharya: Writing – review & editing, Investigation, Validation. Elza Bontempi: Writing – review & editing, figures preparation, addressed referee's comments, response, overall revision. Sartaj Ahmad Bhat: Writing – review & editing, response, suggestions. Abhijit Dey: Conceptualization, Writing – review & editing, Resources, Validation, Visualization, Supervision.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

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