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Conversion of waste plastics into value-added carbon materials

Yueyue Luo¹ · Xiao Lin¹ · Eric Lichtfouse²  · Hongru Jiang³ · Chongqing Wang¹ 

Abstract

Plastic pollution is a major environmental issue worldwide, calling for advanced methods to recycle waste plastics in the context of the circular economy. Here we review methods and strategies to convert waste plastics into value-added carbon materials, with focus on sources, properties, pretreatment of waste plastics, and on preparation of carbon materials. Pretreatment techniques include mechanical crushing, plastic stabilization and electrospinning. Carbon materials such as carbon nanotubes, graphene, carbon nanosheets, carbon spheres and porous carbon are prepared by oxygen-limited carbonization, catalytic carbonization, the template-based method, and pressure carbonization. We emphasize the conversion of polyethylene terephthalate, polyethylene, polypropylene, polystyrene, halogenated plastics, polyurethane and mixed plastics.

Keywords Carbon materials · Circular economy · Environmental pollution · Waste management · Waste valorization

Introduction

Due to low cost, durability, hygiene, and formability, plastics are widely used in various fields such as building materials, electronic equipment, automotive manufacturing, medical devices, and packaging materials. According to Plastics Europe 2023, global plastic production in 2021 was 390.7 million tons. However, the rapid growth of plastic production combined with short shelf life results in a large amount of waste plastics (Zhang et al. 2023). By 2050, the total amount of waste plastics may reach 850–950 metric tons, causing great harm to natural ecosystems and public health (Degnan and Shinde 2019; Singh et al. 2022). Currently, the major methods for disposing waste plastics are landfill and incineration. Due to the chemical stability and low bio-degradability, traditional landfilling not only consumes

valuable land resources, but also causes environmental pollution (Islam 2018; Nanda and Berruti 2021a; Wang et al. 2022e). During the slow degradation process of waste plastics in landfill sites, toxic leachate streams and microplastics are continuously released, causing significant pollution of the environment (Naqash et al. 2020; Chia et al. 2021; Jiang et al. 2023). Additionally, direct incineration of waste plastics will release a large number of organic compounds and volatile gases, causing serious air pollution. Moreover, heavy metals such as lead, mercury, and cadmium may be released into the environment along with ash and gas during the incineration process (Islam 2018; Padervand et al. 2020; Zhang et al. 2021a). The analysis of current incineration practice shows that the efficiency of energy recovery through incineration is usually very low (Degnan and Shinde 2019).

In recent years, nano-carbon materials and carbon-based composites have broad application prospects in catalysis, separation, environment, energy, and fuel due to their excellent properties. Waste plastics contain a large amount of carbon, especially in polyolefins (85.7%). Therefore, converting waste plastics into high value-added carbon materials is a promising method for management of waste plastics, favoring the reduction of environment pollution and the resource recycling (Chen et al. 2020; Gong et al. 2019; Sun et al. 2022; Huang et al. 2022). Waste plastics, such as polyvinyl chloride, polystyrene, polyethylene terephthalate, polyethylene, and polypropylene, has been studied for fabricating carbon materials, such as graphene, carbon nanosheets, carbon

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nanotubes, and porous carbon (Chen et al. 2022; Hou et al. 2021). Waste plastics can undergo different carbonization methods to obtain carbon materials with different properties. Carbon materials with high porosity, large surface area, abundant surface groups, and good conductivity have been widely used in batteries, supercapacitors, water electrolysis, pollutant removal, solar energy evaporation, and carbon dioxide capture (Al-Enizi et al. 2020b; Deka et al. 2020; Gim et al. 2021; Kaur et al. 2019b; Kumari et al. 2022; Luo et al. 2023).

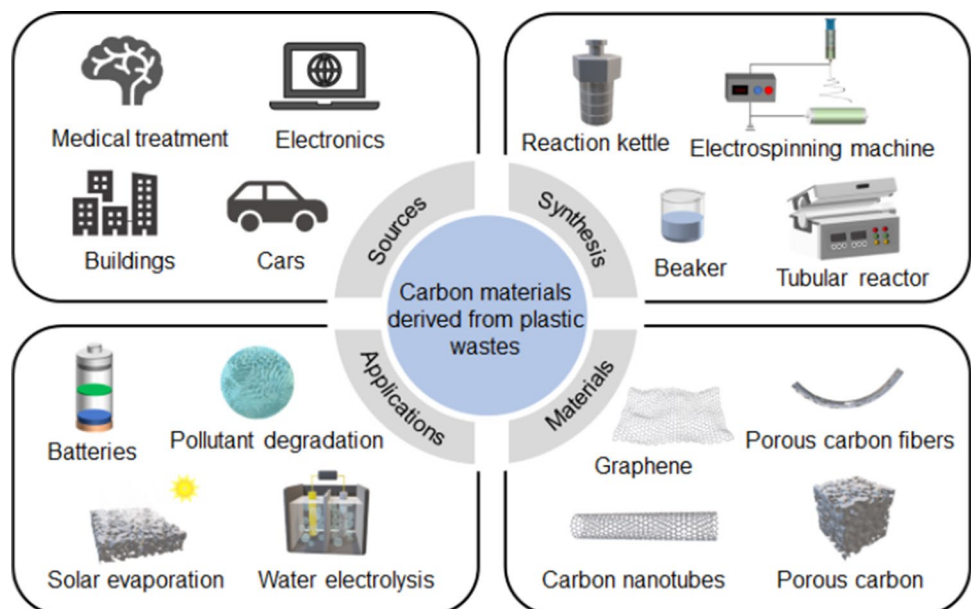
The conversion of waste plastics valuable carbon materials through thermochemical processes has many benefits from both social and industrial aspects. This strategy reduces environmental pollution resulted from waste plastics, promoting the sustainable of our society. As to industrial aspect, recycling waste plastics can decline the consumption of fossil feedstocks, and the functional carbon derived waste plastics can be applied in various industries such as energy, environment, and fuel. Due to increasing attention and extensive studies on carbon materials derived waste plastics, review papers have been published to summary carbonization methods (Dai et al. 2023; Jiang et al. 2022a), graphene-based materials (Vieira et al. 2022), carbon nanomaterials (Ren et al. 2022), and energy and environmental applications (Chen et al. 2022). Currently, this is still no comprehensive summary of the sources and properties of waste plastics, the carbonization methods, and the application of carbon materials derived from waste plastics. Here we survey the plastic sources, synthesis methods, and various applications of carbon materials derived from waste plastics (Fig. 1). The properties, pre-treatment methods, carbonization methods, and factors affecting the morphology of carbon materials are described. The review discusses the applications of

different types of carbon materials derived from waste plastics in batteries, supercapacitors, water electrolysis, pollutant removal, solar evaporation, and carbon dioxide capture in recent years. This work gives a better understanding of carbonization methods, carbonization mechanism, and the properties and application of carbon materials derived from waste plastics.

Sources and properties of waste plastics

Waste plastics originates from different sources, mainly involving daily plastics such as packaging materials and disposable plastic products, industrial wastes such as leftovers and defective products, agricultural materials such as plastic films and irrigation pipes, as well as building materials, electrical equipment, and automobiles. Waste plastics are difficult to handle due to its complex composition and large quantity, and the recycling of waste plastics in green methods gains global attention (Nanda and Berruti 2021b; Nandhini et al. 2022). The polymers are different for different plastics. Waste plastics can be divided into oxygen-containing plastics and oxygen-free plastics based on the presence of oxygen atoms in the polymers. Herein, oxygen-containing plastics means the presence of oxygen atoms in main chains of polymers such as polyethylene terephthalate. Plastics such as polyacrylonitrile, polypropylene, polystyrene, and polyvinyl chloride are oxygen-free plastics due to the absence of oxygen atoms in polymers. The main chains of oxygen-containing plastics do not decompose during carbonization, but form carbon materials through cyclization, aromatization and cross-linking. During carbonization of oxygen-free plastics, the main chain of these plastics breaks,

Fig. 1 Waste plastics from different industries can be converted into carbon materials by different synthesis methods, then applied for different applications such as batteries, solar evaporation, and pollutant degradation



and small molecules such as propylene, methane, and benzene are generated through dehydrogenation, cyclization, and aromatization, resulting in low yield of carbon product. In order to improve carbon yield, pre-treatment of these plastics can be conducted to stabilize the carbon chain, and catalysts or templates can be added during carbonization to promote the generation of carbon materials from small molecules (Chen et al. 2020). The information of common plastics is summarized in Table 1, including chemical formula, source, and properties. Waste plastics are derived from various industries, and show different properties. Except Polyurethane, most plastics have high carbon content and are potential precursor for fabricating carbon materials.

Polyethylene terephthalate is a thermoplastic polymer that is chemically and physically stable, lightweight, and transparent. Coupled with high availability and low cost, polyethylene terephthalate is widely used as packaging materials, with an annual production of approximately

26 million tons and generating approximately 62.8 billion plastic bottles (Sang et al. 2020). How to dispose waste polyethylene terephthalate has become one of the most urgent problems (Hu et al. 2014a; Kaur et al. 2019a; Dhaka et al. 2022).

For waste plastics that do not contain oxygen in the main chain of polymer, they can be classified based on the heteroatoms such as Cl, N, and S in the polymers. Polyethylene, polypropylene, and polystyrene have no heteroatoms in their polymer molecules, only containing C and H atoms. The carbon content of these plastics higher than 80% makes them suitable for producing carbon materials. Polypropylene is a thermoplastic plastic commonly used in packaging, textiles, and automotive, while polystyrene and polypropylene are thermoplastic plastic commonly used as single-use food packing and disposable masks. Carbonization of waste polyethylene, polypropylene and polystyrene with high carbon content to obtain functional

Table 1 Common plastics used for preparing carbon materials

Polymer	Structural formula	Carbon content (wt%)	Sources of waste plastics	Properties
Polyethylene		85.6	Household, industrial packaging plastics, and agricultural plastics	Excellent low-temperature resistance, chemical stability, and electrical insulation
Polypropylene		85.6	Household, industrial packaging, and automotive	Chemical resistance, heat resistance, good electrical insulation, and high mechanical strength
Polystyrene		92.2	Household, industrial packaging plastics, building, demolition, waste of electric and electronic equipment	Good electrical performance, easy processing, good thermal insulation, and excellent optical performance
Polyethylene terephthalate		67.9	Household packaging plastics	Chemical and physical stability, light weight and transparency, high availability, low cost
Polyacrylonitrile		67.9	Products of everyday use	Good stability and construction,
Polyurethane		20.3	Building, demolition, automotive	High C and N content, good thermosetting and flexible structure
Polyvinyl chloride		38.4	Building	Good chemical stability and thermal stability, easy to discharge harmful by-products
Polyphenylene sulfide		66.7	Electronics, machinery, automotive, and chemical	High mechanical strength, good stability, and good electrical performance
Polycarbonate		75.6	Glass, automotive, and electronics	Good mechanical properties, heat aging resistance, solvent resistance, and excellent insulation
Polymethyl methacrylate		60.0	Building and sanitary ware	High transparency and easy to machine
Polyamide		63.7	Parts and chemical	Tough, soft, wear-resistant, and highly absorbent

carbon materials is recognized as a convenient and attractive option for treating wastes plastics (Ma et al. 2020).

Polyurethane, polyacrylonitrile and polyphenylene sulfide with N, S atoms in the polymer chain can also be potential carbon sources for fabricating functional carbon materials. Self-doped N and S heteroatoms can enhance the chemical properties of carbon materials, improving the conductivity, surface wettability, and pseudo-capacitance. In addition, heteroatom doping can increase the active sites on the surface of carbon materials and improve the adsorption performance for pollutants (Xiang et al. 2017; Yuan et al. 2020a). The main component of packaging materials, sponges, upholstered furniture, and car seats is polyurethane, and approximately 19 million tons of waste polyurethane is generated annually (Deka et al. 2020; Schneidermann et al. 2019). Polyacrylonitrile is mainly used to manufacture synthetic fibers that are mainly used in daily clothing and woolen fabrics. The production of high-performance carbon materials using the high melting point of polyacrylonitrile has been reported (Yin et al. 2022). Polyphenylene sulfide is widely used due to its high mechanical strength, good thermal stability, and excellent electrochemical performance, and a large amount of waste polyphenylene sulfide is generated and accumulated in the environment (Guo et al. 2018a). Therefore, using waste polyurethane, polyacrylonitrile, and polyphenylene sulfide plastics as carbon sources to prepare multifunctional carbon materials will be a promising method for sustainable treatment of waste plastics.

For waste plastics containing halogens such as fluorine and chlorine, polyvinylidene chloride and polyvinyl chloride are also used to synthesize carbon materials. Polyvinyl chloride is widely used in healthcare, packaging, and building materials. Polyvinyl chloride has very good chemical stability and thermal stability. A large amount of waste polyvinyl chloride causes significant problems. During the process of incineration or landfill, extremely harmful by-products of Cl_2 , HCl, and organochlorinated compounds are emitted, which will lead to serious environmental pollution (Chang et al. 2018).

Pretreatment of waste plastics

Commonly, waste plastics need to be pretreated before carbonization. Mechanical crushing is the most used pretreatment for sufficient carbonization or uniformly mixing materials with waste plastics. Pretreatment of oxygen-free plastics is essential to increase the yield of carbon products. Moreover, pretreatment of waste plastics is conducted to obtain carbon products with special morphology and properties, such as electrospinning for carbon microfiber and metal-organic framework for porous carbon loaded with metals. Pretreatment of waste plastics is examined to

improve the yield, components, structure, or morphology of carbon products.

Mechanical crushing

Waste plastics derived from real plastic products are often large in size, and reducing the size of waste plastic is often necessary for sufficient carbonization. Mechanical crushing of waste plastics results in uniform particles or fragment of plastics with small size, and this is favorable for mixing with additional substances and subsequent carbonization. The modes of mechanical crushing are different for plastics, mainly involving ball milling, grinding, and shearing. Shear milling is suitable for reducing plastic size due to the good flexibility of waste plastics, for example flexible polyethylene terephthalate and polyvinyl chloride (Liu et al. 2020, 2022b). Waste polyethylene bags were not easy to cut and grind, and ball milling was used to evenly mix them with other substances before carbonization (Lian et al. 2019b). Moreover, a ball mill tank was used to reduce the size of polyurethane plastic, and then it was thoroughly mixed with potassium carbonate as activator and urea for N-doping in the ball mill tank for sufficient mixing, and finally carbonization was conducted to obtain carbon material (Schneidermann et al. 2019).

Plastic stabilization

The carbon chain of oxygen-free plastics will decompose into gases such as CO_2 , H_2O , and H_2 during the carbonization process, resulting in low carbon yield. Introducing oxygen-containing groups or chemical treatments to obtain cross-linked or trapezoidal structures is essential to stabilize the carbon chain of oxygen-free plastics. Direct injection of oxygen into the carbonization process of waste plastics is the most commonly used stabilization method. When polyacrylonitrile was carbonized in air, the oxygen atoms helped to improve its stability, reduced the exothermic rate, and improved the final carbon yield (Duan et al. 2019). Compared to polyacrylonitrile, it is relatively difficult to stabilize polyolefins and polystyrene chains through simple thermal oxidation. After chemical stabilization, polyethylene and polystyrene can also be further carbonized and converted into carbon materials at high temperatures. Chemical treatment typically utilizes sulfuric acid to introduce sulfonic acid groups and stabilize polymer carbon chains (Chen et al. 2020). Intermolecular or intramolecular crosslinking inhibits the decomposition of macromolecular chains during the carbonization process, promotes the carbonization of polymers, and greatly improves the carbon yield. For polyethylene, the carbon chain was chemically stabilized by sulfonation with Oleum (Hu et al. 2019). The chemical stability of polystyrene can be achieved not only through

sulfonation, but also through Friedel Crafts reaction with the phenyl group of polystyrene. Through Friedel Crafts reaction, the high-density carbonyl cross-linked bridge formed between polystyrene chains contains an appropriate amount of oxygen atoms, which has good carbonization performance (Zou et al. 2010).

Electrospinning

Electrospinning is considered to be an ideal method for manufacturing nanofibers with adjustable pore size. Electrospinning can be used to fabricate carbon fibers using waste plastics, and dissolution of plastics using organic solvents is imperative to prepare polymer solution for electrospinning. The fiber density and size distribution can be controlled by changing the feed rate and humidity of electrospinning, and the fiber structure before carbonization can be maintained even after high temperature carbonization (Mirjalili et al. 2020). Benefiting from the versatility of electrospinning, metal coordination compounds and polymer solutions can be encapsulated in the electrospinning precursor (Jin et al. 2017). For N-doping of carbon fibers, electrospinning of the solution of dicyandiamide, polyacrylonitrile and nickel acetophenone was conducted to prepare carbon fibers, and porous carbon nanofiber loaded with NiO was obtained after carbonization (Fig. 2) (Li et al. 2018b). Nickel oxide particles were uniformly distributed on the surface of porous carbon nanofibers, providing many electroactive sites for high carbon dioxide absorption.

Metal–organic framework materials

Recently, metal–organic frameworks have attracted much attention due to the high surface area and excellent porosity. Polyethylene terephthalate derived from plastic bottles was depolymerized with ethylene glycol to form benzene-1,4-dicarboxylic acid as the precursor of the metal–organic

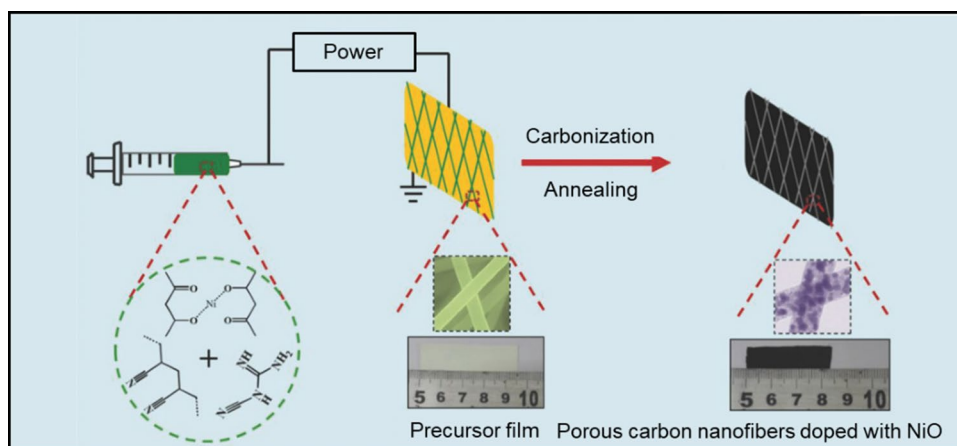
framework (Al-Enizi et al. 2020a). N-doped mesoporous carbon with high surface area was prepared by carbonizing the metal–organic framework-5 structure (Ubaidullah et al. 2021). In addition, the metal oxide nanoparticles were embedded in the metal–organic framework by chemical methods to obtain the pristine metal–organic framework-5 and Co-metal–organic framework. Subsequently, the carbonization of metal–organic frameworks produces metal oxides containing carbon networks, which promotes the enhancement of surface area, conductivity, and stability. Metal–organic framework improves the surface area and porosity of carbon materials, and metal oxide nanoparticles improve the electrochemical performance and stability of carbon materials. Therefore, it is economically feasible to convert waste plastics into metal–organic framework (Al-Enizi et al. 2020a, 2020b).

Pretreatment of waste plastics prior to carbonization can change the physical and chemical properties of plastics. Reducing the size of waste plastics and stabilizing the carbon chains of oxygen-free plastics are the main strategies, while using electrospinning technology and converting waste plastics into metal–organic framework can help prepare carbon materials with the desired morphology and functionality through carbonization.

Preparation of carbon materials

Waste plastics usually need to be converted into carbon materials through high-temperature carbonization under different atmospheres, catalysts, templates, and pressure conditions. By changing the conditions during the carbonization process, carbon products with different structures and properties can be obtained, such as activated carbon, carbon fibers, carbon spheres, carbon nanotubes, and graphene (Hou et al. 2021; Hussin et al. 2021; Kumari et al. 2022). This section introduces the carbonization methods,

Fig. 2 N-doped porous carbon nanofiber loaded with NiO using electrospinning and carbonization methods. Dicyandiamide, polyacrylonitrile and nickel acetophenone were electrospun and carbonized to fabricate carbon nanofiber loaded with NiO. Reprinted with permission of Wiley from Li et al. (2018b)



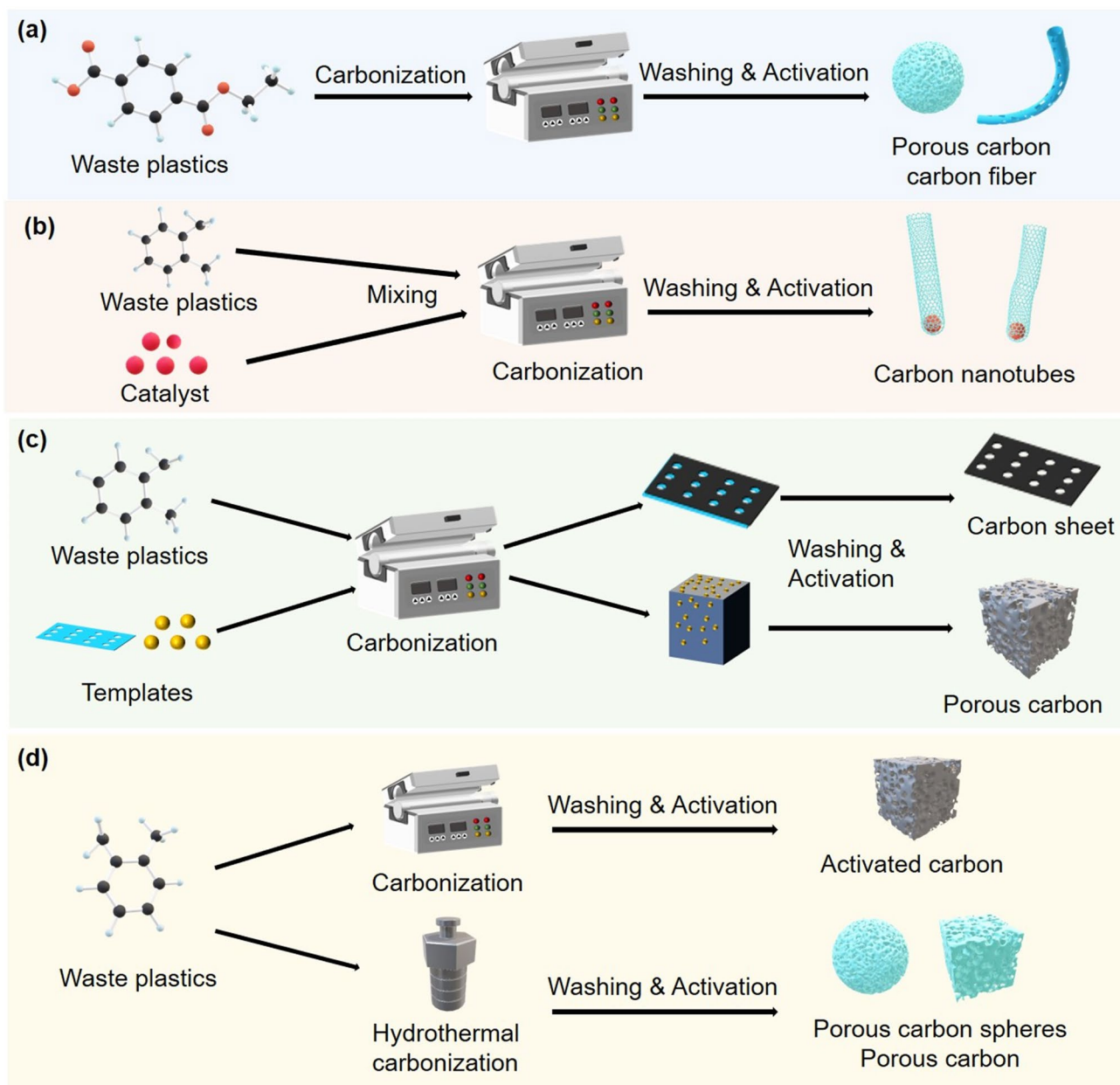


Fig. 3 The commonly used carbonization methods of waste plastics. **a** Oxygen-limited carbonization: carbonization of waste plastics into carbon materials under oxygen limiting conditions. **b** Catalytic carbonization: carbonization of waste plastics into carbon materials in

the presence of catalysts. **c** Template-based method: carbonization of waste plastics into carbon materials assisted by templates. **d** Pressure carbonization: two ways of pressure carbonization to carbonize waste plastics into carbon materials

and Fig. 3 shows the commonly used methods, including oxygen-limited carbonization, catalytic carbonization, template-based method, and pressure carbonization. The general features of carbonization methods are summarized in Table 2, including carbonization conditions, obtained carbon materials, and advantages and disadvantages.

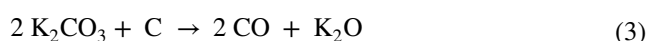
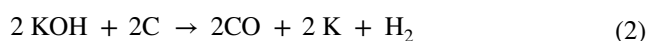
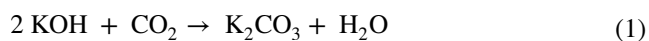
Oxygen-depleted carbonization

For oxygen-containing plastics, oxygen-limited carbonization is a commonly used carbonization method. Usually, inert gases N_2 or Ar are introduced in a tube furnace for high-temperature carbonization of waste plastic. The

Table 2 Carbonization methods for synthesizing carbon materials from waste plastics

Methods	Conditions	Typical plastics	Carbon materials	Advantages	Disadvantages
Oxygen-limited carbonization	Inert atmosphere or in molten salt, 500–1000 °C stabilization if needed, activation if needed	Polyethylene terephthalate, polyacrylonitrile, polyvinyl chloride, polyethylene, polystyrene, polyolefin	Activated carbon, mesoporous carbon, carbon fibers	Simple, low equipment requirements, relatively, low cost, applicable for most plastics	Low carbon yield relatively high energy consumption
Catalytic carbonization	Inert atmosphere 400–900 °C, catalysts	Polyethylene, polypropylene, polystyrene, polyvinyl chloride, polyvinylidene fluoride, polytetrafluoroethene, polyvinyl alcohol, polyethylene terephthalate	Carbon nanotubes, graphene, carbon spheres, carbon nanofibers	Applicable for most plastics, generation of graphitic carbons	Needs catalysts, relatively high energy consumption
Template-based method	Hard template (SiO ₂ , Zn), soft template (MgO, organic modified montmorillonite, Fe ₂ O ₃), 600–900 °C, under inert atmosphere	Polystyrene, polyacrylonitrile, polytetrafluoroethene, polyethylene, polyvinyl chloride, polypropylene, polyethylene terephthalate	Carbon spheres, carbon nanosheets, porous carbon	Low cost, easy to purify, adjustable, easy to control the parameters of carbon materials and improve the carbonization yield	Acid or alkali pollutes the environment, the production process becomes complex
Pressure carbonization	Sealed reactor at 600–850 °C or hydrothermal reaction at 150–300 °C	Polypropylene, polyethylene, polyvinyl chloride, polystyrene, polyethylene terephthalate	Activated carbon, carbon dots, carbon spheres	Sophisticated techniques, high carbon yields	High equipment, requirements, relatively high energy consumption
Flash Joule heating	Vacuum reactors, at high current density in a short time	Polyethylene terephthalate, polyethylene, polyvinyl chloride, polypropylene, polystyrene	Graphene	Simple, low energy consumption, fast preparation, applicable for most plastics	Difficult management of volatile products, high current involved, needs conductive substances
Microwave conversion	Microwave reactors, microwave irradiation, catalysts if needed	Polyethylene, polypropylene, polystyrene	Carbon nanotubes, char	Simple, fast preparation, ensure control of reaction conditions, such as temperature and reaction time	Relatively high energy consumption, limited carbon yields, expensive, not suitable for mass production

physical and chemical properties of carbon materials, such as carbon structure, morphology, composition, and surface groups, can be regulated by changing carbonization temperature. Carbonization temperatures higher than 700 °C can improve the porosity and conductivity of carbon materials, but reduce oxygen-containing functional groups. Carbon materials formed by carbonization at a lower temperature of around 500 °C retain relatively more surface groups, making them more suitable as adsorbents of pollutants. Adding activators can adjust the porosity of carbon materials and improve the adsorption capacity, and the common activators are NaOH, KOH, or ZnCl₂. For KOH, the activation reactions can be shown as Eqs. 1–4 (Yuan et al. 2020c). The thermal decomposition of plastics generates volatile compounds such as CO₂ and CO, which react with KOH. KOH also reacts with carbon to release CO, H₂, and vaporized metal potassium, while the formed K₂CO₃ and K₂O can react with carbon to release more CO and regulate the porosity of carbon materials. Physical activation of O₂ or air is an alternative activation method. The reaction process between carbon and oxygen has high energy efficiency, and the activation takes place at relatively low temperatures, commonly less than 500 °C. The reactions in physical activation can be shown as Eqs. (5–9) (Zhou et al. 2021).



In the process of preparing carbon materials, chemical modification (acid oxidation or heteroatom-doping) of carbon materials can increase their surface-active sites and improve their ability to adsorb pollutants. For example, using waste polyethylene terephthalate urea, and sodium hydroxide as the carbon source, nitrogen source, and activator, N-doped microporous carbon was synthesized and exhibited high CO₂ absorption capacity (Yuan et al. 2020a).

Catalytic carbonization

Catalytic carbonization is an effective strategy to converting waste plastics into liquid or gas products. In the process of catalytic carbonization, the decomposition products can be converted into carbon materials on the surface of catalysts. Catalysts play a dual role in promoting polymer decomposition at the beginning and catalyzing the formation of carbon materials later (Li et al. 2017a). Catalysts containing Ni, Co, Al and Fe can be used in the catalytic process to convert waste plastics into carbon materials such as carbon nanotubes (Ribeiro et al. 2022), carbon nanoflakes (Liu et al. 2021b), and layered porous carbon (Ma et al. 2020). During the catalytic carbonization of plastics, the surface of Fe–Ni bimetallic catalyst showed high hydrogen and carbon deposition yield, which was attributed to the enhanced reducibility and synergistic effect of Fe–Ni species (Yao and Wang 2020). Cup-shaped carbon nanotubes were synthesized through the combined catalysis of different halogenated compounds and nickel oxide (Gong et al. 2014d). During the synthesis process, halogenated compounds promoted the decomposition of polypropylene into light hydrocarbons and aromatics, and the decomposition products promoted the aggregation and reconstruction of catalyst. Then, under the catalysis of diamond shaped nickel oxide, light hydrocarbons and aromatics were converted into cup-shaped carbon nanotubes. How to improve the carbon yield has been paid much attention for catalytic carbonization of waste plastics. Carbon nanosheets with a yield of up to 62.8% were obtained from waste polypropylene by the combined catalytic action of ferrocene and sulfur (Liu et al. 2021b). The iron particles derived from ferrocene not only accelerated the large dehydrogenation and aromatization of waste polypropylene, but also reacted with high-pressure sulfur vapor to generate Fe₇S₈ nanoparticles, forming carbon nanosheets loaded with Fe₇S₈ (Fig. 4a).

Template-based method

Templates can be used in carbonization of waste plastics to regulate the morphology of carbon products. Template-based carbonization is usually divided into soft template-based carbonization and hard template-based carbonization based on the properties of the templates. Hard templates such as SiO₂ and Zn have higher carbonization temperature than sacrificial templates, and porous carbon materials are obtained after removing the templates through chemical etching (Ma et al. 2020; Min et al. 2019; Wang et al. 2022a). The plastics are converted into carbon material in an inert atmosphere, and the void or pore between particles in the templates is infiltrated by plastic precursor that transforms from solid to liquid during carbonization. In addition, the metal additives in polyvinyl chloride were used as a hard

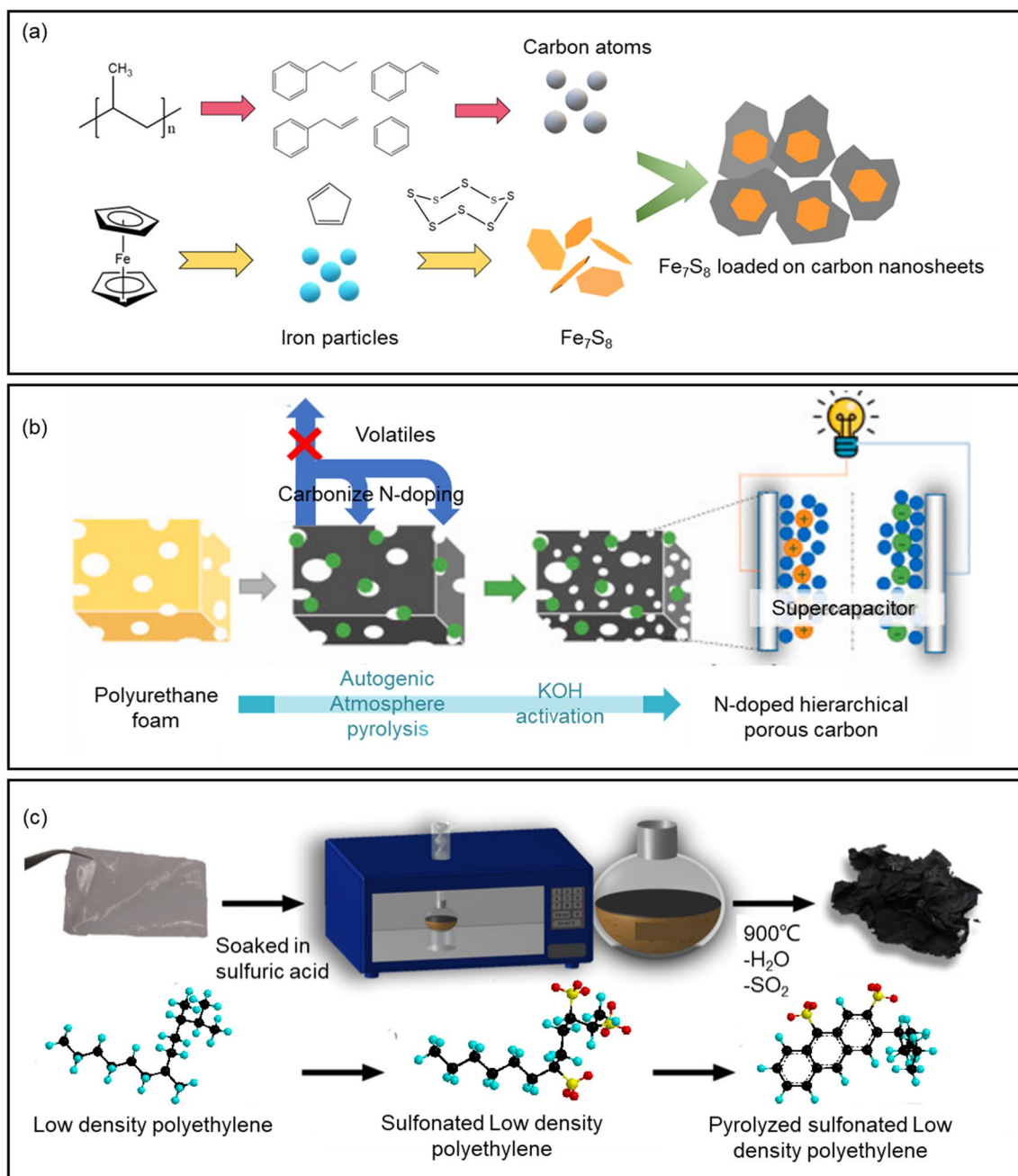


Fig. 4 Preparation of carbon materials using different carbonization methods. **a** Formation of carbon nanosheets loaded with Fe_7S_8 : pyrolysis of polypropylene into carbon atoms, iron particles from ferrocene pyrolysis reacted with high-pressure sulfur vapor to generate Fe_7S_8 nanoparticles. Reprinted with permission of Elsevier from Liu et al. (2021b). **b** N-doped gradient porous carbon materials extracted

from polyurethane waste plastics using in situ atmosphere pyrolysis and KOH activation. Reprinted with permission of Elsevier from Zhou et al. (2022). **c** Preparation of porous carbon scaffolds with sulfonic groups by sulfonation reaction and microwave carbonization. Reprinted with permission of American Chemical Society from Kim et al. (2018)

template to recover up to 92% of calcium and titanium compounds in polyvinyl chloride through KOH activation and acid washing, which was conducive to the development of micropores and CO_2 adsorption (Liu et al. 2022b).

Soft templates can not only serve as a sacrificial precursor for porous carbon, but also catalyze and promote the

formation of carbon materials during the carbonization process. For example, the organically modified montmorillonite active template not only controlled the morphology of carbon materials, but also catalyzed polymer degradation and improved the carbonization yield (Ma et al. 2020; Min et al. 2019; Gong et al. 2014c). In addition, to improve the thermal

stability and flame retardancy of plastics during carbonization, basic magnesium carbonate pentahydrate was added to waste polyethylene plastics to provide MgO templates. The prepared porous carbon had excellent capacitance performance and excellent cycling stability in supercapacitors (Lian et al. 2019a, 2019b).

Pressure carbonization

Pressure carbonization refers to the high-pressure carbonization of waste plastics in a sealed reactor. Based on different pressure sources, pressure carbonization can be divided into direct pressure carbonization and hydrothermal carbonization with self-generated pressure. Direct pressure carbonization either uses additive substituents or catalysts, or requires higher pressure conditions exceeding 30 MPa. The used catalysts or additives may pollute the environment, while the latter requires stringent equipment requirement (Chen et al. 2022). The autogenous pressure generated by plastic carbonization promotes the carbonization process, which is simple to operate and does not need to add external pressure. Moreover, autogenous pressure carbonization greatly improves the carbonization yield. Low density polyethylene, as a precursor, will not produce carbon products during carbonization at atmospheric pressure, while 45% of carbon yield can be obtained by autogenous pressure carbonization in a closed system (Zhang et al. 2019b). The polyurethane foam was pyrolyzed into N-doped porous carbon under in situ atmosphere, and the yield of hierarchical porous carbon obtained by KOH activation reached 55.0% (Fig. 4b) (Zhou et al. 2022).

The hydrothermal carbonization takes place under pressurized conditions containing water or solvent vapor. According to the hydrothermal reaction temperature, hydrothermal carbonization can be divided into low-temperature carbonization below 250 °C and high-temperature carbonization above 250 °C. Low-temperature hydrothermal carbonization produces hydrogen carbon through dehydration and decarboxylation, while high-temperature hydrothermal carbonization produces highly graphitized carbon products such as graphite carbon, activated carbon, and carbon nanotubes as the reaction temperature increases (Chen et al. 2020, 2022). Low-temperature hydrothermal carbonization can be employed for dehydrochlorination of waste polyvinyl chloride, which is crucial for the subsequent formation of polyvinyl chloride dichloride and aromatic structure (Xu et al. 2022). In addition to the temperature, solvent also affects the physical properties of carbon materials obtained from hydrothermal carbonization. For example, the higher the concentration of hydrogen peroxide solution, the smaller the particle size of photoluminescence carbon nanoparticles synthesized by hydrothermal carbonization of waste plastic bags in hydrogen peroxide solution (Hu et al. 2014b).

Other methods for carbonization of waste plastics

For oxygen-containing plastics, they can be carbonized directly under oxygen-limited conditions, while for oxygen-free plastics, templates or catalysts need to be used to promote the formation of carbon materials from small molecules generated by plastic pyrolysis, thereby improving carbon yield. In addition, the self-generated pressure formed by plastic pyrolysis can also improve carbon yield. In order to quickly and efficiently obtain high-quality graphene and carbon nanotubes, flash Joule heating and microwave carbonization are also good choices.

Flash Joule heating is a promising method for rapid synthesis of high-quality graphene. In the carbonization process, there is no need for a furnace, solvent, or reaction gas, nor for purification steps. The plastic is heated to high temperature in a short period of time, and most non-carbon atoms are removed through sublimation to obtain high-quality turbine layer flash graphene, with a yield of over 90% (Luong et al. 2020). The conversion of waste rubber to turbine layer flash vaporized graphene was optimized using flash Joule heating. Carbon black derived from waste rubber tires was converted into graphene, which was used as a reinforcing additive in cement materials (Advincula et al. 2021). Through flash joule heating technology, the byproduct of waste plastics beneficiation process was rapidly converted into high-purity turbine layer flash graphene (Wyss et al. 2021).

Similar to rapid Joule heating, the carbonization of waste plastics assisted by microwave greatly shortens heating time and prepares high-value carbon materials and hydrogen fuels (Suresh et al. 2021). Using inexpensive iron-based catalysts as microwave sensors, a rapid catalytic decomposition process of plastic was initiated for 30–90 s, converting mechanically crushed commercial plastics into 55.6 mmol/g high yield hydrogen and multi walled carbon nanotubes (Jie et al. 2020). In addition, it was found that microwave promoted the sulfonation reaction of low-density polyethylene, and induced a large number of pores in the sulfonated low-density polyethylene plastic (Fig. 4c). The sulfonation reaction cooperated with microwave successfully prepared the porous carbon scaffold with sulfonic group from low-density polyethylene plastic (Kim et al. 2018).

Carbon materials derived from waste plastics

Waste plastics can be converted into different forms of carbon materials, depending on plastic types and carbonization method. Compared to other plastics, polyethylene is an excellent precursor for producing carbon nanotubes, as it can produce light hydrocarbons that contribute to the formation of carbon nanotubes during the carbonization

process (Cai et al. 2021). Similar to polyethylene, polypropylene is an excellent precursor for producing carbon nanotubes, graphene, and carbon spheres. During the carbonization process, polypropylene undergoes random cleavage of C–C bonds to form oligomers, which then undergoes β -Cracking to further decomposes into small molecules such as hydrogen, methane, and propylene, which are then catalyzed and carbonized to form carbon nanotubes, graphene, and carbon spheres (Vollmer et al. 2020).

Due to the presence of benzene ring in polystyrene and polyethylene terephthalate, aromatics and oil compounds are easily formed during carbonization, which are the main raw materials for the formation of amorphous carbon (Cai et al. 2021; Zhang et al. 2021b). Polystyrene and polyethylene terephthalate can also be converted into porous carbon after activation. Compared with other plastics, polyvinyl chloride has the lowest carbon content and is prone to generating harmful gases such as HCl during carbonization. Apart from being used for synthesizing porous carbon, polyvinyl chloride is not an ideal raw material for synthesizing other carbon materials. The type of waste plastics, carbonization processes, and catalyst types are important factors that affect the morphology and properties of carbon materials. Choosing appropriate plastics as carbon sources, carbonization conditions, and carbonization methods can generate ideal carbon materials. The preparation of carbon materials from waste plastics reported in recent studies is summarized in Table 3. Carbon materials derived from waste plastics exhibit different carbon yield due to the difference of plastics, reaction equipment and conditions.

Carbon nanotubes

For the production of carbon nanotubes, catalyst, temperature, and carbonization method are decisive factors in the carbonization process. In terms of carbonization methods, the traditional method is to use transition metal catalysts to produce carbon nanotubes from waste plastics. Recently, microwave carbonization has attracted much attention as a new method for efficiently and rapidly converting waste plastics into carbon nanotubes and hydrogen (Jie et al. 2020). Meanwhile, increasing the carbonization temperature is beneficial for the decomposition of plastic polymers and obtaining high-quality and highly graphitized carbon nanotubes. In addition, the morphology and particle size of metal catalysts have a profound impact on the morphology of carbon nanotubes. For example, the diamond shape of nickel catalysts can promote the formation of cup-shaped stacked carbon nanotubes (Shah et al. 2022). Graphene layer was first formed on the surface of the catalyst was parallel to its surface. Later, due to the angle between the two sides of the diamond shaped catalyst, the

graphene layer grew at the same angle, forming an angle of 17–25° with its growth axis, resulting in the formation of cup-shaped carbon stacked nanotubes.

Graphene

Chemical vapor deposition and flash joule heating are effective methods for converting waste plastics into graphene (Algozeeb et al. 2022; Cui et al. 2017). In the process of chemical vapor deposition, graphene layers are controlled by adjusting the flow rate of H₂ or Ar (Sharma et al. 2014). Although flash Joule heating cannot control the graphene layer, it can quickly and effectively convert mixed waste plastics into graphene within a few seconds, and the carbon yield of graphene is higher than that of chemical vapor deposition, reaching 20–30 wt% (Algozeeb et al. 2022). During the heating process, the thermal stability of plastics will affect the rate of carbon generation during the flash Joule heating process. Choosing plastics with high stability during the carbonization process will result in slower thermal decomposition, slower carbon supply, and more time for the generated carbon to react with metal catalysts, thereby increasing carbon production (Cui et al. 2017). Cu and Ni are the most commonly used metal catalysts in method of chemical vapor deposition. Single-layer graphene can be synthesized in different gas environments using the low carbon source solubility of Cu. Compared to Cu, Ni's low carbon source solubility has a stronger chemical adsorption on graphene and is easier to form graphene (Ren et al. 2022).

Carbon nanosheets

The main reactors for preparing nanosheets include quartz tube reactors and sealed reactors. The quartz tube reactor is simple to operate and has a high security, while the sealed autoclave reactor can prevent carbon volatiles from escaping with the gas and improve the carbon yield. It is reported that the carbonization of plastic polymers containing polycyclic aromatic hydrocarbons can produce more carbon products, such as polystyrene, which is easy to produce carbon nanosheets under the same conditions (Ma et al. 2018). MgO and the organically modified montmorillonite are reported as the template catalysts for the production of carbon nanosheets. Porous MgO template can not only promote the decomposition of polymers, but also promote the formation of porous carbon nanosheets as a sacrificial template, while organically modified montmorillonite, as an active template, can introduce more Brønsted acid sites to catalyze the decomposition of plastics and improve carbon emissions, but it cannot generate pores on carbon nanosheets (Wen et al. 2019). Compared with other plastics, aromatic-rich polystyrene is

Table 3 Carbon materials prepared from waste plastics

Carbonization method	Plastics	Reaction equipment	Reaction conditions	Carbon material	Carbon yield (wt%)	References
Flash Joule heating	Polyethylene terephthalate, high- or low-density polyethylene, polyvinyl chloride, polypropylene polyacrylonitrile, rubber tires	Quartz or ceramic tube	Greater than 3000 K, ~400 V, Less than 100 m s	Graphene	80–90	Luong et al. (2020)
Microwave conversion	Low-density polyethylene, high-density polyethylene, polypropylene and polystyrene	Microwave reactor	~573 K, 220V, 30–90 s	Carbon nanotubes	57.6–73.1	Jie et al. (2020)
Oxygen-limited carbonization	Polyethylene terephthalate	Quartz tube furnace	973 K, 2 h	Activated carbon	–	Kaur et al. (2019b)
Oxygen-limited carbonization	Polyethylene terephthalate	Quartz tube furnace	998 K, 2 h	Activated carbon	22.0	Moura et al. (2018)
Oxygen-limited carbonization	Polyethylene terephthalate	Quartz tube furnace	773 K or 1073 K, 2 h	Activated carbon	–	de Castro et al. (2018)
Oxygen-limited carbonization	Polyethylene terephthalate	Quartz tube furnace	873 K, 1 h	Porous carbon	–	Yuan et al. (2020a)
Oxygen-limited carbonization	Polyethylene terephthalate	Horizontal cylindrical furnace	873 K, 1 h	Porous carbon	–	Yuan et al. (2020c)
Oxygen-limited carbonization	Polyethylene terephthalate	Tube furnace	873 K, 2 h	Porous carbon	–	Zhu et al. (2021)
Oxygen-limited carbonization	Polyethylene terephthalate	Quartz tube furnace	773 K, 1 h	Porous carbon	–	Liu et al. (2020)
Oxygen-limited carbonization	Polyethylene terephthalate	Horizontal cylindrical furnace	873 K, 1 h	Porous carbon	–	Yuan et al. (2020b)
Oxygen-limited carbonization	Polyethylene terephthalate	Autoclave reactor	873 K or 1073 K, 5 h	Graphene	–	Elessawy et al. (2019)
Catalytic carbonization	Polypropylene	Quartz tube furnace	773 K, 20 min	Carbon nanotubes	–	Yao and Wang (2020),
Catalytic carbonization	Polyethylene	Tube furnace	773–1073 K, 2 h	Carbon nanotubes	59.0	Huang et al. (2021)
Catalytic carbonization	High-density polyethylene	Quartz tube furnace	773 K, 3 h	Carbon nanotubes	–	Nath et al. (2021)
Catalytic carbonization	Low-density polyethylene	Tubular furnace	723 K and 1123 K, 1 h	Carbon nanotubes	–	Ribeiro et al. (2022)
Catalytic carbonization	Polypropylene	Crucible	973 K, 5 min	Carbon nanotubes	–	Gong et al. (2014d)
Catalytic carbonization	Polyethylene terephthalate	Quartz tube furnace	973 K, 2 h	Carbon nanosheets	45.2	Wen et al. (2020)
Catalytic carbonization	Polypropylene	Autoclave	973 K, 1.5 h	Carbon nanosheets	62.8	Liu et al. (2021b)
Catalytic carbonization	Polypropylene	Tube furnace	873 K, 2 h	Nanowires	–	Li et al. (2022a)
Catalytic carbonization	Polystyrene	Reaction kettle, tube furnace	973 K, 1 h	Porous carbon	–	Ma et al. (2020)
Template-based method	Polystyrene	Autoclave	973 K, 2 h	Porous carbon flakes	–	Min et al. (2019)
Template-based method	Polystyrene	Reaction kettle	973 K, 1 h	–	–	Ma et al. (2019a)

Table 3 (continued)

Carbonization method	Plastics	Reaction equipment	Reaction conditions	Carbon material	Carbon yield (wt%)	References
Template-based method	Polystyrene	Tube furnace	1173 K, 3 h		–	Wang et al., 2018)
Template-based method	Polytetrafluoroethene	Tube furnace	973 K, 2 h	Porous carbon	–	Chen et al. (2014),
Template-based method	Polyethylene	Tube furnace	1173 K, 1 h		–	Lian et al. (2019a)
Template-based method	Polyvinyl chloride	Tube furnace	873–1073 K, 1 h	Activated carbon	–	Liu et al. (2022b)
Template-based method	Polypropylene, polyethylene, polystyrene and polyvinyl chloride	Autoclave reactor	1073 K, 3 h	Porous carbon flakes loaded with hollow carbon spheres	–	Min et al. (2022)
Template-based method	Poly(vinylidene chloride)	Tube furnace	1073 K, 3 h	Carbon spheres	–	Li et al. (2021c)
Pressure carbonization	Polypropylene	Autoclave reactor	673 K, 4 h	Hetero carbon	–	Mir et al. (2020b)
	Polyethylene terephthalate,	Autoclave reactor	973 K, 0.5 h	Activated carbon	–	Zhang et al. (2021b)
Pressure carbonization	Low-Density Polyethylene	Autoclave reactor	873 K, 0.5 h	Carbon Spheres	–	Zhang et al. (2019b)
	Polyurethane	Autoclave reactor	973 K, 0.5 h	Porous carbon	55.0	Zhou et al. (2022)

an ideal candidate for preparing carbon nanosheets. Using MgO and organically modified montmorillonite as template and catalyst, carbonization in a sealed autoclave effectively increases the porosity and yield of carbon nanosheets.

Carbon spheres

Generally, carbon spheres are synthesized from waste plastics through self-generated pressure carbonization and atmospheric pressure carbonization. Self-generated pressure carbonization can obtain carbon sphere with smooth surfaces, while atmospheric pressure carbonization obtains carbon sphere with rough surfaces and aggregated carbon (Gong et al. 2014a; Zhang et al. 2019b). The carbonization of oxygen-free plastics such as polypropylene and polyethylene will form oil containing aromatic hydrocarbons, which is an ideal raw material for carbon sphere synthesis. In addition, increasing the carbonization time and temperature can improve the graphitization degree of carbon spheres. Therefore, in order to obtain high-quality carbon spheres with smooth surface, it is recommended to use appropriate plastics and increase the carbonization temperature and reaction time (Ren et al. 2022).

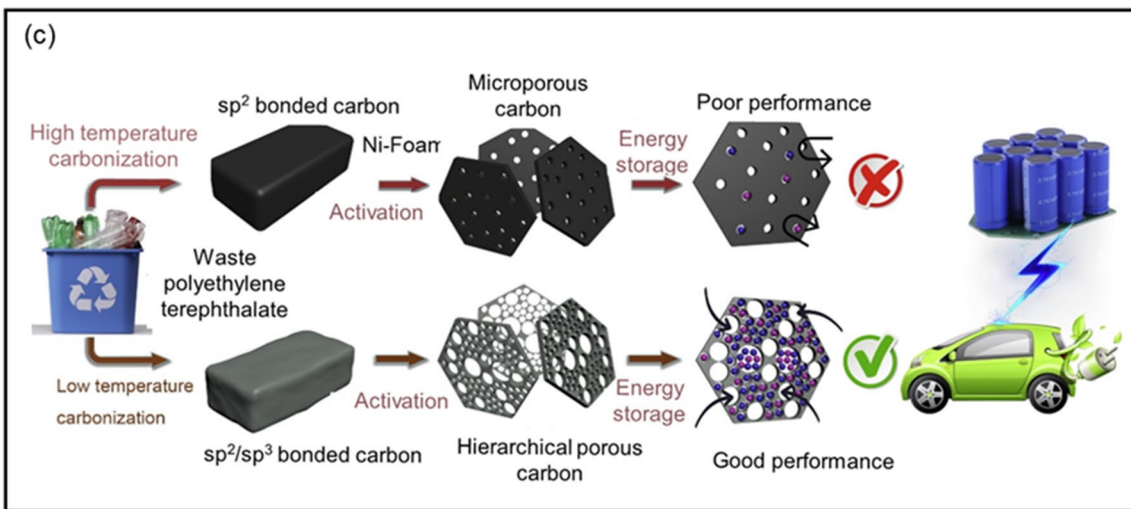
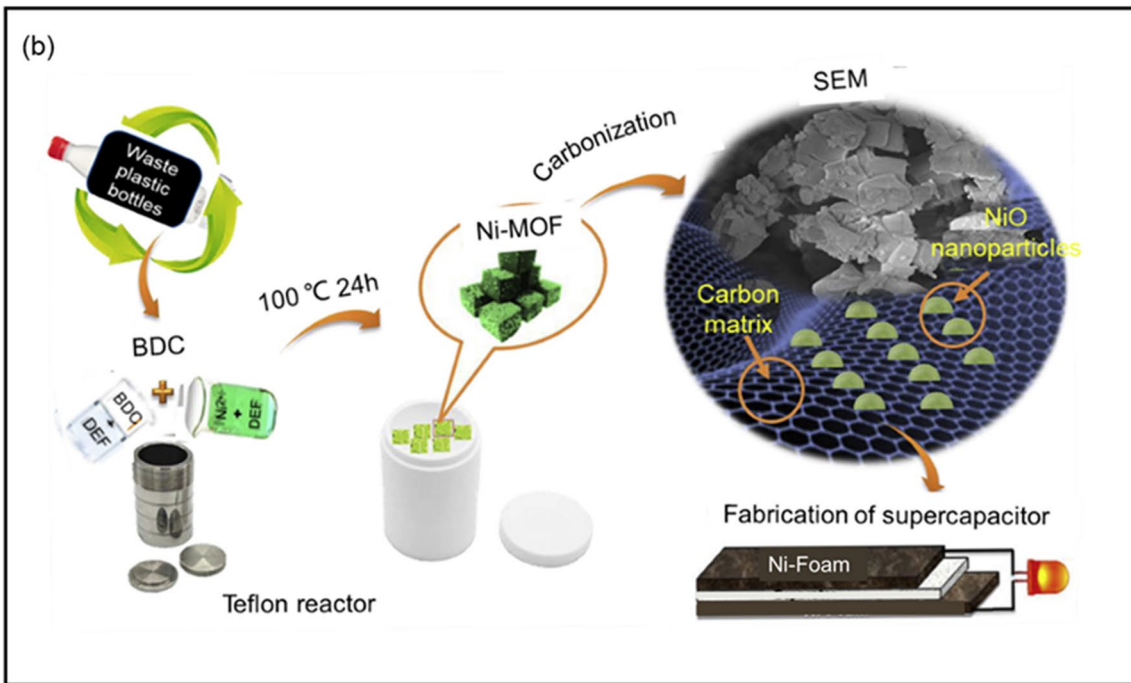
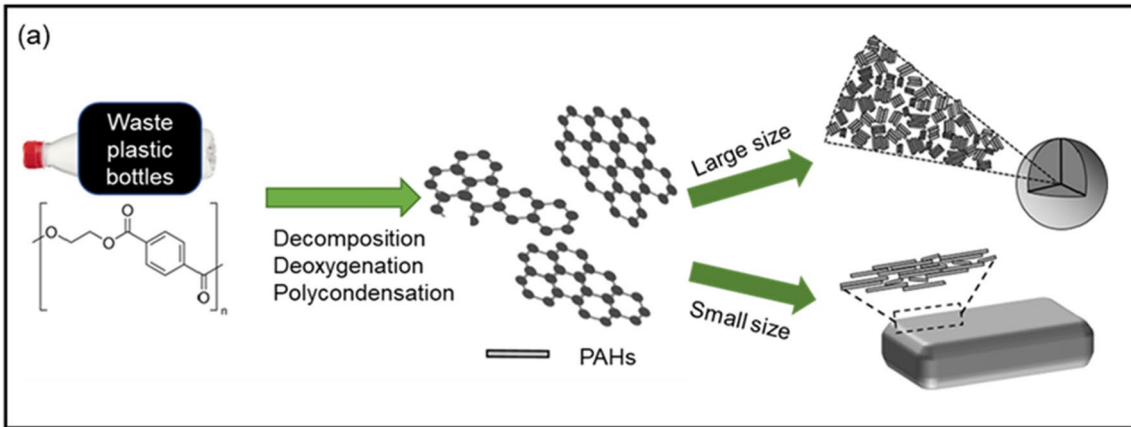
Porous carbon

The fabrication of porous carbon involves the carbonization of plastics and the generation of pores. Among different

plastics, plastics such as polyethylene terephthalate and polyvinyl chloride are more likely to produce porous carbon than polyethylene and polypropylene (Algozeeb et al. 2022). Currently, the most common template is MgO, and Mg(OH)₂ that can be converted into MgO at high temperatures. Other materials such as silica are also hard templates for synthesizing porous carbon. Among various activators, the most commonly used KOH is mainly used to promote the formation of a large number of micropores and a small amount of mesopores in carbon materials. ZnCl₂ as an activator only produces mesopores, but promotes the graphitization degree of carbon materials. The activation process of K₂CO₃ introduces a large number of defect structures and oxygen-containing groups on the carbon surface. Compared to KOH, K₂CO₃ has less corrosiveness (Liew et al. 2019; Min et al. 2020; Zhang et al. 2021b, 2018).

Other carbon materials derived from waste plastics

Carbon nanodots are spherical carbon nanoparticles with a size of 1–10 nm, mainly containing sp³ hybrid carbon, and the most distinctive property is strong photoluminescence (Georgakilas et al. 2015). Hydrothermal carbonization, carbonization or oxidation are usually used to produce carbon nanodots from polymers (Arpita et al. 2023). Hydrothermal carbonization can control the size and surface chemical properties of carbon nanoparticles, and has been used for carbonization of discarded plastics in recent years



◀**Fig. 5** Carbon materials derived from polyethene terephthalate for energy applications. **a** Mechanism for the generation of porous carbon during the autogenic pressure carbonization. Reprinted with permission of Elsevier from Zhang et al. (2021b). **b** Synthesis of carbon composite materials doped with NiO nanoparticles using waste plastics. Reprinted with permission of Elsevier from Al-Enizi et al. (2020b). **c** Effects of two carbonization temperatures on the properties of carbon materials prepared from waste plastics. Reprinted with permission of Elsevier from Liu et al. (2020)

(Adolfsson et al. 2018). Combustion oxidation is suitable for aromatic polymers as they are prone to pyrolysis into carbon nanoparticles. Waste polystyrene was carbonized in an oxygen-free environment and then oxidized to produce green fluorescent onion like carbon nanoparticles (MalikaáTripathi and KumaráSonkar 2014). The use of strong acid oxidation can easily lead to low product yield. Therefore, it is crucial to seek green and efficient methods to manufacture carbon nanodots from waste polymers.

Electrospinning is the main equipment for mass production of carbon fibers or porous carbon nanofibers. The produced fiber materials have the advantages of large specific surface area, chemical composition, morphology, adjustable fiber diameter, and high porosity (Zhu and Nie 2021). During the spinning process, the concentration of waste polymer solution is the most important factor affecting the fiber diameter. With the increase of the proportion of waste polymer, the fiber diameter of electrospinning will also increase (Bonfim et al. 2021). In addition, adding other metal coordination compounds and N-containing precursors to the polymer solution could regulate the chemical composition and porosity of carbon fibers (Li et al. 2018b). Using electrospinning to produce carbon fiber is a potential attractive choice.

Application of carbon materials derived from waste plastics

Carbon materials synthesized from waste plastics through carbonization have different characteristics and can be applied to different fields. Carbon materials with electrocatalytic activity, good conductivity, and pore structure can be applied in batteries, capacitors, and water electrolysis, playing an important role in sustainable green energy systems. Additionally, carbon materials with high surface area, large porosity, and abundant surface groups have shown great potential in pollutant removal, solar evaporation, and CO₂ capture. This section summarizes the applications of carbon materials derived from waste plastics based on plastic types.

Polyethene terephthalate

In order to effectively store and use energy, supercapacitors with high specific power density, good cycle stability and

long life, fast charging or discharging and wide operating temperature range are preferred for energy storage devices (Pandey et al. 2021). Carbon materials obtained from waste plastics, such as carbon nanotubes, carbon spheres, carbon nanosheets, layered porous carbon, and carbon-based composites, have been applied in supercapacitors due to the unique properties such as porosity, large surface area, controllable morphology, and heteroatom-doping (Uteti-wabo et al. 2020). Activated carbon with abundant surface groups and high surface area can also be prepared by using the autogenous carbonization (Zhang et al. 2021b; Zhu et al. 2021). Activated carbon as supercapacitor electrodes showed excellent specific capacitance of 325 F/g when the current density was 0.5 A/g. Waste polyethylene terephthalate was first decomposed and deoxygenated, and under autogenic pressure pyrolysis, the oxygen-containing components were completely deoxygenated to form aromatics, which further condensed to form polycyclic aromatic hydrocarbons of different sizes. Smaller aromatics formed carbon spheres, while larger aromatics formed blocky carbon materials (Fig. 5a).

Metal oxide nanoparticles NiO, ZnO and Co₃O₄ were loaded into the metal–organic framework with high surface area and excellent porosity transformed by polyethylene terephthalate, which improved the capacitance and stability of carbon materials, thus improving the performance of supercapacitors (Al-Enizi et al. 2020a, 2020b; Ubaidullah et al. 2021). To further improve the conductivity and stability of metal–organic frameworks, the benzene-1,4-dicarboxylic acid after polyethylene terephthalate depolymerization was mixed with two other reagents, and the obtained Ni-metal–organic framework crystal was carbonized at high temperature to form a porous carbon composite material loaded with NiO (Fig. 5b). The prepared carbon material as a composite electrode showed improved conductivity and stability, exhibiting an excellent specific capacitance of 581.30 F/g in supercapacitors (Al-Enizi et al. 2020b). In addition, the ultra-long carbon fiber with uniform diameter produced by electrospinning technology was a mixture of amorphous carbon and reduced graphite oxide, which increased pseudocapacitance in capacitors, providing an opportunity for further mass production of carbon materials with high capacitance in the future (Mirjalili et al. 2020).

Porous carbon with high surface area and reasonable micropores, mesopores, and macroporous layered structures is an ideal electrode material for capacitors. By utilizing catalytic carbonization and KOH activation, polyethylene terephthalate from waste beverage bottles was effectively converted into layered porous carbon nanosheets with ultra-high specific surface area, and exhibited excellent electrochemical performance in capacitors (Wen et al. 2019). After high-temperature carbonization, waste polyethylene terephthalate mainly generates sp² hybrid carbon, and the activated microporous carbon exhibits lower capacitance. Under

low-temperature carbonization conditions, waste polyethylene terephthalate generates sp^2/sp^3 hybrid carbon, which, after activation, generates layered pores in the carbon material, exhibiting good capacitance (Fig. 5c). The co-etching effect of sp^2/sp^3 hybrid carbon prepared at low temperature was utilized to generate layered porous carbon with a high specific surface area of $2238\text{ m}^2/\text{g}$. Using porous carbon as electrode material, the specific capacitance of the capacitor was increased to 413 F/g at 0.5 A/g , with a good energy storage capacity of 25 W h/kg (Liu et al. 2020). By changing the surface composition of carbon materials and doping N, O, S, and other heteroatoms, the conductivity, surface wettability, and pseudocapacitance of carbon materials in capacitors could be further improved (Hossain and Sahajwalla 2021). The 3D sponge shaped N-doped graphene electrode material prepared by mixing waste polyethylene terephthalate with urea had a specific capacitance of 405 F/g at 1 A/g , and its energy density and the maximum power density reached 68.1 W/h kg and 558.5 W/kg (Elessawy et al. 2019).

Hydrogen energy is considered as the most promising clean energy because of its high energy density and zero carbon emission. And, hydrogen energy plays an important role in achieving carbon neutrality. Water electrolysis for hydrogen production is considered a green and environmentally friendly method, and it is divided into oxygen evolution reaction and hydrogen evolution reaction (Ubaidullah et al. 2020). The efficiency of water electrolysis largely depends on the electrocatalytic performance of the used catalysts. Economical, stable, efficient, and highly active electrocatalysts are crucial for efficient hydrogen and oxygen evolution reactions. Carbon materials prepared from waste plastics with excellent properties make them suitable as catalysts for water electrolysis reactions (Chen et al. 2020). N-doped mesoporous carbon functionalized zinc oxide synthesized from waste polyethylene terephthalate as catalyst provided a large number of active sites and easy charge transfer for water electrolysis (Ubaidullah et al. 2020). The composite material effectively promoted the oxygen evolution reaction, with Tafel slope and overpotential of $\sim 318\text{ mV/dec}$ and $\sim 0.57\text{ V}$, respectively.

Adsorbents used for gas separation or storage through physical adsorption should have some ideal characteristics: mainly micropores, high surface area, hydrophobic surface, and good selectivity for the adsorbed gas (Wiersum et al. 2013). Waste polyethylene terephthalate underwent physical activation to obtain a series of nano-porous carbon (Moura et al. 2018). By determining the adsorption and selectivity of porous carbon on CO_2 under different conditions, it was found that the higher the activation degree of carbon favored the adsorption of CO_2 , while narrow carbon pore was beneficial for CO_2 selectivity. Carbon materials derived from polyethylene terephthalate activated by KOH have the highest CO_2 adsorption capacity compared to activators

including H_3PO_4 , NaOH , ZnCl_2 and H_2SO_4 (Adibfar et al. 2014; Yuan et al. 2020b). On this basis, the optimal ratio of KOH and appropriate carbonization temperature were further studied to prepare carbon materials with a large surface area of $1690\text{ m}^2/\text{g}$, obtaining a maximum CO_2 absorption capacity of 2.31 mmol/g at $30\text{ }^\circ\text{C}$ (Kaur et al. 2019a, 2019b). The high alkalinity provided by nitrogen functional groups increased the affinity for attaching acidic CO_2 molecules, and N-doping improved the absorption and selectivity of carbon materials towards CO_2 (El-Mahdy et al. 2020). The carbon material obtained from the carbonization of waste plastic bottles at $600\text{ }^\circ\text{C}$ was first activated with KOH, and then injected with urea, which was called two-pot pyrolysis. The simultaneous activation of carbon materials with urea and KOH in a tubular furnace was called one-pot synthesis. N-doped carbon materials synthesized by one-pot method exhibited a maximum adsorption capacity of 6.23 mmol/g for CO_2 at $0\text{ }^\circ\text{C}$ and 1 atmospheric pressure (Yuan et al. 2020a).

The method of utilizing solar-driven interface evaporation and limited heating of the water–air interface has been widely used for water purification, seawater desalination, and steam generation due to its low heat loss and high photothermal conversion efficiency. Using porous carbon materials with high porosity, low thermal conductivity, and wide absorption rate as photothermal materials, the evaporation rate of the photothermal conversion interface can be greatly improved in solar steam power generation systems (Chen et al. 2019; Li et al. 2019a, 2019b, 2017b). Irregular and interconnected layered nano-porous carbon was obtained by carbonization of waste polyethylene terephthalate assisted by molten salt of ZnCl_2 and NaCl , showing high surface area, high evaporation rate, high conversion efficiency, and low thermal conductivity. The porous carbon exhibited an evaporation rate of up to 1.68 kg/m^2 per hour and had an energy conversion efficiency of up to 97% in seawater (Zhang et al. 2019a).

Partial destruction of the cross-linked structure during the heating process results in a reduction of the surface area of carbon materials. The addition of molten salt is an effective strategy to solve this problem. The presence of melamine during the carbonization process not only introduced nitrogen groups but also reacted with the degradation products of polyethylene terephthalate to form a strong cross-linked structure, resulting in a more stable N-doped porous carbon which had a high CO_2 adsorption capacity of 6.47 mmol/g and an evaporation rate of $1.62\text{ kg}/(\text{m}^2\cdot\text{h})$ (Song et al. 2022). To introduce hydrophilic groups, reduce the water evaporation enthalpy of foam carbon and significantly increase the evaporation rate, waste polyethylene terephthalate, melamine and molten salt were carbonized by at a low temperature of $340\text{ }^\circ\text{C}$ to generate N- and O-doped foam carbon with super hydrophilicity

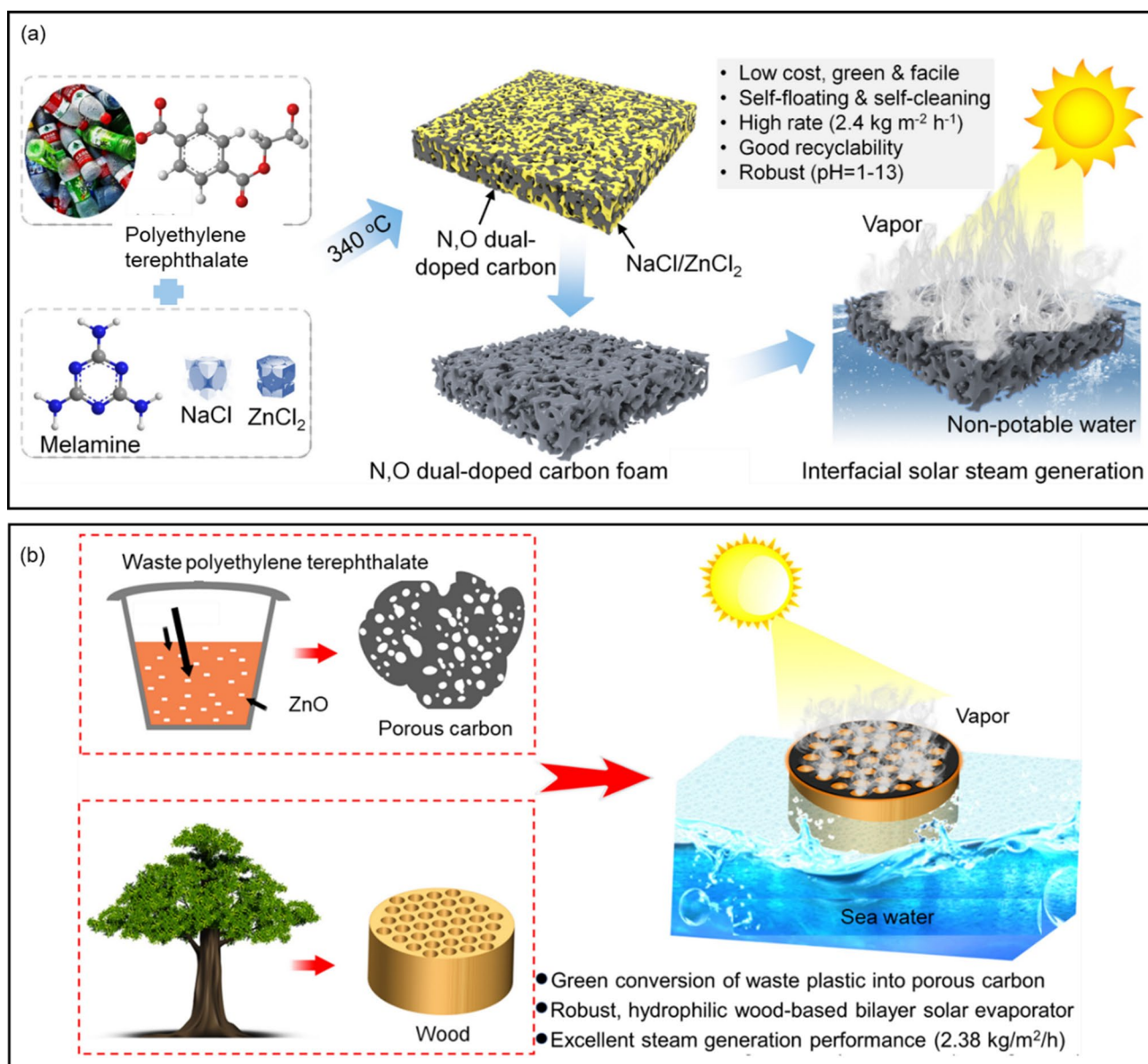


Fig. 6 Carbon materials derived from polyethylene terephthalate for solar evaporation. **a** Carbon foam prepared from waste polyethylene terephthalate carbonized at low temperature for interfacial solar evaporation. Reprinted with permission of American Chemical Soci-

ety from Bai et al. (2022). **b** Preparation of a porous carbon coated wood double layer solar evaporator for solar steam power generation to produce fresh water. Reprinted with permission of Wiley from Liu et al. (2022a)

and ultra-low thermal conductivity. The modification not only achieved about 99% light absorption and photothermal conversion, but also promoted the formation of water groups, reducing the evaporation enthalpy of about 37% water (Fig. 6a) (Chen et al. 2019). Firstly, polyethylene terephthalate was carbonized under the catalysis of ZnO to prepare structurally controllable porous carbon materials. Then, porous carbon was coated on the top surface of the wooden block to construct a wood-based bilayer solar evaporator (Fig. 6b). Due to the synergistic advantage of wood and porous carbon, the wood-based bilayer solar

evaporator had an evaporation rate of up to 2.38 kg/(m²·h). The natural wood structure is conducive to the rapid transmission of water, and the graded porous carbon coated on wood with oxygen-containing groups is beneficial for light absorption (Liu et al. 2022c).

Adsorption is efficient, cost-effective, easy and practical method for removing pollutants (Wang and Wang 2018; Kang et al. 2022). Due to the developed porosity, large surface area, high adsorption efficiency, and chemical stability, carbon materials are often used as excellent adsorbents to remove pollutants (Wei and Kamali 2020).

The effects of physical and chemical activation methods, as well as the types of activators, on the pore structure and surface properties of activated carbon prepared from polyethylene terephthalate were studied (Mendoza-Carrasco et al. 2016). Although the surface area of activated carbon obtained by steam activation reached $1235 \text{ m}^2/\text{g}$, which was greater than that obtained by potassium hydroxide activation. The yield of activated carbon prepared by potassium hydroxide reached 24.62–32.07%, which was significantly higher than that obtained by steam activation. The influence of the impregnation state and potassium hydroxide addition on the preparation of activated carbon was explored. The dry impregnation with a weight ratio of 1:5 polyethylene terephthalate to potassium hydroxide achieved a maximum activation rate of 75.8%, and the activated carbon had a surface area of $1990 \text{ m}^2/\text{g}$, which had a layered porous structure and was more favorable for the adsorption of bisphenol A (Gomez-Serrano et al., 2021). ZnCl_2 and K_2CO_3 were used as activators for the preparation of carbon materials (de Castro et al. 2018). The mesoporous carbon prepared by K_2CO_3 activation had a surface area of $1400 \text{ m}^2/\text{g}$, much higher than that prepared by ZnCl_2 activation, and the adsorption of methylene blue and Victoria blue B reached 625 mg/g and 323 mg/g , respectively.

In addition to the porous structure and large surface area, the π - π bond interaction and electrostatic attraction between the adsorbent and the adsorbate are important factors affecting the adsorption process. To improve the conductivity of carbon materials and provide more π - π interactions to adsorb more aromatic ion dyes, a two-step method based on air carbonization and thermal oxidation control was proposed to convert polyethylene terephthalate into porous carbon materials with conductivity of 37 S/m , demonstrating excellent adsorption performance for methyl orange (Wei and Kamali 2020). To increase active adsorption sites on the surface of carbon materials, ferromagnetic iron oxide was embedded into the activated carbon matrix, and obtained a composite material with an adsorption capacity of 71.42 mg/g for cephalexin, which was three times higher than that of pristine activated carbon (Rai and Singh 2018). The carbon matrix served as a stable carrier, while magnetic metal oxides not only provided magnetic mobility and facilitated controlled navigation of composites in the application process, but also provided Fe-O bonds as nucleation sites to enhance cephalexin adsorption. The polyethylene terephthalate derived carbon had a high porosity and available Cu (II) adsorption center, with an adsorption capacity of up to 62.9 mg/g for dibenzothiophene (Fayazi and Ghanei-Motlagh 2021). The tomatoes and carrots were combined with polyethylene terephthalate after activation to prepare a composite adsorbent and the adsorption capacity was 312.50 mg/g Co (II) (Changmai et al. 2018)).

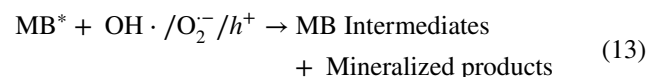
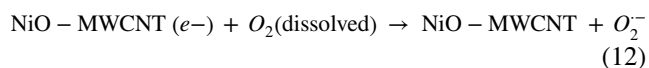
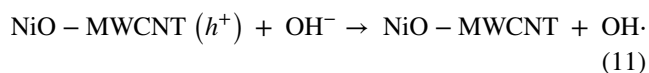
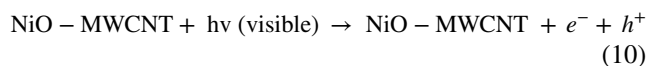
Polyethylene

Polyethylene can be easily decomposed into small molecules upon heating due to its unstable molecular chains. The melting point of low-density polyethylene is between $120 \text{ }^\circ\text{C}$ and $180 \text{ }^\circ\text{C}$, resulting in poor thermal stability during carbonization (Khan et al. 2017; Li et al. 2018a). Layered porous carbon with large surface area and abundant surface groups was obtained after carbonization and activation of low-density polyethylene under autogenous pressure (Zhang et al. 2019b). Gas substances generated from thermal decomposition of polyethylene formed a high-pressure environment and the short chain aliphatic hydrocarbons underwent aromatization and further condensed to form a carbon layer. The capacitance of the porous carbon electrode reached 355 F/g under the condition of 0.2 A/g , and the power density was 450 W/kg .

In order to avoid the use of expensive and toxic NH_3 as activators, graphene/mesoporous carbon composites with large surface area and a large number of mesopores were obtained by adding the optimal proportion of graphite oxide. The combined action of alkaline magnesium carbonate and graphite oxide improved the thermal stability and flame retardancy of waste polyethylene, thus greatly increasing the final carbon yield (Lian et al. 2019b). The composite carbon material had an energy density of 63.3 W h/kg in symmetric supercapacitors, and the cycling stability improved to 89.3% after 5000 cycles (Lian et al. 2019b, 2019a).

Sulfonation is a crosslinking method that can improve the thermal stability of polyethylene. In order to achieve deep sulfonation, porous polyethylene reprecipitation blocks were prepared in toluene and water mixed system (Li et al. 2016). The thermal stability of polyethylene was significantly improved, and the carbonization yield at $700 \text{ }^\circ\text{C}$ was 51.9%. However, the carbon yield of the method is limited for potential application. The innovative solvent thermal cycling method generated high pressure at low temperatures and improved polyethylene sulfonation, increasing the total mass retention rates of low-density polyethylene and high-density polyethylene in sulfonated materials to 50% and 46% (Villagomez-Salas et al. 2018). Lithium ion battery composite anodes using carbon materials derived from low-density polyethylene and high-density polyethylene generated specific capacities of 230 and 350 m Ah/g , respectively. In addition, the use of microwave technology not only promoted the sulfonation of low-density polyethylene, but also induced a large number of pores in the carbon derived from sulfonated polyethylene (Kim et al. 2018). The as-prepared porous carbon was a conductive support with negative charge. When the porous carbon was used as the intermediate layer of lithium-sulfur battery, the capacity of the sulfur cathode at 0.5 C was 776 mA h/g , and the cycle retention rate reached 79% in 200 cycles.

Carbon materials derived from waste plastics have been used as catalysts for oxidation degradation of organic pollutants in wastewater (Wang et al. 2022b, 2023). Photocatalysis is an attractive strategy to utilize renewable solar energy to degrade pollutants (Ivanets et al. 2021). During the photocatalytic process, when exposed to light of appropriate wavelengths, photocatalysts generate excited electrons and strong oxidation holes, which can quickly degrade pollutants. In addition, hydroxyl radicals can be generated during the photocatalytic process, breaking down organic pollutants into non-toxic or less toxic compounds such as CO₂ and H₂O (Li et al. 2021a; Liu et al. 2022c; Wang et al. 2022c). Multi-walled carbon nanotubes or carbon and metal oxide composites have been used as photocatalysts to degrade organic pollutants under visible light (Mohamed and Alsanea 2020; Nath et al. 2021). The band gap of nickel oxide–multiwall carbon nanotube composite derived from waste polyethylene was 3.02 eV, which absorbed visible light and induced the degradation of methylene blue, with an efficiency of 92.4% (Nath et al. 2021). The conduction band and valence band of nickel oxide–multiwall carbon nanotube generated electrons and holes separately under visible light irradiation (Eq. 10). Hydroxyl ions adsorbed on nickel oxide–multiwall carbon nanotube catalysts containing holes to generate hydroxyl radicals (Eq. 11). The electrons in the conduction band reacted with dissolved oxygen to generate oxygen radicals (Eq. 12). Subsequently, free radicals reacted with methylene blue dye for decolorization (Eq. 13).



In addition, advanced oxidation process is another effective way to degrade organic pollutants, based on the activation of persulfates or hydrogen peroxide to produce active radicals for oxidation of pollutants (Liu et al. 2023a, b). With its high chemical stability, low cost and high oxidation potential, persulfates have been widely used as oxidants in the in situ chemical oxidation of groundwater or soil remediation (Wu et al. 2021). Non-noble metals such as Co and Fe can activate persulfates without any light source or heat, and porous materials as anchoring support of metal particles greatly enhance the activation ability (Pi et al. 2019; Pu et al. 2020; Zhang et al. 2019c). The iron carbon composite prepared by co-carbonization of polyethylene and goethite activated persulfate to produce OH· and SO₄^{·-} for the oxidation

of amaranth (Kwon et al. 2021). The catalytic ability of the composite well maintained after 10 cycles for amaranth degradation. Carbon nanotubes produced from waste plastics were tested in advanced oxidation process for persulfate activation to remove micropollutants (Ribeiro et al. 2022). Using low-density polyethylene as carbon source, carbon nanotubes were grown on Al₂O₃, Ni, Fe and Al catalysts by chemical vapor deposition, and the carbon nanotubes showed the best performance of venlafaxine removal of 3.17 mg/g/h in ultrapure water.

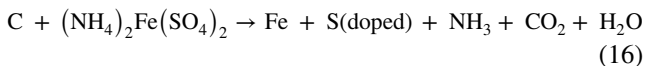
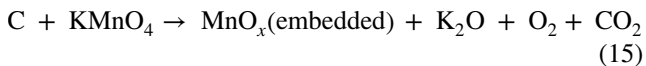
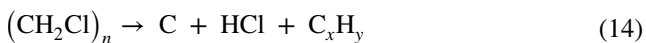
In order to increase the high yield of carbon nanotubes, oleamine can be used as a protective agent. Using waste polyethylene and cobalt nitrate as carbon sources and catalyst precursors, carbon nanotubes with the yield of 59.0% were obtained under the protection of oleamine, and the adsorption capacity for methylene blue reached 107.1 mg/g. By combining carbon nanotubes with graphite oxide through hydrothermal and freeze-drying processes, graphene carbon nanotube aerogel was successfully prepared and exhibited low density, high porosity and excellent hydrophobicity, manifesting high adsorption capacity of 410 mg/g oil or organic solvent (Huang et al. 2021).

Waste from halogenated plastic

Waste plastic containing F and Cl can emit extremely dangerous byproducts during carbonization, such as Cl₂, HCl, and organic chlorinated compounds. Therefore, halogenated plastics need to be dehalogenated before carbonization. An effective dehalogenation method of converting polyvinyl chloride into carbon materials was by ball milling with KOH and N- or S-doping, while forming clean KCl and H₂O by-products. In water-based symmetrical supercapacitors, carbon materials derived from polyvinyl chloride were used as electrodes and exhibited excellent performance. At 1.0 A/g, the specific capacitance reached 399 F/g (Chang et al. 2018).

A simple in situ synthesis method of S-doped graphitized carbon composite using polyvinyl chloride as a carbon source was reported (Gao et al. 2015). Pyrolysis of polyvinyl chloride underwent dehalogenation, producing carbon monomers and hydrocarbons (Eq. 14). KMnO₄ was also thermally decomposed and reduced, producing MnO_x and emitting CO₂ and O₂ (Eq. 15). (NH₄)₂Fe(SO₄)₂ serves as a graphitization catalyst and doped S source. Polyvinyl chloride carbon reduced Fe²⁺ ions to Fe metals at high temperatures, and the SO₄²⁻ anion was also reduced by carbon to S, allowing S to be doped into the graphitized carbon during the graphitization process (Eq. 16). Under the catalysis of Fe, polyvinyl chloride underwent thermal decomposition and carbonization, ultimately forming an S-doped graphitized carbon supported MnO_x hybrid. The oxides of Mn and S in the composite improved the catalytic activity of oxygen evolution and oxygen reduction reactions. Molybdenum carbide

is one of the transition metal carbides. Due to the change of its electronic characteristics, it has reached a special level similar to Pt as a catalyst and has received special attention. The synthesis of molybdenum carbide carbon nanocomposites using waste plastics promoted electrocatalytic activity and exhibited stable electrocyclic performance (Mir and Pandey 2019).



The recovery of calcium-based compounds in polyvinyl chloride through activation and acid washing was beneficial for the formation of micropores and the adsorption of carbon dioxide (Liu et al. 2022b). Structural characterization showed that the prepared carbon had a high specific surface area and pore volume, up to 2507 m²/g and 1.11 cm³/g, respectively. Porous carbon materials prepared from polyvinyl chloride exhibited excellent CO₂ adsorption capacity of 6.90 mmol/g. Spherical carbon materials reduced the flow resistance and wear inside the adsorption bed at the macro level, and had a large surface area, high chemical stability, and good recyclability at the micro level, thus possessing large CO₂ capture ability (Pardakhti et al. 2019).

Polyvinylidene chloride and melamine were used as carbon source and nitrogen source for co-carbonization in alginate gel beads to develop a high compressive strength N-doped porous carbon, showing excellent CO₂ capture capacity (Li et al. 2021c). During the carbonization process, melamine was not only used as a nitrogen source, but also as a template for macroporous structures. Due to the thermoplastic nature of polyvinyl chloride, direct carbonization of polyvinyl chloride cannot produce target shapes. However, the use of tetrabutylammonium bromide and NaOH promoted dechlorination and oxidative crosslinking within the polyvinyl chloride sphere, transforming thermoplastic polyvinyl chloride into thermosetting and maintaining its sphericity. The porous carbon spheres obtained after carbonization had a large surface area and good microporous structure, with CO₂ adsorption capacity of 8.93 mmol/g at 0 °C (Wang et al. 2020).

Hydrothermal treatment at a relatively low temperature of 160–300 °C can be used for dehydrochlorination of waste polyvinyl chloride (Ma et al. 2019). Sulfonation introduces a large number of surface groups of carbon materials, such as –OH, –COOH and lactone, as well as –SO₃H groups, thus improving the hydrophobic properties (Konwar et al. 2019). Carbon derived from polyvinyl chloride was synthesized through hydrothermal treatment and sulfonation reaction.

The removal rates of Cu (II) and Cr (VI) by polyvinyl chloride derived carbon were 81.2% and 60.3%, respectively (Xu et al. 2022).

Polypropylene and polystyrene

Due to the high carbon content of waste polystyrene, it has been studied for the preparation of carbon materials suitable for different fields. Using MgO as a template and KOH as an activator, the carbon nanosheets produced by the carbonization of polystyrene exhibited good specific capacitance and rate capacity, as well as excellent cycling stability (Ma et al. 2020). Iron coagulation can effectively separate polystyrene microplastics from aqueous solution (Wang et al. 2021, 2022d). Then the high-temperature carbonization of coagulated waste plastics promoted the reduction of iron, improved the catalytic activity of iron and carbon nanomaterials, and the removal rate of Rhodamine B reached 97.57%. A series of porous carbon nanosheets were prepared using templates such as MgO, Mg(OH)₂, MnO₂, and Fe₂O₃. The carbon nanosheets used as electrodes showed improved electrochemical performance of supercapacitors (Ma et al. 2020; Min et al. 2019). Using MgO as a template and KOH as an activator, the carbon nanosheets with mesopores, micropores, and high surface area were produced by carbonization of polystyrene. Porous carbon nanosheets exhibited good specific capacitance and rate capacity, as well as excellent cycling stability (Ma et al. 2020). As a transition metal oxide, MnO₂ is one of the most promising pseudo-capacitor materials. To improve the inherent conductivity, MnO₂ was deposited on the porous carbon nanosheets from polystyrene. The high surface area and conductivity of the porous carbon had a positive synergistic effect with the inherent specific capacity of MnO₂. The obtained composite exhibited excellent capacitance retention of 93.4% at 10,000 cycles of 10 A/g (Min et al. 2019). The addition of Fe₂O₃ and urea carbonization to polystyrene resulted in the formation of 3D porous carbon. The porous carbon was activated by KOH to form a 3D hierarchically porous carbon with micropores and coexisting hollows (Fig. 7a) (Ma et al. 2020). When the 3D hierarchically porous carbon was used as magnetic nanocarbon adsorbent, the adsorption capacity of Tetrabromobisphenol A reached 117.0 mg/g. After five cycles, the adsorption capacity of Tetrabromobisphenol A remained about 85.5%.

Polypropylene is investigated for preparing carbon materials such as carbon nanosheets, carbon nanotubes, porous carbon, and carbon composites. To increase the yield of carbon nanosheets, the combination catalyst of ferrocene and sulfur was used for efficient carbonization of waste polypropylene into carbon nanosheets. After catalytic activation, the thickness of the nanosheets was only 4–4.5 nm, exhibiting a porous structure and a high specific capacitance of 349 F/g

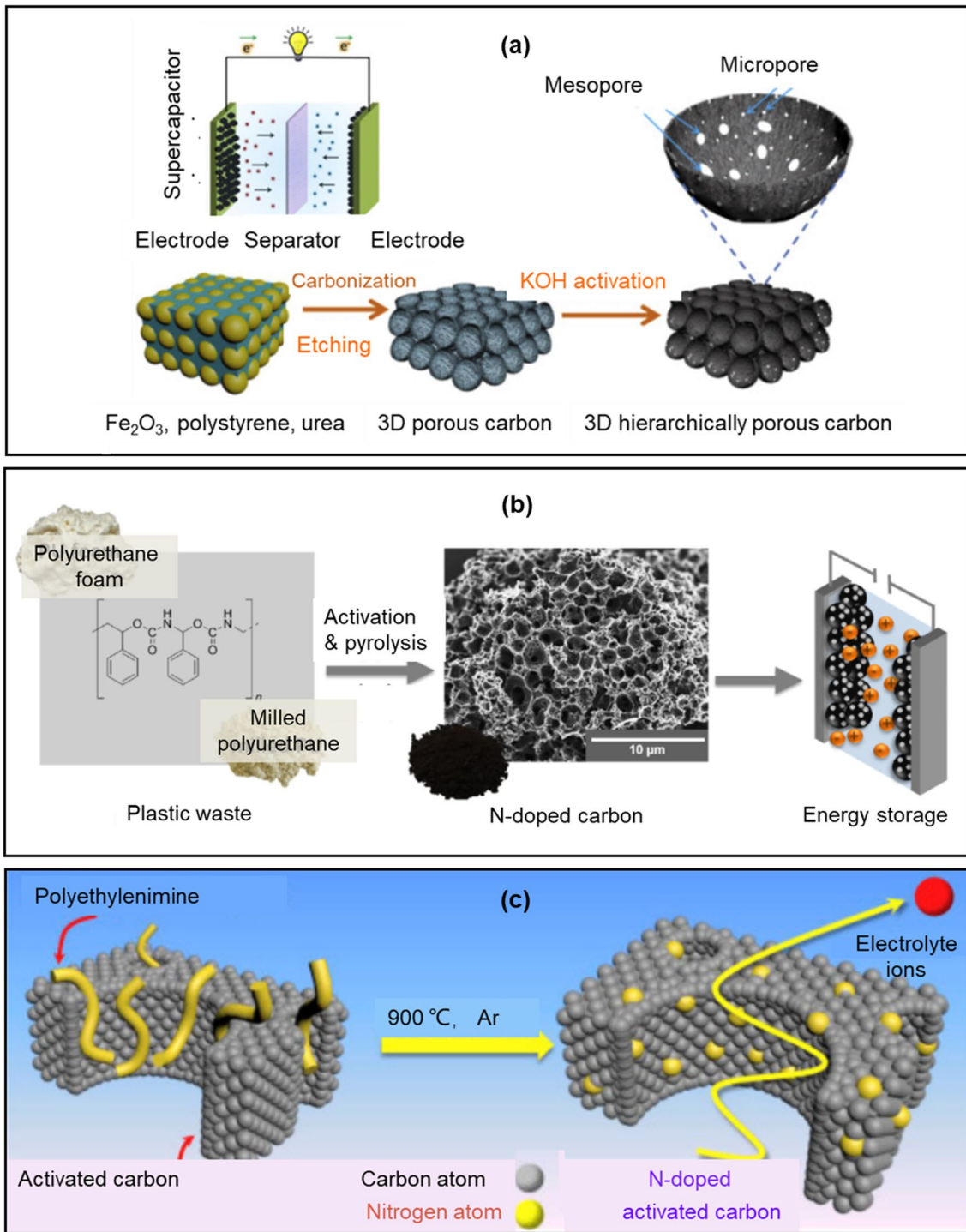


Fig. 7 Carbon materials with different morphology obtained from polystyrene, polyurethane, and polyethylenimine. **a** Synthesis of 3D porous carbon prepared by carbonization of polystyrene. Reprinted with permission of Elsevier from Ma et al. (2020). **b** N-doped porous carbon prepared from carbonized polyurethane foam for supercapaci-

tor. Reprinted with permission of Beilstein-Institut from Schneidermann et al. (2019). **c** Preparation of N-doped activated carbon by the carbonization of polyethylenimine. Reprinted with permission of Elsevier from Zhang et al. (2019d)

(Liu et al. 2021b). Although high surface area and porous structure help improve the accessibility of electrolyte ions, improving the graphitization and crystallinity of carbon

materials can reduce the internal resistance of electrodes. A method of combining catalyst and template was reported to obtain graphitic carbon with high surface area and

conductivity (Urgunde et al. 2020). Using nickel composite ink as a catalyst and macroporous sugar as a soft template, the conductive carbon graphite obtained as an electrode had a specific capacitance of about 158 F/g at 1 A/g, exhibiting excellent cycling stability.

After the COVID-19 epidemic, a large number of disposal masks were discarded, which caused some pollution to the environment (Jiang et al. 2022b, 2022c; Dharmaraj et al. 2022). The preparation of valuable carbon materials from waste disposal masks mainly composed of polypropylene through different carbonization methods is a promising solution (Mghilia et al. 2022). Using melt blown cloth from discarded masks as precursor and nickel metal catalysis, carbon-based composites were obtained and used as negative electrode materials for lithium-ion batteries, providing a specific capacity of 479 m Ah/g (Li et al. 2022a). Another sulfonation and carbonization method produced a type of carbon electrode material with a hollow fiber porous structure (Hu and Lin 2021). Due to the combined action of sulfonic acid groups and KOH, the formation of dense porous carbon structure was promoted, which favored the rapid diffusion of ions, resulting in a high specific capacitance of 328.9 F/g at 1 A/g. In addition, the problem of low carbon yield during the chemical vapor deposition in catalytic carbonization has been solved through microwave assisted hydrothermal method and catalytic carbonization (Gong et al. 2014b; Lee et al. 2022). The polypropylene-based disposable masks were sulphonated by sulfuric acid and then heated to 2400 °C to convert into non-graphitized carbon powder. Used as the anode material of sodium-ion battery, the graphitized carbon electrode had the highest reversible capacity of 340 m Ah/g and superior rate performance at a current of 0.01 A/g (Lee et al. 2022).

In recent decades, efforts have been made to develop low-cost, efficient, and stable hydrogen evolution reaction electrocatalysts to replace low abundance and high cost platinum based electrocatalysts. A key challenge in designing electrocatalysts is to obtain a large surface area, and the hetero carbon structure prepared by high-pressure carbonization of waste plastics has a higher surface area compared to other reports, making it an efficient and low-cost candidate for hydrogen evolution reaction electrocatalysts (Louisia et al. 2018; Mir et al. 2020b; Padilla et al. 2018).

Molybdenum carbide is considered to be the most promising electro-catalyst to replace platinum-based catalysts due to its high conductivity and similar D band structure (Miao et al. 2017). The composite formed by loading Mo₂C onto a carbon material derived from waste polypropylene exhibited higher stability and improved electrocatalytic hydrogen evolution reaction in acidic media (Mir and Pandey 2018). By comparing the impacts of amorphous and graphite coatings on the properties of the composite, amorphous carbon coatings exhibited better electrocatalytic stability in acidic media

(Liu et al. 2019; Mir and Pandey 2018; Wei et al. 2018). On this basis, a method of loading Mo₂C onto N-doped carbon was developed in autoclave using waste plastic as carbon source. The synergistic effect of N-doped carbon coating and Mo₂C improved the electronic conductivity and charge storage capacity of the composite, and the material surface provided a large number of active sites, which enhanced the activity and stability of hydrogen evolution reaction, showing a higher current density of 60 mA/cm², and the stability reached 2000-V ampere cycles (Mir et al. 2020a).

In order to explore the relationship between the morphology of carbon materials and the performance of solar steam generators, a method for preparing Ni and carbon nanocomposite was proposed through carbonization of waste polypropylene, NiO, and poly (ionic liquid) (Song et al. 2020). The composites had a large surface area and three-dimensional network structures with porous structure. The morphology and structural properties of the composite material was adjusted by adding a small amount of poly(ionic liquid). The synergistic effect of Ni and cup-shaped carbon nanotubes in solar energy absorption endowed the composites with excellent photothermal conversion performance, resulting in excellent performance in solar energy absorption, water permeability, and thermal conductivity. This composite material had a high moisture evaporation rate of 1.67 kg/m²/h and an excellent solar steam conversion efficiency of 94.9%.

In addition to using catalysts to induce the formation of carbon nanotubes on its surface, the combination of halogen compounds and NiO catalysts effectively synthesized cup-shaped carbon nanotubes, exhibiting high performance in adsorbing heavy metals and organic dyes (Gong et al. 2014d). Low content halogenated compounds promoted the formation of light hydrocarbons and aromatic hydrocarbons, improved the aggregation and reconstruction of NiO catalysts towards diamond-shaped structures. The diamond-shaped NiO catalyzed the conversion of light hydrocarbons and aromatic hydrocarbons into cup-shaped carbon nanotubes. Moreover, polypropylene is considered as an excellent additive for biomass carbonization, which can be used as a hydrogen supplement to promote pore formation and generate porous carbon materials (Li et al. 2021b). The porous carbon obtained from the carbonization of blue-green algae and polypropylene plastic had a high surface area and pore volume, exhibiting excellent adsorption capacity of 667 mg/g for methylene blue (Li et al. 2022b).

Polyurethane

Polyurethane is an ideal raw material for preparing N-doped porous carbon due to its high C and N content. However, during the carbonization process, the cracking of polyurethane bonds and the evaporation of volatile products result in a particularly low yield of carbon materials. The

polyurethane foam was successfully converted into N-doped porous carbon by in situ atmosphere carbonization and KOH activation, and the N-doped porous carbon as capacitor electrode had a high specific capacitance of 342 F/g at 0.5A/g, energy density of 11.3 W h/kg, and power density of 250 W/kg (Zhou et al. 2022). In addition, N-containing carbon materials synthesized by mechanical milling and carbonization of polyurethane foam had high surface area and porosity, which enhanced the amplification ability of supercapacitors (Fig. 7b) (Schneidermann et al. 2019).

Waste polyurethane contains abundant O and N heteroatoms, which can improve the adsorption capacity of carbon materials. The CO₂ adsorption capacity of porous carbon prepared from waste polyurethane foam under the optimal conditions was 6.67 mg/g at 0 °C. Physical adsorption dominated by micropores played an important role in CO₂ adsorption, with approximately 80% of CO₂ adsorption capacity coming from physical adsorption, and the remaining 20% from chemical adsorption caused by the interaction between alkaline N groups and acidic CO₂ molecules (Duan et al. 2018; Ge et al. 2016). After carbonization of waste polyurethane, it was beneficial for the preservation and utilization of nitrogen and oxygen elements in carbon materials, and did not cause secondary pollution. Activated carbon prepared by carbonization and physical activation had a maximum adsorption capacity of 1428 mg/g for malachite green dye. The malachite green in wastewater was removed through physical adsorption, and electrostatic attraction, oxygen-containing groups, and π - π interactions were the driving forces for the excellent adsorption performance (Li et al. 2021d).

Other waste plastics

In order to prepare highly active carbon materials, N, B, P and S atoms were doped into carbon matrix, and this can adjust the electronic state and create active sites. However, nitrogen sources into carbon materials have the drawbacks of low doping and uneven mixing. Due to that low boiling point or decomposition temperature, nitrogen sources such as NH₃, aminomethane, urea are prone to decomposition under high-temperature carbonization, resulting in low nitrogen doping in carbon materials. Some nitrogen sources have low solubility in a range of solvents, making it difficult to form a uniform mixture with plastics. Polyethyleneimide has excellent water solubility and high viscosity, which delayed the diffusion of nitrogen atoms in the process of nitrogen doping, extended the contact time with carbon at high temperature, and improved the nitrogen doping level of carbon materials. N-doping was successfully obtained through mixing activated carbon and polyethyleneimide and high temperature carbonization (Fig. 7c) (Zhang et al. 2019d). The N-doped layered porous carbon derived from

polyacrylonitrile had excellent specific capacitance, large surface area, high mesoporous content, and fast ion transport ability. N-doped porous carbon as an electrode material for capacitive deionization provided high electro adsorption capacity of 19.61 mg/g and had the ability to remove heavy metal ions such as Pb²⁺, Cd²⁺, and Cu²⁺, with capacities of 21.5, 30.02, and 36.3 mg/g, respectively (Wang et al. 2022a).

Doping sulfur-containing groups into the carbon matrix can obtain carbon materials which had unique physical and chemical properties such as good conductivity, excellent catalytic activity and excellent chemical stability (Kiciński et al. 2014). The S-doping process makes the sulfur group uniformly distributed in the whole matrix and permanently fused into the carbon skeleton. The obtained carbon showed excellent performance in the activation of persulfate and was used for the catalytic oxidation of aqueous organic pollutants (Guo et al. 2017, 2018a, c). Using polyphenylene sulfide as precursor and KOH as activator, the S-doped activated carbon was prepared and exhibited high performance in the adsorption and oxidation removal of phenol organic compounds (Guo et al. 2018b). In this process, the organics were preferentially degraded in situ to accelerate adsorption, and then adsorption and oxidation synergize to promote the effective removal of organics.

Mixed plastics

Previously reported methods were mostly limited to single plastic, while "real world" waste plastics typically contain many components, such as polypropylene, polyethylene, polystyrene, polyethylene terephthalate, and polyvinyl chloride, severely hindering the application of previous methods (López et al. 2011). Wen et al. carbonized the waste plastics, such as waste woven bags, waste containers, waste foam sheets, waste beverage bottles and waste sewage pipes to produce porous carbon nanosheets with multi-stage porous structure and high surface area (Wen et al. 2019). Zhao et al. used industrial waste plastics such as melamine and polyurethane to prepare conductive N-doped carbon carrier through combining with highly catalytic MoS₂ nanosheets, and it improved the conductivity and electrocatalytic activity of the composite material and promoted the progress of hydrogen evolution reaction (Zhao et al. 2020). In order to improve the photocatalytic activity of carbon materials for pollutant degradation, carbon-based TiO₂ nanocomposite from waste car bumper was used as catalyst for photocatalytic degradation of methylene blue (Mohamed and Alsanea 2020).

Waste printer plastics, waste bicycle rubber tubes, and waste blister packs were used to prepare high-performance carbon materials. Using waste printer plastic as the precursor obtained the activated porous carbon which exhibited excellent rate capacity with a transmission capacity of reached 3 mA h/g at 190 mA/g (Kumar et al. 2019). The defective

engineering graphene turbine layer carbon prepared by the waste blister packs at a higher activation temperature had a pleated shape similar to graphene. When it was used as anode of lithium-ion battery, it provided excellent electrochemical characteristics and promoted faster Li^+ diffusion. At a current rate of 0.1 C, the storage capacity of Li-ion was 594 mA h/g after 200 cycles (Kumar et al. 2022).

Recently, a large number of studies showed that electrochemical activity of lithium ion battery anode was developed by carrying metal oxide core and porous carbon shell structure (Hong et al. 2021; Liu et al. 2021a). Min et al. obtained the core-shell structure of SnO_2 loaded on porous carbon sheets by uniformly inserting nano- SnO_2 spheres and cubes, block shaped SnO_2 sheets and blocks into hollow carbon spheres derived from waste plastics. The high storage capacity SnO_2 egg yolk and hollow carbon shells were closely connected, providing sufficient internal space, limiting the fragmentation of nanospheres and cubic SnO_2 , enhancing the storage capacity and capacity of Li^+ (Min et al. 2022).

In addition, in order to limit the gradual diffusion of lithium polysulfide from the cathode interface caused by the shuttle effect, which disrupted the cycling stability of lithium-sulfur batteries, the pyrolysis residue of waste plastic was used as the cathode sulfur main body of lithium-sulfur batteries to limit the shuttle effect. The significant N defects in the prepared carbon material facilitated chemical interaction with the Li portion in polysulfides, while the $\text{TiO}_2\text{-x}$ formed after heat treatment effectively inhibited the diffusion of intermediates. N defects and $\text{TiO}_2\text{-x}$ inhibited the escape of lithium polysulfide from the bulk electrolyte through chemical adsorption, resulting in a decrease in the decay rate of the prepared carbon at 1 C to 0.089% per cycle until 500 cycles, with a capacity of 512 mA h/g (Kim et al. 2022). In addition, a barrier layer outside the cathode to suppress the shuttle effect was studied (Lee et al. 2019; Park et al. 2020). Through heat treatment of waste plastics with CaCO_3 nanoparticles and boric acid, the porous bridge carbon was obtained and used as lithium sulfur batteries modified separator (Gim et al. 2021). The co-doping of boron and nitrogen provided strong attraction for lithium polysulfide, accelerating the electrochemical redox reaction and exhibited excellent electrochemical performance and cycle stability.

Based on the porous carbon nanosheets which obtained from carbonization of mixed waste plastics, the adsorption capacity of porous carbon nanosheets for pollutants was further studied. The adsorption capacity of porous carbon nanosheets for methylene blue was 769.2 mg/g, significantly higher than most reported adsorbents, and carbon nanosheets had excellent recyclability. After 10 cycles, approximately 90% of porous carbon nanosheets were recovered (Gong et al. 2015, 2014c). In addition, waste plastics were converted into activated carbon with large surface area and

abundant surface groups, improving the removal performance of dye. The removal efficiency of thymol blue dye was up to 98.05% observed on the activated carbon (Kumari et al. 2022).

The adsorption capacity of char derived from was plastics for absorb arsenic not only depended on the char dosage or the solution pH, but also on the sources of plastics (Singh et al. 2020). The adsorption effect of low-cost carbon synthesized by carbonization of waste polyvinyl chloride, polyethylene terephthalate, and polyethylene on arsenic was compared, and polyethylene and polyvinyl chloride mixed char had the highest removal rate of arsenic, ranging from 71.6% to 99.4%. Through a more environmentally friendly and economical carbon dioxide capture route, porous carbon with high CO_2 capture capacity was obtained by using waste plastic for carbonization in the presence of potassium salt (Algozeeb et al. 2022).

Perspective

One of the main challenges in producing carbon materials from waste plastics is the economic feasibility of the production process. Currently, although waste plastics have a wide range of sources and low price, their composition are complex and lacking efficient and cost-effective carbonization methods. The production cost of carbon derived from waste plastics is higher than that of traditional carbon materials. It is particularly important to explore the preparation methods of mixed plastics, providing more methods and avenues for treating mixed plastic products in the environment.

Another challenge is the environmental impact associated with the carbonization of waste plastics. For the pretreatment of oxygen free polymers such as polypropylene, polystyrene, polyvinyl chloride, it is necessary to stabilize the carbon chain using sulfuric acid or use catalyst templates to catalyze the production of carbon materials, and then remove the templates through acid washing. If the former is not properly controlled, it generates harmful emissions, such as volatile organic compounds and greenhouse gases. If the latter is not properly handled, strong corrosive acids may pollute the environment and even the public health.

From the perspective of carbon source selection, the composition of waste plastics is complex and it is difficult to extract individual plastic components. Moreover, previous methods are mostly used to prepare carbon-based materials from single plastic, while it remains challenging for preparing carbon materials from mixed plastics. Therefore, we should explore more effective carbonization methods to treat mixed waste plastics, and reduce the harm of waste plastics to the environment.

It is worth noting that the use of flash Joule heating and microwave conversion technology can quickly and efficiently

produce high-quality graphene and carbon nanotubes. In the carbonization process, we should pay more attention to the process optimization of the methods and explore feasible methods on a large scale. It is particularly important for quickly treating accumulated waste plastics and reducing environmental pressure.

Designing low-cost catalysts is crucial for converting plastics into carbon materials. Although carbon materials and their composites derived from waste plastics using catalysts have shown good performance in applications, the mechanism by which they catalyze the formation of carbon materials during the experimental process is still unclear. The use of instruments to monitor the in situ conversion of plastics is crucial for understanding their catalytic mechanisms and designing low-cost catalysts.

Several factors need to be considered in the design of the next generation of functional carbon materials derived from waste plastics. First of all, it is important to design the porosity of carbon materials. Existing chemical activation methods which improve the porosity and surface area of carbon may be harmful to the environment, and more green methods should be explored to mitigate environmental hazards. In addition, chemical doping and the introduction of functional groups significantly improve the physical and chemical properties of carbon materials, but high-temperature carbonization may damage their elemental doping content. The most appropriate balance between temperature and elemental doping should be explored to maximize the performance of carbon materials. In addition, composite materials by combining carbon materials derived from waste plastic with other materials, including transition metal oxides, single atom catalysts, and transition metal sulfides have received more attention.

Conclusion

Waste plastics from various sources such as packaging, agricultural and building industries can be used to fabricate functional carbon materials. Plastics with different polymer types or applications exhibit different physicochemical properties. By using different carbonization methods such as oxygen-limited carbonization, template-based carbonization, catalytic carbonization, pressure carbonization, flash Joule heating, and microwave conversion, waste plastics are converted into diverse carbon materials, such as carbon nanotubes, graphene, carbon nanosheets, carbon sphere, and porous carbon. Factors affecting the morphology and properties of the prepared carbon materials are discussed, and carbonization methods, plastic sources, catalysts, and carbonization temperature are the main factors affecting the morphology of carbon materials. By adjusting its porosity, surface area, heteroatom doping or functional groups,

the electrochemical, adsorption, and catalytic performance of carbon materials in batteries, supercapacitors, pollutant removal by adsorption or degradation, solar evaporation, and carbon dioxide capture systems are improved. Transforming waste plastics into functional carbon materials enables the recycling of waste plastics and the mitigation of environmental pollution, favoring circular economy.

Author contributions All authors contributed to the study conception and design. Material preparation, data collection and analysis were performed by YL and CW. EL, XL, and HJ contributed to the revision of the manuscript.

Declarations

Conflict of interest The authors have no relevant financial or non-financial interests to disclose.

Consent for publication All authors read the manuscript and approved for publication.

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