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Generation and consequence of nano/microplastics from medical waste and household plastic during the COVID-19 pandemic

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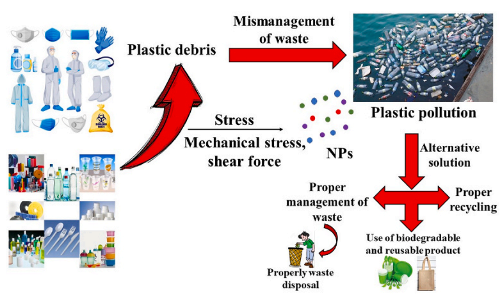
HIGHLIGHTS

- Majority of Covid-19 plastic waste ends up in landfills in underdeveloped nations.
- Impacts of nano/microplastics (NPs/MPs) on humans and organisms were reviewed.
- NP/MPs release from personal protective equipment (PPE) because of weathering effects.
- Novel research methods are needed to assess the toxicity of NP/MPs.

GRAPHICAL ABSTRACT



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ABSTRACT

Since the end of 2019, the world has faced a major crisis because of the outbreak of COVID-19 disease which has created a severe threat to humanity. To control this pandemic, the World Health Organization gave some guidelines like wearing PPE (personal protective equipment) (e.g., face masks, overshoes, gloves), social distancing, hand hygiene and shutting down all modes of public transport services. During this pandemic, plastic products (e.g., household plastics, PPE and sanitizer bottles) have substantially prevented the spread of this virus. Since the outbreak, approximately 1.6 million tons of plastic waste have been generated daily. However, single-use PPE like face masks (N95), surgical masks and hand gloves contain many non-biodegradable plastics materials. These abandoned products have created a huge number of plastic debris which ended up as microplastics (MPs) followed by nanoplastics (NPs) in nature that are hazardous to the eco-system. These MPs and NPs also act as vectors for the various pathogenic contaminants. The goal of this review is to offer an extensive discussion on the formation of NPs and MPs from all of these abandoned plastics and their long-term impact on the environment as well as human health. This review paper also attempts to assess the present global scenario and the main challenge of waste management to reduce the potential NP/MPs pollution to improve the eco-systems.

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1. Introduction

The world has been affected by the disease since December 2019, which is the cause of COVID-19, a severe respiratory infection induced by a novel coronavirus (SARS-CoV-2) (WHO, 2020). It is an enveloped gram-positive single-stranded long RNA beta coronavirus (Velavan and Meyer, 2020; Liu et al., 2020). It is highly contagious that has already spread very rapidly among 215 countries affecting 7.3 M people (WHO, 2020), and the World Health Organization (WHO) declared the virus a pandemic on March 11, 2020 (WHO, 2020). To prevent the virus from spreading further, the WHO gave guidelines like the complete shutdown of public places (transport, market, hotel, restaurant and academic institutes), travel restrictions, social distances, and the use of masks and other PPE. Wearing masks and PPE are the mandatory guidelines declared by WHO during the pandemic. As a result, this cumulative pandemic has increased the demand for PPE, made of plastic, for frontline healthcare workers and civilians.

Plastic-made products have contributed a lot to the prosperity of mankind. It is cheaper than conventional material and has been of great use in the preparation of single-use products (SUP). Plastic polymers such as polystyrene (PS), polypropylene (PP), polyester (PEs), polyacrylonitrile (PAN) and polyurethane (PU) are mainly used in one-time use face masks, gloves, N95 masks, boots, aprons and face shields (Sangkham, 2020., Aragaw, 2020; Ardusso et al., 2021). Fabric masks are made from about 60% of clothing materials that contain plastic, such as acrylic, polyester, and nylon fabrics (UNEP, 2019). Moreover, polyethylene (PE), latex, and nitrile are commonly used in the preparation of gloves (Nowakowski et al., 2020). Because of the COVID-19 pandemic, individuals have been forced to utilize a huge number of plastic-made items, such as face masks, PPE, hand gloves, plastic bottles of sanitizer and handwash, COVID test kits and vaccine syringes. It has been reported that globally approximately 1.6 M goggles, 76 M gloves, and 89 M medical masks are used by only healthcare workers per month (WHO, 2020). The monthly estimated number of gloves and face masks consumed worldwide is 65 billion (B) and 129 B, respectively (Prata et al., 2020). The poor waste management system has become responsible for the environmental pollution caused by random consumption and medical and non-medical plastic like household plastics disposal during the COVID-19 pandemic (Shruti et al., 2020).

Plastic materials have become a great threat to the environment because of their non-biodegradability and pervasiveness (Yu et al., 2019; Li et al., 2016). Hospitals and several quarantine zones are the sources of generating toxic biomedical wastes (BMW) (UNEP. UN Environment programme, 2020a). Powerful winds can carry these pollutants, storms and tides to various water sources if they are not properly managed (Li et al., 2016; Moore, 2008). Powerful tides, ultraviolet (UV) light, and mechanical abrasion against rocks encourage the erosion and weathering process are responsible for the degradation of the plastic particles into tiny plastics (Paul-Pont et al., 2018; Wang et al., 2017). The size of these plastic particles determines whether they are classified as meso, micro or nano plastics. Mesoplastics are small fragments of plastic ranging from 5 to 25 mm. Plastic particles having a size smaller than 5 mm is known as microplastic (MP), and having a size of 1 nm to 1 μm in diameter are known as nanoplastics (NP) which are produced from large plastics by degradation process or from commercial products during the manufacturing process (Ardusso et al., 2021; Pramanik et al., 2021; Paul-Pont et al., 2018). Furthermore, each of these plastic particles has the potential to spread other contaminants or even be consumed by marine species in the food web.

Several review articles have been published in which the authors have focused on the comprehensive review of the rising use of plastic products and plastic pollution in a particular region during the pandemic. Notably, review articles by Silva et al. (2020) and Shams et al. (2021) discussed the worldwide scenario because of increased medical waste and PPE, waste management and recycling during the pandemic and recommended further studies. A short review article has been published by Yuan et al. (2021) on the increasing amount of plastic waste during the COVID-19 pandemic who also discussed some environmentally friendly alternatives of plastics products like biodegradable plastics. More recently, a review article has been published by Mittal et al. (2022) on the generation of plastic pollution during the pandemic. They also noted the substitute of plastics like bioplastic used in India as an alternative of environmentally friendly plastic. However, none of these articles gives a clear view of the mechanism of producing MP/NPs from medical and household plastics and their effect on both environment and human life. There is a significant gap in current review papers considering the mechanism of generation MP/NPs from plastic waste and their chemical degradation due to weathering. Therefore, this article presented a complete analysis of the mechanism of generation of MP and NP pollution during COVID-19 and its possible consequences on human health and the environment in long- and short-term contexts worldwide. This study also aimed to discuss the chemistry of degradation of these plastic materials due to shear forces, photocatalysis and environmental corrosion and the adsorption of various harmful organic compounds by them, highlighting the key issues and proposing potential solutions.

2. Present scenario of plastic waste due to pandemic

Due to lightweight, durability and low-cost production, plastic materials have become a great choice for daily use. As a result, single-use plastics (SUP), made from plastics and used for a single time like water bottles, coffee cups and plastic bags, have had a substantial impact throughout the COVID-19 pandemic. During the pandemic, SUP like plastic wrappers and garbage bags are used to avoid direct contact everywhere. However, the excessive use of plastics and poor management of these wastes has an adverse effect on the environment. Plastic can take 400–1000 y to decompose naturally (Harussani et al., 2020), and some forms of plastic are non-degradable. Moreover, these plastics could be degraded to the micro or nano level because of shear forces. The present scenario of the increased plastic consumption due to the COVID-19 pandemic is discussed in the following section.

COVID-19 cases started to increase rapidly, all around the world, from March 2020. The most preventive action taken by the governments of various countries was the lockdown (i.e., "stay home") system. However, the chances of occurring the world economic crisis made the government and people think about other options rather than the lockdown (Tran et al., 2020). As a result, the compulsory usage of SUPs, both for frontline health workers and civilians, was one of the proposed ways to prevent the spreading of the coronavirus from human to human. The majority of these PPE (gloves, masks, face shields, protective aprons), sanitizer containers, safety glasses, medical gowns and plastic shoes are comprised of nonwoven fabrics including polypropylene (Silva et al., 2020). Shops and supermarkets are practicing the usage of SUP wrappers to wrap vegetables and fruits to ensure hygiene, increasing the amount of household plastic. Moreover, the government and health specialists have discouraged the reuse of these SUPs which is a major cause of the uprising demand for plastic materials (Nzediegwu and Chang, 2020). On the other hand, the demand for plastic production was enhanced due to the heavy consumption of these products in case of online shopping and home delivery service, which has sped up the sales growth in the USA and Spain by 14% and 40%, respectively during the pandemic in 2020 (Jribi et al., 2020; WEF, 2020). To meet the increasing demand for plastic packaging materials, it has been estimated that the production rate would be increased from US dollars (USD) 909.2 B in 2019 to 1012.6 B in 2021 (Business Insider, 2020; Parashar and Hait, 2020). Moreover, the plastic parts of corona testing equipment are disposed of after single use to satisfy the safety concern which is an additional source of plastic waste generation. Plastic waste could be minimized by recycling them. However, recycling has become difficult due to lockdown and other safety concerns in this pandemic. For this reason, the manufacturing industries have chosen to make virgin plastic products instead of recycling them. This decision has accelerated the growth of plastic wastes due to mismanagement and decelerated the recycling trend. For example, a report has shown that countries in South-East Asia are less interested in the plastic recycling process, due to which plastic recycling had a fall in the range of 30–40% (BIR, 2020; Parashar and Hait, 2020). Additionally, the maintenance of social distancing, lockdown and avoiding gatherings has limited the activities of the workers who used to manage and dispose of the plastic waste. The worldwide oceans and aquatic system are threatened by over 10 Mt of plastic materials annually as it has exacerbated the existing plastic pollution challenges (Jambeck et al., 2015; Kane et al., 2020). Only 1% of face masks can generate around 30,000–40,000 kg of waste every day if they are not properly managed (World Wildlife Fund, 2020; Chowdhury et al., 2021).

The consumption of plastic materials has increased significantly during pandemics globally. The gloves and face masks needed to fight this severe situation were estimated at approximately 65 B and 129 B per month, respectively. As a result, the demand for plastic products increased by 40% in packaging (Prata et al., 2020). Another data by the WHO estimates a monthly need of 76 M gloves, 89 M facial masks, 1.6 M goggles, 2.9 M hand sanitizers, and 30 M gowns for frontline health workers, resulting in a 40% rise in the percentage of the supply chain of diverse clinical safety items (WHO, 2020). Plastic garbage has been generated at 1.6 Mt per day since the pandemic began. Because of the COVID-19 outbreak, an estimated 3.4 B face shields or single-use face-masks are wasted every day (Benson et al., 2021). The following model formula was used to perform the estimation.

$$\text{Total monthly facemask generated} = 3.0 \times 10^{-3}\,(T_p \times U_p \times A_r \times A_c)$$

$$\text{Total daily facemask generated} = (T_p \times U_p \times A_r \times A_c)/10{,}000$$

where T_p = Estimated country population.
U_p = Urban population of the country (in percentage).
A_r = Acceptance rate of face mask (in percentage).
A_c = Use of face masks per capita daily on average.

30 days per year was estimated to be the average number of days in a month.

According to the estimates, 445 M, 1.8 B, 380 M, 411 M, 22 M and 244 M facemasks are discarded per capita every day in Europe, Asia, Latin America and the Caribbean, Africa, Oceania and North America, respectively (Benson et al., 2021). Table 1 shows the quantity of face masks used, discarded and total estimated plastic waste in selected countries.

The outbreak of COVID-19 has halted the US government's efforts to limit pollution caused by SUPs by prohibiting the usage of straws and takeout containers, as well as asking people to bring their reusable bags (Klemeš et al., 2020). Similarly, the rate of SUP manufacture has surged by 30% in Thailand, despite the government's prohibition on throw-away plastic items, which was implemented in January 2020 (TEI, 2020; Parashar and Hait, 2020). Since the coronavirus outbreak in Bangladesh, approximately 14,500 t of plastic garbage including household plastics has been produced. Dhaka alone contributed about 3076 t of waste, including masks, gloves and polybags (ESDO, 2020). In addition, about 3039 t of disposable plastic wastes has been produced due to the consumption of about 1216 M hand gloves. The bulk consumption of surgical masks and gloves and hospitals and pathological testing laboratories have contributed 250 t of medical and 1.1 t of SUP wastes in this pandemic period (Parashar and Hait, 2020). As a result, special attention is required to manage this drastic change in plastic waste generation to ensure a healthy environment for all.

3. Fragmentation of plastic into MPs and NPs

Plastic polymers have numerous societal benefits, allowing for single-use in a range of applications, with consumers favouring hygiene over cost (van Doremalen et al., 2020) which led to an increase in the disposal and usage of plastic-based goods during the pandemic. This problem arises from the inappropriate disposal of household and

Table 1
Face mask used, discarded and total estimated plastic waste in selected countries.

Country name	Population[a]	Face mask used/day (d)[b]	Estimated daily facemask discarded[b]	Total estimated plastic waste (t)[b]	Mismanaged waste (t)[d]	% Plastic in mismanaged solid waste[c]
Bangladesh	164,689,383	32,120,094	51,383,087	12,351,703.70	65,786.13	4.67
China	1,439,323,776	68,925,427	702,390,002	107,949,283.20	37,573.37	9.8
Indonesia	273,523,615	1,95,483,225	122,538,579	20,514,271.10	250,371.39	14
India	1,380,004,385	76,539,522	386,401,228	103,500,328.90	128,007.22	9.5
Vietnam	97,338,579	6 1,364,918	29,590,928	7,300,393.43	83,140.58	12.15
Philippines	109,581,078	98,192,700	41,202,485	8,218,580.85	153,824.65	10.55
Thailand	69,799,978	8,940,211	28,478,391	5,234,998.35	11,780.97	17.59
Pakistan	220,892,340	1,1 77,478	61,849,855	16,566,925.50	1794.92	9
Malaysia	32,365,999	27,463,951	20,196,383	2,427,449.93	11,558.40	15
Japan	126,476,461	97,062,192	93,086,675	9,485,734.58	31,438.50	11
South Korea	51,269,185	18,372,547	33,632,585	3,845,188.88	777.9	24.3
Russia	145,934,462	12,426,840	86,393,201	10,945,084.70	25,651.47	14.21
United Kingdom	67,886,011	46,478,383	45,076,311	5,091,450.83	4498.53	20.2
Spain	46,754,778	29,626,206	29,923,058	3,506,608.35	1254.36	9
France	65,273,511	9,069,540	42,819,423	4,895,513.33	387.82	9
Germany	83,783,942	1,214,017	50,940,637	6,283,795.65	103.3	13
Italy	60,461,826	34,777,596	33,374,928	4,534,636.95	9585.86	11.6
Saudi Arabia	34,813,871	2,610,018	23,394,921	2,611,040.33	110.52	11
Iran	83,992,949	3,068,467	51,067,713	6,299,471.18	4827.27	8.5
Nigeria	206,139,589	12,397,554	75,034,810	15,460,469.20	21,519.67	4.8
South Africa	59,308,690	6,948,840	27,815,775	4,448,151.75	294.26	7.9
Turkey	84,339,067	22,926,773	51,278,153	6,325,430.03	22,812.72	3
USA	331,002,651	45,362,076	219,785,760	24,825,198.80	2871.34	13.1
Canada	37,742,154	1,682,366	24,456,916	2,830,661.55	71.25	3
Argentina	45,195,774	7,765,326	31,524,052	3,389,683.05	4044.14	14.61
Brazil	212,559,417	25,464,565	140,289,215	15,941,956.30	13,589.92	13.5
Colombia	50,882,891	3,964,224	30,529,735	3,816,216.83	503.49	12.83
Mexico	128,932,753	9,136,514	81,227,634	9,669,956.48	4448.51	10.9

[a] https://www.worldometers.info/population/.
[b] Benson et al. (2021).
[c] Chowdhury et al. (2021), d = Law et al., 2020.

medical plastic garbage as solid waste. Because of the ban on the cross border, some developing countries that depend on foreign recycling technology dispose of their waste rather than recycling (Sarkodie and Owusu, 2021). The world has already lacked over two billion people for waste collection, whereas over three billion people for waste disposal create a great challenge in the waste management sector (Sarkodie and Owusu, 2021). The mismanagement of plastic solid waste, combined with the enormous manufacturing capacity of plastic items, provides a progressive study that confirms that MPs and NPs have universally invaded the aquatic ecosystem nowadays; however, MPs and NPs fragments are dependent on the plastic age have health and environmental consequences. Obviously, plastic debris in the marine environment comes from solid waste, but it can also originate from municipal leachate and runoff from city littering (Aragaw, 2020). On the other hand, hazardous medical waste needs more precautions like decontamination before going to landfilling or other disposal systems than normal household waste because of the chances of cross-contamination (Misra and Pandey, 2005).

The main purpose of face masks is to keep people from being infected with the SARS-CoV-2 virus and spreading it to others. Depending on the filtration system, three types of masks are now in use: N95 and FFP2 respirator masks (83–99%), non-certified disposable masks (cloth masks) (16–23%), and medical or surgical masks (42–88%) (Sankhyan et al., 2021). Surgical face masks (to use and dispose of) and PPE can be made from various polymeric materials. Depending on the customer's order, polypropylene (PE), polyurethane (PU), polyacrylonitrile (PAN), polyethylene (PE), polyvinyl chloride (PVC), polyamide (PA), polystyrene (PS), or polyester like polyethylene terephthalate (PET) are used. These polymeric substances, in particular, were used as feedstock in the production of various plastic products (Fig. 1).

Disposable masks comprise three layers: an inner fibre layer, a layer in the middle (filter component with melted gusts), and an exterior layer (a water-resistant and coloured nonwoven). A single surgical mask contains approximately 4.5 g of PP, whereas an N95 mask contains roughly 11 g (Liebsch, 2020; Abbasi et al., 2020). It is indicated that cheaper PPE is more commonly used and/or disposed of than more expensive types of PPE and blue face masks and transparent gloves were the most common type of PPE. This is because of using high-density polyethylene (HDPE) to make those gloves (HDPE) and the masks as mentioned earlier which are usually constructed of nano- and micro-PP fibres. Therefore, they can increase the quantity of MPs with a low density (0.92 and 0.95 g/cm^3, respectively) which is a significant concern for the environment (Fadare and Okoffo, 2020; Abbasi et al., 2020). Degradation is defined as any change in physical or chemical characteristics caused by biological, chemical or physicochemical processes (i.e., mechanical degradation, thermal degradation, and photo-degradation).

Hydrolysis and oxidation are the principal polymer breakdown mechanisms caused by chemical or biological processes (Smith, 2005). The decomposition of a material caused by the action of light is known as photo-degradation which is the most common cause of polymeric substrate degradation (Pramanik et al., 2020; Sait et al., 2021). The majority of synthetic polymers are susceptible to UV and visible light-induced breakdown. In most cases, the life expectancy of polymeric materials used in outdoor applications is determined by the sun's near-UV radiation (290–400 nm). The energies of the near-UV light quanta (290–400 nm) range from 72 to 97 kcal/mol, or 3.1–4.3 eV (Rånby, 1989). This indicates that those UV quanta have sufficient power to disrupt the most significant number of molecular bonds. However, photo and thermal deterioration are the same in typical situations (Singh and Sharma, 2008). Biodegradation is influenced by various parameters, including polymer properties, organism type and pretreatment method. Molecular weight, crystallinity, tacticity, mobility, the variety of substituents and functional groups contained in the structure of a polymer, and the additives or plasticizers inserted into the polymer could take part in its decomposition (Artham and Doble, 2008; Monira et al., 2021b).

The first disintegration of polymers can be caused by a range of biological and physical processes (Swift, 1998). Biodegradation is divided into various stages, each with its own terminology (Francois-Heude et al., 2014). For example, biodeterioration is the initial step in biodegradation and involves the combined action of microbial populations. Deterioration is a type of surface degradation that affects the mechanical, physical and chemical properties of the materials (Lucas et al., 2008). The second phase is depolymerization, which involves microorganisms secreting catalytic agents that cleave polymeric molecules into monomers, dimers, or oligomers. The assimilation process comes next, followed by mineralization. The assimilation of chemicals carried through the cytoplasm by microbial metabolism to produce new biomass, energy, storage vesicles, as well as a range of secondary and primary metabolites is known as assimilation. Mineralization is the process through which simple and diverse ions and complex compounds

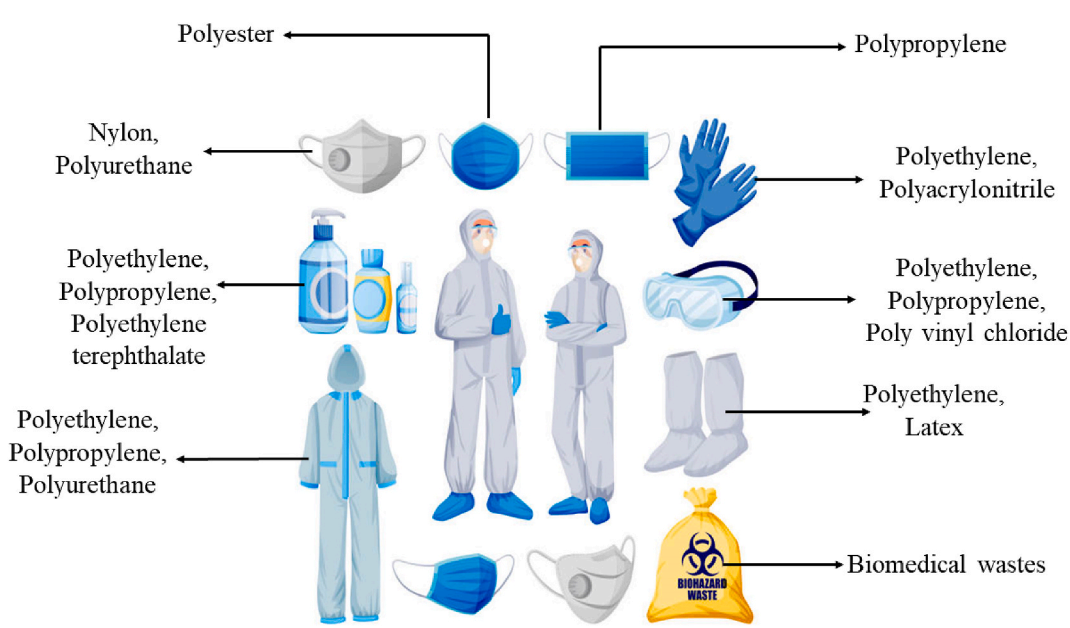


Fig. 1. Different types of PPE is made from different type of plastics.

are discharged into the extracellular environment (Francois-Heude et al., 2014). PPE items may have varying fates and sink depending on their properties once they reach the maritime environment like other plastic debris (Fadare and Okoffo, 2020). Plastic polymers could be negatively, neutrally, or positively buoyant in the water environment (Table 2).

Polyvinyl alcohol (PVA), polyester (PEs), and polyvinyl chloride (PVC) are high-density polymers that are prone to sink and settle in the aquatic environment. Less dense polymers, such as PE, PS and PP, float in seawater because of their density (Monira et al., 2021b). However, different businesses or brands are responsible for the materials used to produce certain PPE. For this reason, several PPE pieces are projected to persist in the ecosystem for extended periods, possibly susceptible to surface oceanic currents. In contrast, others are expected to get embedded in sediments and eventually become a chunk of the geological record, as documented with other types of plastic pollutants (De-la-Torre et al., 2021). Various mechanical forces fragmented this plastic waste into tiny particles, resulting in secondary plastics (Roychand and Pramanik, 2020). These secondary plastics are subjected to shear pressures, releasing MPs and NPs into the environment (Fig. 2). NPs are formed when MP is fragmented by mechanical forces or UV radiation, such as sand grain abrasion on beaches (Monira et al., 2021a). The leaching of plasticizers can enhance brittleness and fragmentation susceptibility. MP released in water would most likely be downsized to NPs due to water shear forces. Enfrin et al. (2020) stated that due to water shear pressures, MP discharged into the water would most likely be reduced to NPs. Mechanical weathering is assumed to initiate plastic degradation by introducing defects such as cracks within the material leading to the fragmentation of the plastic item.

After being exposed to UV light in water and the outside environment, plastic pellets such as PE (Fig. 3a), PP (Fig. 3b), PET (Fig. 3c), PS (Fig. 3d), PU (Fig. 3e, PA (Fig. 3f) and PVC (Fig. 3g) could be oxidized (Lambert et al., 2013; Lambert and Wagner, 2016a, 2016b). Though hydrolysis is not the most common way for polymers to be downsized, it is common to form NP (Kim et al., 2020). Fig. 3 depicts the degradation pathways of PS, PET, PP, PE, PU, PA and PVA. Reactive oxygen species mainly cause the photodegradation of plastics. The number of free radicals including hydroxyl (•OH), alkyl (R•), alkoxyl (RO•) and peroxyl (ROO•) radicals, which are commonly produced by UV radiation, cause chain scission, leading to a reduction in the size of the particles.

The MP/NP generated from discarded PPE can act as a vector for different disease transmission because of the interactions with microorganisms and other toxic chemical components (Ngo et al., 2019; Kampf et al., 2020; Fadare and Okoffo, 2020). The interaction of plastic with organic chemicals and heavy metals includes a variety of sorption mechanisms such as electrostatic and hydrophobic interactions (Mei et al., 2020; Fred-Ahmadu et al., 2020; Mohana et al., 2022). Additionally, the environmental conditions encourage harmful compounds such as polychlorinated biphenyls and flame retardants to leach from plastic goods (Bejgarn et al., 2015; De-la-Torre et al., 2020). The chemical release or sorption efficacy varies according to ambient conditions and physicochemical properties of the plastic products. The majority of organic pollutants in the environment are nonpolar organisms with limited solubility in water, making them hydrophobic in nature. The sorption of metals and organic molecules has improved when plastic surfaces are altered. Li et al. (2018) found that the ciprofloxacin (a hydrophilic organic molecule) interacts with UV-accelerated aged polyvinylchloride and polystyrene which had a higher sorption capacity compared with pristine polymeric products. The incidence of polymer surface oxidation caused by light and functional groups having oxygen on the plastic surface was attributed. Hüffer and Hofmann (2016) found that when plastics age and their hydrophobicity decreases, it enhances the sorption capacity of the hydrophilic pollutants. Goedecke et al. (2017) investigated how a polar medication (metformin) interacted with a non-polar fungicide (difenoconazole) on virgin polypropylene (PP), polystyrene (PS), and polyamide (PA) type of MPs and NPs. The amount of difenoconazole adsorption on the plastic particles was significantly influenced by agitation. The adsorption of pollutants was improved by artificial ageing of PA and enhanced the surface area of PP. The non-polar chemical binds to the NP/MP more strongly, but the polar compound barely interacted. Due to greater contaminant sorption, this evidence indicates that weathered plastics are possibly more harmful than virgin plastics under a similar type of polymeric materials (Table 3).

Table 2
Characteristics of some plastics used in daily products, PPE and packaging (Haque, 2019; Li et al., 2016).

Used product		Plastic material	Density (g/cm^3)	Specific gravity
Face mask	Non-woven type	PP	0.89–0.91	0.85–0.83
		PE	0.93–0.98	0.91–0.96
		PAN	1.184	1.06–1.08
	Woven type	Polyamide	1.14	1.13–1.35
		PEs	1.38	1.40
Protective gown, disposable apron		LDPE	0.91–0.93	0.91–0.93
		PP	0.89–0.91	0.85–0.83
Face shield		PP	0.89–0.91	0.85–0.83
		PE	0.93–0.98	0.91–0.96
Hand gloves		PU	0.08	1.067
		PS	1.04–1.11	1.08
		PAN	1.184	1.06–1.08
Boots		PU	0.08	1.067
		PAN	1.184	1.06–1.08
		PVC	1.20–1.45	1.4
Plastic bottles		HDPE	0.93–0.97	0.94
		PP	0.89–0.91	0.85–0.83
		PET	1.38–1.39	1.37
Single used Plastic		PE	0.93–0.98	0.91–0.96
		PET	1.38–1.39	1.37

4. Adverse effect on environment and biota because of increased quantity of plastic waste in the pandemic

COVID-19 pandemic causes an unanticipated surge in household plastic and medical waste produced by health care facilities, which makes Governments to experience a vulnerable situation.

Due to its non-biodegradable nature, a plastic derived from medical waste and household products constitutes a substantial hazard to the terrestrial, marine ecosystem and aerial (Haque, 2019). The cloud cover and climatic conditions influence air-sea interactions which affect the global movement of atmospheric particles (Takahashi and Hayasaka, 2020). Even single-use plastic bags can release MP/NP into both indoor and outdoor air (Sobhani et al., 2020). When PPE and plastic materials are littered randomly in environments, they are likely to cause blocking sewage systems, as well as resist the entrance of water and disturb the agricultural land fertility (Haque, 2019). The persistence and ubiquity of plastic debris represent major dangers to biological lives as they can be swallowed comfortably and thus create different severe physical problems (Monteiro et al., 2018; Connors et al., 2017).

Plastic accounts for 60–80% of all solid garbage on the planet (Haque, 2019). Although there are several options for the disposal of plastic wastes, only 63% of plastic garbage is adequately managed. The remaining 37% find their way to the aquatic system from land-based sources, where it is constantly fragmented, confined and ingested by aquatic species (Mourshed et al., 2017; Dalberg Advisors et al., 2019). Only 12% of the total produced plastics was burnt between 1950 and 2015, 9% was recycled, and 60% ended up in the natural environment or landfills (UNEP, 2018; Geyer et al., 2017). Based on current generation trends, a portion (12,000 t) of a plastic garbage can be burnt, and another portion (9000 metric t) can be recycled (Geyer et al., 2017), while the rest of the garbage would be thrown away in landfills or gathered in the nature within few years.

Macro, micro and nano plastics are three different forms of

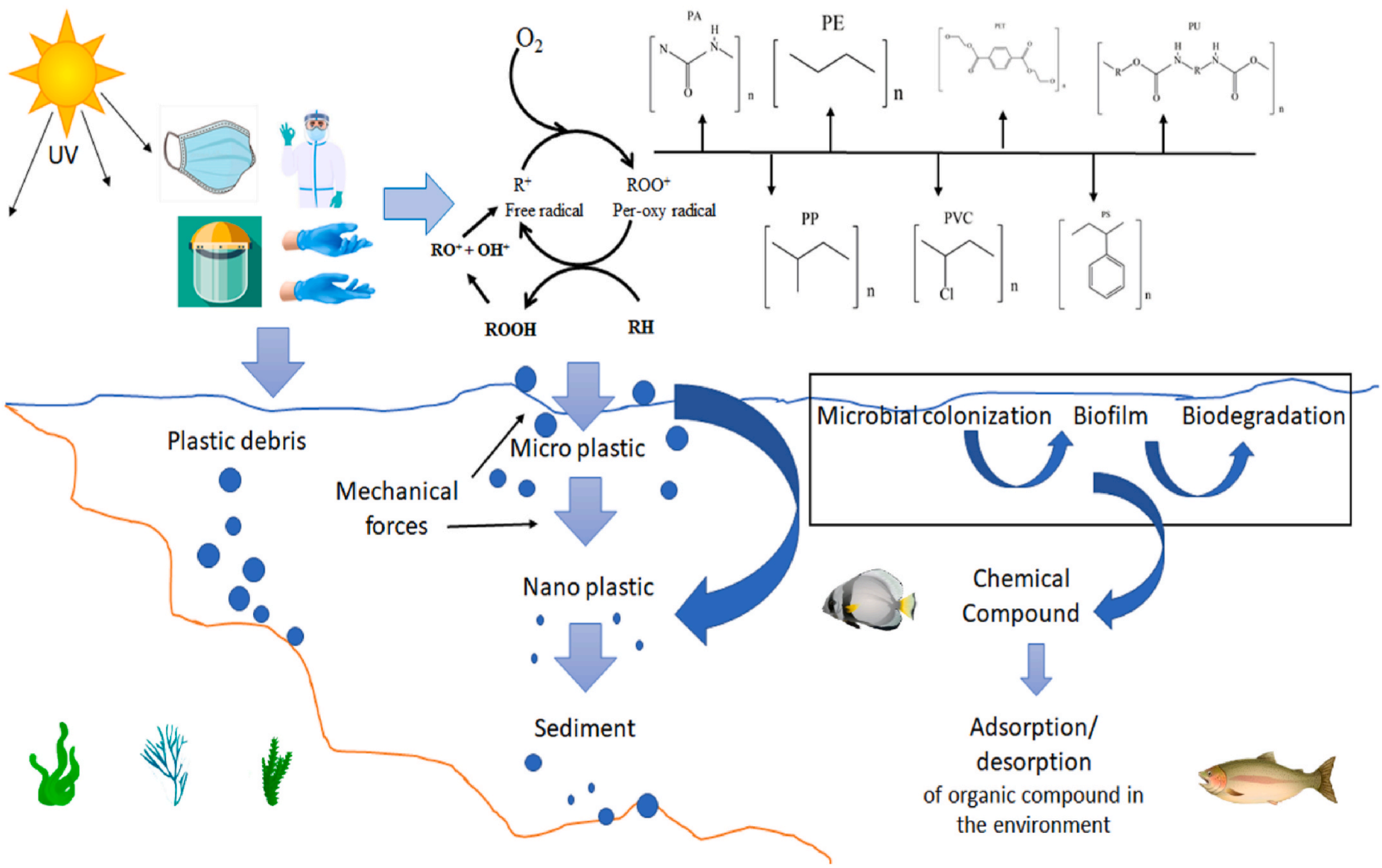


Fig. 2. Fragmentation of face mask and other PPE into MPs and NPs in the environment.

hazardous plastic particles responsible for the pollution of the world's aquatic environment per annum (4.80–12.70 t) as well as for air (Worm et al., 2017). Asian nations like Vietnam, Thailand, Indonesia, the Philippines and China contribute 50% of plastic garbage in the oceans with 58,000 t of plastic debris per day (Mansor, 2020). MPs are well-known for being consumed by aquatic animals, bioaccumulation and biomagnification through the food chain (Santillán et al., 2020; De-la-Torre, 2020), such as difficulties in the reproduction of aquatic organisms, resulting in a reduction in their growth rate (Garcés-Ordóez et al., 2020; Santillán et al., 2020).

Plastics are also linked to a lot of greenhouse gas emissions. The thermal treatment (pyrolysis, incineration, burning autoclaving, and microwave or plasma treatment), production and recycling of these products produce around 400 Mt of CO_2 each year (Windfeld and Brooks, 2015; Liu et al., 2015; Grodzińska-Jurczak et al., 2020). Most treatment facilities are built to control the medical waste composition and typical flow rate. The recent estimation illustrates that the availability of hazardous waste treatment is insufficient regarding the quantity of medical waste produced throughout the corona pandemic. In reality, reducing capacity just by waste compression or suppression is ineffective. Moreover, the absence of pathogens in these wastes should be confirmed. It is reasonable to expect a substantial volume of untreated waste should be found in landfills which would be a significant source of environmental pollution (Yu et al., 2020). Aquatic living might intake MP/NP from their surroundings directly or indirectly through their prey (Lusher et al., 2013). MP/NP are well-known for their ingestion by marine creatures, biomagnification, and bioaccumulation in the food chain (Zhang et al., 2019; Avio et al., 2020). Seafood containing MP/NP could be a modern danger, though the effect of MP/NP on the human body is still obscure (Smith et al., 2018; Akhbarizadeh et al., 2020). MP/NP can enter the human body through both ingestion and inhalation which can cause a prolonged effect on the human body like triggering oxidative stress and inflammation, cardiovascular and respiratory diseases, lung cancer, and interaction with the immune system. NP also can affect the placenta, fetus, and brain; (Kelly and Fussell, 2020). Consequently, people in coastal areas should be more careful about their diet, especially where plastic pollution is severe. MPs are also harmful to planktons, the most important component of marine ecology. When exposed to MPs, heterotrophic plankton undergoes phagocytosis and keeps these minute plastic bits in their tissues. On the other hand, MPs can abate the absorption process of chlorophyll when it penetrates phytoplankton cells (Nerland et al., 2014). Most of the time, these MP/NPs are mistakenly taken as food by aquatic living due to their perseverance throughout marine nature. MP/NP could cause fatality to the marine species as they can be a source of both entanglement and diet (Sharma and Chatterjee, 2017). However, PPE items may be consumed completely by apex predators and marine megafauna like sharks, seabirds, whales, mammals and turtles (Kühn and van Franeker, 2020; Fernández and Anastasopoulou, 2019).

5. Proper management of waste

The momentum of reducing plastic waste has been interrupted by the COVID-19 situation. Plastic waste management during the pre-pandemic situation was already insufficient regarding waste production, and the increasing number of plastics during the pandemic worsened the situation. On the other hand, it is extremely likely to overburden existing infrastructures, disrupting regular operations. Therefore, we must learn how to handle plastics to maintain the benefits of plastics without jeopardizing the environment. During the pandemic, plastic trash and waste management faces significant problems for various components, including source identification, collection, transportation, treatment or disposal, and proper training for the labourer. As a result, numerous international organizations like the WHO, the United

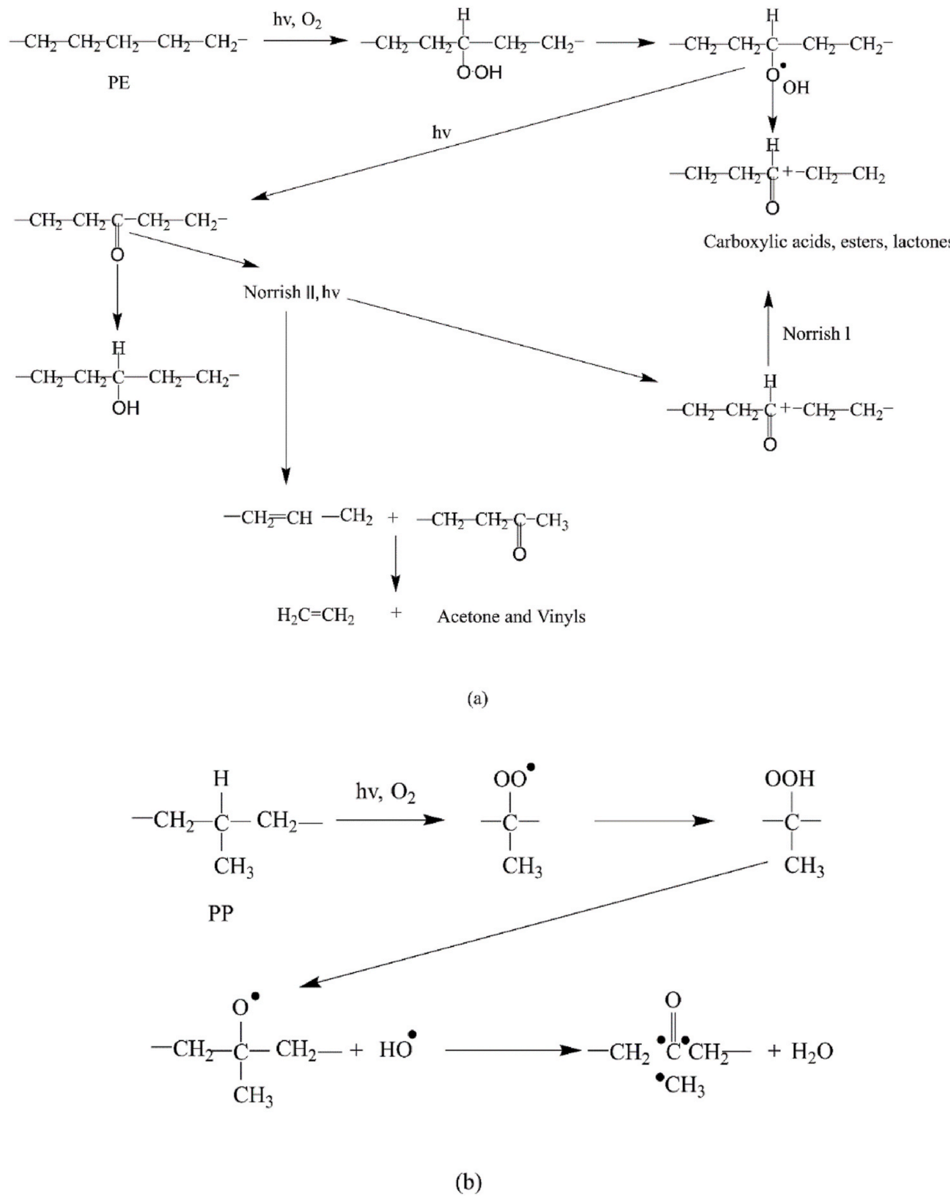


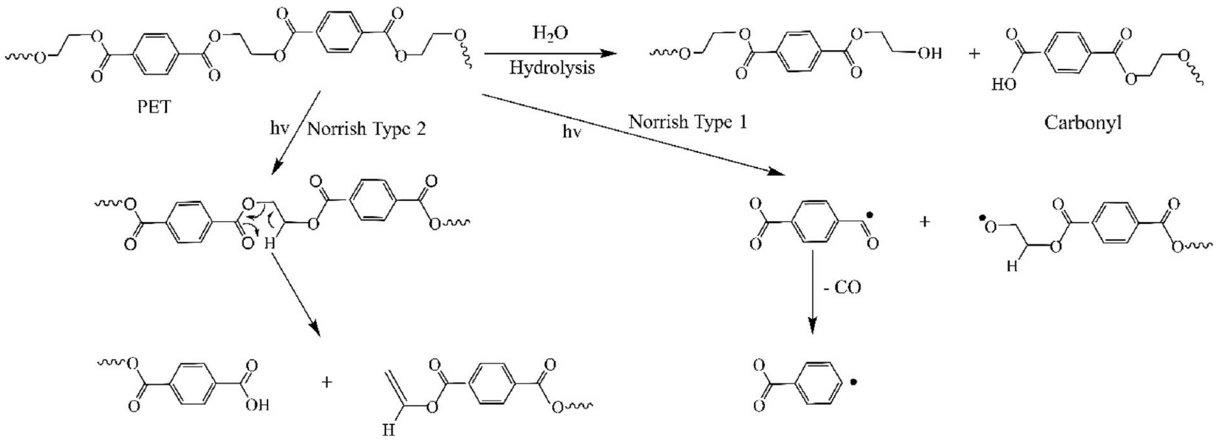
Fig. 3. Photocatalytic degradation mechanism of common plastics used in PPE, (a) photo-oxidation of PE by UV irradiation, (b) photodegradation of PP, (c) hydrolysis and photodegradation of PET, (d) photodegradation of PS (e) photodegradation PU, (f) photodegradation PA and (g) photodegradation of PVC (Mohana et al., 2021; Fotopoulou and Karapanagioti, 2017; Tyler, 2004).

Nations Environment Programme, the United Nations Children's Fund, and others have lately released specific instructions and advisories on dealing with plastic waste (Parashar and Hait, 2020). The majority of the guidelines are initially focused on maintaining hygiene parameters and properly managing these potentially contaminated wastes in this worrying circumstance (Yang et al., 2021; Penteado and de Castro, 2021).

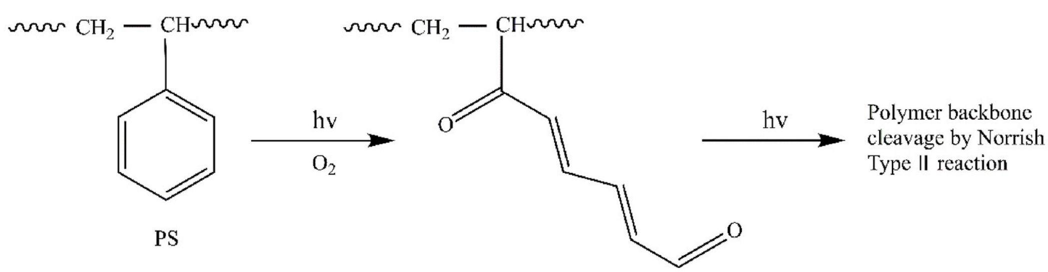
Though there are several strict rules and regulations for managing plastic waste, some Asian countries are not following them, thus, adequately accumulating the production of plastic debris. The Philippines, Cambodia, India, Thailand, Indonesia, Malaysia, Palestine, Vietnam and Bangladesh, to name a few countries, were accused of discarding hazardous biomedical wastes in open landfills. That might be a new avenue for the viral infection to spread in the environment as a result of poor management (Sangkham, 2020).

5.1. *Enhancement of municipal waste management*

Estimating the amount and type of waste generated throughout the pandemic has become difficult and collecting information about recycled plastics to determine what should be thermally treated or disposed of. It is also critical to set realistic goals to preserve resources, such as adhering to rules and maintaining the hierarchy of waste management (reduce, reuse, recycle, and recover) (Prata et al., 2019). Similarly, the usage of PPE by waste management professionals should be made necessary and reinforced. As a result, municipalities in charge of garbage collection and treatment should develop waste reduction suggestions, collection rates, end-of-life procedures and preventative measures to use during pandemics.



(c)



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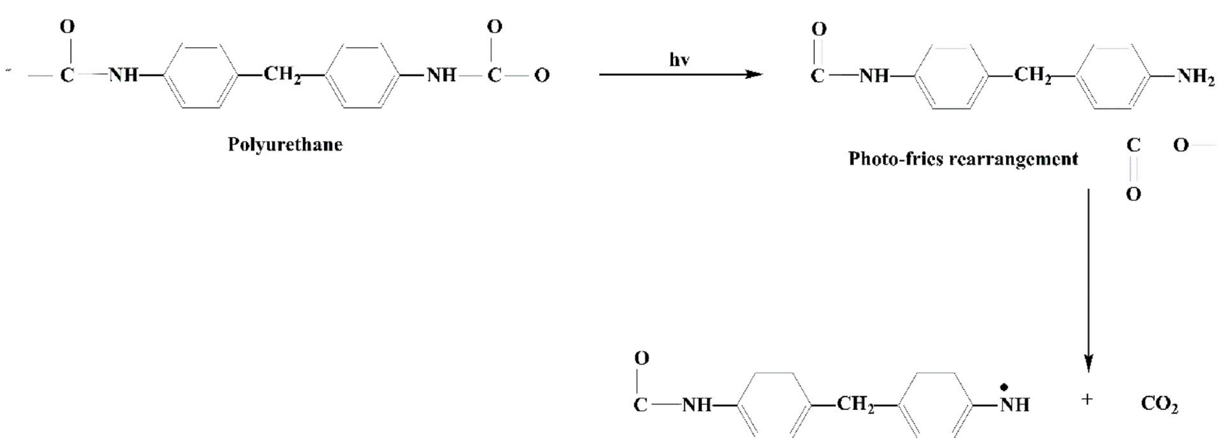


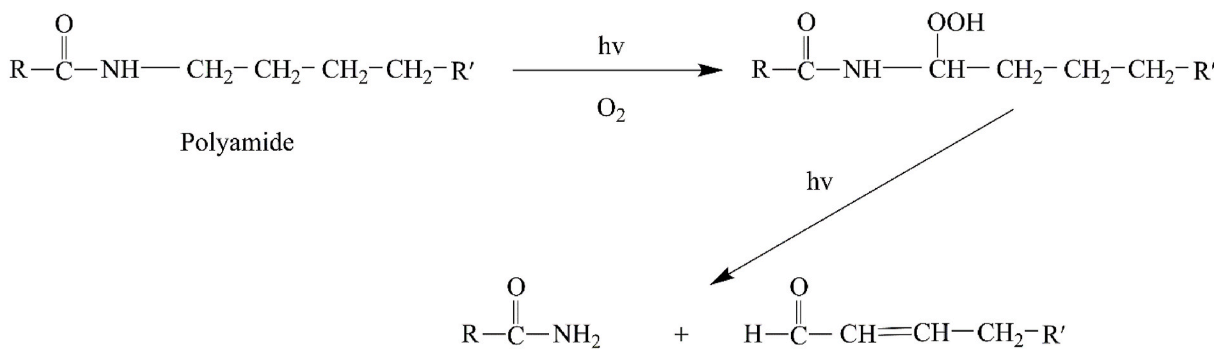
(e)

Fig. 3. (*continued*).

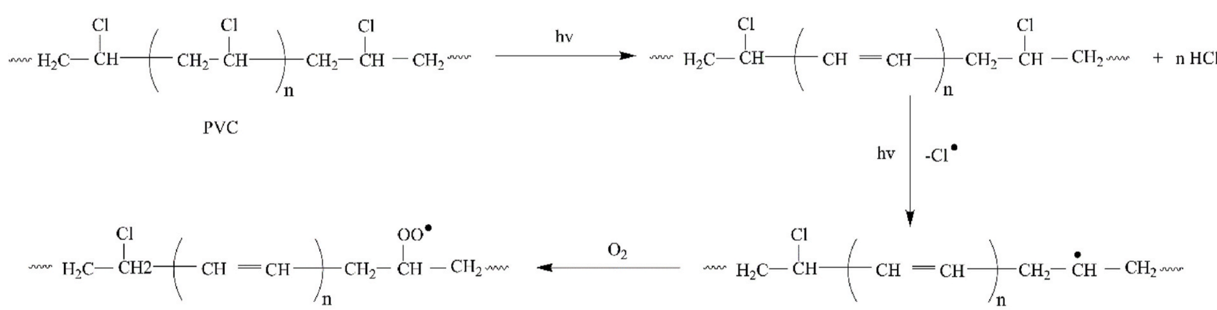
5.2. Decontamination of PPE and medical wastes allowing for safe recycling

To ensure health safety during pandemics and avoid cross-contamination, all plastic waste and PPE should be closely checked by specialists trained to handle hazardous plastic waste. Disinfection technologies such as UV, ozone or bioengineering techniques can provide a long-term solution in this space (Dennis et al., 2020; Hamzavi et al., 2020). The amount of waste, type of waste, expenditures, and maintenance should be considered while selecting a disinfection system.

Incineration remains the best solution for huge amounts of infectious medical waste (>10 t/d) because entire harmful microorganisms are eliminated because of the extreme temperature above 800 °C. On the other hand, chemical or physical disinfection could be an alternative option (Gertsman et al., 2020). Decontamination of personal protective equipment including N95 respirators, face shields and surgical masks, may also be beneficial in maintaining enough supplies and promoting its prolonged reuse and recyclability possibilities. Furthermore, recycling technologies for nonwoven fabrics, which make up the majority of PPE, are still limited due to a scarcity of technology and their composition (e.



(f)



(g)

Fig. 3. (*continued*).

g., a combination of components like composites) (Yalcin et al., 2013). Ionized hydrogen peroxide, ozone gas, UV-C light, microwave and heat-based decontamination, as well as microwave and heat-based decontamination, appear to be viable disinfection processes for use on N95 masks and PPE, enhancing reusability and minimizing waste generation (Dennis et al., 2020; Gertsman et al., 2020; Hamzavi et al., 2020; Cheng et al., 2020a, b).

5.3. Landfilling, recycling and thermal treatment

In developing countries, landfilling has become an accepted approach for the disposal of plastic trash (Parashar and Hait, 2020). Recycling plastics as an energy source could be an alternative to the current scenario. However, there are certain challenges to overcome. Most recycling methods require a high level of purity. In the future, the energy obtained from waste or recycled plastic might be utilized to replace fossil fuels (Cheng et al., 2020a, b; Lee et al., 2019). Compared to mechanical recycling, incineration is far more efficient in dealing with various non-recyclable plastic waste due to the added benefit of treating waste regardless of segregation, cross-contamination, additives and contaminants. On the other hand, a frequently utilized thermal treatment named incineration is used to manage plastic waste. This process could be a reasonable alternative as it requires less labor and has a lower risk of contamination. The plastic waste is destructed at 800–1000 °C temperature range, and the waste heat is recovered (Klemeš et al., 2020). Incineration is widely used in northern Europe to handle MSW (including plastic trash) because of its potential to recover energy. Some affluent countries, such as Sweden, Denmark and Poland, have incorporated advanced and enhanced air pollution control technology in their waste-to-energy technology (Malinauskaite et al., 2017). Sweden is an excellent example of energy output recovery (23%) from municipal and industrial trash incineration (Ericsson and Werner, 2016). On the other hand, Sweden is required by the European Union to follow the waste hierarchy and reach specific targets, such as 55% plastic package recycling by 2030, to minimize its reliance on waste to energy (Milios et al., 2018). Energy recovery technologies such as thermal and catalytic pyrolysis, gasification and plasma arc gasification can also be alternative methods of recycling plastics (Nizami et al., 2015; Ouda et al., 2016). Liquid oil, solid residue (char) and gases can be produced from plastic waste by pyrolysis at high temperatures (300–900 °C) via thermal decomposition. Liquid oil produced from plastic pyrolysis has the potential to be used as an alternative source of energy. Although thermal treatment can be used as a short-term option in the face of COVID issues, a waste hierarchy dominated by the concepts of reducing, reusing, and recycling is always suggested for a long-term and ideal scenario.

5.4. Alternatives for plastic to reduce plastic wastes

Along with these technologies, biodegradable composites and other biodegradable plastics may be a better solution because of their biocompatibility and biodegradability. A number of experts are working to develop biodegradable composites that can replace non-biodegradable plastics. Tian and Tang, 2012 showed the application of biodegradable polymer can be increased by functionalizing it. Another study by Rahaman et al. (2019) found that a biodegradable composite made of poly (lactic acid) and oligo (D-lactic acid) grafted cellulose has

Table 3
Name of various chemicals adsorbed by MP or NP.

MP/NP type	Size	Chemical sorbate	Reference
Bio-degradable PE, PBAT and PS	400, 2338 ± 486 and 250 μm, respectively	Phenanthrene	Zuo et al. (2019)
UV-accelerated PVC and PS	75 μm	Ciprofloxacin	Li et al. (2018)
Pristine and aged PS	125–250 μm	Organic compounds (not named)	Hüffer et al. (2018)
Virgin and beached PS	0.45–1 mm	Oxytetracycline	Zhang et al., (2018)
HDPE, PVC and PS	100–150 μm	Pyrene	Wang and Wang (2018a)
PE	45–48 μm	Propranolol, Sulfamethoxazole, Sertraline	Razanajatovo et al. (2018)
PP, PVC, PE, PS and PA	75–180 μm	Amoxicillin, Sulfadiazine, Tetracycline, Trimethoprim Ciprofloxacin	Li et al. (2018)
PE	150 μm	Sulfamethoxazole	Xu et al. (2018)
PVC, PP, PE, and PS	200 mesh	Tylosin	Guo et al. (2018)
PE, PS and PVC	100–150 μm	Phenanthrene and pyrene	Wang and Wang (2018b)
Virgin PA, PP and PS	3–5 mm	Metformin and Difenoconazole	Goedecke et al. (2017)
PP	0.18–0.425, 0.425–0.85, 0.85–2, 2–5 mm	3,3 ′,4,4 ′ tetrachloro biphenyl	Zhan et al. (2016)
PE, PA, PS and PVC	22–220 nm	Naphthalene, Ethyl benzene, Cyclohexane, n-hexane, Benzene, Chlorobenzene, and Toluene	Hüffer and Hofmann (2016)
PS	<100 nm	Organic compounds (not named)	Koelmans et al. (2020)
PE, LDPE		Pharmaceutical compound, non-polymer nanomaterial	Koelmans et al. (2015)

qualities that can easily replace plastics and could be a superior alternative option. Creating biodegradable plastics (BPs) made from renewable biomass is a hot issue. Renewable raw resources including cellulose, lignin, bioethanol and starch, are commonly used to make BPs. Polyhydroxyalkanoate (PHA), polyhydroxybutyrate valerate (PHBV), polyhydroxybutyrate (PHB), polyhydroxybutyrate valerate (PHBV) and polylactic acid (PLA) are the most common biodegradable and commercially accessible natural polymers on the market today. Biodegradation of BPs is possible without negative consequences (Haider et al., 2019). BPs are primarily employed as soft and hard food packaging materials due to their high biodegradability (Shen et al., 2020). Bio-based biodegradable solutions have additional advantages because they degrade through enzymatic or biological activity (Shen et al., 2020). Furanic-aliphatic polyesters (e.g., PEF, PEF-co-PLA, Polyethylene 2,5-furandicarboxylate –co-PLA and Polyethylene 2,5-furandicarboxylate) as well as aliphatic polyesters (e.g., PHA, and PLA) seem to be of specific importance as building blocks for some other one-time-use plastics and PPE because of their long shelf lives (Sousa et al., 2015). Researchers from National University of Singapore, Singapore have created a biodegradable packaging material using grapefruit seed extract and chitosan that has been shown to double the shelf life of bread in comparison to traditional oil-based film packaging (Kabir et al., 2020). The study of seaweed and cellulose has verified that seaweed and cellulose are compatible for forming biodegradable and cost-effective blend films for a wide range of applications. Several startup companies successfully designed plastic products (e.g., edible tea bags, seasoning sachets, food wrappers, water bottles, and cups) from seaweed (Khalil et al., 2017). Additionally, a study group from AINIA, Spain, has successfully secured PHB from excess whey which is utilized in the cheese business as a substitute for traditional dairy product packaging materials (Nielsen et al., 2017). In another report, Sagnelli et al. (2017) produced polysaccharide-based bioplastics representing important alternatives to conventional plastic because of their intrinsic biodegradable nature. Amylose-only, an engineered barley starch with 99% amylose, was tested to produce cross-linked all-natural bioplastic using normal barley starch as a control. Deng et al. (2022a, 2022b) reported an easy and potentially scalable method to fabricate biodegradable, breathable, biocidal, antiviral and antibacterial cellulose nonwovens PPE which not only gives better protection against coronavirus but is also environmentally friendly. Wiryadinata and Indriani, 2021 also fabricated biodegradable medical-grade PPE using pineapple leaf fiber cellulose. This resultant biodegradable plastic would meet the public needs for everyday household products.

6. Conclusions

The rising consumption and improper disposal of plastic-based PPE, SUP and medical waste during the COVID-19 pandemic has become a concern to the environment, air, land and aquatic. However, all these plastic wastes that are not dumped or recycled properly have increased the level of plastic debris in the environment. This pandemic has turned the tide favouring plastic pollution into the aquatic system. Face masks and other PPE contain a considerable amount of plastic that does not degrade the environment. Those plastic debris undergo various photochemical degradation under UV radiation and mechanical forces and turn them into MPs and NPs which is detrimental to human health and bio-life. The medical health and waste management sectors worldwide have been trying to pull the strings of this surging waste by taking steps including proper disposal and recycling of waste. To eliminate this pollution, some countries have chosen pyrolysis as a recycling process to produce fuel from it due to its cost efficiency and easy conductance. But in this process, some NPs are produced and remain in the residue which is harmful to the environment. As a result, researchers are trying to resolve the problem by providing reliable and eco-friendly waste plastic treatment processes. Because of the preponderance of stable pollutants in water and soil, MPs and NPs have become a global concern compared to global warming. As we cannot overlook the necessity of plastic-like products, replacing plastics with alternative products, similar to plastic in nature but biodegradable, could be revolutionary. However, governments worldwide should take some initiative and fruitful steps to control the production of plastic products and their release into the environment. Some rules and regulations should be imposed on the use of plastic as well as people should be educated about the use, reuse, recycling and management of plastic. Forthcoming work should be directed to the plan for future plastic pollution and plastic waste management, mostly linked with the remediation process because the MPs and NPs are found in the ocean and in surface water and agricultural soil, which is detrimental to both human health and animals. Upcoming research should also be focused on the fate and transport of plastic as they break down into tiny pieces, so change their colloidal nature and hydrodynamic behaviour in water samples. Overall, it is necessary to understand their surface characteristics, size and interaction behaviour during transportation of NP/MP to find a proper solution to plastic pollution.

Credit author statement

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Conceptualization, Project administration, Supervision, Writing - review & editing.

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

No data was used for the research described in the article.

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