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Sustainable management of plastic wastes in COVID-19 pandemic: The biochar solution

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A R T I C L E   I N F O

Keywords:
Plastic pollution
Engineered biochar
Upcycling
Sustainable waste management
Environmental protection
Circular economy

A B S T R A C T

To prevent the COVID-19 transmission, personal protective equipment (PPE) and packaging materials have been extensively used but often managed inappropriately, generating huge amount of plastic waste. In this review, we comprehensively discussed the plastic products utilized and the types and amounts of plastic waste generated since the outbreak of COVID-19, and reviewed the potential treatments for these plastic wastes. Upcycling of plastic waste into biochar was addressed from the perspectives of both environmental protection and practical applications, which can be verified as promising materials for environmental protections and energy storages. Moreover, novel upcycling of plastic waste into biochar is beneficial to mitigate the ubiquitous plastic pollution, avoiding harmful impacts on human and ecosystem through direct and indirect micro-/nano-plastic transmission routes, and achieving the sustainable plastic waste management for value-added products, simultaneously. This suggests that the plastic waste could be treated as a valuable resource in an advanced and green manner.

Credit author statement

Avanthi D. Igalavithana: Conceptualization, Data curation, Formal analysis, Methodology, Writing – original draft. Xiangzhou Yuan: Conceptualization, Data curation, Formal analysis, Methodology, Writing – original draft, review & editing. Chammi P. Attanayake: Validation, Writing – review & editing. Shujun Wang: Validation, Writing – review & editing. Siming You: Validation, Writing – review & editing. Daniel C.W. Tsang: Conceptualization, Writing - review & editing. Ange Nzihou: Conceptualization, Writing - review & editing. Yong Sik Ok: Conceptualization, Funding acquisition, Methodology, Project administration, Resources, Supervision, Writing - original draft, Writing - review & editing.

Information on funding sources

This work was carried out with the support of the Cooperative Research Program for Agriculture Science and Technology Development (Project No. PJ01475801) from Rural Development Administration, the Republic of Korea, the National Research Foundation of Korea (NRF) grant funded by the Korea government (MSIT) (No. 2021R1A1A2C2011734), and Basic Science Research Program through the

Abbreviations: PPE, Personal protective equipment; PCCPs, Personal care and cosmetic products; PCBs, Polychlorinated biphenyls; IUCN, International Union for Conservation of Nature; UNEP, UN Environment Programme; ABS, Acrylonitrile butadiene styrene; PVC, Polyvinyl chloride; PS, Polystyrene; PP, Polypropylene; EVA, Ethylene-vinyl acetate; EVOH, Ethylene vinyl alcohol; LDPE, Low-density polyethylene; HDPE, High-density polyethylene; PET, Polyethylene terephthalate.

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https://doi.org/10.1016/j.envres.2022.113495
Received 17 November 2021; Received in revised form 8 March 2022; Accepted 14 May 2022
Available online 1 June 2022
0013-9351/© 2022 Published by Elsevier Inc.
1. Introduction

1.1. Use of plastic products during COVID-19 pandemic

The infection of SARS-CoV-2 virus had continued to spread all over the world as of today, since the first outbreak of COVID-19 pandemic was reported in Hubei province in China in latter months of 2019 (WHO, 2020). The pandemic has affected the production, usage, disposal, and recycling of plastic products (Yuan et al., 2021b). Personal protective equipment (PPE) has been increasingly used by public. The disposable PPE (e.g., face masks, gloves, gowns, eye protection and filtering face-piece respirators) are made from plastics. Over 50 countries had made it mandatory to wear a face mask or a face covering at public places as reported by June 2020 (Patrício Silva et al., 2020). Early this year, the European Centre for Disease Prevention and Control (2021) recommends wearing face masks in areas with community outbreaks to prevent the spread of the virus. It is estimated that 1.6 million tons/day of plastic wastes is being generated worldwide since the outbreak of COVID-19 (Benson et al., 2021). This amounts to an annual plastic waste generation of 75 kg per capita. It has been estimated that globally 129 billion face masks are used monthly and it is 65 billion for gloves (Prata et al., 2020). Approximately 3.4 billion single-use facemasks/face shields are discarded daily around the world (Benson et al., 2021). The face mask market is estimated to grow at a rate of over 5% from 2019 to 2025 (Face Mask Market report, 2020). Much of the face masks are recommended for single-use considering their possible risks to be vectors of SARS-CoV-2 and become less effective in multiple use.

The COVID-19 pandemic has changed the lifestyle of people by demanding to work from home. This has increased the home delivery of meals and groceries, which consequently create a rising demand for single-use plastic bags and food packaging materials. The use of online shopping and takeaway services has increased tremendously (by 78% in US, 65% in Singapore, and 50% in China) during the pandemic (Parashar and Hait, 2021). The centre for Disease Control and Prevention recommends using roadway delivery instead of dine-in and avoiding using sharing food containers and other items in restaurants (CDC, 2020). Some jurisdictions (e.g., Maine, New Hampshire, and Oregon) in the US have reversed or delayed the effective dates of policies to ban using sharing food containers and other items in restaurants (CDC, recommends using driveway delivery instead of dine-in and avoiding)

1.2. Generation of plastic wastes during COVID-19 pandemic

Plastics have become one of the most common and persistent organic pollutants in marine and terrestrial environments, long before the pandemic. About 6.6 billion tons of plastic ended up in landfills or remain in the natural environment annually, worldwide, before the pandemic (UNEP, 2020). This accounts for 80% of annual plastic production. About 4.8 to 12.7 million metric tons of plastic was disposed of into the ocean in 2010 by 192 coastal countries (Jahwbeck et al., 2015). During the pandemic, with the increased use of virgin plastic and lack of efforts and interest on using recycled plastic, it is expected that more plastic waste will end up on land and oceans. Plastics undergo translocation, storage, degradation, and bioaccumulation processes in the environment (Hurley and Nizzetto, 2018).

The effect of plastic waste on the marine ecosystem has been extensively studied in the last decade. Rivers are one of the main paths for the transmission of plastics to oceans, and it has been estimated that 1.15 and 2.41 million tonnes of plastic wastes enter the oceans annually. Moreover, the highest quantity of plastics is released from rivers in Asia which accounts for 67% of the global total (Lerbreton et al., 2017). Plastics in ocean have threatened marine species via entanglement and ingestion. Lives of about 117 species, that have been listed in IUCN Red List as near threatened, vulnerable, endangered or critically endangered have been threatened due to entanglement or by ingestion of marine debris, of which 92% is plastic waste (Gall and Thompson, 2015). The marine organisms that are mostly susceptible to entanglement and ingestion of plastics are sea turtles, marine mammals, and sea birds (Thushari and Senevirathna, 2020). Moreover, ingestion of plastics increases the PCBs accumulated in fat tissues and eggs in Great Shearwaters (Ryan et al., 1988). Sedimentation of plastic debris on the sea floor can disrupt the marine ecosystem, by blocking the gas exchange between sediments and water (Moore, 2008).

The fragmented plastic produces micro- and nano-plastic particles. From the plastics in surface layer of oceans, 83.7% are macroplastics (> 5 mm), 13.8% are microplastics (335 μm–5 mm), and 2.5% are nanoplastics (< 0.335 mm) (Koelmans et al., 2017). The micro and nano-plastics can sorb potentially toxic organic molecules (Nikki et al., 2021; Wu et al., 2016; Liu et al., 2019; Xu et al., 2019; Wang et al., 2019; Zhan et al., 2016; Lee et al., 2014; Guo et al., 2012) and heavy metals in the environment (Yang et al., 2019; Godoy et al., 2019; Guo and Wang, 2021). They increase the life time of persistent organic pollutants in the environment (Jambbeck et al., 2015). Nanoplastics have the potential to contaminate groundwater via leaching (Hurley and Nizzetto, 2018; Blasing and Ameilung, 2018). The plastic waste added into the terrestrial environment is 4–23 times higher than that in oceans; however, the studies on the effect/fate/transformation of plastics in soil are limited (Hurley and Nizzetto, 2018; Horton et al., 2017; Rillig, 2012; Qi et al., 2020).

Plastics in the environment can be degraded and disintegrated and produce microplastic which are < 5 mm and nanoplastics which are < 0.1 μm. These micro- and nanoplastics subjected to various weathering processes due to ultraviolet radiation, microbial degradation, physical disintegration, and chemical oxidation (Igalavithana et al., 2022). Agricultural soils can be contaminated by plastics via plastic mulch, organic amendments such as sewage sludge, and irrigation and flood water (Blasing and Ameilung, 2018). Effects of direct ingestion and inhalation of microplastics by food on human health are yet to be investigated.

Additives in plastics enhance the negative impacts of plastic waste in the environment. Phthalic acid esters are such an additive that is widely employed in many plastic products used in medical equipment, building...
materials, and in plastic film for food packaging and various agricultural uses (He et al., 2015). Alarming concentrations of phthalic acid esters have been reported in agricultural and urban soils in China (He et al., 2015; Kong et al., 2012). Moreover, it has been reported that plasticizer was identified in samples of human tissue taken from patients who had received transfusions of blood stored in plastic bags. The additive has been related to cancer, reproductive, and endocrine-disruptive effects (Kong et al., 2012; Bornehag et al., 2005). Furthermore, micro- and nano-plastics have been identified as potential carriers of organic and inorganic pollutants (e.g., potentially toxic metals) which could increase the mobility of the pollutants in the environment (Igalavithana et al., 2022; Hüffer et al., 2019).

Contamination of food web via plastics and additives threatens the terrestrial ecosystem (Kumar et al., 2020). Plastics can enter food web and cause health effects for animals and humans (Bradney et al., 2019). Studies revealed that the injected microplastics may cause cellular proliferation, inflammation in tissue, and necrosis and may compromise immune cells in humans and animals (Wright and Kelly, 2017). It has been observed that hemocyte aggregation stimulation and respiratory function reduction in blue crabs (Callinectes sapidus) were due to plastic microspheres ingested (Johnson et al., 2011). The injected virgin polyethylene fragments created hepatic stress in Japanese medaka (Oryzias latipes) (Rochman et al., 2013). The health impacts of microplastics in humans and animals depend on the presence, sizes, and frequency of engagement with microplastics (Smith et al., 2018). Plastics in marine environments provide habitats for microbial colonization and develop biofilms. The role of these microbial communities in the ecosystem onto biodegrade plastics and organic pollutants and their pathogenicity are yet to be understood (Wright et al., 2020). Several studies prove that plastics and plastic additives, including plasticizers enter earth worms, which could be potentially transferred to higher levels in the food web (Gaylor et al., 2013; Huerta Lwanga et al., 2016, 2017a; Chae and An, 2018; Cao et al., 2017). Plastics have been found in chicken feces and gizzard (Huerta Lwanga et al., 2017b). There is direct evidence on transfer of plastics from soil to plants. Li et al. (2019) detected micro-plastics via detecting fluorescence markers in lettuce roots and shoots grown in peat soil with added labeled microplastics. The effect of micro- and nano-plastics in the ecosystem is yet to be fully understood. Increased generation of plastic waste creates pressure on the economy as waste management is costly. It has been estimated that removal of 15% of plastic debris every year over a ten-year period from 2020 to 2030, which accounts for 135 million tons of plastic in total, would cost €492 billion to €708 billion (Cordier and Uehara, 2019).

In addition, Fig. 1 demonstrates a scientometric visualization of the top 50 keywords of total 507 peer-reviewed publications within the database of “Web of Science Core Collection” released last 2 years, using “COVID-19” and “plastic” as the searching keywords (topic). It suggests in red circle that plastic waste pollution and management has been extensively attracted. Therefore, it is timely and necessary to provide a comprehensive review of plastic waste management during/post COVID-19 pandemic, which is beneficial to achieve sustainable development and close the plastic loop, simultaneously.

2. Types of plastic wastes and composition

2.1. Personal care and cosmetic products

Personal care and cosmetic products (PCCPs), using microplastics as inputs for a variety of products, often tend to be related to cosmetics but encompass a variety of items such as skin moisturizers, perfumes, lipsticks, fingernail polishes, eye, and facial makeup preparations, shampoos, permanent waves, hair colors, toothpastes, and deodorants.
For example, the facial cleansers are the most analysed PCCPs so far and they contain more plastic particles than other products (Sun et al., 2020). Moreover, it was analysed that 0.05 g/g or 2450 particles/g (geometric mean) were found in facial cleansers, while only 0.02 g/g or 2.15 particles/g (geometric mean) were found in shower gels. Although many plastic types such as polypropylene (PP), poly-styrene (PS) polyvinyl chloride (PVC), acrylonitrile butadiene styrene (ABS) are reported, the polyethylene (PE) is the most abundant, contributing to 93% of the total microplastics (Gouin et al., 2015; Lei et al., 2017). PCCPs are considered as one of the main pollution sources in the environment, due to the accumulation of plastics and derived microplastics (Fendall and Sewell, 2009; Mark et al., 2011). Considering the above-mentioned, a high percentage of the commercialized PCCPs in the market use components such as microbeads, in addition to plastic container packaging. The problem is exacerbated because the packaging is made of different types of plastic that is not being properly disposed of and that, unfortunately, adds to the discouraging recycling statistics (Lebreton and Andrady, 2019).

Thermoplastics and thermostet plastics are main components of PCCPs. The best known in the industry are polyethylene and phthalates that are used as plasticizers (Koniecki et al., 2011). The PCCP industry has had a boom in the market in recent years (Diani et al., 2006). By 2018, the Asia Pacific region played a leadership role, encompassing 40% of the production and sale of PCCP, followed by North America (25%) (Diani et al., 2006). Therefore, it is not surprising that the productive value of this industry rises to 145.2 billion USD worldwide and it is estimated that it will continue to grow (Ridder, 2021). The pollution by these products is significant considering that microplastics are not to be filtered or perceived owing to its size, which implies an ecological risk for terrestrial and aquatic ecosystems (Galloway et al., 2017).

The social behavior has been dramatically influenced by the COVID-19 pandemic. The case of PCCPs is heterogeneous since the number of production and commercialization in cosmetic products and others such as shampoos has decreased due to the lockdown but in relation to personal care products, especially those of skin care and disease prevention such as hand sanitizer, different types of soaps, liquid disinfectants, hands and body lotions have been benefited from the spread of the virus, since these products have come to be considered essential to prevent this disease (CDC, 2020). This substantial increase has had a similar impact on the amount of plastic waste generated during the pandemic, which together with other sources potentially worse the situation of plastic pollution (Sarkodie and Owusu, 2021) since this industry is one of those that has been constantly resilient during this unexpected pandemic (Gerstell et al., 2020).

### 2.2. Medical waste

According to the Occupational Safety and Health Administration Centre, the PPE refers to the equipment used to minimize the risk of diseases or infections that are the result of exposure or contact with dangerous substances of a chemical, radiological type, among others. The PPE is required for taking diagnostic samples, patient care, and medical, and is used mostly by health workers who are regularly exposed during the patient’s attention. Their use increases in the face of pandemics and emerging diseases (Loibner et al., 2019). From the indicated elements, disposable gloves and face masks are the most frequently used. According to their compositions, there are different types such as latex gloves and Polyvinyl chloride (PVC) gloves (Kizilary et al., 2005). However, there are also others, depending on their manufacture, that have polyethylene, vinyl, natural or synthetic rubber latex, and multilayer disposable gloves that are made of thermoplastic material that comprises a mixture of two or more ethylene-based polymers. In contrast, some common disposable masks (e.g., blue surgical masks and protective masks) are composed by 3 layers of some of the following materials, propylene, polyester, ethylene strips with acrylic binders (Leonas and Jones, 2003). In any case, it should be noted that a large amount of medical waste includes polypropylene (PP) and acrylonitrile butadiene styrene (ABS) because these are commonly used in the manufacture of implements for medical applications (Jahneke, 2020).

Since the COVID-19, the production of PPEs has expanded for meeting the skyrocketing demand, resulting in dramatic increase of PPE waste. Fig. 2a and Table 1 present the medical masks and total plastic waste generated since the outbreak of COVID-19. It is estimated that an approximate of 89 million medical masks, 76 million pairs of medical gloves, and 1.6 million pairs of glasses are required but the numbers do not stop growing and China produced 240 tons of medical waste daily during the peak of the pandemic in the city of Wuhan, which means 6 times more than what is normally produced before the COVID-19 pandemic (Singh et al., 2020). The State Council Information Office of China reported that there were 468.9 tons of medical waste related to the pandemic. The cases from other countries are not isolated, for example, some studies provided that if each person in United Kingdom uses a disposable facial mask daily for a year, this country would have generated 66,000 tons of plastic waste that is not recyclable (DHSC, 2020), and in Hong Kong around 7.4 million inhabitants are using single-use masks on a daily basis (Master et al., 2020), which has had a negative impact on ecosystems as plastic waste has already been found on beaches, nature trails and the surrounding sea (Fadare and Okoffo, 2020). Moreover, over 1.56 billion face masks will have entered oceans in 2020, suggesting that COVID-19 brought over 4680 to 6240 metric tonnes of marine plastic pollution (Phelps Bondaroff and Cooke, 2020).

The case of South Korea got attention when the outbreak of COVID-19 occurred in Daegu, and the Korea Centers for Disease Control and Prevention recommended the strict use of PPE for medical care (especially N95-level masks). Glasses, gowns, and other supplements were also extensively used (Kim et al., 2020) and regarding the waste amount, around 295 tons of medical waste were generated in one month from the beginning of February to the beginning of March 2020 (Rhee, 2020), and 20 tons of these hazardous wastes related to the coronavirus was generated per day. It is worth noting that medical waste derived from COVID-19 could be contagious and dangerous, due to that coronavirus strains could survive in plastics for up to 72 h or sometimes up to 9 days depending on the plastic material (Kampf et al., 2020). The UNEP reported that 75% of used masks would end up polluting the environment and issued a warning that if the trend of medical wastes continues to increase, it will be impossible to handling it and the discharge will be uncontrollable. Therefore, concerted effort and adequate disposal should be made accordingly, to achieve the sustainable waste management during and post the COVID-19 pandemic (Sangkham, 2020).

### 2.3. Daily packaging waste

The packaging industry is large and formidable as packaging is a primary component of the supply chain that encompasses an extensive range of services, and also has the function of protecting, preserving and/or storing the products that must be wrapped or packaged to be delivered to users (Chen et al., 2017). Some of the items mass-produced are plastic bottles, plastic bags, wrappers, food containers, personal care products containers, and coffee cups, etc., however, over 79% of these packaging plastics are currently being accumulated in landfills or deliberately dumped into different spaces and natural habitats (Rhodes, 2018). Without concerted efforts to manage/recycle them, worldwide plastic pollution caused by different kinds of daily packaging waste has been intensifying (Chen et al., 2017; Das and Tiwari, 2018).

Several meta-analysis studies reviewed the incidence of different types of plastic waste in aquatic environments. It was found that 92.2% of packaging waste comprised polyethylene (PE) followed by poly-propylene (PP) and polystyrene (PS) (Schwarz et al., 2019), and other studies reaffirmed that PE predominates among these packaging plastic (Luisterburg and Goossens, 2014; Roosen et al., 2020). Moreover, the polyethylene terephthalate (PET) type is a widely known and exploited polymer in the packaging industry, monopolizing the beverage bottles.
market and covering, in the case of Europe, almost 16% of total plastic consumption (Nistico, 2020). In addition, flexible wrappers, widely used for snacks and other food packaging, are impossible to directly recycle, due to the complex compositions including ethylene-vinyl acetate (EVA), ethylene vinyl alcohol (EVOH), high-density and low-density polyethylene (HDPE and LDPE), linear LDPE, PET presented in different combinations (Niaounakis, 2019).

During the COVID-19 pandemic, packaging plastic consumption has skyrocketed. The social distancing rules strongly encouraged people to stay/quarantine at home, effectively preventing out of coronavirus spreading (de Sousa, 2020). Online services and door-to-door deliveries of various items (e.g., cloths, food, bottled water, etc.) have been
3. Management strategies of COVID-19 plastic wastes

Owing to the unexpected COVID-19 pandemic, the waste management chains have been significantly destroyed, skyrocketing causing a pressing environmental and potential public health problem (Yoo et al., 2020). Considering that ubiquitous plastic pollution can spread through the biogeochemical cycle (Fig. 2b) (Bank and Hansson, 2019), sustainable plastic waste management should be paid more attention. In this section, management strategies of plastic waste generated during COVID-19 will be addressed.

3.1. Upcycling

Upcycling serves as one of the most encouraging stages in the waste management hierarchy for sustainable development. The need for upcycling of plastics has been recognized as a major step in mitigation of their hazardous effects. Attempts are being made to upcycle plastics for the production of fuels, chemicals, and various other value-added products (Meyls et al., 2020; Yuan et al., 2021a, Yuan et al., 2022b). State-of-the-art plastic sorting and segregation methods can be employed to demarcate dissimilarity among various plastic variants in order to select their subsequent treatment technique for value-added product synthesis (Rahimi and García, 2017).

PET, the most widely used plastic packaging material has been used as a binder material of concrete mixture based on its excellent mechanical properties (Rahimi and García, 2020). The utilization of plastics as a binder material serve as a cheap and effective means of improving the traditional performance of bitumen but also the management of plastic wastes (Abdelmoti and Mustafa, 2019). The utilization of plastics as a binder material serve as a cheap and effective means of improving the traditional performance of bitumen but also the management of plastic wastes (Abdelmoti and Mustafa, 2019). The utilization of plastics as a binder material serve as a cheap and effective means of improving the traditional performance of bitumen but also the management of plastic wastes (Abdelmoti and Mustafa, 2019). The utilization of plastics as a binder material serve as a cheap and effective means of improving the traditional performance of bitumen but also the management of plastic wastes (Abdelmoti and Mustafa, 2019). The utilization of plastics as a binder material serve as a cheap and effective means of improving the traditional performance of bitumen but also the management of plastic wastes (Abdelmoti and Mustafa, 2019). The utilization of plastics as a binder material serve as a cheap and effective means of improving the traditional performance of bitumen but also the management of plastic wastes (Abdelmoti and Mustafa, 2019). The utilization of plastics as a binder material serve as a cheap and effective means of improving the traditional performance of bitumen but also the management of plastic wastes (Abdelmoti and Mustafa, 2019). The utilization of plastics as a binder material serve as a cheap and effective means of improving the traditional performance of bitumen but also the management of plastic wastes (Abdelmoti and Mustafa, 2019). The utilization of plastics as a binder material serve as a cheap and effective means of improving the traditional performance of bitumen but also the management of plastic wastes (Abdelmoti and Mustafa, 2019). The utilization of plastics as a binder material serve as a cheap and effective means of improving the traditional performance of bitumen but also the management of plastic wastes (Abdelmoti and Mustafa, 2019). The utilization of plastics as a binder material serve as a cheap and effective means of improving the traditional performance of bitumen but also the management of plastic wastes (Abdelmoti and Mustafa, 2019).
the environmental benefits and economic feasibility of converting the industrial-scale waste PET plastic into porous carbons for CO₂ adsorption, Yuan et al. (2022a) highlighted its potential as a multifunctional alternative to conventional CO₂ absorption and plastic waste management technologies.

In addition, plastic polymers have been attempted for conversion into useful compounds through pyrolysis, gasification of thermal oxidation (Ephraim et al., 2016). Nanda and Berruti (2021) reviewed the thermochemical conversion (e.g., including pyrolysis, gasification, and liquefaction) of plastic waste to fuels, and concluded that pyrolysis was by far the most widely researched conversion technology compared to liquefaction and gasification. Owing to the unexpected COVID-19 outbreak, the demand for surgical masks has increased dramatically since early 2020 (You et al., 2020), and mismanagement of single-used surgical masks has resulted in the generation of a large amount of mask waste. Li et al. (2022) upcycled waste surgical mask into liquid fuel with a high heating value (HHV) of 43.5 MJ/kg. More importantly, environmental benefits and advantages of this upcycling approach were verified from a life-cycle perspective, as compared with conventional waste management approaches. Moreover, other studies have reported the co-pyrolysis of plastics and various biomass streams with an impact on the energetic gas, pollutants emission, and biochar composition and characteristics (Ephraim et al., 2018, Block et al., 2019, 2020; Wang et al., 2021a, Ren et al., 2022). Nanda and Berruti (2021) suggested that co-processing technologies such as co-pyrolysis, co-liquefaction and co-gasification, which involve the blending of biomass with plastics have tremendous environmental and economic advantages. Wang et al. (2021a) reviewed the co-pyrolysis of waste plastic and solid biomass for synergistic production of biofuels and chemicals, considering various factors such as plastic type, catalyst loading, pyrolysis reactor, operating conditions, and targeting products. They also addressed the existing challenges and potential opportunities, and proposed a synergistic solution to waste management, climate change mitigation and environmental protection. In pyrolysis, plastics are heated in anoxic conditions until they are converted into gases, oils and biochar (Meyes et al., 2020; Budaereaechai et al., 2019).

Another strategy widely employed for upcycling is selective decomposition of polymer into monomeric units or reactive intermediates through physicochemical treatment. Thermal hydrolysis is a widely employed depolymerization technique for monomer synthesis (Panda et al., 2010; Ryan et al., 2021). But the technique suffers from two major challenges, e.g., low heat transfer and low flow diffusion capacities which restrict the thermal conversion of plastics. It is anticipated that plastic polymers can be depolymerized into monomeric units or short-chain carbon sources through enzymatic action which can be polymerized to form new polymers. The enzyme mediated depolymerization is environmentally friendly, economic and requires lower energy investment; however, the process is very slow and time consuming (Chen et al., 2020). Microplastics on account of being carbonaceous in nature serve as a carbon source for carbon-based products such as carbon nanotubes and nanomaterials (Wang et al., 2020b). The upcycling of plastics into high value carbon nanomaterials is a sustainable solution for plastic waste management with a promising future, but a major challenge in plastic to carbon nanomaterial transformation is the nature and quality of feedstocks. The inconsistent and non-reproducible supply of plastic feedstock with uniform quality can affect the composition, quality and purity of carbon nanomaterials.

Table 2 summarizes pyrolysis and co-pyrolysis of plastic waste is one of the environmentally friendly ways for transforming plastic waste into value-added products (Lam et al., 2019). Research evidences revealed that co-pyrolysis of biomass and plastic wastes exhibited high production of bio-oil and low production biochar (Kumar et al., 2020; Uzoejirina et al., 2018). For instance, co-pyrolysis of pinecone and plastics (e.g., low density polyethylene, polypropylene, and polystyrene) at 500 °C produced high amount of bio-oil due to the synergistic effect in the pyrolysis mixture, and the obtained char showed higher calorific values compared to the pyrolysis of pinecone alone (Brebu et al., 2010). Generally, due to the negative synergistic effect on biochar production, co-pyrolysis produces less biochar but more volatile products. For example, the co-pyrolysis of rice husk and high-density polyethylene (HDPE) showed that the free radicals derived from rice husk facilitated the degradation of HDPE and the formation of hydrocarbon radicals; initiation and secondary radical formation via depolymerization, H transfer, and reaction between radicals are the main steps involved in this (Wantaneeayukl et al., 2021). Similarly, Chen et al. (Chen et al., 2015) observed negative synergistic effects on biochar production in
### Table 2
Sustainable plastic management for environmental protection and energy conversion and storage.

| Refs        | Plastic types | Conversions                          | Applications for produced biochar                                                                 |
|-------------|---------------|--------------------------------------|----------------------------------------------------------------------------------------------------|
| Hao et al.  | PET           | Carbonization using SLS and ZnO      | Solar steam generator: The O,S doped porous carbon presented high performance in solar vapor generation to produce freshwater from wastewater/seawater, reaching the evaporation rate of 1.51 kg/m² under 1 kw/m², and the metallic ion removal efficiency is >99.9%. This study paved a new way for upcycling plastic waste into novel materials with high performance in wastewater treatment. **Methylene blue sorption:** The composite carbon with specific surface area of 2811 m²/g displayed an excellent methylene blue adsorption capacity of 490 mg/g, providing a new strategy to upcycle plastic in high quality composite materials. The composite carbon was beneficial to increase the surface area of porous carbon prepared in this research. | |
| Yuan et al. | PET           | Carbonization followed by KOH activation | CO₂ capture: PET-K (2)-700 gave the high CO₂ adsorption performance of 2.43 mmol/g at 25 °C and 1 bar, exhibiting a great potential to mitigate CO₂ emission from semiconductor industries. **CO₂ capture:** PET-KOH-973, activated with KOH at 700 °C, demonstrated excellent CO₂ adsorption capacity of 4.42 mmol/g at 25 °C and 1 bar. Moreover, it exhibited good CO₂ selectivity over N₂, low energy consumption for sample regeneration, etc., suggesting that PET-to-CO₂ adsorbent route is suitable for practical CO₂ capture. **CO₂ capture:** PET6KN-a-urea: Prepared by KOH activation and urea treatment in a one-pot synthesis at 700 °C, displayed excellent CO₂ uptakes of 6.23 mmol/g at 0 °C and 4.58 mmol/g at 25 °C (1 bar), which is beneficial to achieve the sustainable waste management and mitigate both plastic pollution and **climate change**, simultaneously. **CO₂ capture:** PET6-CO₂ 9, activated in CO₂ atmosphere, showed excellent CO₂ uptakes of 6.25 mmol/g at 0 °C and 3.63 mmol/g at 25 °C (1 bar). Based on techno-economic and life-cycle assessments of the scaled-up industrial processes, authors showed that the physical CO₂ activation approach performs the best in the reduction of carbon emissions, providing the possibility for carbon neutrality while exhibiting financial viability (net present value of at least (19.22 million over the operating life of the project), which could be considered as a multifunctional alternative to conventional CO₂ absorption and plastic waste management technologies. **Energy storage:** The hierarchical porous carbon with specific surface area of 3059 m²/g presented great electrochemical performance with a specific capacitance of 355 F/g at a current density of 0.2 A/g in 6 M KOH electrolyte, a high energy density of 9.81 Wh/kg at a power density of 450 W/kg, and an excellent cycling stability. **Energy storage:** The synthesized sample displayed excellent double layer capacitance and specific capacitance to the tune of 19.46 mF/cm² and 55.6 F/g, respectively. **Energy storage:** The activated carbon nanosheet (specific surface area of 3200 m²/g) based electrode displayed a high specific capacitance of 349 F/g at 0.5 A/g, and it supercapacitor reached a high energy density of 23 Wh/kg at 225 W/kg, verifying this route as a good reference for upcycling plastic waste into energy storage materials. **Energy storage:** PCF: MnO₂ (surface area of 1087 m²/g) exhibits good electrochemical properties as electrode in supercapacitor, reaching ultrahigh capacitance of 308 F/g at 1 m/s and | |
| Li et al.    | PP            | Pyrolysis together with cyanobacteria using K₂CO₃ | Zhang and Shen (2019) | PVC | One-step pyrolysis with KOH and biomass | Liu et al. (2020) | PP | Carbonization using Fe₃S₈ | |
| Liu et al.  | PP            | Pyrolysis together with cyanobacteria using K₂CO₃ | Zhang and Shen (2019) | PVC | One-step pyrolysis with KOH and biomass | Liu et al. (2020) | PP | Carbonization using Fe₃S₈ | |
| Yuan et al. | PET           | Carbonization followed by KOH activation | Carbonization followed by CO₂ physical activation, KOH chemical activation, or KOH/Urea activation | |
| Yuan et al. | PET           | Carbonization followed by KOH activation | Carbonization followed by KOH activation | |
| Yuan et al. | PET           | Carbonization followed by KOH activation | Carbonization followed by KOH activation | |
| Min et al.  | PS            | Carbonization using MgO and KMnO₄, separately | Carbonization followed by KOH activation | |

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co-pyrolysis of newspaper and HDPE. The biochar generated in co-pyrolysis of newspaper and HDPE at 500 °C showed low oxygen-containing functional groups, high calorific values, high porosity, and high fuel ratios, which suggests its greater potential of being used as a solid fuel, soil adsorbent, and activated carbon precursor compared to the newspaper-derived biochar (Chen et al., 2015).

Yuan et al. (2020a) and Wang et al. (2020a) upcycled waste PET plastic bottles into engineered biochar for post-combustion CO2 capture, successfully mitigating two critical environmental issues of plastic pollution and climate change, simultaneously, and this approach was further identified as a closed carbon loop from the life-cycle perspective, which is beneficial to achieve carbon neutrality by 2050 and sustainable plastic management. Rathnayake et al. (2021) studied the properties and environmental applications of biochar produced by co-pyrolyzing biomass and plastic. In their study, spent growing medium and used plastic growing bags were co-pyrolyzed at 550 °C while the plastic content in the feedstock mixture was varied among 0, 0.25, 2.5, 5, and 10%. It showed that increasing the plastic content in the mixture decreased the biochar yield and formation of new surface functional groups such as carboxylate anions, amides, and aromatic groups. Furthermore, all the biochar produced from spent growing medium and plastics did not show any phytotoxicity; however, high phytotoxicity was observed for biochar produced from co-pyrolysis of the bean crop residues with mulching sheets feedstock mixture. Phytotoxicity was significantly reduced after washing the resultant biochar derived from the bean crop residues with mulching sheets feedstock mixture. Similarly, Ro et al. (2014) studied the biochar produced from co-pyrolysis of dewatered swine solids and 10% spent plastic mulch films at 500 °C. There was not any significant difference in surface area and the 1H NMR spectra of dewatered swine solids only biochar and co-pyrolyzed biochar of dewatered swine solids and 10% spent plastic mulch films. The co-pyrolysis of plastic waste with other biomass waste is an environmentally friendly way for treating swine solids and spent plastic mulch films, and co-pyrolyzed biochar can be used in agricultural applications. Li et al. (2021) co-pyrolyzed cyanobacteria and plastics (e.g., polyprene) as a solution for the water crisis. They co-pyrolyzed the biomass and plastic mixture with K2CO3 at different temperatures (e.g., 500–900 °C), and observed that polyprene in the mixture helped to increase the surface area and pore volume of biochar. Furthermore, biochar exhibited increased methylene blue adsorption.

Co-pyrolysis of biomass (rice straw) with plastics (polyprene (PP), polystyrene (PS)) at 550 °C led to an increased carbon content, aromaticity, cation exchange capacity, surface area, and pH of biochar than the rice straw biochar (Oh and Seo, 2016). Furthermore, the co-pyrolyzed biochar showed significantly high sorption of 2,4-dinitrotoluene (DNT) (e.g., 10.3 mg/g) due to high aromaticity and hydrophobicity, and high sorption of Pb (e.g., 62.1 mg/g) due to its high cation exchange capacity, pH, and surface area. Consequently, the study revealed the co-pyrolysis of biomass and plastic is a suitable way to enhance the biochar properties for contaminant sorption. Singh et al. (2021) observed considerable better adsorption of trace metals (e.g., Fe, Ni, Cu, Cr, Cd and Pb) on chars derived from waste plastics of polyethylene (PE), polyethylene terephthalate (PET) and polyvinyl chloride (PVC) compared to the biochar derived from bamboo, sugarcane and neem due to high oxygen content on the surface.

Moreover, the conversion of plastic waste to value added products like carbon nanotubes and other carbon nanomaterials (e.g., porous carbon nanosheets) which can be used in CO2 adsorption and other industrial applications provide useful insights in circular economy (Zhao et al., 2022). For instance, Panahi et al. (2019) studied the production of carbon nanotubes by catalytic supported chemical vapor deposition by passing the gaseous intermediates of pyrolyzed polymers at 800 °C. The properties and yield of carbon nanotubes were affected by the type of catalyst, pretreatment method of catalyst (e.g., acid wash and heating at 800 °C), and type of polymer (e.g., polyethylene terephthalate, polyethylene, polystyrene, and polyprene). Catalytic (e.g., Ni–Fe bimetallic catalyst) pyrolysis of plastic waste which contained polyprene and polyprene effectively produced H2 and carbon nanotubes. Those carbon nanotubes were showed favorable properties such as thermal stability, and high tensile and flexural strength for different industrial applications (Yao et al., 2017).

The environmental consequences of plastics are not completely revealed, however, there are many noticeable long-term impacts on lives on earth. Hence, sustainable upcycling of plastic waste is a vital necessity to slow down the rate of plastic incorporation to environment. Investigations and applications of modern approaches will be provided enormous advantages to overcome environmental threats. Biochar production could be developed as a very sustainable solution to mitigate the plastic waste generation around the world. As discussed above, biochar can be produced by both pyrolysis and co-pyrolysis of plastic wastes. Pyrolysis serves as a viable route for the upcycling of plastics with an advantage of energy recovery along with its simplicity for the production of fuels and gases (Wang et al., 2021b, 2021c). More importantly, the huge labour cost that must be involved in separation of plastics from waste materials can be minimize in pyrolysis. The controlled operational conditions of pyrolysis can reduce secondary pollution. Moreover, char generated by pyrolysis can be activated and used as adsorbent for metal removal, odor, and contaminant removal in wastewater treatment plants (Yuan et al., 2021c; Jamradloedluk and Lertsatitthanakorn, 2014). Several gases such as H2, CO, and CF4 generated by pyrolysis of plastics can also be used as for energy production (Miandad et al., 2019).

5. Conclusions

Plastics are playing a major role in COVID-19 pandemic with the widespread use of protective materials. This environmental issue can pose a significantly greater threat to the human health and ecosystem balance compared to the time before the COVID-19 pandemic. The novel technologies recovering biochar from plastic wastes can be applied as an effective and useful method to remediate not only the environment contaminated with plastic, but also mitigate the environmental issues. Moreover, the technologies need upgrading and proper implementations in large scale to maximize the benefits when treating these plastic wastes as valuable resources from the life-cycle environmental impact.

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.
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