Since January 2020 Elsevier has created a COVID-19 resource centre with free information in English and Mandarin on the novel coronavirus COVID-19. The COVID-19 resource centre is hosted on Elsevier Connect, the company's public news and information website.

Elsevier hereby grants permission to make all its COVID-19-related research that is available on the COVID-19 resource centre - including this research content - immediately available in PubMed Central and other publicly funded repositories, such as the WHO COVID database with rights for unrestricted research re-use and analyses in any form or by any means with acknowledgement of the original source. These permissions are granted for free by Elsevier for as long as the COVID-19 resource centre remains active.
Research Paper

High-value utilization of mask and heavy fraction of bio-oil: From hazardous waste to biochar, bio-oil, and graphene films

Zejun Luo a, Xiefei Zhu a, Jingjing Deng a, Ke Gong b, Xifeng Zhu a,∗

a School of Engineering Science, University of Science and Technology of China, 96 Jinzhai Road, Hefei, Anhui 230026, PR China
b Hefei National Laboratory for Physical Sciences at the Microscale, University of Science and Technology of China, 96 Jinzhai Road, Hefei, Anhui 230026, PR China

ARTICLE INFO

Editor: Prof. G. Lyberatos

Keywords:
Mask
Heavy fraction of bio-oil
Biochar
Bio-oil
Three-dimensional graphene films

ABSTRACT

At present, it is very common to wear mask outdoors in order to avoid coronavirus disease 19 (COVID-19) infection. However, this leads to the formation of numerous plastic wastes that threaten humans and ecosystem. Against this major background, a novel co-pyrolysis coupled chemical vapor deposition (CVD) strategy is proposed to systematically convert mask and heavy fraction of bio-oil (HB) into biochar, bio-oil, and three-dimensional graphene films (3DGFs) is proposed. The biochar exhibits high higher heating value (HHV) (33.22–33.75 MJ/kg) and low ash content (2.34%), which is obviously superior to that of the walnut shell and anthracite coal. The bio-oil contains rich aromatic components, such as 1,2-dimethylbenzene and 2-methylnaphthalene, which can be used as chemical feedstock for insecticides. Furthermore, the 3DGF has a wide range of applications in the fields of oil spill cleanup and oil/water separation according to its fire resistance, high absorbability (40–89 g g−1) and long-term cycling stability. This research sheds new light on converting plastic wastes and industrial by-products into high added-value chemicals.

1. Introduction

COVID-19 has become one of the most serious pandemics today, resulting in high incidence of pneumonia, acute respiratory distress syndrome, and death (Lakas et al., 2020; Trump et al., 2020). It is under this background that the explosive growth of prevent SARS-CoV-2 infection (Freud et al., 2020; Konda et al., 2020). However, it will lead to the subsequent generation of numerous plastic wastes that threaten humans and ecosystem (Huang et al., 2020a, 2020b). Recently, thermochemical transformation methods such as incineration and pyrolysis offer a reliable processing path for plastic waste (Jie et al., 2020; Wong et al., 2015). Among them, incineration of mask is a common practice, but there are technical problems with air pollution controls (APCs) (Makarichi et al., 2018). Once the stoichiometric ratio of mask to oxygen is not adjusted accurately, it will lead to the formation of highly toxic substances such as dioxins, polycyclic aromatic hydrocarbons, and dust (Zhao and Wang, 2018).

Compared with direct combustion, pyrolysis of mask in an inert atmosphere has the advantages of simple treatment and less pollutants (Burra and Gupta, 2018; Panda, 2018). Jung et al. (2021) reported that mask is mainly consisting of polypropylene (PP), polyethylene (PE), and nylon, which can be used to produce syngas and C1−2 hydrocarbons (HCs). Based on our previous works in HB, we found that the practical applications of HB are seriously hampered due to its high viscosity, strong corrosive, and complex composition, which can be regarded as a special industrial waste (Luo et al., 2020). Recently, co-pyrolysis technologies have been successfully applied to upgrade biomass/bio-oil, where biomass/bio-oil is mixed by two or more different materials and then pyrolyzed in an inert atmosphere, decomposing the feedstock into biochar, bio-oil, and permanent gas. Wang et al. (2019) found that co-pyrolysis of bamboo sawdust and waste tire was more conducive to form aromatic hydrocarbons. Ma et al. (2018a, 2018b) confirmed that the yield of bio-oil can be significantly improved by adding kitchen waste oil into raw bio-oil. Inspired by different co-pyrolysis technologies (Diao et al., 2021; Zhu et al., 2018), we report a low-cost and eco-friendly strategy to dispose of HB and mask. HB is a hydrogen-poor material with a low H/C effective (0.36) ratio, which inhibits the formation of aromatics and olefins in the hydrocarbon pool to some extent (Luo et al., 2021). The mask contains a plastic polymer with high H/C effective ratio such as PE (2.67), which can be used as a hydrogen supplier for biomass upgrading to obtain alkanes (Zhang et al., 2016).
Therefore, an addition of mask into HB can increase the average H/C effective ratio of feedstocks, which is conducive to obtain aromatic-rich bio-oil.

Previous studies on upgrading of HB have focused on obtaining high quality bio-oil but ignore the application of biochar and gaseous products (Duan et al., 2017; Zhang et al., 2018). In fact, biochar can be used as a substitute for commercial coal due to its high higher heating value (HHV) (Ghodake et al., 2021). The gaseous product is a mixture (e.g., CH₄, H₂, CO and CO₂) with high HHV, which has broad application prospects in fuel (Diao et al., 2020). However, the low conversion efficiency accompanied by the complex gas purification process seems avoidless. Inspired by graphene catalytic chemical vapor deposition (CVD) synthesis methods (Chen et al., 2011; Huang et al., 2020a, 2020b), we proposed a new method to produce high-quality three-dimensional graphene films (3DGFs) using gaseous product from co-pyrolysis of HB and mask. Up to now, there are two reasons to limit the large-scale synthesis of graphene by catalytic CVD method: (1) Expensive cost due to the vast use of high purity H₂, CH₄, C₂H₂ or other pure chemicals; (2) Equipment potential security issues because of high pressure (Tsai et al., 2009; Zhang et al., 2020a, 2020b). In this paper, the raw materials are derived from industrial by-product and plastic waste and have a lower cost. In addition, the CVD process does not require pressure treatment (atmospheric-pressure), which reduces the potential security hazards or risks.

Herein, we propose a sustainable approach to simultaneously produce high HHV biochar, aromatic-rich bio-oil and high-quality 3DGFs from HB and mask. The HHV of biochar, chemical composition of bio-oil and thickness of 3DGFs can be easily adjusted by controlling the pyrolysis temperature. Specifically, the biochar has a great potential in the field of fuel because of its high HHV (33.75 MJ/kg) and low ash content (2.34%). The bio-oil contains a series of aromatic compounds such as 1,2-dimethylbenzene and 2-methylnaphthalene, which has broad application prospects in pharmaceutical, agricultural, and chemical industry. The 3DGF₂₀₀ has a broad application prospects in the fields of oil spill cleanup and oil/water separation by virtue of its fire-resistant, high absorption capacity (40–89 g g⁻¹) and excellent reusability. The route of systematically converting HB and mask into high added-value products broadens a new horizon in exploring large-scale disposal of industrial by-product and plastic waste.

2. Experimental details

2.1. Materials and reagents

HB was obtained from the liquid products recovered at 120 °C condensing temperature in the pilot plant of biomass pyrolysis liquefaction (500–550 °C) (Ma et al., 2018a, 2018b; Wang et al., 2020). Disposable surgical masks (>95% bacterial filtration efficiency) were purchased from a pharmacy store in Hefei, China. The methanol solvent and other chemicals, such as hydrochloric acid (HCl), NaOH, molecular sieves and desiccant were purchased from Sinopharm Chemical Reagent Co., Ltd. (Shanghai, China). All the above chemicals were used as reserved without further purification.

2.2. Preparation of biochar, bio-oil, and Ni/GF composites

Prior to use, mask was cut into small pieces and dried at 105 °C for 24 h. The sample was first obtained by adding 0.5 g mask and 5 g HB into 10 ml methanol solvent, then the sample was moved to a 105 °C oven for 24 h to remove solvent. The experiment process was divided into three parts: Part 1 (fast co-pyrolysis), Part 2 (bio-oil collection and gas purification), Part 3 (atmospheric-pressure CVD (APCVD)) (Fig. 1). In fast co-pyrolysis process, the sample was pyrolyzed into biochar and vapor/gas mixture (including condensable vapor and non-condensable gas) at different temperatures (700, 800 and 900 °C). The condensable vapor was rapidly cooled to produce bio-oil by the thermostatic circulator (condensing temperature: 0 °C). The non-condensable gas passed through a series of gas purification devices, mainly consisting of anti-suction device, 6 M KOH, molecular sieve, and desiccant. After that, the purified gas was deposited onto the catalyst substrate (nickel foam) in a CVD tube furnace at 950 °C for 15 min under atmospheric pressure. Finally, the sample substrate was rapidly cooled by moving heating zone to obtain Ni/GF composites.

Furthermore, the size of Ni/GF composites could be easily adjusted by using nickel foam substrates with different specifications (from 10 mm × 10 to 40 mm × 40 mm). It is worth noting that the size of nickel foam substrate was increased by 4 × , the as-prepared material still had high quality (Fig. 1).

2.3. Synthesis of 3DGFs

To obtain 3DGFs, Ni/GF composites were placed in 3 M HCl aqueous

Fig. 1. Schematic illustration of the synthesis of high HHV biochar, aromatic-rich bio-oil, and high-quality 3DGFs from HB and mask.
solution at room temperature for 24 h to completely etch the nickel foam substrate. The product was filtered off and placed in an oven at 105 °C for 24 h after washing. According to different co-pyrolysis temperatures, biochar was named as Biochar700, Biochar800 and Biochar900, respectively. Bio-oil was termed as Bio-oil700, Bio-oil800 and Bio-oil900, respectively. 3DGFs was labeled as 3DGFL700, 3DGFL800 and 3DGFL900, respectively. Notably, compared to using only HB or mask as initial feedstock, the mixed samples (HB and mask) have highest graphene yields and best quality (block rather than powder) (Fig. S1).

2.4. Material characterization

The proximate analysis of HB and mask was as performed based on Standard GB/T 28731-2012. Carbon (C), hydrogen (H) and nitrogen (N) contents of sample were characterized by an Elementary VarioEL-III elemental analyzer. The oxygen (O) content was determined by difference. The HHV of sample was calculated from the Channiwala and Parikh formula: HHV (MJ/kg) = 0.3491[C] + 1.1783[H] – 0.1034 [O] – 0.0151[N] – 0.0211[Ash] (Channiwala and Parikh, 2002). Thermogravimetric analysis (TGA) has been employed to study the combustion behavior of sample. In a typical test, the sample was heated to 1000 °C in air atmosphere at 20 °C/min heating rate. Furthermore, the influence of temperature on the fire-resistant quality of 3DGFL800 was tested as follows: 3DGFL800 was first heated to the desired temperature (650, 700 and 750 °C) at 20 °C/min heating rate in nitrogen (N2) condition, and then the sample was held isothermally for 100 min under air atmosphere. HB and bio-oil were analyzed by gas chromatography/mass spectrometer (Trace DSQII, Thermo Scientific, USA) with a TG-5MS capillary column (30 m × 0.25 mm i.d. × 0.25 μm film thickness). The surface morphologies of 3DGFs were observed by field-emission scanning electron microscopy (SEM) (Sirion200, FEI Electron Optics) and field emission-transmission electron microscopy (TEM) (JEM-2100F, Japan Electronics) with HRTEM. Raman spectra were obtained from a 769G05 laser Raman spectrometer (UK). X-ray photoelectron spectroscopy (XPS, Thermo ESCALAB 250, USA) was used to analyze the surface functional groups of samples. X-ray diffraction (XRD) measurements were carried out using a D8 ADVANCE A25 X-ray powder diffractometer (Germany) with Cu Kα radiation from 2θ = 10–80.

2.5. Organic solvent and oil absorption measurements

3DGFL800 was soaked in the solvent (n-hexane, acetone, ethanol, HB, methylbenzene, dichloromethane, or pump oil) for 10 min to measure the saturation absorption capacity. The sample containing organic solvent and oil was weighed after no dropping, and the saturation absorption capacity (Q) was calculated by the follow equation:

\[ Q = \frac{m_r - m_s}{m_s} \times 100\% \]  

(1)

where \( m_s \) represents the mass (mg) after adsorption, \( m_r \) implies the mass (mg) before adsorption.

The recycle performance of 3DGFL800 was evaluated by extrusion and combustion methods, respectively. For extrusion method, 3DGFL800 was first compressed with a self-made extrusion device (Fig. S2). After that, the sample was soaked in n-hexane for 10 min. Finally, the n-hexane was completely removed by squeezing the sample. For combustion method, the sample containing n-hexane was combusted by using an alcohol lamp to eliminate the adsorbed organic solvent. All the absorption extrusion/combustion cycles were conducted 10 times. The saturation absorption capacity (Q) in each experiment was acquired according to Eq. (1).

3. Results and discussions

The detailed procedure for the preparation of high HHV biochar, aromatic-rich bio-oil and high-quality 3DGFs from HB and mask is shown in Fig. 1. The method involves mixing of HB into mask, followed by heating to obtain biochar and vapor/gas mixture, Condensate to prepare bio-oil, CVD growth of the graphene layers, and finally the removal of the Ni foam substrate.

3.1. Ultimate analysis, HHV and combustion behavior of biochar

The ultimate analysis (Table 1 and Table S1) indicates that biochar has a higher carbon content (91.25–93.37 wt%) than HB (51.12 wt%), mask (85.46 wt%), anthracite coal (83.25 wt%) and walnut shell (51.12 wt%). Meanwhile, the HHV of biochar (33.22–33.75 MJ/kg) is higher than the above four feedstocks (HB (19.50 MJ/kg), mask (31.48 MJ/kg), anthracite coal (30.63 MJ/kg) and walnut shell (19.47 MJ/kg)). Thermogravimetric analysis (TGA) has been applied to evaluate the combustion behavior of biochar, anthracite coal, and walnut shell (Fig. 2). As the co-pyrolysis temperature increasing, the thermogravimetric and maximum weight loss rate curves gradually shift to the high temperature zone. Compared with walnut shell combustion behavior, mainly consisting of volatiles evaporation stage and fixed carbon burning phase, biochar and anthracite coal have only fixed carbon burning phase. In addition, the ash content of biochar (2.34%) is between walnut shell (1.22%) and anthracite coal (8.83%), which is conducive to the subsequent cleaning of the combustion device. All results indicate that the as-obtained biochar can be used as a potential alternative to anthracite coal.

3.2. Chemical compounds of bio-oil

The chemical compounds of HB and bio-oil were studied by GC-MS (Fig. 3), and all chemical compounds in HB, bio-oil700, bio-oil800, and bio-oil900 are listed in Tables S2. The results show HB contains a series of oxygenated monomers including phenolic compounds, such as phenol, o-cresol, guaiacol, and 2-methoxy-4-methylphenol. The concentrations of aromatics in bio-oil depicted an increasing trend accompanied by a simultaneous decrease in phenols with the temperature rising, which might be due to the decomposition, radical recombination and polymerization reactions intensified at high temperatures (Wu et al., 2017). The obtained bio-oil has broad application prospects in pharmaceutical, agricultural, and chemical industry by virtue of its relatively rich aromatic components, such as 1,2-dimethylenzene and 2,4-dimethyphenol, which can be used as chemical feedstock for insecticides.

3.3. Physicochemical property of 3DGFs

3.3.1. Surface morphologies of 3DGFs

The field-emission scanning electron microscopy (SEM) in Fig. 4(a-c) show that 3DGFs have a 3D network without significant cracks or collapse after removing the Ni foam substrate. Fig. 4(d) indicates that 3DGFs consists of numerous interconnected pores, which provides a large surface area and volume for its practical application in the fields of oil spill cleanup and oil/water separation. Only a strong carbon signal

| Sample       | Ultimate analysis wt% | HHV (MJ/kg) |
|--------------|-----------------------|-------------|
|              | C    | H    | N    | O    |         |
| Biochar700   | 91.25 | 1.71 | 1.33 | 5.71 | 33.22   |
| Biochar800   | 92.37 | 1.59 | 1.32 | 4.72 | 33.57   |
| Biochar900   | 93.37 | 1.39 | 1.19 | 4.05 | 33.75   |
| Anthracite coal | 83.25 | 2.66 | 0.92 | 13.17 | 30.63   |
| Walnut shell | 51.12 | 5.21 | 0.29 | 43.38 | 19.47   |
(99.8 at%) and a weak oxygen signal (0.2 at%) are detected by energy-dispersive spectroscopy (EDS) (Fig. 4(e)), indicating a shortage of defects in 3DGFs. Field emission-transmission electron microscopy (TEM) shows large ultrathin graphene sheets with high transparency in 3DGFs (Fig. 4(f-h)). The insets in Fig. 4(f-h) depict that the selected area electron diffraction (SAED) pattern show a hexagonal array of spots. High-resolution TEM (HRTEM) images in Fig. 4(i-k) display that the 3DGFs is composed of few-layers graphene sheets (4–30 layers). These results all indicate that the APCVD growth method has successfully obtained high-quality graphene sheets. In addition, compared with previous literature reports (Chen et al., 2011; Leong et al., 2019), the template-removal process does not require poly (methyl methacrylate) (PMMA) or paraffin support layer, which not only simplifies the technical process, but also avoids the introduction of unnecessary impurities.

3.3.2. Chemical composition and purity of 3DGFs

Fig. 5(a) depicts the 3DGF800 is lightweight with a density of 16.46 mg cm\(^{-3}\), which is superior or at least comparable to other graphite foams (5–20 mg cm\(^{-3}\)) grown on commercial Ni foams that have been reported previously (Chen et al., 2011; Ji et al., 2012). The 3DGF800 shows good flexibility and can be bent without significant breaking or cracking (Fig. 5(b)). It was found that the water contact angle of 3DGF800 is up to 104° (Fig. 5(c)), demonstrating its hydrophobic nature (Zhang et al., 2020a, 2020b), which is conducive to selective adsorption of oil or other organic solvents from water. The Raman spectra (Fig. 5(d)) show only two visible peaks at 1580 cm\(^{-1}\) (G-band, assigned to graphitic in-plane sp\(^2\) carbons) and 2715 cm\(^{-1}\) (2D-band, corresponded to multi-layer graphene) (Algozeeb et al., 2020), indicating that the graphene sheets have a high quality. As shown in Fig. 5(e), only a strong C1s peak (96.43–97.66 at%) and a weak O1s peak (2.34–3.57 at%) are detected by XPS spectrum, which confirms the graphene structure of 3DGFs. In addition, XRD patterns (Fig. 5(f)) of 3DGFs present two obvious diffraction peaks observed at 26.4° (002 planes of graphite) and 54.5° (004 planes of graphite) (Huang et al., 2020a, 2020b), revealing a pure graphene foam without any residues from the Ni foam substrate.
Fig. 4. The SEM images of the (a) 3DGF$_{700}$, (b) 3DGF$_{800}$, and (c) 3DGF$_{900}$ after etching the nickel foam; (d–e) FESEM image and corresponding EDS mappings of 3DGF$_{800}$. TEM image of the thin graphene sheets in (f) 3DGF$_{700}$, (j) 3DGF$_{800}$, and (b) 3DGF$_{900}$. The inset is the corresponding SAED pattern; HRTEM images of 3DGFS with different numbers of layers (i: 4 layers; g: 8 layers; k: 30 layers).

Fig. 5. Photographs of (a) ultralight and (b) flexible 3DGF$_{800}$ (ca. 40 mm × 40 mm). (c) Water contact angle of 3DGF$_{800}$. (d) Raman spectra, (e) high-resolution XPS spectrum, and (f) XRD patterns of 3DGFS.
Fig. 6(a–c) display the photographs for 3DGF$_{800}$ on an ethanol flame for different times. The shape of the 3DGF$_{800}$ is well maintained even combustion in air for 120 s, which are related to the anisotropic thermal properties and oxygen insulating ability of the 3DGF$_{800}$. The combustion behavior of 3DGF$_{800}$ was evaluated by using a thermogravimetric analysis instrument. As can be seen in Fig. 6(d), the 3DGF$_{800}$ shows a $T_{10}$ (the temperature of 10% decomposition) of 730–758 $^\circ$C. This value is also much higher than that of polymer (Yang et al., 2015), metallic oxide (Wicklein et al., 2015), metal hydroxide based flame-retardant materials (Lazar et al., 2020) and their composites (Lazar et al., 2020). The residual weight percentage of 3DGFs at a temperature of up to 1000 $^\circ$C in air is still maintained in the range 9.8–12.8%. Furthermore, the thermal stability of 3DGF$_{800}$ was also measured at different temperatures (650, 700 and 750 $^\circ$C) under air atmosphere (Fig. 6(e)). As the combustion temperature increases, the burning-out time gradually decreases. It is worth noting that the burning-out time of 3DGF$_{800}$ still takes 18 min even at 750 $^\circ$C, showing excellent fire-resistance and suitable for some flame-retardant applications.

3.3.3. Organic solvent and oil absorption capacity of 3DGF$_{800}$

The adsorption capacities (Q) of 3DGF$_{800}$ for various organic solvents and oils is shown in Fig. 6(f). The 3DGF$_{800}$ exhibited excellent adsorption performance against diverse organic liquids and oils with the adsorption capacity in the range of 40–89 g g$^{-1}$. In actual use, the high absorption capacity not only depends on the light weight, porosity, and hydrophobicity of 3DGF$_{800}$, but also relies on the density, surface tension, and viscosity of adsorbate. The adsorption performance of various graphene-based absorbents for different absorbates is listed.

As critical parameters, Fig. 6(g) records the recyclability of 3DGF$_{800}$ for adsorbed n-hexane by extrusion method. The maximum absorption capacity for n-hexane can reach 10 times its own weight (10 g g$^{-1}$ for gravimetric absorption capacity) and slightly changed after 10 adsorption-extrusion cycles, demonstrating its stable adsorption capacity of this 3DGF$_{800}$ in repeated adsorption. In addition, combined with the fire resistance of 3DGF$_{800}$, the combustion method is another alternative to remove the adsorbed n-hexane. As shown in Fig. 6(h), the 3DGF$_{800}$ has an excellent maximum absorption capacity up to 40 g g$^{-1}$ for n-hexane. It is worth noting that the n-hexane can be easily removed by burning 3DGF$_{800}$ on the external flame of the alcohol lamp. 3DGF$_{800}$
can still maintain an excellent adsorption capacity of 38 g g\(^{-1}\) after 10 adsorption-combustion cycles, highlighting the good recyclability. There are no significant differences in HRTEM (Fig. 6 (i) and Fig. S3) images before and after combustion of absorbed n-hexane, indicating the excellent thermal and chemical stability of 3DGF\(_{800}\). These results indicate that 3DGF\(_{800}\) has a broad application prospects in the fields of oil spill cleanup and oil/water separation by virtue of its high absorption capacity and excellent reusability.

4. Conclusion

A low-cost and eco-friendly strategy is proposed to produce high HHV biochar, aromatic-rich bio-oil and high-quality 3DFGs from HB and disposable surgical mask simultaneously. The biochar has a significantly high HHV (33.22–33.75 MJ/kg) and low ash content (2.34%), which can be used as a potential alternative to the anthracite coal. The bio-oil contains a series of aromatics compounds such as 1,2-dimethylbenzene and 2-methylphenanthrene, which has broad application prospects in pharmaceutical, agricultural, and chemical industry. The 3DGF\(_{800}\) has the advantages of light weight (16.46 mg cm\(^{-3}\)), low oxygen impurity (3.57 at%), high porosity, hydrophobicity and fire-resistant. Benefiting from these advantages, the adsorption capacity of 3DGF\(_{800}\) can reach 40–89 g g\(^{-1}\) at various organic liquids and oils. The maximum absorption capacity of 3DGF\(_{800}\) can still be maintained at 10 g g\(^{-1}\) after 10 adsorption- evaporation cycles. In addition, there are no significant structure damage after 10 adsorption-combustion cycles, indicating that 3DGF\(_{800}\) has broad application prospects in the fields of oil spill cleanup and oil/water separation. This work suggests a safe, economic, and sustainable approach for the large-scale preparation of high value-added products (biochar, bio-oil, and 3DFGs) from industrial by-product and medical waste.

CRediT authorship contribution statement

Zejun Luo: Conceptualization, Investigation, Visualization, Methodology, Writing-original draft. Xiefie Zhu: Investigation, Validation, Writing-original draft. Jingying Deng: Investigation, Visualization, Writing-review & editing. Ke Gong: Investigation. Xifeng Zhu: Investigation, Writing-original draft, Supervision.

Declaration of Competing Interest

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

Acknowledgments

This work was supported by the National Key R&D Program of China (2018YFB1501040). X.Z. thanks the funding of the Hong Kong Scholar Program (XJ20200022). In addition, the authors also acknowledge the extended help from the Instruments’ Center for Physical Science of University of Science and Technology of China and the Fundamental Research Funds for the Central Universities (WK2090000037).

Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.jhazmat.2021.126570.

References

Algozeeb, W.A., Savas, P.E., Luong, D.X., Chen, W., Kittrell, C., Bhat, M., Shahsvarsani, R., Tour, J.M., 2020. Flash graphene from plastic waste. ACS Nano 14 (11), 15595–15604.
Wang, C., Sun, M., Deng, J., Zhu, X., 2020. Experimental study on composition evolution of biomass pyrolysis vapors with condensing temperature in a vertical tubular condenser. Bioresour. Technol. 307, 123252.

Wang, J., Zhong, Z., Ding, K., Li, M., Hao, N., Meng, X., Ruan, R., Ragauskas, A.J., 2019. Catalytic fast co-pyrolysis of bamboo sawdust and waste tire using a tandem reactor with cascade bubbling fluidized bed and fixed bed system. Energy Convers. Manag. 180, 60-71.

Wicklein, B., Kocjan, A., Salazar-Alvarez, G., Carosio, F., Camino, G., Antonietti, M., Bergstrom, L., 2015. Thermally insulating and fire-retardant lightweight anisotropic foams based on nanocellulose and graphene oxide. Nat. Nanotechnol. 10 (3), 277–283.

Wong, S.L., Ngadi, N., Abdullah, T.A.T., Inuwa, I.M., 2015. Current state and future prospects of plastic waste as source of fuel: a review. Renew. Sustain. Energy Rev. 50, 1167–1180.

Wu, J., Liu, Q., Wang, R., He, W., Shi, L., Guo, X., Chen, Z., Ji, L., Liu, Z., 2017. Coke formation during thermal reaction of tar from pyrolysis of a subbituminous coal. Fuel Process. Technol. 155, 68–73.

Yang, S., Chen, L., Mu, L., Hao, B., Chen, J., Ma, P.-C., 2016. Graphene foam with hierarchical structures for the removal of organic pollutants from water. RSC Adv. 6 (6), 4889–4898.

Zhang, H., Li, L., Jiang, B., Zhang, Q., Ma, J., Tang, D., Song, Y., 2020a. Highly thermally insulated and superhydrophilic corn straw for efficient solar vapor generation. ACS Appl. Mater. Interfaces 12 (14), 16503–16511.

Zhang, S., Jiang, S., Huang, B., Shen, X., Chen, W., Zhou, T., Cheng, H., Cheng, B., Wu, C., Li, W., Jiang, H., Yu, H., 2020b. Sustainable production of value-added carbon nanomaterials from biomass pyrolysis. Nat. Sustain. 3 (9), 753–760.

Zhang, X., Lei, H., Zhu, L., Qian, M., Zhu, X., Wu, J., Chen, S., 2016. Enhancement of jet fuel range alkanes from co-feeding of ligninolulosic biomass with plastics via tandem catalytic conversions. Appl. Energy 173, 418–430.

Zhang, X., Tang, W., Zhang, Q., Li, Y., Chen, L., Xu, Y., Wang, C., Ma, L., 2018. Production of hydrocarbon fuels from heavy fraction of bio-oil through hydrodeoxygenative upgrading with Ru-based catalyst. Fuel 215, 825–834.

Zhao, H., Wang, J., 2018. Chemical-looping combustion of plastic wastes for in situ inhibition of dioxins. Combust. Flame 191, 9–16.

Zhu, X., Zhang, Y., Ding, H., Huang, L., Zhu, X., 2018. Comprehensive study on pyrolysis and co-pyrolysis of walnut shell and bio-oil distillation residue. Energy Convers. Manag. 168, 178–187.