Science of the Total Environment 867 (2023) 161390

Contents lists available at ScienceDirect

Science of the Total Environment

journal homepage: www.elsevier.com/locate/scitotenv

Post-pandemic micro/nanoplastic pollution: Toward a sustainable management

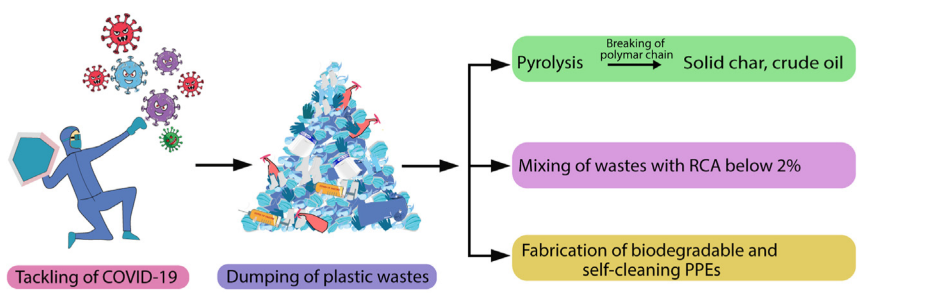
Thuhin K. Dey [a,e], Md. Rasel [b,e], Tapati Roy [c,e], Md. Elias Uddin [a,e], Biplob K. Pramanik [d], Mamun Jamal [b,e,⁎]

[a] Department of Leather Engineering, Faculty of Mechanical Engineering, Khulna University of Engineering & Technology, Khulna 9203, Bangladesh
[b] Department of Chemistry, Faculty of Civil Engineering, Khulna University of Engineering & Technology, Khulna 9203, Bangladesh
[c] Department of Agronomy, Faculty of Agriculture, Khulna Agricultural University, Khulna, Bangladesh
[d] Department of Civil and Infrastructure Engineering, RMIT University, Australia
[e] Microplastics Solution Ltd., Incubation Centre, KUET Business Park, Khulna, Bangladesh

HIGHLIGHTS

- Integrated approach on recycling PP-based waste is crucial for sustainability.
- Pyrolysis reactors require customization to make them environmentally friendly.
- Fabrication of smart PPEs can be considered plastic waste mitigation strategy.
- Using waste PPEs into civil construction significantly reduces pollution.
- Currently, 9 % of the plastic waste is recycled globally.

GRAPHICAL ABSTRACT



ARTICLE INFO

Editor: Fang Wang

Keywords:
Biochar
Biofuel
COVID-19
Facemask
Plastic waste management
Pyrolysis

ABSTRACT

The global health crisis caused by the COVID-19 pandemic has resulted in massive plastic pollution from the use of personal protection equipment (PPE), with polypropylene (PP) being a major component. Owing to the weathering of exposed PPEs, such contamination causes microplastic (MP) and nanoplastic (NP) pollution and is extremely likely to act as a vector for the transportation of COVID-19 from one area to another. Thus, a post-pandemic scenario can forecast with certainty that a significant amount of plastic garbage combined with MP/NP formation has an adverse effect on the ecosystem. Therefore, updating traditional waste management practices, such as landfilling and incineration, is essential for making plastic waste management sustainable to avert this looming catastrophe. This study investigates the post-pandemic scenario of MP/NP pollution and provides an outlook on an integrated approach to the recycling of PP-based plastic wastes. The recovery of crude oil, solid char, hydrocarbon gases, and construction materials by approximately 75, 33, 55, and 2 %, respectively, could be achieved in an environmentally friendly and cost-effective manner. Furthermore, the development of biodegradable and self-sanitizing smart PPEs has been identified as a promising alternative for drastically reducing plastic pollution.

Contents

⁎ Corresponding author at: Department of Chemistry, Faculty of Civil Engineering, Khulna University of Engineering & Technology, Khulna 9203, Bangladesh.
E-mail address: mamun.jamal@chem.kuet.ac.bd (M. Jamal).

http://dx.doi.org/10.1016/j.scitotenv.2023.161390
Received 28 October 2022; Received in revised form 29 December 2022; Accepted 1 January 2023
Available online 5 January 2023

1. Introduction

The world is experiencing a massive disaster due to the novel coronavirus (SARS-CoV-2), and the World Health Organization (WHO) declared it a pandemic (Patrício Silva et al., 2021). The number of people infected with this virus has surpassed 146 million, with three million deaths worldwide (Ju et al., 2021). Personal protective equipment (PPEs) must be worn by healthcare personnel (especially physicians and nurses) and the general public to avoid the spread of this fatal coronavirus (Nzediegwu and Chang, 2020). In particular, PPEs is frequently utilized as protective equipment against viral infections, chemical exposure, and other risks. Polymeric materials such as polypropylene (PP), polystyrene (PS), polyurethane (PU), polycarbonate (PC), polyacrylonitrile (PAN), and polyethylene (PE) are used to manufacture PPEs, such as facemasks (medical and respirator), hand gloves, face shields, goggles, and aprons (Abbasi et al., 2020). Facemasks are an effective tool for inhibiting man-to-man transmission of COVID-19 (Wu et al., 2020); hence, their manufacturing has expanded dramatically. Even after the pandemic, the use of facemasks has remained high because of the global embrace of sanitary lifestyles. Most of these items are single-use and must be appropriately disposed. According to a recent online survey, approximately 9 % of people worldwide discarded used masks improperly (Fadare and Okoffo, 2020). According to one study, 1 % of all used masks are incorrectly disposed of in the environment, which equates to 10 million disposable masks each month, resulting in 30 to 40 tons of plastic waste (Kwak and An, 2021), that posing a threat to living species ((Lee and Kim, 2022; Neto et al., 2021; Prata et al., 2020). Furthermore, a recent study has demonstrated that plastic pollution can significantly contribute to climate change via carbon emissions (Shen et al., 2020). In addition, plastic waste greatly contributes to the discharge of microplastics (MPs) and nanoplastics (NPs) (MPs size <5 mm and NPs size <500 nm), which pose serious environmental threats (Dey et al., 2021). The COVID-19 virus may persist in aerosol droplets for three hours and on plastic surfaces for upto three days (van Doremalen et al., 2020). As MPs/NPs can travel up to 100 km by air, facilitating COVID-19 transmission to the most remote places, even where there is no contamination (Allen et al., 2019).

Currently, 79 % of plastic waste ends up in landfills or other environmental media, 13 % is burned, and 9 % is reused (Geyer et al., 2017), raising global concerns. However, existing waste management systems such as landfilling and incineration are insufficient for managing this massive waste. In addition, incineration is expensive and generates ash that is harmful to both the environment and humans. Moreover, plastic waste is unsuitable for incineration because it does not burn well in the presence of oxygen, and in some circumstances, explodes. Thus, careful segregation is required to choose plastics for incineration to minimize the explosive mishaps caused by non-combustible wastes, which reduces process efficiency (Evode et al., 2021). Furthermore, burning medical waste increases the possibility of viral infections spreading within the surrounding community (Corburn et al., 2020). Landfilling, on the other hand, is particularly unsuitable because of the contagious nature of COVID-19-related medical waste, that is, groundwater or soil contamination. Some researchers have suggested digging a deep hole to dispose of waste, which would not particularly suit plastic waste, as it would not decompose naturally but rather contaminate rivers, canals, and pond water through underground leaching (Harussani et al., 2022). Moreover, recycling contaminated plastic waste may generate toxic fumes such as sulfur, carbon, and ash. Therefore, it is crucial to address the gap in the safe disposal of post-pandemic plastic waste as well as the simultaneous conversion of plastic waste materials into commercially feasible products.

Recently, Saberial et al. examined different percentages of shredded face masks (SFM) added to recycled concrete aggregate (RCA) for road-base and subbase applications. The experimental results showed that RCA mixed with three different percentages (i.e., 1, 2, and 3 %) of SFM satisfied the stiffness and strength requirements for pavement bases/subbases. The introduction of the shredded face mask not only increased the strength and stiffness but also improved the ductility and flexibility of the RCA/SFM blends. Specifically, the incorporation of 1 % SFM into RCA increased the compressive strength and resilient modulus to 216 kPa and 314.35 MPa respectively. However, >2 % SFM to RCA content leads to a decrease in the strength and stiffness of the RCA (Saberian et al., 2021). To convert plastic waste into industrially feasible products, Aragaw et al. recycled medical plastics into high oil content, particularly via pyrolysis, and >75 % of the waste PPEs was converted to bio-crude oil (tar). Thus, the volume of waste PPEs can potentially be reduced by using energy conversion pathways (Aragaw and Mekonnen, 2021). Pandey et al. used an upcycling process to convert waste plastics into value-added products such as graphene nanosheets (GNs) and showed their subsequent applications in dye-sensitized solar cells (DSSCs) and supercapacitors. The use of GNs in supercapacitor electrodes (as an active layer material) ensured a high specific capacitance of 398 F/g at a scan rate of 0.005 V/s. The energy and power densities of GN-based supercapacitors were 38 Wh/kg and 1009.74 W/kg, respectively. On the contrary, GNs-based DSSC also exhibited a high fill factor of 86.4 % and a high VOC of 0.77 V, respectively (Pandey et al., 2021). Currently, Harussani et al. reviewed the recovery process of PP plastic to the fuel-like liquid oil (up to 80 %) and solid char (1.54–33.50%wt) through the pyrolysis process (Harussani et al., 2022). Even researchers are also working on fabricating smart PPEs, which are fabricated using either non-plastics or biodegradable plastic materials. To fabricate smart PPEs, Zhong et al. constructed GO-based self-sanitizing surgical facemasks with photothermal properties (Zhong et al., 2020). Shan et al. fabricated an updated graphene-coated face mask that does not require sunlight exposure (Shan et al., 2020). Soni et al. used a coating of single-walled carbon nanotubes (SWCNTs) on the surface of a face mask and achieved 99.9 % antibacterial activity (including viruses) compared to a conventional polymeric mask (Soni et al., 2021). However, there is a gap in the sustainable management of unconventional medical waste on a large scale. To fill this research gap, this paper discusses the relationship between COVID-19 and MP/NP pollution, existing plastic waste management systems and their limitations, novel and sustainable plastic waste management strategies for converting waste into value-added products, and the fabrication of biodegradable and self-cleaning PPEs. In addition, it introduces an integrated approach that requires local authorities, researchers, and industries to implement this design and upcycle the process in a sustainable manner.

2. Micro/nano plastics as a mode of transport for COVID-19

COVID-19 spreads rapidly via a variety of routes, including respiratory transmission, touching a COVID-19-contaminated surface, and propelling the virus toward the nose, mouth, and eyes, either intentionally or unintentionally (Kraemer et al., 2020). Inhalation of virus-infected droplets is the primary mode of COVID-19 transmission, and research on this topic continues (Morawska and Cao, 2020; Prather et al., 2020). Specifically, Zhang et al. conducted research on the airborne transmission of COVID-19 and asserted that airborne transmission is a crucial pathway for rapid virus contamination (Zhang et al., 2020a, 2020b). Owing to the coupled effects of their small size and light weight, MPs/NPs are easily transferable from the place of disposal to the place of deposition (such as roadsides or vegetation) by means of natural wind or drafts via vehicle movement (Spennemann, 2021).

However, face masks are required to prevent the inhalation of contaminated droplets during airborne virus transmission. Various plastics, including PS, PU, and PP, are used to create facemasks, and these synthetic masks are discarded as plastic trash after use. It is well known that plastic wastes do not degrade rapidly, resulting in the formation of MPs/NPs via weathering processes such as natural sunlight, wind, aging, and abrasion (Zhang et al., 2020a, 2020b). Environmental weathering changes the physical and chemical properties of polymers through abiotic processes, such as light, temperature, air, water, and mechanical forces (Sadia et al., 2022). On the other hand, the photo-degradation of plastics is caused due to the involvement of free radical-mediated reactions that are initiated by solar irradiation. High-energy ultraviolet radiation (290–315 nm) and medium-energy radiation (315–400 nm) were mainly responsible for the plastic degradation of MPs/NPs. Likewise, the thermal degradation of plastics can occur owing to high-temperature exposure. In such cases, plastics undergo thermo-oxidative reactions, and a sufficient amount of heat is absorbed to overcome the energy barrier and break long polymer chains, resulting in the generation of free radicals. Mechanical degradation (due to external forces) and biotic degradation (due to microorganisms) mechanisms are noteworthy degradation pathways of plastics into MPs/NPs (Zhang et al., 2021; Allouzi et al., 2021). The generation of MPs/NPs from plastic waste is highly dependent on a number of characteristics such as anisotropy, stiffness, density, and thickness of the waste materials. As a result, MPs/NPs can readily be suspended in the air and quickly transported by natural winds (Zhang et al., 2020a, 2020b). A recent study has shown that COVID-19 virus may live for three hours in aerosol droplets and for >72 h on the surface of plastics at a temperature of 20 °C and a relative humidity of 40 % (van Doremalen et al., 2020). Allen et al. (Allen et al., 2019) established that with the assistance of wind, airborne MPs/NPs can travel >95 km from their sources (Fig. 1).

However, understanding the transfer mechanisms involved is essential. Here, either the disposal of infected plastic materials, such as PPEs, is directly disposed to the environment while contaminating adjacent particles and weathered into MPs/NPs, or the deposition of viruses on the surface of MPs/NPs from diseased persons. Moreover, because of the surface runoff of rainwater and wind action, these MPs/NPs were also observed to be deposited in freshwater sources, such as ponds and canals. This may also create the possibility of MPs/NPs being transferred to the arable land through irrigation. This implies that the objects used to protect people today have become pollutants of great concern after being used tomorrow. In fact, the strict management of waste plastics is unavoidable.

3. Plastic waste generation during the pandemic

Medical waste generation has increased dramatically in different countries, including Spain, Catalonia, and China, by 350, 340, and 370 %, respectively (Klemeš et al., 2020). Globally, plastic usage is predicted to expand by 40 % in packaging alone but by 17 % in other sectors, such as the medical industry (Prata et al., 2020). During the COVID-19 pandemic,

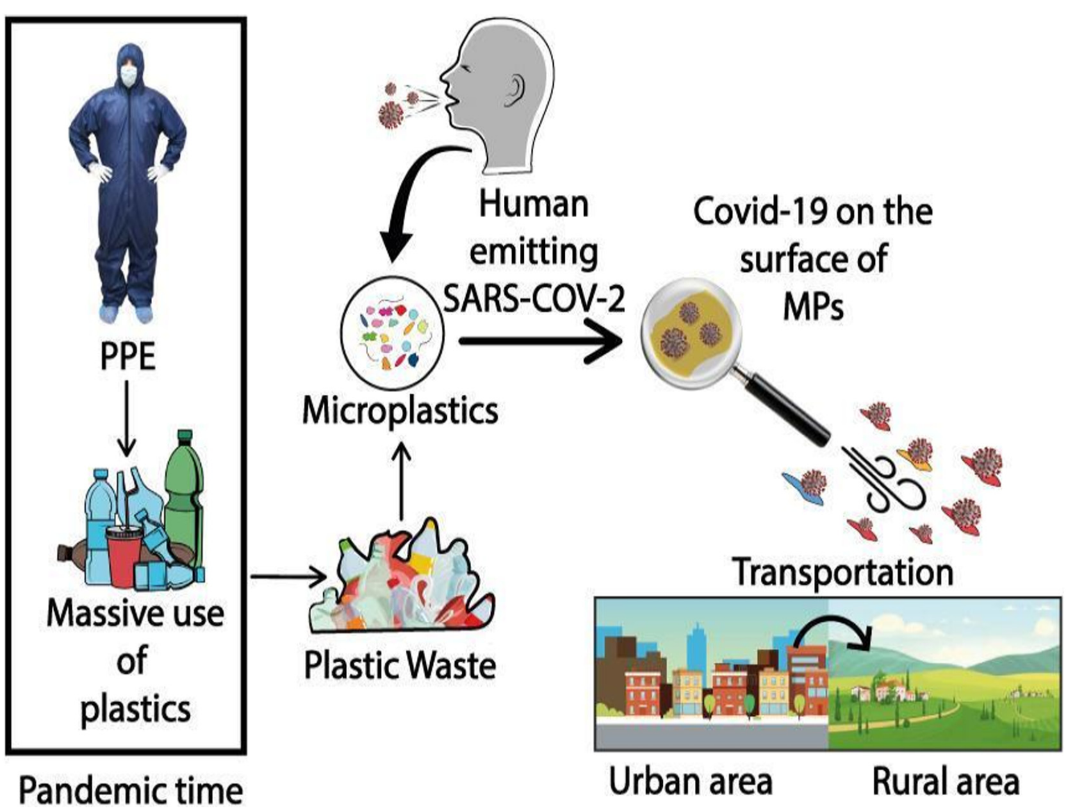


Fig. 1. Relation between COVID-19 and MPs/NPs pollution.

security concerns associated with supermarket purchases are driving up the demand for plastics in fresh food packaging (to prevent contamination and extend shelf life), as well as in the use of single-use food wrapping and trash bags to transport goods. As a result, medical waste is expected to be mixed with municipal solid garbage during the COVID-19 pandemic as recycling facilities become rare globally. To illustrate the preceding statement, if every resident of the country for example United Kingdom (population 66.7 million) wore one mask daily, the country would generate at least 60,000 tons of waste plastic garbage daily, and similar phenomena are quite common in all countries (Klemeš et al., 2020; Silva et al., 2020). Plastic contamination was already dangerously high prior to COVID-19, especially in terrestrial ecosystems (soil and plants) (Roy et al., 2023), aquatic environments, and atmospheric habitats (Fig. 2) (Xanthos and Walker, 2017). According to a study, approximately 4.8–12.7 million tons of plastic waste was generated on land but transported to the ocean via rivers (Lebreton et al., 2017), with a significant amount of this debris (1.2–2.4 million tons) subsequently swallowed by marine species (Jambeck et al., 2015). This problem became more serious when MPs/NPs were discovered in N95 masks made of PP and PET polymers as a result of natural weathering. Medical gloves and surgical masks consisting of spun materials, such as PE, PP, and PET-based polymers, also generate similar plastic particles (Martínez Silva and Nanny, 2020; Prata et al., 2020). Among the medical plastic wastes, 70 % are polyethylene, polypropylene, polystyrene, and polyvinyl chloride; 20 % are polyamides, nylons, polyesters, polycarbonates, polyurethanes, acrylics, and acetals; other 10 % include polyimides, polysulfones, fluoropolymers, liquid crystalline polymers, biopolymers, polyetherimides etc. (Walker, 2021).

Thus, dumping plastic waste in open areas perpetuates the "never-ending story" of plastic waste in the entire environment. Moreover, the continuous degradation of MPs results in the formation of smaller plastic particles known as nanoplastics (plastic particles with a size range of 1–1000 nm), which are more toxic than MPs (Connors, 2017; Monteiro et al., 2018; Prata et al., 2020). Owing to their increased surface area, these tiny plastic particles are prone to carrying a variety of contaminants, such as heavy metals and micro-pollutants, invading species, and viruses such as SARS-CoV-2 (Andrady, 2017; Hartmann et al., 2017). The COVID-19 virus continues to spread worldwide, and its random use, as well as the improper disposal of plastic waste by billions of people, is rapidly becoming a global and growing concern. A summarization of the amount of plastic generated and its management in various countries has been provided in Table 1.

However, the amount of solid waste generated varies between countries. As shown in Table 1, India was the highest producer of medical solid wastes (6491.49 tons/day), while Japan produced the lowest one (130.54 tons/day). However, China uses the highest number of facemasks on a daily basis due to its larger population (1194.64 million units/day), whereas Saudi Arabia exhibits the opposite phenomenon (23.40 million units/day). The total population of the country is a significant factor in this census. The critical concern for Bangladesh is that 63 % of the population wears facemasks, and 77 % of these contaminated used masks are directly disposed into landfills, with the remainder ending up at an incineration plant. However, the natural weathering of such waste masks results in the formation of countless MPs, contributing to disasters. China has the highest population, but surprisingly generates a lower amount of medical wastes (332.78 tons/day). This is because China strictly trying to follow the sustainable waste management code set by the concerned authorities. Similarly, Japan (126.47 Millions) has a higher population than Singapore (5.80 Millions) but produces less medical waste. Thus, it can be

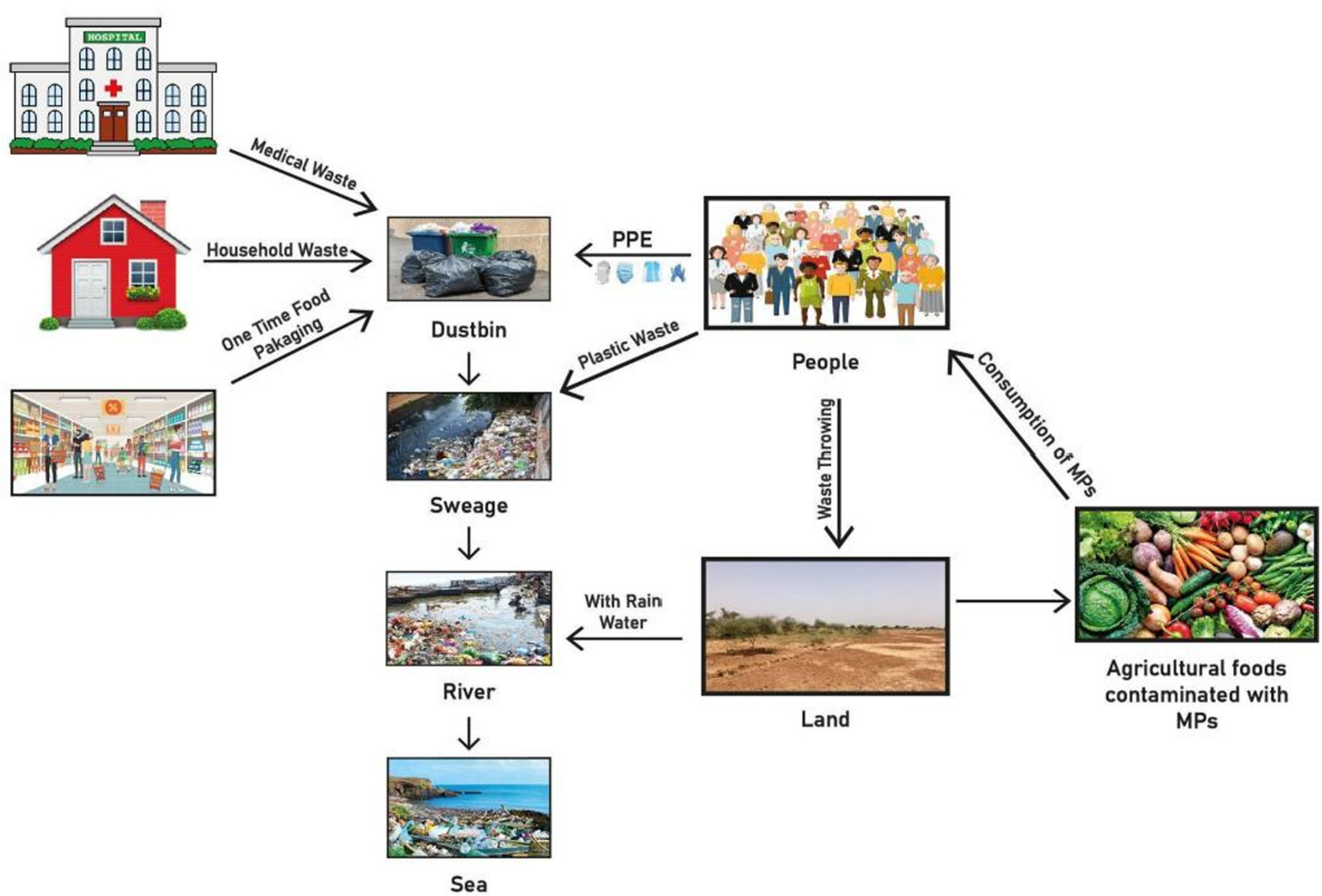


Fig. 2. Plastic waste generation during the pandemic.

Table 1
Comparison between waste generation and management in different countries (Hasan et al., 2021; Rahman, 2020; Sangkham, 2020).

Countries	Number of Population (Millions)	% of mask usages	Number of masks used/day (Million units)	Medical waste generation (tons/day)	Landfill rate (%)
China	1439.22	83.00	1194.64	332.78	72.55
Japan	126.47	80.00	96.12	130.54	0.99
Singapore	5.80	80.00	43.64	204.65	–
Iraq	40.20	80.00	30.90	908.07	–
Iran	84.08	80.00	50.64	1191.04	–
Saudi Arabia	34.80	80.00	23.40	1083.17	–
Turkey	84.40	80.00	26.00	908.07	16.87
Bangladesh	164.70	63.00	51.40	927.81	77.70
India	1380.00	80.00	381.17	6491.49	–
Pakistan	220.90	80.00	61.80	1099.30	–

considered that Japan also strictly follows the waste management code to address large amounts of waste.

The United Nations (UN) established Sustainable Development Goals (SDGs) in 2015, with approximately 15 SDGs related to plastics, specifically MPs waste management (Walker, 2021). To ensure the success of the SDGs, a large number of researchers are working on the sustainable management of plastic waste, and numerous research articles have been published in this area since the Paris Accord (Table 2). A scientometric visualization of the top 50 keywords from the database of "Web of Science Core Collection" released in the last 7 years, using "plastic waste" as the searching keywords (article) (Fig. 3). The blue circle in Fig. 3 shows a strong emphasis on plastic waste pollution and management. Thus, all of these data and explanations argue for the critical need for a sustainable plastic waste management system, and the following sections would provide a critical review of different plastic waste management options.

Table 2
The number of research articles published from various countries following the UN treaty; using "plastic waste" as the searching keyword (article) from the "Web of Science Core Collection" database.

Country	Documents	Country	Documents	Country	Documents
China	436	Hungary	19	Chile	4
India	286	Ethiopia	18	Colombia	4
USA	199	Greece	18	Ecuador	4
England	136	Austria	17	Bahrain	3
Australia	95	Denmark	17	Bosnia & Herceg	3
South Korea	93	Ghana	17	Cyprus	3
Italy	90	Romania	17	Latvia	3
Spain	82	Qatar	16	Mauritius	3
Malaysia	74	UAE	16	Morocco	3
Saudi Arabia	67	Vietnam	16	Palestine	3
Germany	66	Kuwait	15	Ukraine	3
Canada	56	Russia	15	Belarus	2
Poland	56	Sweden	14	Benin	2
Pakistan	55	Mexico	13	Bhutan	2
Japan	54	Scotland	13	Fiji	2
Egypt	48	Norway	11	Georgia	2
Thailand	48	Switzerland	11	Peru	2
Indonesia	47	New Zealand	10	Serbia	2
Turkey	46	Oman	10	Sri Lanka	2
Brazil	41	Philippines	9	Uganda	2
France	41	Wales	9	Albania	1
Belgium	40	Bangladesh	8	Angola	1
Singapore	39	North Ireland	8	Bulgaria	1
Taiwan	36	Argentina	7	Jamaica	1
Iran	33	Ireland	7	Libya	1
Iraq	32	Jordan	7	Macedonia	1
Nigeria	30	Lebanon	6	Malawi	1
South Africa	29	Slovakia	6	Mali	1
Portugal	27	Croatia	5	Malta	1
Algeria	26	Israel	5	Mozambique	1
Netherlands	26	Kazakhstan	5	Myanmar	1
Algeria	26	Kenya	5	Nepal	1
Netherlands	26	Lithuania	5	Niger	1
Finland	23	Slovenia	5	Northern Ireland	1
Czech Republic	21	Tunisia	5	Samoa	1

4. Systems for the sustainable management of plastic waste

Currently, most waste management technologies, such as landfilling and incineration, cannot address the vast majority of plastic waste as there is a substantial risk of deteriorating air quality and hazardous exposure (Organization, 2020). Owing to the contagious nature of COVID-19-related medical waste, landfilling is a poor choice because of the potential for viral spread within the neighboring population (Corburn et al., 2020). Additionally, the water supply is jeopardized because of the ease with which hazardous medical waste can be disposed of in surface waters (Harussani et al., 2022; Sadia et al., 2022). Consequently, there is a deficit in terms of sustainable medical waste management that ensures minimum carbon emissions, prevention of secondary viral transmission, and the lowest possible health risks. Medical gloves and surgical masks consisting of spun materials, such as PE, PP, and PET-based polymers, also generate similar plastic particles (Martínez Silva and Nanny, 2020; Prata et al., 2020; Yuan et al., 2021). Thus, in this review, sustainable plastic waste management systems are critically analyzed from a different perspective, considering COVID-19-related plastic wastes as raw materials (Fig. 4). The following pathways have been proposed on this: (i) preparation of carbonaceous materials, (ii) pyrolysis-based fuel production, and (iii) recycling waste materials in civil construction.

4.1. Preparation of carbonaceous materials

Pyrolysis is a widely used thermal decontamination method and long-term management strategy for medical solid waste (related to COVID-19) (Igalavithana et al., 2022). To summarize, this process converts plastic waste into simple shorter chains with lower molecular weight (Fig. 5) (Kairytė et al., 2020). Generally, gaseous products such as methane, hydrogen, and carbon monoxide are produced during the pyrolysis of plastics, whereas liquid-like end-products such as methanol, acetic acid, solvent oil, acetone, and various organic compounds are frequently produced during this thermochemical process. In addition, pyrolysis produces solid-like end products such as char, coke, and carbon black (Fig. 6) (Harussani et al., 2022). Pyrolysis is an efficient method for converting PPE-based plastic waste into hydrocarbon blends, and can significantly reduce the amount of plastic waste in the environment. However, several parameters must be controlled during pyrolysis to ensure byproduct formation. The process temperature, contact time, heating rate, and availability of the catalysts are noteworthy parameters (Harussani et al., 2022). Research has established that PP-based plastic waste pyrolyzes slowly at a rate of 5 °C/min. Slow pyrolysis is defined as the occurrence of pyrolytic breakdown at a lower system temperature and slower heating rate, with an extended remaining solid and vapor time. This extended stay is advantageous for the production of char, coal, and tar (Martín-Lara et al., 2021). In summary, the slow pyrolysis of PP-based waste products at a low heating rate (10 °C/min) produced 10 % more solid char than quick pyrolysis (2 % solid char).

Additionally, research indicates that slow pyrolysis produces more oil than fast pyrolysis (Parku et al., 2020). This phenomenon is demonstrated by the fact that slow pyrolysis results in the formation of CO, C_5H_{12}, H_2, and CH_4, whereas fast pyrolysis primarily produces gases (Harussani et al., 2021a, 2021b, 2021c). Moreover, it has been demonstrated that pyrolysis at low temperatures is more suitable for increasing liquid oil and char production than at higher temperatures, which require increased gas production (Parku et al., 2020). Consequently, slow pyrolysis at lower temperatures was more conducive to the production of char materials.

4.1.1. Fabrication of graphene and carbon nanotube

The fabrication of graphene and related materials from waste plastics has a great potential for use in supercapacitors and dye-sensitive solar

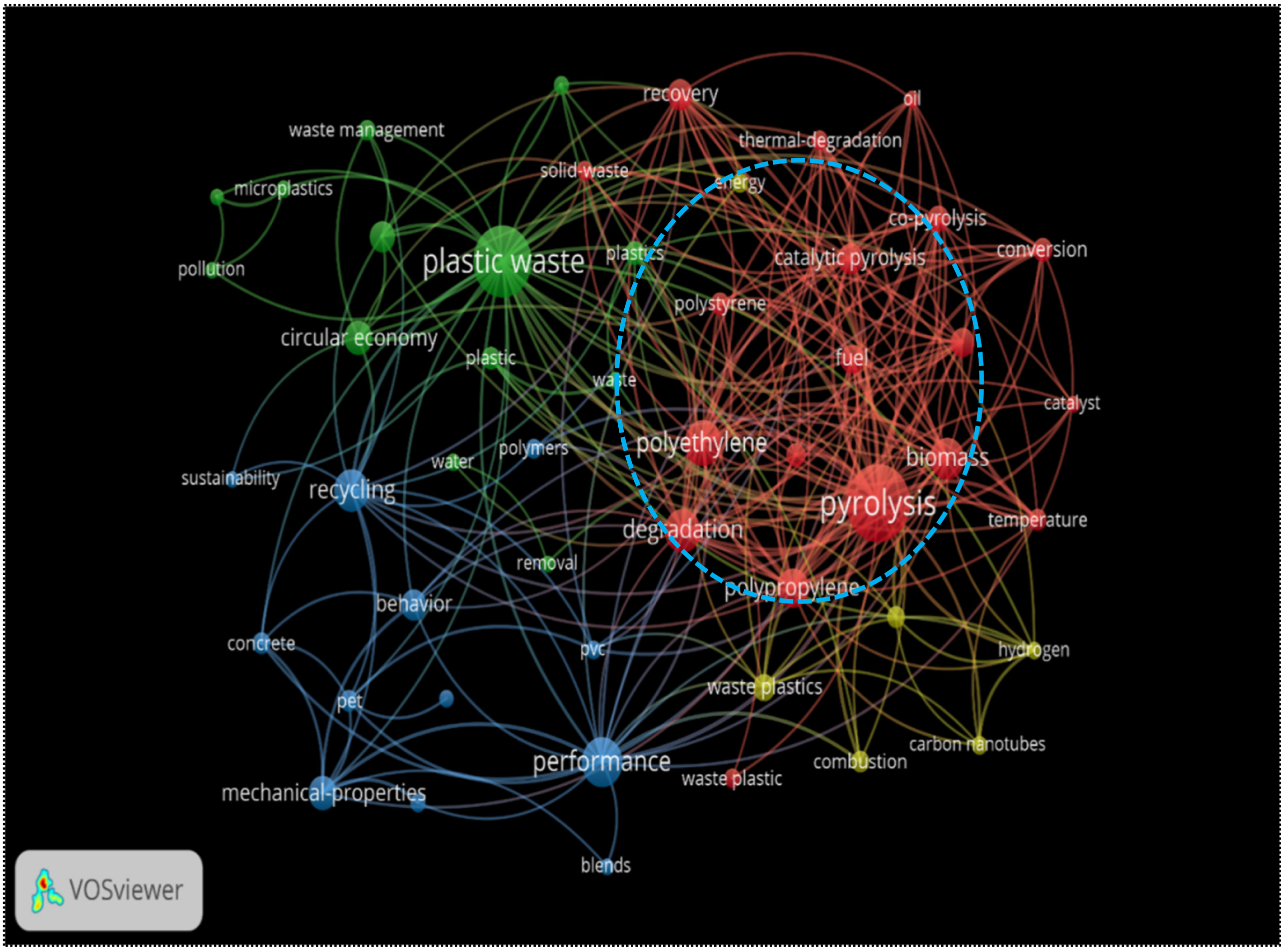


Fig. 3. Scientometric visualization of the top 50 keywords from all peer-reviewed publications published in the previous seven years. Total of 1283 publications were retrieved from the Web of Science with “plastic waste” as the searching keyword (article), and the database was selected as the “Web of Science Core Collection”. The collected data were analyzed using the minimum co-occurrence number of all keywords, which were plotted in VOSviewer in “Network visualization”, “overlay visualization (year)”, and “density visualization”. Each circle represents a keyword, and its size represents the number of times a pair of keywords have appeared together in publications. The legend in various colors represents the average year of occurrence of each keyword. (The reader is directed to the Web version of this article for interpretation of the color references in this figure legend).

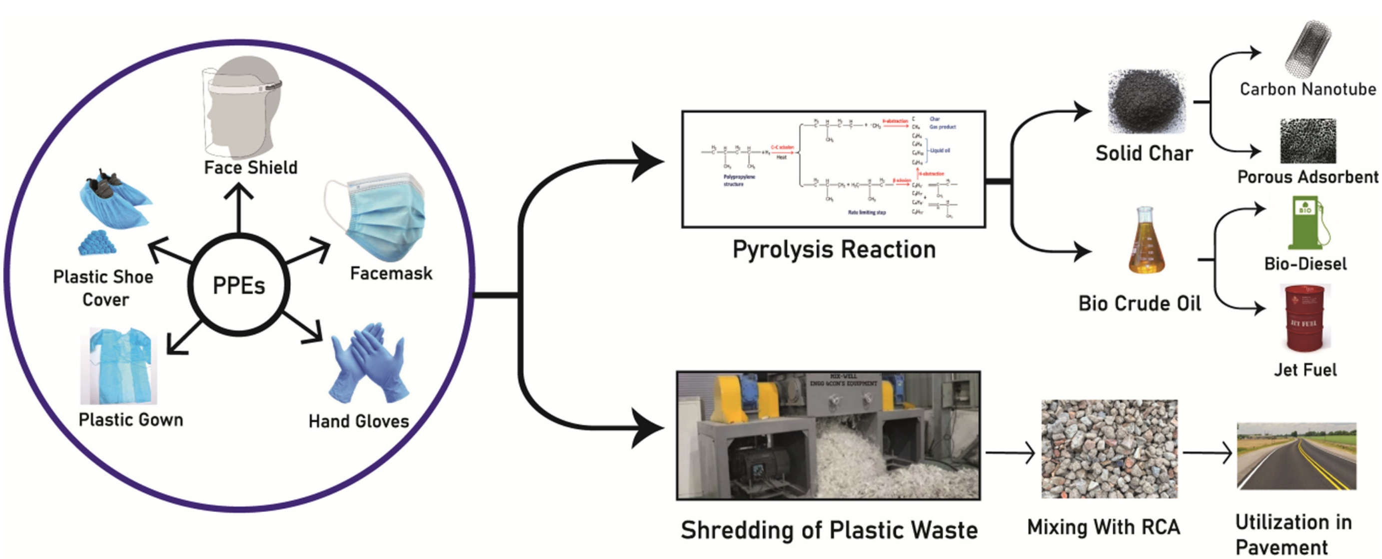


Fig. 4. Sustainable plastic waste management systems.

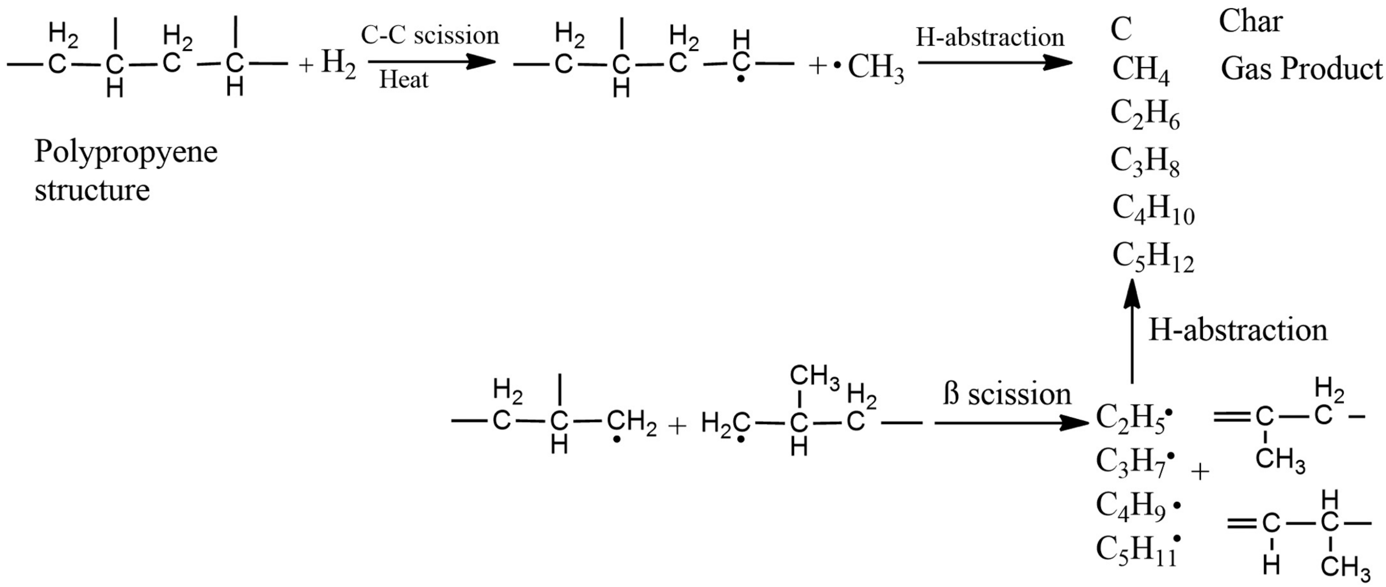


Fig. 5. Pyrolysis reaction for polypropylene polymer (Yan et al., 2015).

cells. Based on this motivation, Pandey et al. (Pandey et al., 2021) fabricated of graphene nanosheets (GN) via a two-step pyrolysis process. In addition, the authors used these nanosheets as active layers in supercapacitor electrodes and discovered significant specific capacitances, power densities, and energy densities of approximately 398, 1000, and 40 W/cm^3, respectively. In contrast, multiwalled carbon nanotubes (MWCNTs) have

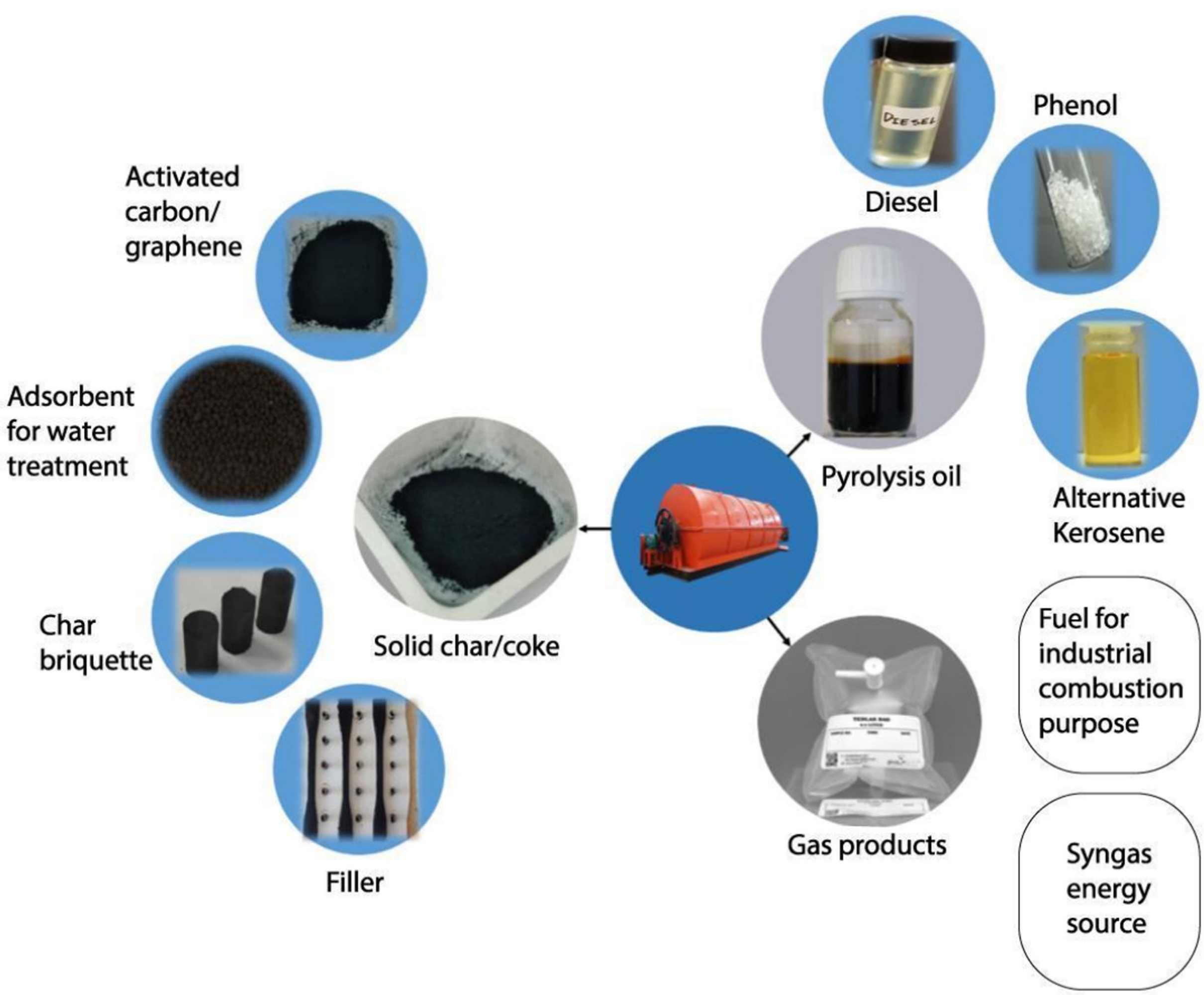


Fig. 6. Pyrolysis oil and char products yielded were utilized in several applications (Harussani et al., 2021c; Harussani et al., 2021a).

been synthesized through the pyrolysis of PP in the presence of catalysts (nickel and organic-modified montmorillonite nanoclays). However, It has been demonstrated that the production of MWCNTs is affected by the Ni-Fe-based catalyst and system operational parameters, such as steam-to-plastic ratios and catalyst temperatures. The mechanism underlying this process involves the production of Ni during the reduction of Ni compounds in the presence of hydrocarbon gases and hydrogen. Additionally, MWCNTs can be synthesized from PP-based plastic waste using chemical

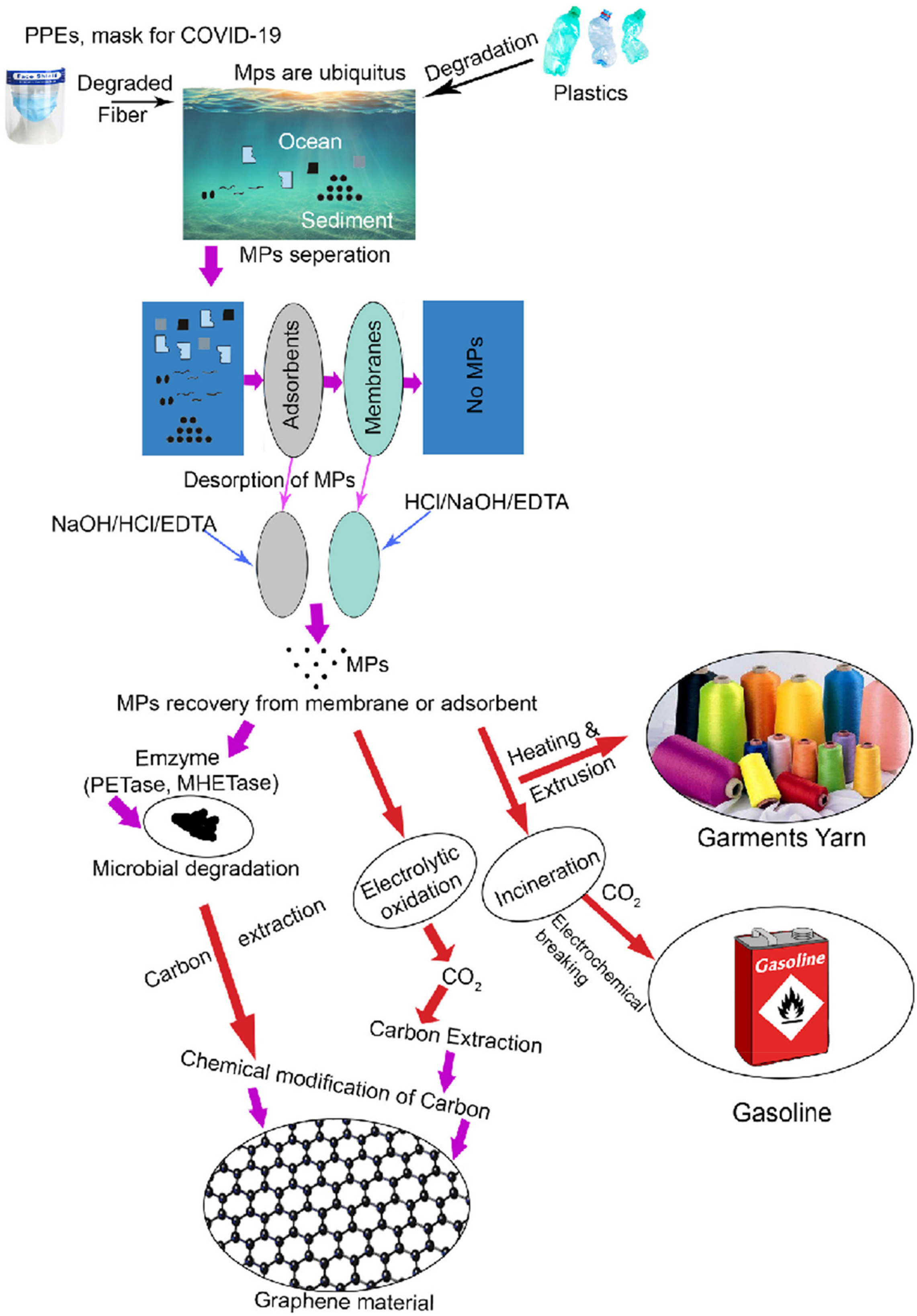


Fig. 7. The hypothesis of microplastics recycling (Dey and Jamal, 2021).

vapor deposition, although the use of a nickel catalyst is strongly recommended. Dey et al. (Dey and Jamal, 2021) also proposed a management strategy for synthetic polymer-based MPs/NPs derived from plastic waste and used it to fabricate graphene and related products in 2021. The authors noted that electrocatalytic oxidation followed by chemical modification could aid the preparation of graphene from MPs/NPs (Fig. 7). For example, Prof. Patrick Drogui, scientists at INRS, Canada, experimented with the degradation of PP-based MPs in wastewater into non-toxic CO_2 and water (Kiendrebeogo et al., 2021). Ward et al. also investigated the conversion of polystyrene into CO_2 using natural sunlight (Ward et al., 2019).

Later, Liu et al. (Liu et al., 2020) fabricated graphene using CO_2 in two steps. In the first step, CO_2 is converted into carbon through carbonate-based electrolysis. In the second step, graphene is formed by the electrochemical exfoliation of carbon. In this process, oxygen is generated as a by-product. The authors also recommended changing the carbonate electrolysis time and carbonate mixture to ensure more lateral dimensions of graphene and to make this conversion more efficient and cost-effective.

4.1.2. Fabrication of char-based adsorbent

Solid char obtained by the pyrolysis of plastic waste has great potential for use as an adsorbent material. This is due to the high porosity of ~0.0403 cm^3/g and large surface area of ca. 67.11 m^2/g (Martín-Lara et al., 2021). To date, several studies have been conducted on the production of char from plastic wastes such as PP, PS, and PEE, followed by the preparation of activated carbon for use as an adsorbent (Serafin et al., 2022). They found that the adsorbent fabricated from char material could adsorb a significant amount of lead (Pb) (II) from wastewater, with a capacity of 26 mg/g. Moreover, the authors concluded that the Pb (II) removal capacity of pyrolyzed char was extraordinary in terms of the metal adsorption capacity per unit surface area compared with that of commercial activated carbon (0.5157 mg/m^2 for Pb (II)). This was due to the higher porosity and surface area compared to those of the commercial activated carbon. Later, experiments were conducted to upgrade the adsorption capacity of plastic waste-based char, and the removal of methylene blue dye from wastewater using plastic char was considered. It was found that 3.6–322.2 mg/g of dye adsorption could be achieved during the experiments. The authors claimed that pyrolyzed char consists of different heteroatoms, including sulfur, oxygen, and nitrogen, which are directly responsible for the availability of polar functional groups on the surface of char and are more likely to adsorb organic and inorganic pollutants at higher concentrations. Additionally, PS-based plastic waste was used for pyrolysis to fabricate a double-layered carbon-metal composite-based nano-adsorbent to adsorb Congo red (CR) from wastewater (Miandad et al., 2018).

4.2. Pyrolysis-based fuel production

Undoubtedly, after the COVID-19 pandemic, sustainable management of waste PPEs has become a top priority for the research community. However, plastic recycling may prolong the final disposal of plastic and pollute the environment in the long run (Yan, 2022). However, landfilling plastics do not ensure sustainability because of the high resistance of such polymers to microorganisms and weathering (Jain et al., 2022). Additionally, the incineration of PPEs has disadvantages owing to the production of hazardous fumes, such as furans and dioxins (Ilyas et al., 2020). Thus, pyrolysis can be used to overcome the existing limitations of waste management systems. In particular, pyrolysis has a high probability of reducing the carbon footprint of plastic materials compared to thermal treatments (Al-Salem et al., 2017; Li et al., 2022). Additionally, this process can be used to produce crude bio-oil, which has high potential for commercial applications. Aragaw et al. (Aragaw and Mekonnen, 2021) investigated pyrolysis of COVID-19-associated medical waste for fuel generation recently. The entire system (Fig. 8) was designed by the authors to conduct pyrolysis in an inert environment. Liquid oil was the most abundant pyrolysis product and solid char was also produced. A substantial amount of feed material, including face masks and hand gloves, was sealed at 400 °C in a heating chamber for 1 h. At the end of the pyrolysis process, the products (crude oil and solid char) were transferred to a water jacket and cooled to room temperature. Approximately 75 % of biofuel and 10 % of solid char were produced, while the rest of the percentages were non-condensable gases. Thus, the approach of producing fuel from PP-based waste plastics can help alleviate the enormous burden on the ecosystem, particularly in the management of plastic waste generated after COVID-19. The utilization of plastic is not a problem as long as it is not released into the environment in an indiscriminate manner. Owing to the strength and durability of plastics, it is nearly impossible to avoid manufacturing PPEs to combat COVID-19. Additionally, the production, use, and disposal of PPEs are increasing at an eye-blinking rate. The demand for PPEs did not decrease during the post-pandemic period.

Thus, pyrolysis of plastic waste, production of biodegradable PPE, and recycling of plastic materials may be the most sustainable strategies in the long term. Currently, approximately 75 % of PPE waste can be converted into bio-crude oil (tar) on a laboratory scale. However, the pyrolysis reaction can be accelerated by optimizing the system temperature (300–500 °C) and by using a compatible catalyst.

4.3. Waste materials recycling in civil constructions

To mitigate the imminent threat of plastic waste, recycling it in large quantities is praiseworthy, and research indicates that reusing discarded plastics in civil construction is highly promising (Saberian et al., 2021). During the current pandemic, sterilized face masks are frequently used in civil construction. For the first time, Saberian et al. (Saberian et al., 2021) conducted such experiments with the goal of establishing a sustainable waste management system. Sterilized and shredded surgical face masks (2 cm in length and 0.5 cm in width) were used in this experiment. The ear loops and metal strips were carefully removed before the experiment. Then, recycled concrete aggregate (RCA) was mixed with three different percentages, including 1, 2, and 3 % of shredded face mask (SFM), to satisfy the strength and stiffness requirements for the construction of the pavement base. The following tests were used to characterize the RCA: specific gravity, organic content, pH, particle density, particle size distribution, Los Angeles (LA) abrasion, flakiness index, and aggregate crushing value. In contrast, tensile strength, melting point, specific gravity, and water absorption tests were performed on the ragged face mask. Various performance analyses of the mixtures (RCA/SFM blends), such as compaction and resilient modulus, were conducted to confirm their commercial viability. The authors found that the utilization of SFM not only increased the strength and stiffness of the composite blends but also made them ductile and flexible. Particularly, utilization of 1 % SFM in RCA resulted in compressive strength and resilient modulus of to 216 kPa and 314 MPa, respectively. However, utilization of SFM >2 % can lead to a decrease in strength and stiffness of composite pavement. The authors also stated that the reason for this result, such as the increase in SFM concentration in the blend, was directly responsible for increasing the optimum moisture content and decreased maximum dry density (MDD). However, the reduction in MDD was responsible for the lower specific gravity of SFM than that of RCA. In contrast, in the case of flexibility, the addition of SFM made the pavement more flexible because of the higher flexibility of the SFM fibers compared to RCA particles. The addition of 1 to 2 % SFM with RCA resulted in higher strength and stiffness of the blends of SFM/RCA owing to the reinforcing role of SFM fibers and the bridging effect between fibers and RCA, which successfully resisted the development of tension cracks. On the other hand, the amount of SFM fiber of >2 % was resulting in a reduction in strength and stiffness, as the availability of excessive fiber caused higher volume of voids in composite pavement. Saberian et al. (Saberian et al., 2021) stated that this method may be applicable to other types of PPEs. Therefore, more experiments with polymers other than PP, such as polyvinyl chloride and nitrile butadiene rubber, are strongly recommended (facemasks). Furthermore, this technology can be used to manage many non-plastic face masks

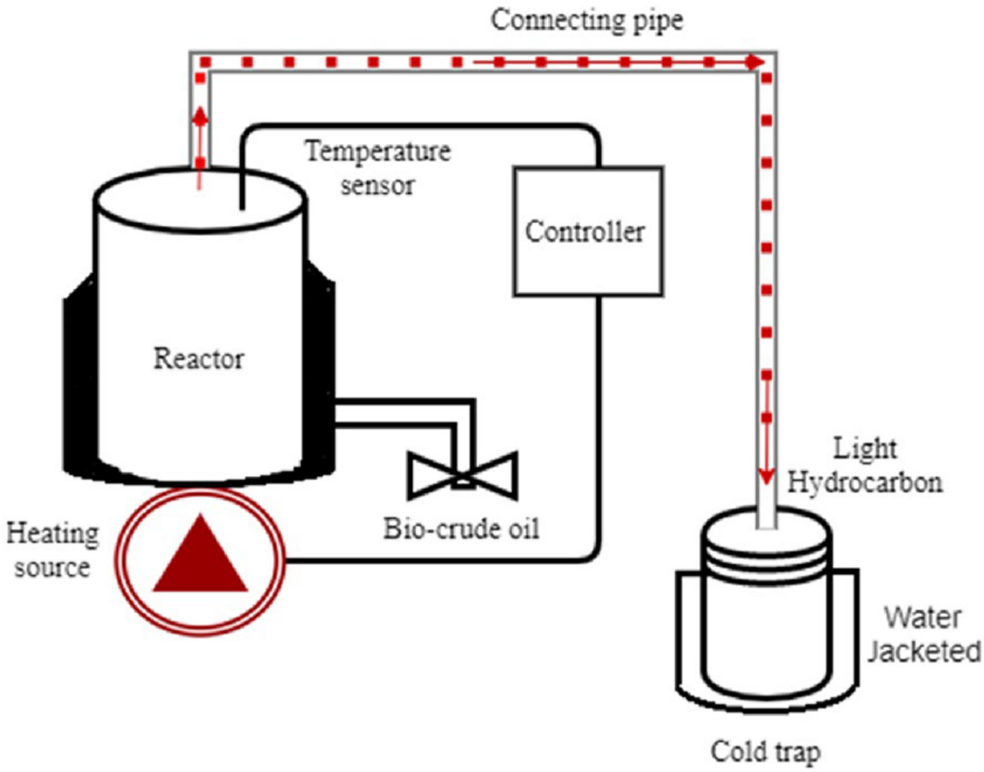


Fig. 8. A bench top pyrolysis setup for fuel production (Aragaw and Mekonnen, 2021).

simultaneously. However, in the case of polymers, the ratio of SFM to RCA as pavement base/sub base materials should be kept below 2 %, else the strength and stiffness of the RCA would be greatly reduced.

Table 3 highlights several plastic waste management strategies, and their advantages and disadvantages. In terms of cost and process simplicity, landfilling, road construction, and concrete production with waste plastics

Table 3
Plastics waste management strategies.

Waste management strategy	Advantages	Disadvantages	Challenges	References
Landfilling	(i) Low energy required (ii) Cost-effective strategy (iii) No prior skills needed (iv) Easy to construct and compatible in everywhere	(i) Significant amount of land is required (ii) High chance to emit carbon during the incineration at the landfill areas (iii) High chance to pollute land and water	Environmentally unsustainable in the long run	(Lazarevic et al., 2010; Evode et al., 2021; Kedzierski et al., 2020; Liang et al., 2021)
Pyrolysis	(i) Small area required to setup a reactor (ii) Lower chance for carbon emissions due to the oxygen-independent process (iii) Generates valuable products including fuels, char, and nanomaterials	(i) Demands high energy to maintain elevated temperatures as well as pressures (ii) Needed expensive equipment's (iii) Required high skilled workers	High installment cost along with process complexity make this process challenging to start	(Al-Salem et al., 2017; Anuar et al., 2016; Qureshi et al., 2020)
Liquefaction	(i) Small area required for a hydrothermal reactor (ii) Lower chance for carbon emissions due to the oxygen-independent process (iii) Generates valuable products including liquid fuels and charcoal	(i) Demands higher energy to initiate thermal degradation (ii) Costly equipments needed (iii) Highly skilled worker required for reactor management	High installment cost along with process complexity make this process challenging to start	(Zhang et al., 2016; Gopinath et al., 2020; Hongthong et al., 2020)
Road construction and tar	(i) Low carbon emissions (ii) Lower cost (iii) No prior skills required	(i) Suitable for small scale constructions	Difficult to manage in a bulk scale	(Manju and Sagar, 2017; Gopinath et al., 2020)
Concrete production	(i) Required small space (ii) Low carbon emissions (iii) Low energy required (iv) Low operational cost (v) Utilization of plastic waste materials in building construction ensures the quick management of home and municipal plastic waste	(i) Suitable for small private constructions	Difficult to manage in a bulk scale waste materials	(Basha et al., 2020; Evode et al., 2021)

are highly convenient; however, these processes are only applicable to managing a small amount of plastic waste. In particular, low operational costs, less skilled worker engagement, and lower carbon emission behavior make these processes highly applicable to small-scale waste management. In contrast, maintaining sustainability in the long run remains a great challenge to overcome in the case of these processes. However, in the post-pandemic scenario, the bulk of plastic materials must be managed without the possibility of secondary pollution. To attain this management, pyrolysis is a highly prominent approach to decomposing as well as converting waste plastic materials into valuable products including fuel, char, and different carbonaceous materials. However, their drawbacks also limit their wide applicability in tackling post-pandemic plastic waste digesters. More specifically, higher energy demand, installment cost, and process complexity make it challenging to manage the bulk of unusual medical plastic waste. Thus, in the future, more research is required to overcome the existing limitations of the pyrolysis process to tackle waste PPEs in the post-pandemic period. In particular, several recommendations for future research can be made, as follows: (i) minimization of energy consumption by the pyrolysis reactor. In this case, advanced technologies can be introduced, such as the integration of renewable solar or hydro energy, pyrolysis-based polymer products, and the utilization of catalysts during the combustion of plastic waste, to ensure the highest economic and environmental sustainability; (ii) assurance of more commercial benefits through the re-utilization of pyrolysis by-products, such as refinery oil, hydrocarbon gases, and char residue on a greater scale.

4.4. Use of smart PPEs as waste mitigation strategy

Synthetic polymers are mostly used to fabricate face masks and other PPEs to tackle pandemics such as COVID-19 (Corrêa and Corrêa, 2020; Ray and Bandyopadhyay, 2021). In particular, hydrophobic surgical facemasks are currently being used by many populations to prevent the transmission of COVID-19 via aerosols or droplets. As a result, additional strains are introduced into the entire environment and must be reduced immediately. So, if it is possible to use the same PPEs several times, the pollution load from waste plastics can be reduced. Biodegradable and self-cleaning PPEs are likely to be introduced in such cases. Therefore, an experiment was carried out to determine the antimicrobial performance of graphene oxide (GO) and reduced graphene oxide (rGO) instead of polymers. The authors highlighted the antiviral mechanism of the negatively charged GO nanosheets. This study highlights the dire need for the use of GO nanosheets against COVID-19. Zhong et al. (Zhong et al., 2020) constructed a GO-based self-sanitizing surgical facemask along with photothermal properties. In this experiment, several layers of graphene were coated on the surface of a traditional face mask. Consequently, the face mask became more hydrophobic in repelling microbes, along with a self-cleaning capacity. The conductive behavior of graphene increases the temperature of the face mask surface to 80 °C during exposure to the sun. Recently, Shan et al. (Shan et al., 2020) fabricated a more updated graphene-coated face mask that did not require any sunlight exposure. In this case, a low voltage was used to increase the surface temperature to rapidly kill viruses. Simultaneously, the author ensured comfort during the use of face masks.

Another carbonaceous nanomaterial, carbon nanotubes-based face masks, are also praiseworthy owing to their self-cleaning capacity. In brief, Soni et al. (Soni et al., 2021) used a coating of SWCNTs on the surface of face masks. The presence of SWCNTs made face masks more hydrophobic (156.2° ± 1.8) and capable of repelling more microbes as well. Similar to graphene, this nanomaterial is also capable of imparting photothermal effects and increasing the surface temperature to 90 °C. In consequence, 99.9 % antibacterial activity (including virus) of face masks was noted compared to the conventional polymeric mask. Here, noteworthy points such as the health effects of nanomaterials are crucial for critical consideration. Currently, graphene and its derivatives are being rapidly used to modify traditional polymeric PPEs against COVID-19. However, another health risk arises from the introduction of these nanomaterials into face masks. Accidental inhalation or the consumption of graphene nanoparticles can react with pulmonary surfactants and increase the probability of alveolar coating. In detail, consumed GO-based nanosheets can form pores on pulmonary surfactant films, malfunction their biophysical properties, and rupture the ultrastructure of pulmonary surfactant films. Drasler et al. (Drasler et al., 2018) justified this statement during experimentation with a human lung model (3D structure). In addition to graphene, the inhalation of CNTs may also be responsible for lung cancer. However, no solid conclusions have been reached regarding the harmful health effects of such nanomaterial. Thus, more research is still required to make a justified statement regarding the long-term exposure effect of CNTs on human health.

Apart from carbonaceous nanomaterial, silver nanoparticles (AgNPs) are well-established antimicrobial agents. It has a large capacity to infuse inside microbial cells and is capable of rupturing DNA replication systems and destroying the reproduction system of microbes (Yin et al., 2020). Therefore, an experiment was carried out to determine the antimicrobial capacity of silver nitrate and titanium dioxide-coated face masks. The author secured a 100 % antimicrobial effect of fabricated face masks against *E. coli* and *S. aureus*. The authors also ensured the comfort of the face mask from the viewpoint of skin inflammation and maximum inhibition of microbes. To check for the consequences of accidental leakage of these nanoparticles, many studies have been carried out and have not found any major abnormalities in lung function. Therefore, the aforementioned explanations advocate the prospective use of AgNPs as antimicrobial agents, without additional health hazards. Thus, AgNPs are highly promising agents for the treatment of COVID-19.

In addition to COVID-19, airborne MPs are also a concern for the research community. The transmission of COVID-19 along with airborne MPs up to long distances is also fueling researchers to introduce more smart PPEs to tackle both MPs and the COVID-19 virus. Therefore, composite materials are required to decompose airborne MPs and viruses. In addition, the mitigation of plastic pollution is crucial for inhibiting the emission of numerous MPs from polymeric PPEs. Therefore, biodegradable polymers (PVA, PEG, and natural cellulose) can be used instead of synthetic polymers such as polypropylene. This study intends to trigger such a point with the intention of filling the vacuum of review articles regarding smart materials to tackle airborne MPs pollution and COVID-19 simultaneously. Nanocomposite materials such as Ag-ZnO are promising for mitigating the aforementioned problems. It has already been proven that synthesized Ag-ZnO nanocomposite can impart antimicrobial performance along with photocatalytic activity (Ibănescu et al., 2014). Thus, the coating of this progressive nanomaterial can be used to manufacture smart PPEs (Fig. 9). The antimicrobial performance has already been proven with a proper explanation. Therefore, the working mechanism of photocatalytic degradation needs to be mentioned critically, and the following equations highlight the reaction mechanism (*equation i to vii*):

Here MO stands for metal oxide:

$$UV + MO \rightarrow MO\left(h^{+} + e^{-}\right) \quad \text{(i)}$$

Oxidative reactions due to photocatalytic effect:

$$h^{+} + H_2O \rightarrow H^{+} + \bullet OH \quad \text{(ii)}$$

$$2\,h^{+} + 2H_2O \rightarrow 2\,H^{+} + H_2O_2 \quad \text{(iii)}$$

$$H_2O_2 \rightarrow 2 \bullet OH \quad \text{(iv)}$$

Reductive reactions due to photocatalytic effect:

$$e^{-} + O_2 \rightarrow \bullet O_2^{-} \quad \text{(v)}$$

$$\bullet O_2^{-} + 2HO\bullet + H^{+} \rightarrow H_2O_2 + O_2 \quad \text{(vi)}$$

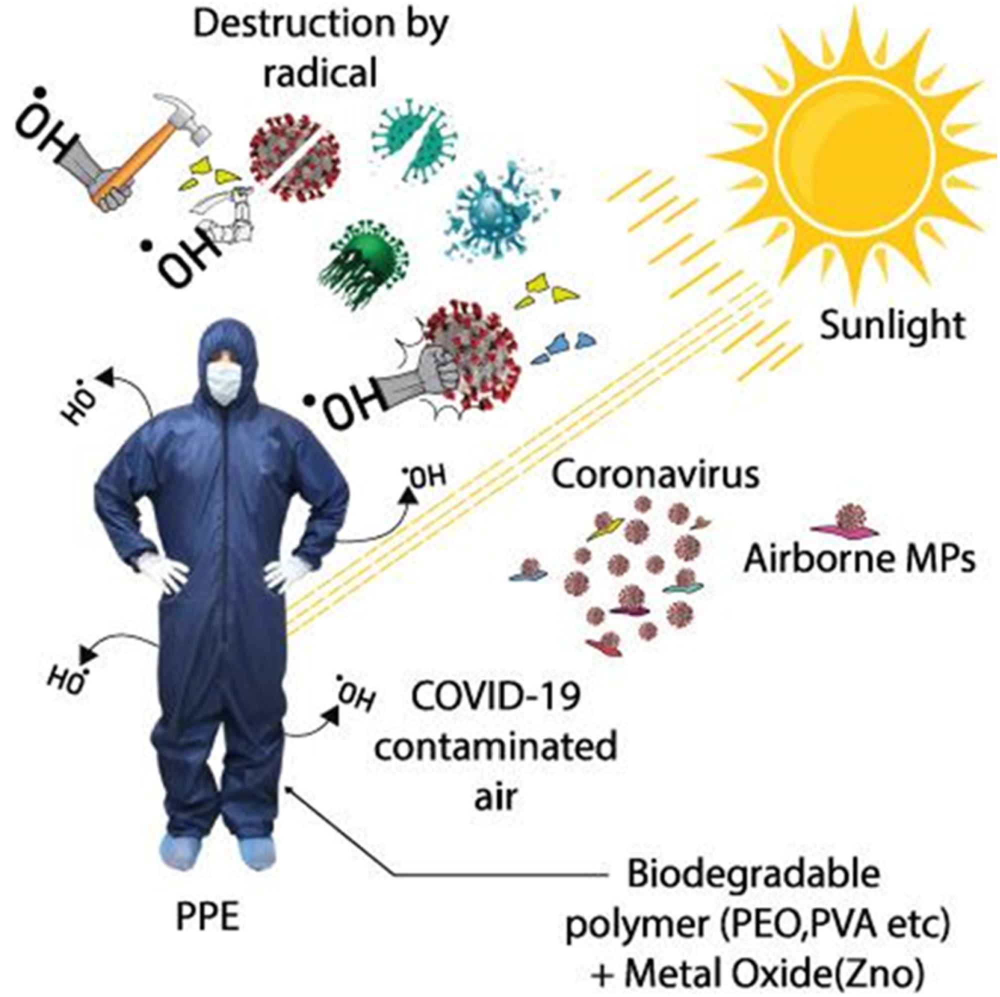


Fig. 9. Proposed smart PPE.

$$HOOH \rightarrow HO\bullet + \bullet OH \quad \text{(vii)}$$

During photocatalytic reactions, the free radicals generated, such as •OH and •O_2 under light radiation can destroy bacteria, fungi, and viruses, including COVID-19 (Regmi et al., 2018; Kabir et al., 2022). Based on this principle, the proposed composite is capable of infusing additional antimicrobial performance from photocatalytic ZnO along with AgNPs. Li et al. (Li et al., 2021) for the first time introduced photocatalytic facemasks to tackle COVID-19 with long-term sustainability. During the experiment, the author considered nitrogen-doped TiO_2 containing a face mask with a self-sterilizing capacity under light irradiation for a short period (10 min). Two bacterial strains, *Staphylococcus aureus* and *Escherichia coli* were used to evaluate the antimicrobial and rejuvenating properties of the face masks. After the introduction of bacteria, the photocatalytic masks were exposed to irradiation with a xenon lamp light (200–2500 nm, 50 W) emulating 0.1 sun. To control the system temperature induced by light irritation, the space between the sample, the light source, and the exposure time was precisely optimized. The system temperature remained between 25.5 and 34.0 °C. However, the fabricated photocatalytic face mask could inhibit 100 % bacterial growth under artificial sunlight (200–2500 nm, 106 $W.m^{-2}$) within 10 min. In this study, we only considered TiO_2, which is expensive and incompatible with bulk production at a low price rate. Among such phenomena, ZnO is highly promising owing to its availability, low cost, and biodegradability.

In addition to disinfection, the coating of Ag-ZnO nanocomposite on the surface of PPEs is also competitive for the photocatalytic degradation of MPs. Photocatalytic oxides can mineralize MPs in water and CO_2. Here, the degradation mechanism is initiated at the interface between the free radicals (•OH) and polymer. The catalyst particles formed cavities around themselves and gradually propagated the degradation of MPs. Later, the generated carbon-centered radicals caused carbon chain cleavage and oxygen insertion. Finally, intermediates with carbonyl and carboxyl groups gradually photo-oxidize into H_2O, CO_2, and volatile organics, including ethane, butane, formaldehyde, and ethanol (Zhong et al., 2020). TiO_2, nanotubes, and nanoparticles have been widely studied to increase photocatalytic efficiency (Li et al., 2021). It is also important to highlight that photocatalytic materials react with H_2O available in atmospheric air to form •OH radicals and initiate MPs mineralization (Shan et al., 2020). However, in 2022, Uheida et al. (Uheida et al., 2021) proved the effectiveness of the photocatalytic activity of ZnO against polypropylene-based MPs. Therefore, this experiment also supports our proposed nano-composite, such as Ag-ZnO. Therefore, this nano-composite is undoubtedly capable of degrading airborne MPs from polypropylene-based waste PPEs along with COVID-19. Consequently, advancements in reusable, biodegradable, and high-quality masks may encourage the use of biodegradable and renewable polymers (Shadman et al., 2022). This will inspire the use of photocatalytic compounds and sophisticated technologies in the manufacture of next-generation PPEs with minimal post-handling and environmental effects. In addition, the development of antimicrobial PPEs, such as face masks, is an evolving process; therefore, researchers have to put more emphasis on the safety and cost-effectiveness of wearing masks.

5. Conclusions

The global pandemic COVID-19 is exacerbated by plastic pollution, resulting in the MP/NP problem. Currently, there is no sustainable waste management approach to address this issue, although traditional disposal methods, such as incineration and landfilling, are widely used. The results of this study show that the pyrolysis of PP-based plastic wastes has high potential for producing valuable byproducts and ensuring their potential applications. Pyrolysis generates bio-crude oil, solid char, and other gaseous byproducts. As a result, >75 % of plastic waste can be transformed into bio-crude oil, while slow pyrolysis of plastic waste can yield up to 33.50 % solid char. Furthermore, the rapid catalytic pyrolysis of PP-based plastic waste can yield up to 55.1 % of hydrocarbon gases, which can be used in gas turbines, fuel cells, and gas engines. On the other hand, pyrolysis has a lower than 50 % climate change impact and life cycle energy use than the traditional approach of energy generation from raw plastic waste. Slow pyrolysis ensures the complete breakdown of plastic waste prior to the extraction of the desired by-products without the production of secondary pollutants, such as leaching or emission of hazardous compounds into the soil, water, and atmosphere. In terms of life cycle environmental implications, pyrolysis has a lower than 50 % climate change impact and life cycle energy use than the approach of energy generation using plastic waste as raw materials. In terms of product yield, the impact of plastic waste recycled products has 124 % lower climate change than the production of these products from virgin raw materials. In addition, the recycling of plastic waste has a lower life-cycle energy consumption and lower environmental toxicity than the use of virgin materials. Furthermore, pyrolysis recycling of plastic waste has a substantially smaller climate change impact (−0.45 vs. 1.89 t CO_2 eq. t/t plastic) than those manufactured from virgin fossil fuels. This article also shows how to design and use self-cleaning smart PPE that can be repeatedly used. Layers of graphene oxide, carbon nanotubes, and Ag-ZnO nanocomposites can be coated onto biodegradable PPEs to provide self-sanitizing capacity. The use of PPE in RCA is also a competitive strategy for reducing massive amounts of plastic waste in a shorter period of time.

5.1. Recommendations and future challenges

Pyrolysis is a highly viable technology for fully digesting COVID-19 pandemic plastic waste. However, this strategy requires more energy because of its temperature and cooling control system. To ensure sustainability, low-cost, simple processes and energy-saving technologies are required to digest massive amounts of plastic trash. Therefore, plasma technology can be considered an excellent alternative to pyrolysis. In particular, cold plasma pyrolysis can be investigated for dealing with contagious medical plastic waste because it uses excited hot electrons (from electrodes) to rupture the chemical bonds in plastics within a shorter duration. In addition to the use of PP-based plastic waste in civil engineering, other polymers, such as PVC and nitrile butadiene rubber, can be investigated to ensure sustainable waste disposal. Further investigations are required to use non-plastic face masks and other PPEs as future smart materials. Renewable and biodegradable polymers such as PVA, PEG, natural cellulose, biopolymers, and photocatalytic nanocomposites (Ag-ZnO, nitrogen-doped TiO_2) are promising materials for use in the production of next-generation PPEs.

CRediT authorship contribution statement

Thuhin K. Dey: Conceptualization, Formal analysis, Investigation, Methodology, Writing – original draft. **Md. Rasel:** Data curation, Project administration, Writing – review & editing. **Tapati Roy:** Data curation, Project administration. **Md. Elias Uddin:** Data curation, Project administration. **Biplob K. Pramanik:** Conceptualization, Writing – review & editing. **Mamun Jamal:** Conceptualization, Funding acquisition, Formal analysis, Investigation, Methodology, Writing – original draft, Writing – review & editing.

Data availability

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

Declaration of Competing Interest

The authors declare no competing interest.

Acknowledgements

The authors are grateful to the University Grant Commission of Bangladesh (Research Support 2019 − 2020) for funding this study. We also thank the reviewers for their excellent review, which has allowed us to improve our manuscript significantly.

References

Abbasi, S.A., Khalil, A.B., Arslan, M., 2020. Extensive use of face masks during COVID-19 pandemic: (micro-) plastic pollution and potential health concerns in the arabian peninsula. Saudi J. Biol. Sci. 27 (12), 3181–3186.
Allen, S., Allen, D., Phoenix, V.R., Le Roux, G., Durántez Jiménez, P., Simonneau, A., Binet, S., Galop, D., 2019. Atmospheric transport and deposition of microplastics in a remote mountain catchment. Nat. Geosci. 12 (5), 339–344.
Allouzi, M.M.A., Tang, D.Y.Y., Chew, K.W., Rinklebe, J., Bolan, N., Allouzi, S.M.A., Show, P.L., 2021. Micro (nano) plastic pollution: the ecological influence on soil-plant system and human health. Sci. Total Environ. 788, 147815.
Al-Salem, S., Antelava, A., Constantinou, A., Manos, G., Dutta, A., 2017. A review on thermal and catalytic pyrolysis of plastic solid waste (PSW). J. Environ. Manag. 197, 177–198.
Andrady, A.L., 2017. The plastic in microplastics: a review. Mar. Pollut. Bull. 119 (1), 12–22.
Anuar, S.S.D., Abnisa, F., Wan, D.W.M.A., Aroua, M.K., 2016. A review on pyrolysis of plastic wastes. Energy Convers. Manag. 115, 308–326.
Aragaw, T.A., Mekonnen, B.A., 2021. Current plastics pollution threats due to COVID-19 and its possible mitigation techniques: a waste-to-energy conversion via pyrolysis. Environ. Syst. Res. 10 (1), 1–11.
Basha, S.I., Ali, M., Al-Dulaijan, S., Maslehuddin, M., 2020. Mechanical and thermal properties of lightweight recycled plastic aggregate concrete. J. Build. Eng. 32, 101710.
Connors, E.J., 2017. Distribution and biological implications of plastic pollution on the fringing reef of Mo'orea, French Polynesia. PeerJ 5, e3733.
Corburn, J., Vlahov, D., Mberu, B., Riley, L., Caiaffa, W.T., Rashid, S.F., Ko, A., Patel, S., Jukur, S., Martínez-Herrera, E., 2020. Slum health: arresting COVID-19 and improving well-being in urban informal settlements. J. Urban Health 97 (3), 348–357.
Corrêa, H.L., Corrêa, D.G., 2020. Polymer applications for medical care in the COVID-19 pandemic crisis: will we still speak ill of these materials? Front. Mater. 7.
Dey, T.K., Jamal, M., 2021. Separation of microplastics from water-what next? J. Water Process. Eng. 44, 102332.
Dey, T.K., Uddin, M., Jamal, M., 2021. Detection and removal of microplastics in wastewater: evolution and impact. Environ. Sci. Pollut. Res. 28 (14), 16925–16947.
Drasler, B., Kucki, M., Delhaes, F., Buerki-Thurnherr, T., Vanhecke, D., Korejwo, D., Chortarea, S., Barosova, H., Hirsch, C., Petri-Fink, A., Rothen-Rutishauser, B., Wick, P., 2018. Single exposure to aerosolized graphene oxide and graphene nanoplatelets did not initiate an acute biological response in a 3D human lung model. Carbon 137, 125–135.
Evode, N., Qamar, S.A., Bilal, M., Barceló, D., Iqbal, H.M., 2021. Plastic waste and its management strategies for environmental sustainability. Case Stud. Chem. Environ. Eng. 4, 100142.
Fadare, O.O., Okoffo, E.D., 2020. Covid-19 face masks: a potential source of microplastic fibers in the environment. Sci. Total Environ. 737, 140279.
Geyer, R., Jambeck, J.R., Law, K.L., 2017. Production, use, and fate of all plastics ever made. Sci. Adv. 3 (7), e1700782.
Gopinath, K.P., Nagarajan, V.M., Krishnan, A., Malolan, R., 2020. A critical review on the influence of energy, environmental and economic factors on various processes used to handle and recycle plastic wastes: development of a comprehensive index. J. Clean. Prod. 274, 123031.
Hartmann, N.B., Rist, S., Bodin, J., Jensen, L.H., Schmidt, S.N., Mayer, P., Meibom, A., Baun, A., 2017. Microplastics as vectors for environmental contaminants: exploring sorption, desorption, and transfer to biota. Integr. Environ. Assess. Manag. 13 (3), 488–493.
Harussani, M.M., Salit, M.S., Rashid, U., Abdan, K., 2021. Plastic waste conversion into electrical, thermal and fuel energy via incinerations and pyrolysis amidst COVID-19 pandemic. AIUE Proceedings of the 2nd Energy and Human Habitat Conference.
Harussani, M.M., Sapuan, S.M., Khalina, A., Rashid, U., Tarique, J., 2021. Slow pyrolysis of disinfected COVID-19 non-woven polypropylene (PP) waste. Proceedings of the International Symposium on Applied Sciences and Engineering ISASE2021, Erzurum, Turkey. 3.
Harussani, M., Sapuan, S., Rashid, U., Khalina, A., 2021. Development and characterization of polypropylene waste from personal protective equipment (PPE)-derived char-filled sugar palm starch biocomposite briquettes. Polymers 13 (11), 1707.
Harussani, M., Sapuan, S., Rashid, U., Khalina, A., Ilyas, R., 2022. Pyrolysis of polypropylene plastic waste into carbonaceous char: priority of plastic waste management amidst COVID-19 pandemic. Sci. Total Environ. 803, 149911.
Hasan, N.A., Heal, R.D., Bashar, A., Haque, M.M., 2021. Face masks: protecting the wearer but neglecting the aquatic environment?-a perspective from Bangladesh. Environ. Chall. 4, 100126.

Hongthong, S., Raikova, S., Leese, H.S., Chuck, C.J., 2020. Co-processing of common plastics with pistachio hulls via hydrothermal liquefaction. Waste Manag. 102, 351–361.

Ibănescu, M., Muşat, V., Textor, T., Badilita, V., Mahltig, B., 2014. Photocatalytic and antimicrobial Ag/ZnO nanocomposites for functionalization of textile fabrics. J. Alloys Compd. 610, 244–249.

Igalavithana, A.D., Yuan, X., Attanayake, C.P., Wang, S., You, S., Tsang, D.C., Nzihou, A., Ok, Y.S., 2022. Sustainable management of plastic wastes in COVID-19 pandemic: the biochar solution. Environ. Res. 212, 113495.

Ilyas, S., Srivastava, R.R., Kim, H., 2020. Disinfection technology and strategies for COVID-19 hospital and bio-medical waste management. Sci. Total Environ. 749, 141652.

Jain, S., Yadav, L.B., Kumar, S., Singh, D., 2022. Strategy for repurposing of disposed PPE kits by production of biofuel: pressing priority amidst COVID-19 pandemic. Biofuels 13 (5), 545–549.

Jambeck, J.R., Geyer, R., Wilcox, C., Siegler, T.R., Perryman, M., Andrady, A., Narayan, R., Law, K.L., 2015. Plastic waste inputs from land into the ocean. Science 347 (6223), 768–771.

Ju, J.T., Boisvert, L.N., Zuo, Y.Y., 2021. Face masks against COVID-19: standards, efficacy, testing and decontamination methods. Adv. Colloid Interf. Sci. 292, 102435.

Kabir, S.B., Khalekuzzaman, M., Hossain, N., Jamal, M., Alam, M.A., Abomohra, A.E.F., 2022. Progress in biohythane production from microalgae-wastewater sludge co-digestion: an integrated biorefinery approach. Biotechnol. Adv. 107933.

Kairytė, A., Kremensas, A., Vaitkus, S., Członka, S., Strąkowska, A., 2020. Fire suppression and thermal behavior of biobased rigid polyurethane foam filled with biomass incineration waste ash. Polymers 12 (3), 683.

Kedzierski, M., Frère, D., Le Maguer, G., Bruzaud, S., 2020. Why is there plastic packaging in the natural environment? Understanding the roots of our individual plastic waste management behaviours. Sci. Total Environ. 740, 139985.

Kiendrebeogo, M., Estahbanati, M.K., Mostafazadeh, A.K., Drogui, P., Tyagi, R.D., 2021. Treatment of microplastics in water by anodic oxidation: a case study for polystyrene. Environ. Pollut. 269, 116168.

Klemeš, J.J., Van Fan, Y., Tan, R.R., Jiang, P., 2020. Minimising the present and future plastic waste, energy and environmental footprints related to COVID-19. Renew. Sust. Energ. Rev. 127, 109883.

Kraemer, M.U., Yang, C.H., Gutierrez, B., Wu, C.H., Klein, B., Pigott, D.M., Group, O.C.D.W., Du-Plessis, L., Faria, N.R., Li, R., 2020. The effect of human mobility and control measures on the COVID-19 epidemic in China. Science 368 (6490), 493–497.

Kwak, J.I., An, Y.J., 2021. Post COVID-19 pandemic: biofragmentation and soil ecotoxicological effects of microplastics derived from face masks. J. Hazard. Mater. 416, 126169.

Lazarevic, D., Aoustin, E., Buclet, N., Brandt, N., 2010. Plastic waste management in the context of a european recycling society: comparing results and uncertainties in a life cycle perspective. Resour. Conserv. Recycl. 55 (2), 246–259.

Lebreton, L., Van Der, Z.J., Damsteeg, J.W., Slat, B., Andrady, A., Reisser, J., 2017. River plastic emissions to the world's oceans. Nat. Commun. 8 (1), 1–10.

Lee, M., Kim, H., 2022. COVID-19 pandemic and microplastic pollution. Nanomaterials 12 (5), 851.

Li, Q., Yin, Y., Cao, D., Wang, Y., Luan, P., Sun, X., Liang, W., Zhu, H., 2021. Photocatalytic rejuvenation enabled self-sanitizing, reusable, and biodegradable masks against COVID-19. ACS Nano 15 (7), 11992–12005.

Li, C., Yuan, X., Sun, Z., Suvarna, M., Hu, X., Wang, X., Ok, Y.S., 2022. Pyrolysis of waste surgical masks into liquid fuel and its life-cycle assessment. Bioresour. Technol. 346, 126582.

Liang, Y., Tan, Q., Song, Q., Li, J., 2021. An analysis of the plastic waste trade and management in Asia. Waste Manag. 119, 242–253.

Liu, X., Wang, X., Licht, G., Licht, S., 2020. Transformation of the greenhouse gas carbon dioxide to graphene. J. CO2 Util. 36, 288–294.

Manju, S., Sagar, N., 2017. Renewable energy integrated desalination: a sustainable solution to overcome future fresh-water scarcity in India. Renew. Sust. Energ. Rev. 73, 594–609.

Martínez Silva, P., Nanny, M.A., 2020. Impact of microplastic fibers from the degradation of nonwoven synthetic textiles to the Magdalena River water column and river sediments by the City of Neiva, Huila (Colombia). Water 12 (4), 1210.

Martín-Lara, M., Piñar, A., Ligero, A., Blázquez, G., Calero, M., 2021. Characterization and use of char produced from pyrolysis of post-consumer mixed plastic waste. Water 13 (9), 1188.

Miandad, R., Kumar, R., Barakat, M., Basheer, C., Aburiazaiza, A., Nizami, A., Rehan, M., 2018. Untapped conversion of plastic waste char into carbon-metal LDOs for the adsorption of Congo red. J. Colloid Interface Sci. 511, 402–410.

Monteiro, R.C., do Sul, J.A.I., Costa, M.F., 2018. Plastic pollution in islands of the Atlantic Ocean. Environ. Pollut. 238, 103–110.

Morawska, L., Cao, J., 2020. Airborne transmission of SARS-CoV-2: the world should face the reality. Environ. Int. 139, 105730.

Neto, H.G., Bantel, C.G., Browning, J., Della Fina, N., Ballabio, T.A., de Santana, F.T., Barbosa, C.B., e Britto, M.D.K., 2021. Mortality of a juvenile Magellanic penguin (Spheniscus magellanicus, Spheniscidae) associated with the ingestion of a PFF-2 protective mask during the Covid-19 pandemic. Mar. Pollut. Bull. 166, 112232.

Nzediegwu, C., Chang, S.X., 2020. Improper solid waste management increases potential for COVID-19 spread in developing countries. Resour. Conserv. Recycl. 161, 104947.

Pandey, S., Karakoti, M., Surana, K., Dhapola, P.S., SanthiBhushan, B., Ganguly, S., Singh, P.K., Abbas, A., Srivastava, A., Sahoo, N.G., 2021. Graphene nanosheets derived from plastic waste for the application of DSSCs and supercapacitors. Sci. Rep. 11 (1), 1–17.

Parku, G.K., Collard, F.X., Görgens, J.F., 2020. Pyrolysis of waste polypropylene plastics for energy recovery: influence of heating rate and vacuum conditions on composition of fuel product. Fuel Process. Technol. 209, 106522.

Patrício Silva, A.L., Prata, J.C., Walker, T.R., Duarte, A.C., Ouyang, W., Barcelò, D., Rocha-Santos, T., 2021. Increased plastic pollution due to COVID-19 pandemic: challenges and recommendations. Chem. Eng. J. 405, 126683.

Prata, J.C., Silva, A.L., Walker, T.R., Duarte, A.C., Rocha-Santos, T., 2020. COVID-19 pandemic repercussions on the use and management of plastics. Environ. Sci. Technol. 54 (13), 7760–7765.

Prather, K.A., Wang, C.C., Schooley, R.T., 2020. Reducing transmission of SARS-CoV-2. Science 368 (6498), 1422–1424.

Qureshi, M.S., Oasmaa, A., Pihkola, H., Deviatkin, I., Tenhunen, A., Mannila, J., et al., 2020. Pyrolysis of plastic waste: opportunities and challenges. J. Anal. Appl. Pyrolysis 152, 104804.

Rahman, M.H., 2020. Inappropriate use and disposal of face masks may promote the spread of COVID-19 in Bangladesh. Popul. Med. 2 (November), 1–2.

Ray, S.S., Bandyopadhyay, J., 2021. Nanotechnology-enabled biomedical engineering: current trends, future scopes, and perspectives. Nanotechnol. Rev. 10 (1), 728–743.

Regmi, C., Joshi, B., Ray, S.K., Gyawali, G., Pandey, R.P., 2018. Understanding mechanism of photocatalytic microbial decontamination of environmental wastewater. Front. Chem. 6.

Roy, T., Dey, T.K., Jamal, M., 2023. Microplastic/nanoplastic toxicity in plants: an imminent concern. Environ. Monit. Assess. 195, 27.

Saberian, M., Li, J., Kilmartin-Lynch, S., Boroujeni, M., 2021. Repurposing of COVID-19 single-use face masks for pavements base/subbase. Sci. Total Environ. 769, 145527.

Sadia, M., Mahmood, A., Ibrahim, M., Irshad, M.K., Quddusi, A.H.A., Bokhari, A., Mubashir, M., Chuah, L.F., Show, P.L., 2022. Microplastics pollution from wastewater treatment plants: a critical review on challenges, detection, sustainable removal techniques and circular economy. Environ. Technol. Innov. 28, 102946.

Sangkham, S., 2020. Face mask and medical waste disposal during the novel COVID-19 pandemic in Asia. Case Stud. Chem. Environ. Eng. 2, 100052.

Serafin, J., Sreńscek-Nazzal, J., Kamińska, A., Paszkiewicz, O., Michalkiewicz, B., 2022. Management of surgical mask waste to activated carbons for CO2 capture. J. CO2 Util. 59, 101970.

Shadman, S., Chin, C.M., Sakundarini, N., Yap, E.H., Fairuz, S., Wong, X.Y., Khalid, P.A., Karimi, F., Karaman, C., Mofijur, M., Koyande, A.K., 2022. A system dynamics approach to pollution remediation and mitigation based on increasing the share of renewable resources. Environ. Res. 205, 112458.

Shan, X., Zhang, H., Liu, C., Yu, L., Di, Y., Zhang, X., Dong, L., Gan, Z., 2020. Reusable self-sterilization masks based on electrothermal graphene filters. ACS Appl. Mater. Interfaces 12 (50), 56579–56586.

Shen, M., Ye, S., Zeng, G., Zhang, Y., Xing, L., Tang, W., Wen, X., Liu, S., 2020. Can microplastics pose a threat to ocean carbon sequestration? Mar. Pollut. Bull. 150, 110712.

Silva, A.L.P., Prata, J.C., Walker, T.R., Campos, D., Duarte, A.C., Soares, A.M., Barcelò, D., Rocha-Santos, T., 2020. Rethinking and optimizing plastic waste management under COVID-19 pandemic: policy solutions based on redesign and reduction of single-use plastics and personal protective equipment. Sci. Total Environ. 742, 140565.

Soni, R., Joshi, S.R., Karmacharya, M., Min, H., Kim, S.K., Kumar, S., Kim, G.H., Cho, Y.K., Lee, C.Y., 2021. Superhydrophobic and self-sterilizing surgical masks spray-coated with carbon nanotubes. ACS Appl. Nano Mater. 4 (8), 8491–8499.

Spennemann, D.H., 2021. COVID-19 face masks as a long-term source of microplastics in recycled urban green waste. Sustainability 14 (1), 207.

Uheida, A., Mejía, H.G., Abdel-Rehim, M., Hamd, W., Dutta, J., 2021. Visible light photocatalytic degradation of polypropylene microplastics in a continuous water flow system. J. Hazard. Mater. 406, 124299.

van Doremalen, N., Bushmaker, T., Morris, D.H., Holbrook, M.G., Gamble, A., Williamson, B.N., Tamin, A., Harcourt, J.L., Thornburg, N.J., Gerber, S.I., Lloyd-Smith, J.O., de Wit, E., Munster, V.J., 2020. Aerosol and surface stability of SARS-CoV-2 as compared with SARS-CoV-1. N. Engl. J. Med. 382 (16), 1564–1567.

Walker, T.R., 2021. (Micro)plastics and the UN Sustainable Development Goals. Current Opinion in Green and Sustainable Chemistry 30, 100497.

Ward, C.P., Armstrong, C.J., Walsh, A.N., Jackson, J.H., Reddy, C.M., 2019. Sunlight converts polystyrene to carbon dioxide and dissolved organic carbon. Environ. Sci. Technol. Lett. 6 (11), 669–674.

Wu, H., Huang, J., Zhang, C.J., He, Z., Ming, W.K., 2020. Facemask shortage and the novel coronavirus disease (COVID-19) outbreak: reflections on public health measures. eClinicalMedicine 21, 100329.

Xanthos, D., Walker, T.R., 2017. International policies to reduce plastic marine pollution from single-use plastics (plastic bags and microbeads): a review. Mar. Pollut. Bull. 118 (1–2), 17–26.

Yan, N., 2022. Recycling plastic using a hybrid process. Science 378 (6616), 132–133.

Yan, G., Jing, X., Wen, H., Xiang, S., 2015. Thermal cracking of virgin and waste plastics of PP and LDPE in a semibatch reactor under atmospheric pressure. Energy Fuel 29 (4), 2289–2298.

Yin, I.X., Zhang, J., Zhao, I.S., Mei, M.L., Li, Q., Chu, C.H., 2020. The antibacterial mechanism of silver nanoparticles and its application in dentistry. Int. J. Nanomedicine 15, 2555–2562.

Yuan, X., Wang, X., Sarkar, B., Ok, Y.S., 2021. The COVID-19 pandemic necessitates a shift to a plastic circular economy. Nat. Rev. Earth Environ. 2 (10), 659–660.

Zhang, X., Lei, H., Zhu, L., Zhu, X., Qian, M., Yadavalli, G., Wu, J., Chen, S., 2016. Thermal behavior and kinetic study for catalytic co-pyrolysis of biomass with plastics. Bioresour. Technol. 220, 233–238.

Zhang, Q., Xu, E.G., Li, J., Chen, Q., Ma, L., Zeng, E.Y., Shi, H., 2020. A review of microplastics in table salt, drinking water, and air: direct human exposure. Environ. Sci. Technol. 54 (7), 3740–3751.

Zhang, R., Li, Y., Zhang, A.L., Wang, Y., Molina, M.J., 2020. Identifying airborne transmission as the dominant route for the spread of COVID-19. Proc. Natil. Acad. Sci. 117 (26), 14857–14863.

Zhang, K., Hamidian, A.H., Tubić, A., Zhang, Y., Fang, J.K., Wu, C., Lam, P.K., 2021. Understanding plastic degradation and microplastic formation in the environment: a review. Environ. Pollut. 274, 116554.

Zhong, H., Zhu, Z., Lin, J., Cheung, C.F., Lu, V.L., Yan, F., Chan, C.Y., Li, G., 2020. Reusable and recyclable graphene masks with outstanding superhydrophobic and photothermal performances. ACS Nano 14 (5), 6213–6221.