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

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Abstract

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.

Keywords

Plastic pollution; Engineered biochar; Upcycling; Sustainable waste management; Environmental protection

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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[1]. The pandemic has affected the production, usage, disposal, and recycling of plastic products[2]. Personal Protective equipment (PPE) has been increasingly used by public. The disposable PPE (e.g., face masks, gloves, gowns, eye protection and filtering facepiece 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[3]. Early this year, the European Centre for Disease Prevention and Control recommends wearing face masks in areas with community outbreaks to prevent the spread of the virus[4]. It is estimated that 1.6 million tons/day of plastic wastes is being generated worldwide since the outbreak of COVID-19[5]. 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[6]. Approximately 3.4 billion single-use facemasks/face shields are discarded daily around the world[5]. The face mask market is estimated to grow at a rate of over 5% from 2019 to 2025[7]. 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[8]. The center for Disease Control and Prevention recommends using driveway delivery instead of dine-in and avoiding using sharing food containers and other items in restaurants[9]. Some jurisdictions (e.g., Maine, New Hampshire, and Oregon) in the US have reversed or delayed the effective dates of policies to ban polythene bags and single-use packaging materials[6]. Many countries were to temporally postpone the plastic use reduction policies and plastic waste management strategies[10]. Furthermore, use of reusable bags have been discouraged to minimize the infection risks of shop workers by surviving viruses on bag surfaces, owing to that there are evidence of COVID-19 transmission via food, food containers, or food packaging[11,12]. The demand for single-use grocery packaging is expected to rise by 14% in the US due to the pandemic[13]. The market demand for plastic-based food containers made for ready-to-eat, ready-to-heat, and other grab-and-go purposes is expected to be doubled from 2021 to 2025[14]. Regardless of the increase of single-use plastic products, consumer concerns grow over the environmental impact and safety of food and beverage packed and delivered in plastics. The market demand for green-packaging including use of recycled plastic and biodegradable plastic is predicted to increase by 5-7 % during 2021-2026[15,16].

Oil price had reduced due to a lowering demand for oil as a result of the halting of industries and transportation activities during the early stage of the pandemic. This unavoidably led to lower production cost of virgin plastic than recycling plastics[17]. The profit margin for recycling plastics also dropped, discouraging plastic manufacturer to recycle[8]. Pressure on management of plastic waste has been constantly increased due to the surge plastic waste generation during the pandemic. It has disrupted the waste management process ranging from segregation, collection, transport, storage, and recycling, to proper disposal.

1.2. Generation of plastic wastes during COVID-19 pandemic

Plastics had 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[18]. 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[19]. 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[20].

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[21]. Plastics in oceans 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 on or by ingestion of marine debris, of which 92% is plastic waste[22]. The marine organisms that are mostly susceptible to entanglement and ingestion of plastics are sea turtles, marine mammals, and sea birds[23]. Moreover, ingestion of plastics increases the PCBs accumulated in fat tissues and eggs in Great Shearwaters[24]. Sedimentation of plastic debris on the sea floor can disrupt the marine ecosystem, by blocking the gas exchange between sediments and water[25].

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)[26]. The micro and nanoplastics can sorb potentially toxic organic molecules[27–34] and heavy metals in the environment[35–37]. They increase the life time of persistent organic pollutants in the environment[19]. Nanoplastics have the potential to contaminate groundwater via leaching [20,38]. The plastic waste added into the terrestrial environment is 4 to 23 times higher than that in oceans; however, the studies on the effect/fate/transformation of plastics in soil are limited[20,39–41]. 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[42]. Agricultural soils can be contaminated by plastics via plastic mulch, organic amendments such as sewage sludge, and irrigation and flood water[38]. 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[43]. Alarming concentrations of phthalic acid esters have been reported in agricultural and urban soils in China[43,44]. 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[44,45]. Furthermore, micro- and nanoplastics 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[42,46].

Contamination of food web via plastics and additives threatens the terrestrial ecosystem[47]. Plastics can enter food web and cause health effects for animals and humans[48]. Studies revealed that the injected microplastics may cause cellular proliferation, inflammation in tissue, and necrosis and may compromise immune cells in humans and animals[49]. It has been observed that hemocyte aggregation stimulation and respiratory function reduction in blue crabs (*Callinectes sapidus*) were due to plastic microspheres ingested[50]. The injected virgin polyethylene fragments created hepatic stress in Japanese medaka (*Oryzias latipes*)[51]. The health impacts of microplastics in humans and animals depend on the presence, sizes, and frequency of engagement with microplastics[52]. 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[53]. 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[54–58]. Plastics have been found in chicken feces and gizzard[59]. There is direct evidence on transfer of plastics from soil to plants. Li et al.[60] detected microplastics 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 2020-2030, which accounts for 135 million tons of plastic in total, would cost €492 billion~€708 billion[61].

In addition, **Figure 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 colours, toothpastes, and deodorants[62]. For example, the facial cleansers are the most analysed PCCPs so far and they contain more plastic particles than other products[63]. Moreover, it was analysed that 0.05 g/g or 2,450 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 polypropelene (PP), polystyrene (PS) polyvinyl chloride (PVC), acrylonitrile butadiene styrene (ABS) are reported, the polyethylene (PE) is the most abundant, contributing to 93% of the total microplastics[64,65]. PCCPs are considered as one of the main pollution sources in the environment, due to the accumulation of plastics and derived microplastics[66,67]. 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[68].

Thermoplastics and thermoset plastics are main components of PCCPs (Leslie, 2015). The best known in the industry are polyethylene and phthalates that are used as plasticizers[69]. The PCCP industry has had a boom in the market in recent years[70]. By 2018, the Asia Pacific region played a leadership role, encompassing 40% of the production and sale of PCCP, followed by North America (25%)[70]. 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[71]. 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[72].

The social behaviour 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[73]. 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[74] since this industry is one of those that has been constantly resilient during this unexpected pandemic[75].

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[76]. 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[77]. 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[78]. 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[79]. 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[80].

Since the COVID-19, the production of PPEs has expanded for meeting the skyrocketing demand, resulting in dramatic increase of PPE waste. **Figure 2**a 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[81]. 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[82], and in Hong Kong around 7.4 million inhabitants are using single-use masks on a daily basis[83], which has had a negative impact on ecosystems as plastic waste has already been found on beaches, nature trails and the surrounding sea[84]. Moreover, over 1.56 billion face masks will have entered oceans in 2020, suggesting that COVID-19 brought over 4,680 to 6,240 metric tonnes of marine plastic pollution[85].

The case of South Korea got attention when the outbreak of COVID-19 occurred in Daegu, and the Korea Centres 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[86] 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[87], and 20 tons of these hazardous wastes related to the coronavirus was generated per day[88]. 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 hrs or sometimes up to 9 days depending on the plastic material[89]. 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[90].

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[91]. 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[92]. Without concerted efforts to manage/recycle them, worldwide plastic pollution caused by different kinds of daily packaging waste has been intensifying[91,93].

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 polypropylene (PP) and polystyrene (PS)[94], and other studies reaffirmed that PE predominates among these packaging plastic[95,96]. 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[97]. In addition, flexible wrappers, widely used for snacks and other food packaging, are impossible to directly recycle, due to the complex compositions including ethylene acetate vinyl (EVA), ethylene vinyl alcohol (EVOH), high-density and low-density polyethylene (HDPE and LDPE), linear LDPE, PET presented in different combinations[98].

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[99]. Online services and door-to-door deliveries of various items (e.g., cloths, food, bottled water, etc.) have been becoming popular, transforming the consumption behaviours to mainly the online approach. In Bangkok, the daily plastic waste for takeaway food services increased by 20%, reaching 2,000 tons in May 2020, from 12%-13% in the same period of 2019[100]. The market value for food packaging was estimated over 303 billion USD globally in 2019, which is bound to increase remarkably in 2020[101]. In Singapore, inhabitants generated 1,334 tons of plastic packaging waste in a 2-week quarantine; various countries such as the United States, United Kingdom, Australia, and China have relaxed relevant policies and bans on plastic bags and other disposable products[102]. Moreover, some well-known franchise (e.g., Starbucks) have banned the use of reusable cups and other containers[103], to maintain health and safety conditions for their clients.

3. Management strategies of COVID-19 plastic wastes

Owing to the unexpected COVID-19 pandemic, the waste management chains has been significantly destroyed, skyrocketly causing a pressing environmental and potential public health problem[104]. Considering that ubiquitous plastic pollution can spread through the biogeochemical cycle (**Figure 2**b)[105], 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[106,107]. 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[108].

PET, the most widely used plastic packaging material has been used as a binder material of concrete mixture based on its excellent mechanical properties[109,110]. 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[111]. The major drawback of this approach is the mechanical grinding of the substrate to homogenous fraction which incurring high cost and energy consumption so that the mechanical properties of plastics remain uniform[108]. Thermal degradation of plastic wastes into fuels is another prospective way of upcycling plastics. Plastic variants like polystyrene, polyethylene and polypropylene are the targeted petrochemical polymers that can serve as the feedstock for fuel production. PET has been successfully valorized into porous carbons for carbon capture, demonstrating one closed carbon loop[112–115]. It suggests that PET plastic-derived porous carbons could be beneficial for mitigating CO_2 emissions from large point sources like industries, achieving the closed plastic and carbon loops[108]. Moreover, due to the environmental benefits and economic feasibility of converting the industrial-scale waste PET plastic into porous carbons for CO_2 adsorption, Yuan et al.[115] highlighted its potential as a multifunctional alternative to conventional CO_2 absorption and plastic waste management technologies.

In addition, plastic polymers have been attempted for conversion into useful compounds through pyrolysis, gasification of thermal oxidation[116]. Nanda et al.[117] 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[118], and mismanagement of single-used surgical masks has resulted in the generation of a large amount of mask waste. Li et al.[117] 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[119–122]. Nanda et al.[123] 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.[122] 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[106,124].

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[125,126]. 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[127]. Microplastics on account of being carbonaceous in nature serve as a carbon source for carbon-based products such as carbon nanotubes and nanomaterials[128]. 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[129]. Though the upcycling schemes promote reutilization of plastics for production of new products, several factors such as lack of access to reutilization facilities, the complexity, heterogeneity, and diversity of plastics, limited markets for the upcycled products, mass awareness, and inadequate technology improvements lead to a slow transformation rate. Scientific research and investigation in this field has the potential to promote progresses in sectors of environment, energy, health, pharmaceuticals, and material science that could further transform and revolutionize waste reutilization and management.

In addition, a shift in waste management practices is urgently needed to fully achieve zero-plastic pollution, which requires governments, researchers and industries collaborate towards intelligent design and sustainable upcycling[130]. You et al.[118] clearly highlighted that the design and analysis of sustainable waste management chains (such as upcycling) should be prioritized. Yuan et al[130] reported that with concerted efforts from industries, and financial and policy support from governments, the novel upcycling technologies could be upscaled for commercial applications, promoting net zero development. Martin et al.[131] suggested that social awareness, policies, and plastic waste processing were three pillars toward a paradigm shift in the plastic economy. Korley et al.[132] reported that it was vital to integrate technological considerations, equity analysis, consumer behavior, geographical demands, policy reform, life-cycle assessment, infrastructure alignment, and supply chain partnerships to achieve a more sustainable future of plastic-related society.

3.2. **Incineration**

Incineration is controlled burning of waste in the presence of oxygen to produce ash, flue gas and energy (electricity and/or heat)[133]. The advantages of incineration include significant reductions in waste mass (e.g., by 90%) and recovery energy[134,135]. From the energy recovery perspective, the incineration of plastic waste generates revenues, and also produces more than three times more energy when compared to other materials[136]. Incineration with energy recovery accounts for a large proportion of waste management in many developed and developing countries.

However, the incineration of plastic-based materials like polyvinyl chloride (PVC) generates various toxic chlorinated compounds (e.g., polychlorinated dibenzo-p-dioxins, polychlorinated dibenzofurans) and emissions including carbon dioxide, carbon monoxide, sulfur oxides, nitrogen oxides, ammonia, hydrocarbons, and organic acids[137,138]. In addition, it can produce microplastics due to the complexity of plastic waste composition and the variability of incineration process[139]. The generation of polyaromatic hydrocarbons during incineration could pose a risk on the human and natural environments if the incineration process is not properly controlled and monitored [140]. Additionally, it was shown that low temperature pyrolysis combined with mechanical recycling of plastic waste results in a reduction of the carbon footprint of plastic landfilling by 67% and by 76% compared to plastic incineration[141].

4. Biochar production from plastic wastes

As summarized in **Table 2**, pyrolysis and co-pyrolysis of plastic waste is one of the environmentally friendly ways for transforming plastic waste into value-added products [142]. Research evidences revealed that co-pyrolysis of biomass and plastic wastes exhibited high production of bio-oil and low production biochar [143,144]. 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 [145]. 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[146]. Similarly, Chen et al.[147] observed negative synergistic effects on biochar production in 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 [147].

Yuan et al.[112] and Wang et al.[113] upcycled waste PET plastic bottles into engineered biochar for post-combustion CO_2 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. [148] 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. [149] 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 ^{1}H 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. [150] co-pyrolyzed cyanobacteria and plastics (e.g., polypropylene) as a solution for the water crisis. They co-pyrolyzed the biomass and plastic mixture with K_2CO_3 at different temperatures (e.g., 500-900 °C), and observed that polypropylene 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 (polypropylene (PP), polyethylene (PE), or 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[151]. 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.[152] 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 CO_2 adsorption and other industrial applications provide useful insights in circular economy[153]. For instance, Panahi et al.[154] 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 polypropylene). Catalytic (e.g., Ni-Fe bimetallic catalyst) pyrolysis of plastic waste which contained polyethylene and polypropylene effectively produced H_2 and carbon nanotubes. Those carbon nanotubes were showed favorable properties such as thermal stability, and high tensile and flexural strength for different industrial applications[155].

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 [156,157]. 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 pollutions. Moreover, char generated by pyrolysis can be activated and used as adsorbent for metal removal, odor, and contaminant removal in wastewater treatment plants[158,159]. Several gases such as H_2, CO, and CF_4 generated by pyrolysis of plastics can also be used as for energy production[160].

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.

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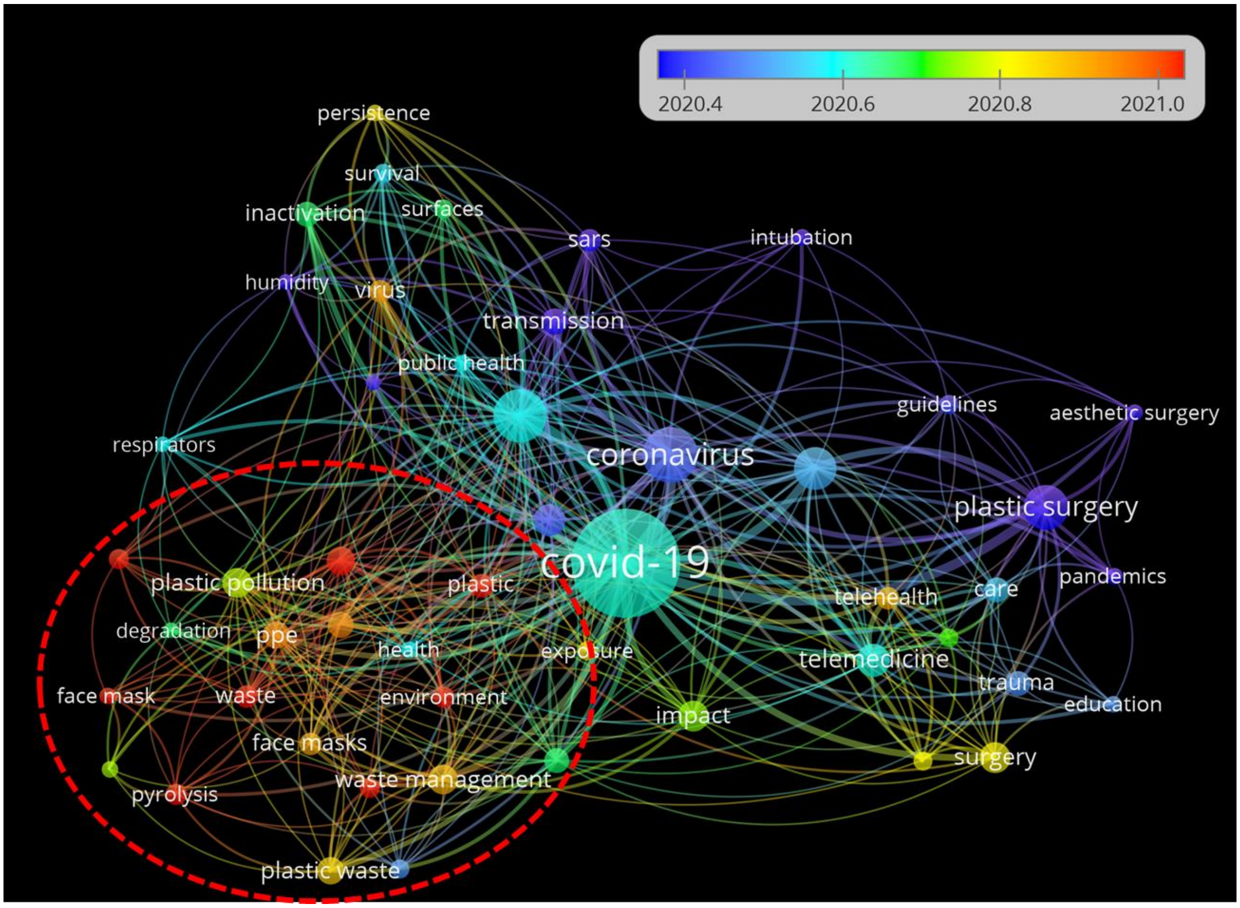

Figure 1. *Scientometric visualization of the top 50 keywords of all peer-reviewed publications released last 2 years. Total 507 publications were retrieved from Web of Science with "COVID-19" and "plastic" as the searching keywords (topic), and the database was selected as the "Web of Science Core Collection". Collected data were analyzed using the built-in function of co-occurrence of all keywords, being plotted in "Network visualization", "overlay visualization (year)", and "density visualization" in VOSviewer. Each circle stands for a keyword while its size represents the number of times that a pair of keywords have co-occurred in publications. The legend with different colors stands for the average year of the occurrence of each keyword.*

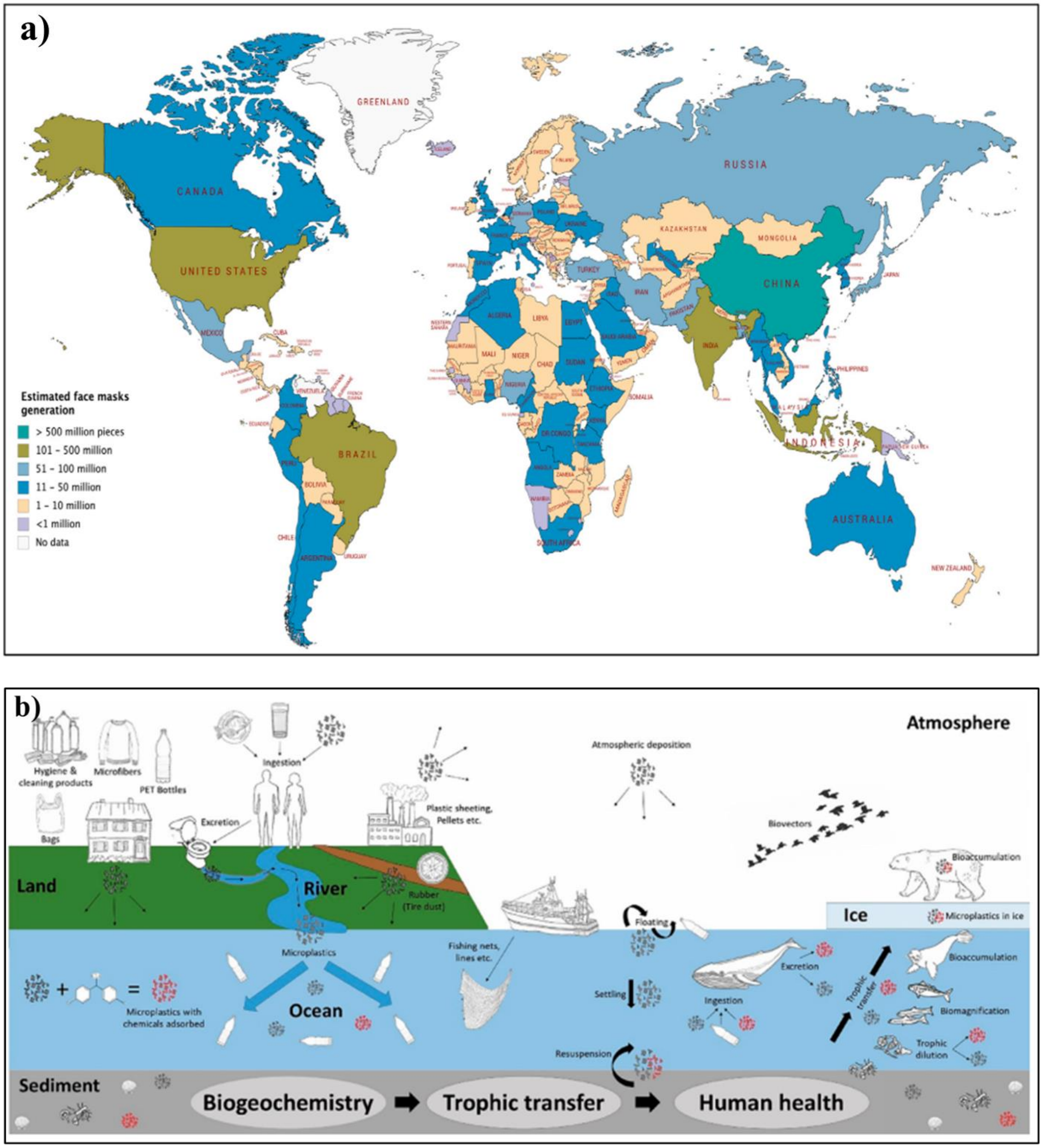

***Figure 2**. a) Estimated global share of face masks discarded as COVID-waste generated from a given country[5], b) Conceptual model of the plastic pollution cycle and the interactions between biogeochemistry, trophic transfer, and human health and exposure[105].*

Table 1. *Estimated daily COVID-19 facemasks and global plastic waste generation by country prior to management*[5].

Rank	Country	Population[a]	Urban population (%)[a]	Facemask acceptance rate by population (%)[b]	Average facemask per capita per day[b]	Estimated daily facemask discarded	Total estimated plastic waste (tonnes)
1	China	1,439,323,776	61	80	1	702,390,002	107,949,283.20
2	India	1,380,004,385	35	80	1	386,401,228	103,500,328.90
3	United States	331,002,651	83	80	1	219,785,760	24,825,198.80
4	Brazil	212,559,417	88	75	1	140,289,215	15,941,956.30
5	Indonesia	273,523,615	56	80	1	122,538,579	20,514,271.10
6	Japan	126,476,461	92	80	1	93,086,675	9,485,734.58
7	Russia	145,934,462	74	80	1	86,393,201	10,945,084.70
8	Mexico	128,932,753	84	75	1	81,227,634	9,669,956.48
9	Nigeria	206,139,589	52	70	1	75,034,810	15,460,469.20
10	Pakistan	220,892,340	35	80	1	61,849,855	16,566,925.50
11	Bangladesh	164,689,383	39	80	1	51,383,087	12,351,703.70
12	Turkey	84,339,067	76	80	1	51,278,153	6,325,430.03
13	Iran	83,992,949	76	80	1	51,067,713	6,299,471.18
14	Germany	83,783,942	76	80	1	50,940,637	6,283,795.65
15	United Kingdom	67,886,011	83	80	1	45,076,311	5,091,450.83
16	France	65,273,511	82	80	1	42,819,423	4,895,513.33
17	Philippines	109,581,078	47	80	1	41,202,485	8,218,580.85
18	South Korea	51,269,185	82	80	1	33,632,585	3,845,188.88
19	Italy	60,461,826	69	80	1	33,374,928	4,534,636.95
20	Argentina	45,195,774	93	75	1	31,524,052	3,389,683.05
21	Egypt	102,334,404	43	70	1	30,802,655	7,675,080.30
22	Colombia	50,882,891	80	75	1	30,529,735	3,816,216.83
23	Spain	46,754,778	80	80	1	29,923,058	3,506,608.35
24	Vietnam	97,338,579	38	80	1	29,590,928	7,300,393.43
25	DR Congo	89,561,403	46	70	1	28,838,772	6,717,105.23
26	Thailand	69,799,978	51	80	1	28,478,391	5,234,998.35

27	South Africa	59,308,690	67	70	1	27,815,775	4,448,151.75
28	Canada	37,742,154	81	80	1	24,456,916	2,830,661.55
29	Ukraine	43,773,762	69	80	1	24,141,037	3,280,032.15
30	Iraq	40,222,493	73	80	1	23,489,935	3,046,686.98
31	Saudi Arabia	34,813,871	84	80	1	23,394,921	2,611,040.33
32	Algeria	43,851,044	73	70	1	22,407,883	3,288,828.30
33	Malaysia	32,365,999	78	80	1	20,196,383	2,427,449.93
34	Peru	32,971,854	79	75	1	19,535,824	2,472,889.05
35	Poland	37,746,611	60	80	1	18,166,373	2,838,495.83

[a] Data retrieved from https://www.worldometers.info/population/ on June 02, 2020.

[b] Hypothetical data.

Table 2. *Sustainable plastic management for environmental protection and energy conversion and storage*

Refs	Plastic types	Conversions	Applications for produced biochar
Hao et al.[161]	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/m^2 under 1 kw/m^2, 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.
Li et al.[162]	PP	Pyrolysis together with cyanobacteria using K_2CO_3	**Methylene blue sorption**: The composite carbon with specific surface area of 2,811 m^2/g displayed a excellent methylene blue adsorption capacity of 490 mg/g, providing a new strategy to upcycle plastic in high quality composite materials.
Zhang et al.[163]	PVC	One-step pyrolysis with KOH and biomass	**Toluene sorption**: The toluene sorption capacity reached 263.4 mg/g, and the mixture of PVC and biomass was beneficial to increase the surface area of porous carbon prepared in this research.
Yuan et al.[164]	PET	Carbonization followed by KOH activation	**CF_4 capture**: PET-K(2)-700 gave the high CF_4 adsorption performance of 2.43 mmol/g at 25 °C and 1 bar, exhibiting a great potential to mitigate CF_4 emission from semiconductor industries.
Yuan et al.[112]	PET	Carbonization followed by KOH or NaOH activation	**CO_2 capture**: PET-KOH-973, activated with KOH at 700 °C, demonstrated excellent CO_2 adsorption capacity of 4.42 mmol/g at 25 °C and 1 bar. Moreover, it exhibited good CO_2 selectivity over N_2, low energy consumption for sample regeneration, etc., suggesting that PET-to-CO_2 adsorbent route is suitable for practical CO_2 capture.
Yuan et al.[114]	PET	Carbonization followed by one-pot modification	**CO_2 capture**: $PET6KN_{one\text{-}pot}$, prepared by KOH activation and urea treatment in a one-pot synthesis at 700 °C, displayed excellent CO_2 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.
Yuan et al.[115]	PET	Carbonization followed by CO_2 physical activation, KOH	**CO_2 capture:** PET6-CO_2-9, activated in CO_2 atmosphere, showed excellent CO_2 uptakes of 6.25 mmol/g at 0 °C and 3.63 mmol/g at 25 °C (1

		chemical activation, or KOH/Urea activation	bar). Based on techno-economic and life-cycle assessments of the scaled-up industrial processes, authors showed that the physical CO_2 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 CO_2 absorption and plastic waste management technologies.
Zhang et al.[165]	LDPE	Carbonization followed by KOH activation	**Energy storage**: The hierarchical porous carbon with specific surface area of 3,059 m^2/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.
Mir et al.[166]	PP	Carbonization using MoO_3 and Mg	**Energy storage**: The synthesized sample displayed excellent double layer capacitance and specific capacitance to the tune of 19.46 mF/cm^2 and 55.6 F/g, respectively.
Liu et al.[167]	PP	Carbonization using Fe_7S_8	**Energy storage**: The activated carbon nanosheet (specific surface area of 3,200 m^2/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 225W/kg, verifying this route as a good reference for upycling plastic waste into energy storage materials.
Min et al.[168]	PS	Carbonization using MgO and $KMnO_4$, separately	**Energy storage**: PCF-MnO_2 (surface area of 1,087 m^2/g) exhibits good electrochemical properties as electrode in supercapacitor, reaching ultrahigh capacitance of 308 F/g at 1 mV/s and 247 F/g at 1 A/g in LiCl electrolyte, and excellent cycle stability.
Min et al.[168]	Mixture of PP, PS, PE, PVC	Carbonization using MgO/Fe(acac)$_3$ template	**Energy storage**: The 3D hollow carbon sphere/porous carbon flake hybrid nanostructure prepared from mixed plastic waste exhibited excellent performance in Li-ion batteries of 802 mAh/g after 500 cycles at 0.5 A/g, presenting a new avenue to upcycle plastic waste into value-added carbon materials.