Advanced Composites and Hybrid Materials (2020) 3:443–461
https://doi.org/10.1007/s42114-020-00190-0

REVIEW

Research progress for plastic waste management and manufacture of value-added products

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Received: 1 October 2020 / Revised: 28 October 2020 / Accepted: 14 November 2020 / Published online: 21 November 2020

Abstract

Nowadays, plastic products are closely related to human life. While it brings convenience to human beings, there are also great health and environmental threats. Most of the plastic products are polymer compounds obtained by addition polymerization or condensation polymerization. It will cause chronic poisoning to humans if long-term use plastic products are used. In addition, due to the relatively low production cost and short service life of plastic products, a large amount of waste plastics is discarded every year, which causes serious environmental problems. Traditional disposal technologies such as landfill and incineration not only waste a lot of resources but also accompany serious secondary pollution problems. In order to meet the needs of sustainable development and green environmental protection, various recycling methods have been explored for waste plastics, which have been used to develop economic and environmentally friendly value-added products. This paper reviews a range of management methods for the increasingly severe problem of discarded plastics and briefly summarizes the advantages and disadvantages of some methods, lists some examples of more valuable recycled products and materials, and finally puts forward the improvement direction and challenge to solve this problem.

Keywords Waste plastics · Recycling · Management methods · Value added products · Challenges

1 Introduction

As a member of three major synthetic materials, plastics have the characteristics of light weight, high strength, good insulation, and corrosion resistance and have brought a huge material civilization wealth to human beings. Plastic is called one of the greatest inventions in modern times [1–4]. With the continuous development of manufacturing technology, plastic products are gradually replacing traditional materials in various fields. Continuous updated data shows that global plastic production has grown at an average rate of 2.7 times per year since 1950. As of 2018, global plastic production is about 359 million tons (MT) [5], as shown in Fig. 1. Among them, China's total plastic product is about 60 MT, which has been the world's largest producer and consumer of plastics. The development experience of countries around the world shows that the more developed the economy, the greater the consumption of plastic products. According to statistics, the annual consumption of plastics per capita in the USA is about 170 kg, Belgium is about 200 kg, China is about 46 kg, and India is only 9.7 kg.

According to the change of physical and chemical properties before and after heat treatment, plastics can be divided into thermoplastics and thermosetting plastics [9, 10]. Thermoplastic plastics such as polyethylene (PE), polyvinyl chloride (PVC), polypropylene (PP), polystyrene (PS), polycarbonate (PC), and polytetrafluoroethylene (PTFE) [11–14] can be softened or melted into any shape under heating conditions and solidified when cooled, which can be repeatedly deformed with typical plasticity [15]. Thermosetting plastic does not undergo plastic deformation when heated; instead, they would be decomposed when the temperature continues to rise [16–18]. Typical representatives are epoxy resin, phenolic

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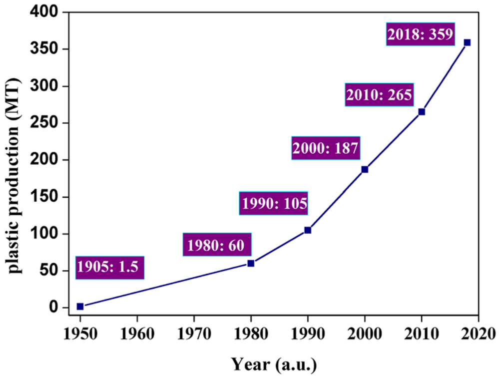


Fig. 1 The global plastic production from 1950 to 2018 (the data is referenced from references [5–8])

resin, urea-formaldehyde resin, organosilicon resin, and so on. According to the specific application, plastics can be divided into general plastics, engineering plastics, and functional plastics [19, 20]. General plastics are rich in sources, large in production, wide in application, low in cost, and easy to shape and process [19, 21]. PE, PVC, PS, PP, polymethyl methacrylate (PMMA), etc. are all general plastics [22, 23]. Engineering plastics have excellent comprehensive properties such as good stiffness, toughness, and temperature resistance, which can be used as engineering structural materials instead of metals [24, 25]. It contains PC, polyethylene terephthalate (PET), polybutylene terephthalate (PBT), polyamide (PA), polyoxymethylene (POM), and so on [26, 27]. Functional plastics have outstanding functions such as corrosion resistance, radiation resistance, electrical conductivity, and magnetic permeability [28, 29]. Typical representatives are organosilicon plastics, electroconductive plastics, magnetic plastics, antibacterial plastics, etc. The details of plastic classification are shown in Table 1.

Due to the large-scale application of plastic products in various industries and daily life, especially the emergence of disposable plastics, the problem of waste plastics is becoming more and more serious [30–33]. There are two main sources of waste plastics. One is the semi-finished, defective and others produced in the process of plastic production [34]. This kind of waste plastic is less polluted and can be reused after reprocessing [35]. The other is mainly from various plastic products (agricultural plastics, packaging plastics, tableware plastics, etc.) that are discarded after use [36–38]. This kind of waste plastic is diverse and even mixed with other materials such as metal, glass, paper, and soil, which make it difficult to manage and recycle waste plastic [39, 40].

According to a report released by the Organization for Economic Co-operation and Development (OECD), more than 300 MT of plastic wastes are flowing into the environment every year. These plastic wastes can be decomposed and release harmful substances under certain temperature conditions, which cause damages to the human liver, kidney, and central nervous system [41, 42]. Meanwhile, since most of the waste plastics are difficult to be degraded naturally, which inevitably causes environmental pollution problems [43, 44], a large amount of released plastic waste into the oceans and rivers destroys the ecosystem and causes the death of fish and other marine life [5, 45, 46]. In addition, it is generally believed that the point of disposal of waste plastics is to eliminate them in a low-cost manner, rather than their beneficial value-added reuse. So a large amount of plastic waste is usually landfilled treatment, which not only takes up a lot of land resources but also seriously affects the physical and chemical properties of the soil and the distribution of biological communities [47].

The demand for plastic products is increasing year by year, but the raw materials (oil and natural gas) used for synthetic plastics are non-renewable resources [48]. Considering the environmental, economic, and resource limitation impacts, how to properly manage waste plastics has become a difficult problem in every country [49–52]. As early as the 1970s, the USA has actively carried out research on the recycling of waste plastics through the establishment of organizations such as the “Degradable Plastics Association.” In 1971, Japanese government established the “plastic treatment promotion association” to carry out the recycling and treatment of waste plastics. In 1991, they formulated the “renewable resources promotion law” to restrict all industries involved in the production and use of plastic products. At present, the recycling and utilization of waste plastics in Japan have realized serialization and industrialization [53]. In 1997, the State Environmental Protection Administration (SEPA) of China clearly stated that it is necessary to use scientific and technological means to strengthen the management and recycling of waste plastic pollution [54]. With the continuous improvement of people’s awareness of environmental protection and

Table 1 The classification of plastics according to their physicochemical properties and applications

Classification of plastics	Physicochemical properties	Thermoplastic plastics	PE, PVC, PP, PS, PC, PTFE, etc.
		Thermosetting plastics	Epoxy resin, phenolic resin, urea-formaldehyde resin, organosilicon resin, etc.
	Applications	General plastics	PE, PVC, PP, PS, PMMA, etc.
		Engineering plastics	PC, PET, PBT, PA, POM, etc.
		Functional plastics	Organosilicon plastics, electroconductive plastics, magnetic plastics, antibacterial plastics, etc.

the national legislation on plastic products, the disposal of postconsumer plastics is increasingly restricted, so there is a growing demand for alternative traditional waste plastics management methods.

In recent years, waste plastics research has attracted increasing attention, and there are many review articles on this topic. However, the research mainly focuses on the management methods (especially cracking) of waste plastics [55–58] and the value-added application in energy fuels [59–64] and construction fillers [65–67] after treatment. The current study provides a comprehensive overview of current management methods of waste plastics and different value-added applications. The purposes of this review are to (1) summarize the current management methods of waste plastics, (2) discuss the advantages and disadvantages of various management methods of waste plastics, (3) list the main value-added application fields of waste plastics, and (4) give future challenges and suggestions.

2 Main management methods for waste plastics

For the management of waste plastics, two aspects need to be considered. First, if waste plastic waste is not treated in a timely and comprehensive manner, it will take a long time to be degraded naturally. More importantly, it will cause a huge waste of resources and energy. Second, if unreasonable recycling treatment methods are used, it may increase the cost of treatment or cause serious environmental pollution problems [68, 69]. Waste plastic management methods usually include landfill, incineration, mechanical pulverization, microbial decomposition, thermal decomposition, modification reuse, and so on. Figure 2 represents several main management methods for waste plastics.

2.1 Landfill

Due to good physical and chemical stability and long durability of waste plastics, it is difficult to disintegrate naturally. Meanwhile, waste plastics are light in weight, which can fly with the wind or float in the water. To simply and efficiently dispose of large amount of waste plastic, people often build landfills with mound pits or natural pits to fill them [70]. However, landfill disposal has serious drawbacks. On one hand, plastic waste has a large volume due to its small density, so landfill occupies a large space, which aggravates the shortage of land resources [71]. On the other hand, plastic waste is difficult to degrade; thus, it will become permanent garbage after landfill, which seriously hampers the penetration of surface water and the circulation of groundwater [72]. Furthermore, the additives such as plasticizers or pigments in plastics can cause secondary pollution, which is not in line with the sustainable development.

2.2 Incineration (thermal energy recycling)

The incineration method can not only deal with waste plastics on a large scale but also recover thermal energy and realize the resource utilization value of garbage [73, 74]. At present, there are nearly 2000 waste plastic incinerators in Japan, and the thermal energy utilization rate is as high as 38%. In Germany, the heat energy from the incineration of waste plastics is used to generate electricity, which accounts for 6% of the total thermal power generation. The main products of waste plastics incineration are carbon dioxide and water, but polycyclic aromatic hydrocarbon compounds, carbon monoxide, and other harmful substances are also produced due to changes in plastics composition and incineration conditions [75]. Such as the thermal decomposition of polyvinyl chloride will produce HCl. Polyacrylonitrile will give birth to HCN [76]. In addition, the waste plastics may contain heavy metal compounds such as Hg, Cd, and Pb. During the incineration process, these heavy metal compounds are discharged along with the soot and survives as incineration residues to pollute the environment [77]. Therefore, incineration is not an ideal way to dispose of waste plastics, as it requires a complete pollutant treatment and purification system (shown in Fig. 3).

2.3 Mechanical pulverization (physical recycling)

Waste plastics can be further recycled after washing and mechanical pulverization. As shown in Fig. 4, for thermosetting waste plastics, due to their excellent mechanical, electrical insulation, and chemical stability, which can be directly recycled as additional materials after mechanical pulverization [16, 78, 79]. Typical applications are as plastic fillers, construction accessories, and concrete aggregates [44, 80, 81]. For most of the thermoplastic waste plastics, the value of reuse can be achieved by mechanical crushing and hot extrusion mixed with an adhesive, such as the refurbishment of plastic bottles and recycled rubber [82]. For waste polymeric membranes such as PE, PVC can be directly transformed into other molding plastic products through simple mechanical pulverization, cleaning and drying, and then hot extrusion. In recent years, the Dutch VolkerWessels construction company has replaced asphalt and stones with waste plastics to develop a new “plastic road” that can withstand a temperature from − 40 to 80 °C [83]. In fact, as early as a dozen years ago, Indian K.K. Plastic Waste Management has researched and tested the use of waste plastic to build roads to replace traditional roads and found that innovative roads have a longer service life than traditional roads [84]. The physical management method has high production efficiency, simple operation, less secondary

Fig. 2 The main management methods for plastic waste

pollution, and low cost, but the remanufactured products have poor performance and low economic benefits.

2.4 Microbial decomposition (biological recycling)

Plastic microbial degradation technology refers to the use of microorganisms such as bacteria, molds (fungi), and algae that exist in nature to decompose waste plastics into substances that can be integrated into the natural environment [85–88]. Due to the special physical and chemical properties of plastics, it still takes about 9 years under the best current biotechnology to achieve complete degradation [89]. Considering the different service time requirements for plastic products in practical applications, the service period required for common daily necessities (such as washing machines, washbasins) and construction materials are long and not easy to be weathered and degraded, while for disposable plastics and other transient consumer goods, this required short use time. Therefore, utilizing the features of plastic degradation to guide the synthesis and production of plastics so that they can be easily degraded or degraded on demand will become the future research direction of R&D teams in various countries. It should fully combine the synthetic cross-linking mechanism of plastics with the degradation mechanism of microorganisms to produce products matching their properties [90]. Recently, the European BIOCLEAN research team composed of several major European plastics manufacturers and the scientific and technological community used organic waste composting combined with microbial degradation of plastic technology to greatly improve the microbial degradation efficiency, and the degradation efficiency was obviously restricted by the geographical environment [91]. In 2015, Chinese researchers

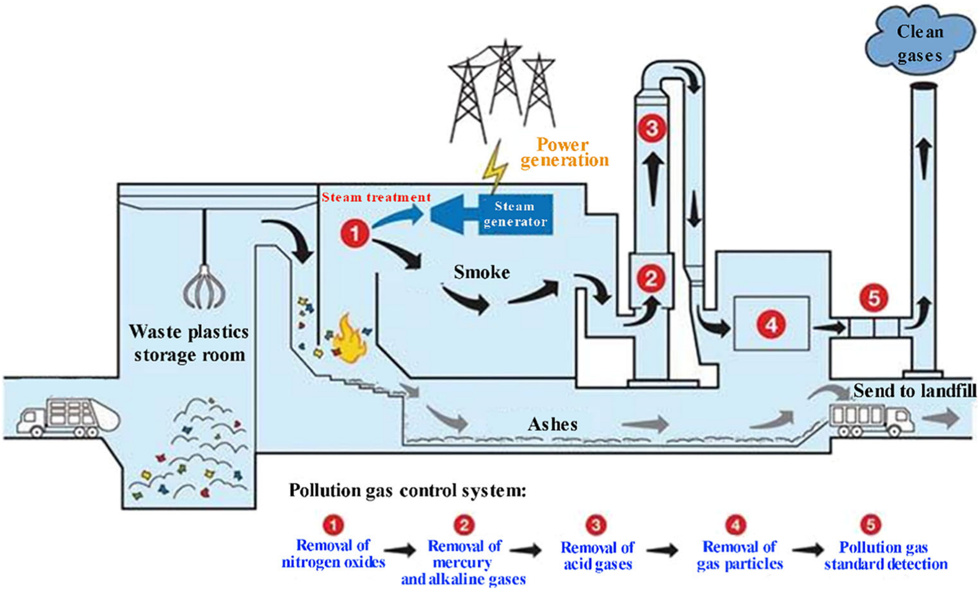


Fig. 3 Purification treatment system required for waste plastic incineration treatment

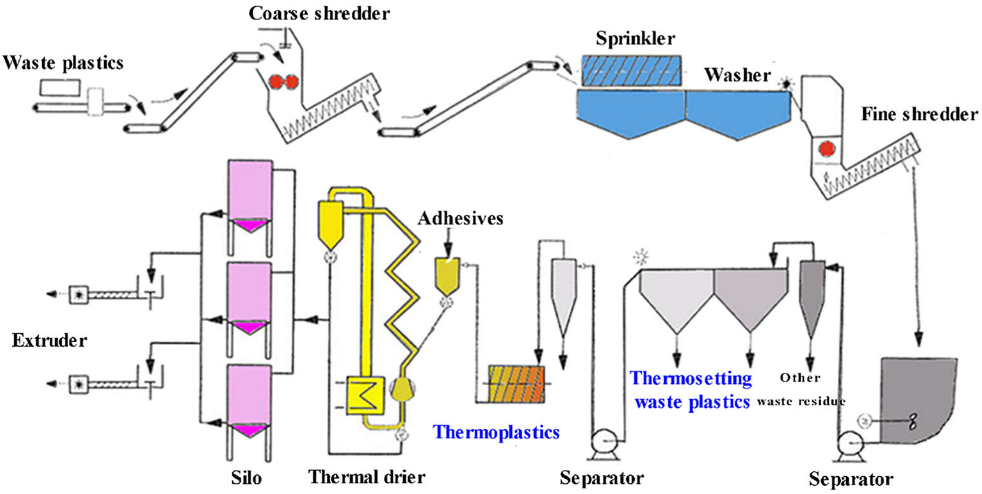


Fig. 4 Flowchart of mechanical treatment cycle of waste plastics

demonstrated that the larvae of mealworms can biodegrade refractory plastics like polystyrene. This breakthrough research shows that mealworms can survive for more than a month by using polystyrene foam as the sole food source, and the polystyrene they eat is completely degraded and mineralized into CO_2 or assimilate into insect body fat [92, 93]. This discovery provides new ideas for solving the global problem of plastic pollution.

In addition, biodegradable plastic is a new type of plastic that can be degraded and disappeared in the natural environment [94]. The ideal biodegradable plastic is a polymer material that has excellent performance properties and eventually exists as an integral part of the carbon cycle in nature. In the USA, Japan, France, China, and other countries and regions, various measures were taken to limit the use of non-degradable plastics, and vigorously developed and biodegradable new materials were used to protect the ecological environment and soil. However, there are many problems with the use of biodegradable plastics [95, 96]. First of all, most of these plastics will only be degraded under special conditions (such as light conditions) [97]. Secondly, anaerobic biodegradable plastics can release methane gas that causes greenhouse effect when degraded [98]. Thirdly, the mixture of recycled degradable plastics and non-degradable plastics increases the difficulty of sorting waste plastics.

2.5 Thermal decomposition (chemical recycling)

The thermal decomposition method is designed to convert waste plastic polymers into original monomers or other valuable low molecular weight chemical products [99, 100]. These products can be used as solid and gaseous fuels or as raw materials for various downstream industrial reproductions. Therefore, thermal decomposition is an important means of chemical recycling of waste plastics, which has the advantages of environmentally friendly with low pollution, high utilization rate, and high value of products [101, 102]. Thermal decomposition mainly includes three technical means: thermal/catalytic cracking, depolymerization, and gasification.

2.5.1 Thermal/catalytic cracking

The thermal cracking of waste plastics is a complex and continuous chemical reaction process in which organic polymer is decomposed into combustible gas, oil, and solid carbon by heating (400–850 °C) under the oxygen-barrier condition (Fig. 5) [103–105]. This chemical method is suitable for cracking all kinds of waste plastics, and its products include gasoline, diesel, heavy oil, and others with high calorific value [106]. German IKV company used fluidized bed to crack PS waste plastics at 450 °C to obtain 62.5% styrene and 20.5% styrene trimer. This process eliminates the need to clean and crush large pieces of waste plastic, and the metal pieces embedded in the plastic can also be easily separated during the cracking process [107].

With the continuous optimization of pyrolysis technology, equipment, and higher requirements for pyrolysis products, catalytic cracking technology has gradually attracted more and more attention. The addition of catalyst not only significantly reduces the activation energy required for polymer pyrolysis and increases the reaction rate but also improves the quality of pyrolysis products or controls the type and distribution of products [108, 109]. The catalysts commonly used in catalytic cracking of waste plastics mainly include mesoporous molecular sieve catalysts (such as MCM-41, ZSM-5, SBA-15, and Y zeolite) [110–112], transition metal catalysts (Mo, Fe, Co, Cu, and Ni) [113, 114], oxide catalysts (such as SiO_2, Al_2O_3, BaO, and ZnO), [106] and fluid catalytic cracking (FCC) catalysts [115]. Catalytic cracking can be divided into one-step catalytic cracking and first cracking followed by catalytic modification methods [116]. The first method is to put the catalyst and waste plastic in the reaction kettle, and directlycatalytic cracking to form the corresponding product.

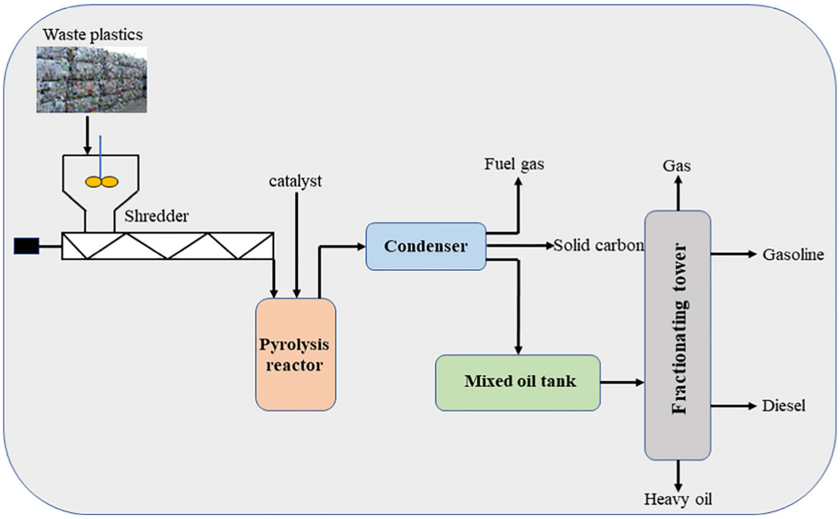


Fig. 5 Schematic diagram of the general pyrolysis process of waste plastics

The second method is to re-catalyze the products of waste plastic after cracking, so that the productisomerized and aromatized to improve the quality and recycling rate of gasoline and other products [117, 118].

At present, although there have been in-depth studies on waste plastics cracking and catalytic cracking at home and abroad, many factors such as heat transfer, chemical composition of waste plastics, temperature, heating speed, reactor type, and distribution of cracking products should be considered comprehensively in industrial application [119].

2.5.2 Thermal depolymerization

Thermal depolymerization is a special case of pyrolysis, which is the process of chain-like organic polymers gradually separated into monomers [120]. For free-radical polymerized plastics such as PP, PE, PVC and PS, depending on the polymerized monomer and pyrolysis mechanism, the temperature and catalyst required for thermal depolymerization are different (Table 2). While for non-radical polycondensation plastics such as polyamide (PA), polyurethane (PU) and polyoxymethylene (POM) are usually decomposed by infrequently used alcoholysis, hydrolysis, ammonolysis, and other chemical methods [123–125].

2.5.3 Gasification

Waste plastics can be decomposed in gasification media such as air, oxygen, or water vapor to produce CO, H_2, and CH_4 syngas [126, 127]. These syngas can be used as raw materials for the production of chemical products such as methanol and ammonia, as well as fuel for power generation and heating [128]. Moving bed gasifier, fluidized bed gasifier, and entrained flow gasifier are the main reactors for gasification of waste plastics [129]. Specifically, as shown in Fig. 6, for a moving bed gasifier, it means that waste plastic raw materials or catalysts are continuously added to the top of the reactor, and the reaction gas passes through the combustion,

Table 2 Suitable temperature and catalyst required for thermal depolymerization of several typical radical polymerized plastics [116, 118, 121, 122]

Plastic type	Monomer	Suitable temperature (°C)	Catalyst
PP	Propylene	300–400	Al_2O_3
		350–450	Al_2O_3-SiO_2
		400–450	Natural zeolites
PE	Ethylene	300–400	Y zeolite
		400–450	Al-SBA-15
		400–500	HZSM-5, FCC
PVC	Chloroethylene	200–300	Cu
		300–400	Sodium silicate
		400–500	$AlCl_3$ and $ZrCl_4$
PS	Styrene	300–400	Cu, ZnO, Fe_2O_3, Y zeolite
		400–450	Transition metal oxide
		450–500	ZnO, Al_2O_3, CuO

gasification, pyrolysis, and preheating beds sequentially from bottom to top. The feedstocks are moved down bed by bed and finally discharged continuously from the bottom [130]. The fluidized bed reactor is a reactor that uses reaction steam or air to pass through the solid bed to make the feedstock in a suspended motion state and carry out the gas-solid phase reaction process [131]. As for entrained flow gasifier, it refers to the device where the discarded plastic feedstick is instantaneously gasified in contact with high-temperature and high-speed reaction gas, so it has the best treatment effect [132]. The Schwarze Pumpe refinery, owned by Germany's Espag Company, processes 1700 tons of waste plastic into urban gas every year. Hoechst company uses Uhde Gmb H's high-temperature Winkler process to vaporize mixed plastics and converts them into water gas as a raw material for synthetic alcohols. Waste plastics treated with this technology do not require fine sorting and have ideal gasification efficiency, while the required equipment and technology are relatively high.

2.6 Modification reuse

The above technologies such as cracking of waste plastics realize the recycling of materials and energy. However, the performance of secondary products in mechanical and other aspects is greatly reduced. In order to achieve or exceed the performance of the original plastic products, the researchers adopted various physical and chemical methods to modify the waste plastics [133].

2.6.1 Physical modification

Incorporating appropriate amount of activated rigid inorganic particles such as fly ash, $CaCO_3$, and $BaSO_4$ into waste plastics can improve the mechanical properties and high-temperature resistance of composite materials [134, 135]. Baheti et al. [136] incorporated fly ash particles with a particle size of less than 500 nm after ball milling into epoxy resin plastic to obtain a three-layer laminated composite of glass fabric and found that the impact strength of the composite material increases from 253.75 to 407.81 kJ/m^2 when filled with 3 wt% fly ash.

As an "eco-friendly material," natural fiber has better mechanical tensile strength and physical properties than most synthetic materials and has the characteristics of being renewable, biodegradable, and naturally abundant, so it is often used as functional fillers for modified materials [137–140]. Laadila et al. [141] obtained biocomposite materials through composite modification of cellulose processed from papermaking solid waste and recycled polylactic acid plastic from the packaging industry. When modified with 2% (w/w) of treated fibers, the mechanical properties of the biocomposite material are greatly improved than the original recycled plastic products (Young's modulus from 64.47 to 887.3 MPa, tensile stress from 29.49 to 41.36 MPa).

2.6.2 Chemical modification

Chemical modification refers to the introduction of other links and functional groups into the original molecular chain by cross-linking, grafting, copolymerization, etc., so that the waste plastic has high impact resistance, excellent heat resistance, and aging resistance [142–144]. Specific examples of chemical modification of waste plastics include cross-linking modification of recycled polyethylene [145], chlorination modification of recycled polyethylene [146], chlorination modification of random polypropylene [147], chlorination modification of recycled polyvinyl chloride [148], and copolymerization modification of recycled polypropylene [149]. In China, waste plastics have been successfully formulated into water-based microemulsions for water-based substrates of building exterior walls through chemical modification, which has a high added value [150].

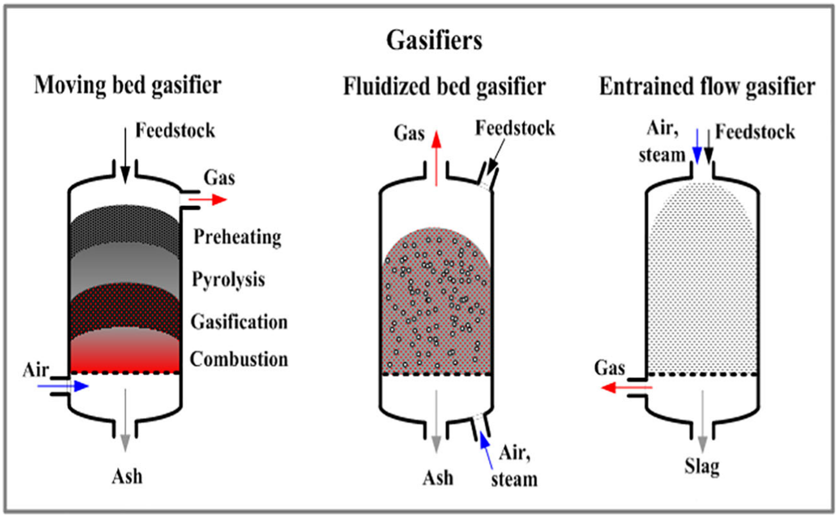


Fig. 6 Three common reactors for gasification of waste plastics

Table 3 The advantages and disadvantages of various management methods for waste plastics

Management methods	Recyclability	Secondary pollution control	Raw material pretreatment	Technical level	Operating costs	Treatment efficiency	Recycled product value
Landfill	/	Weak	No	Low	Low	High	/
Incineration	Thermal energy recycling	Weak	No	Low	Low	High	/
Mechanical pulverization	Physical recycling	Relatively weak	Need to pick and sort	Low	Relatively low	Relatively high	Low
Microbial decomposition	Biological recycling	Strong	/	High	High	Low	/
Thermal decomposition	Chemical recycling	Relatively strong	Need to pick, clean and sort	High	High	Relatively high	High
Modification reuse	Physical and chemical recycling	Relatively strong	Need to pick and clean	High	High	Relatively low	High

Based on the above various management methods of waste plastics, it can be concluded that methods such as landfill, incineration, and mechanical pulverization can treat in large quantities but will form secondary pollution and have a low economic benefit. The methods such as thermal decomposition and modification reuse have high economic value but require relatively complicated operation processes; the microbial degradation technology is environmentally friendly but requires a high level of technical. Table 3 lists the advantages and disadvantages of various management methods for waste plastics. Among them, landfill is currently the most common method, thermal decomposition is a more mature method, microbial degradation is an ideal method, and modification reuse is the most promising method. Therefore, various countries and governments should combine their own situation to formulate rational and efficient treatment methods for waste plastics.

3 Value-added application of waste plastics

Over the past 30 years, countries around the world have carried out extensive research on the value-added utilization of waste plastic recycling and achieved gratifying results, which can be summarized as the following aspects.

3.1 Applied in the energy and chemical industry

Among the above waste plastics management method, the cracking technology absence of oxygen resists the formation of harmful substance dioxin [151]. More importantly, cracking can produce liquid and gaseous fuels and other value-added products [116, 119, 152–154]. Miandad et al. [119] used natural and synthetic zeolite catalysts to catalytic cracking three plastic wastes (PE, PS, and PP) and their mixtures at 450 °C. From the results of catalytic cracking (Fig. 7), it was found that PS plastic waste showed the highest liquid oil yield of 54% using natural zeolite and 50% using synthetic zeolite. Moreover, all mixtures of PS with PP and PE have higher yields of liquid oil than the individual plastic feedstock using two catalysts. Gas chromatography coupled with mass spectrophotometry (GC-MS) analysis results show that the pyrolysis liquid oil of all waste plastics is mainly composed of aromatic hydrocarbons with a small amount of aliphatic hydrocarbon compounds and the resulted liquid oil has high heating value (40–45 MJ/kg) similar to ordinary diesel (as shown in Table 4).

Stanislav et al. [155] pyrolyzed PE, PP, PS, PVC, PET, and mixed waste plastics from Japan (JP m.), Europe (EU m.), and USA (US m.) under isothermal conditions at 500, 700, and 900 °C and found that various raw material pyrolysis gases were similar to or even better than natural gas (NG) and propane in the performance of flame speed factor and combustion

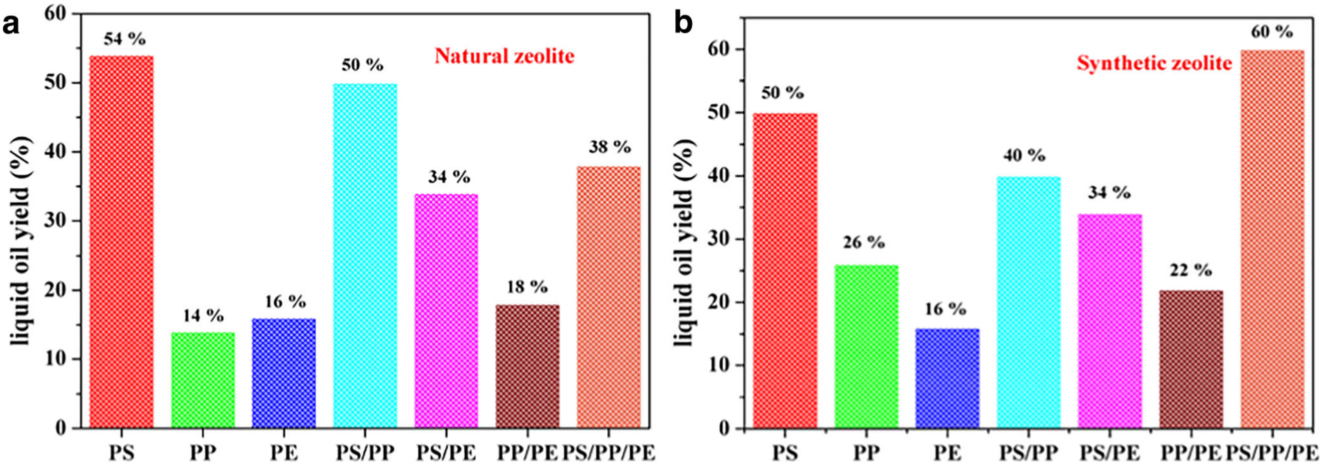


Fig. 7 Catalytic cracking liquid oil yields by using natural (**a**) and synthetic (**b**) zeolites catalysts

potential (as shown in Fig. 8), which showed that waste plastic pyrolysis gases had great potential to replace natural gas (NG) and propane.

Japan's Showa electric K.K. (SDK) has successfully gasified packaging materials and waste plastics collected from homes and factories into liquid ammonia and other chemicals. The study did not require removal of PVC from plastic waste, and the resulting gas was neutralized with alkali for the production of chlor-alkali. In addition, the sulfur is recycled into sodium bisulfite [156]. Therefore, with the help of chemical value-added means, the value contained in waste plastics can be fully exploited to obtain higher value chemical products and raw materials. In my opinion, the development of mild catalyst and the innovation of production process are the important ways to improve the recovery rate and economic benefit of waste plastics in this field.

3.2 Applied in construction materials industry

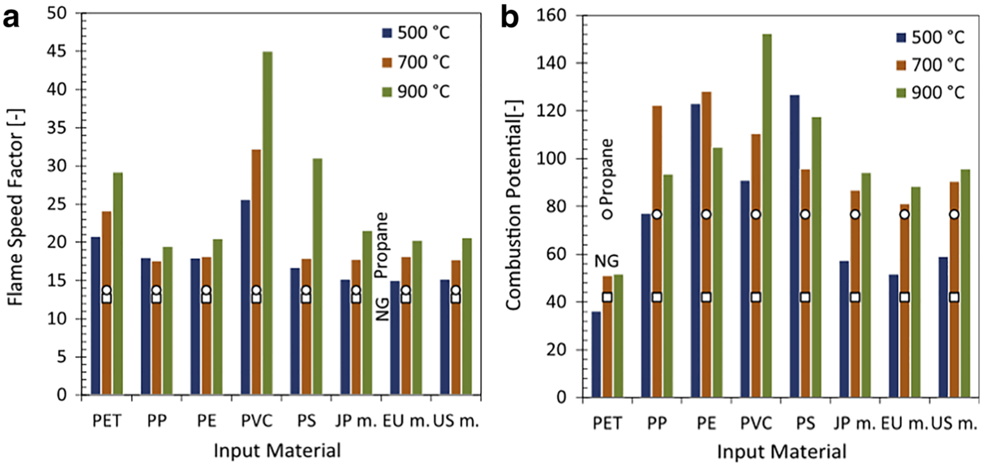
Asphalt is the most common paving material in the world. In addition to its basic function in transportation roads [157, 158], it also helps to consume a lot of waste tyre rubber and waste plastic [159, 160]. The use of crumb rubber (CR) in asphalt helps improve the rut resistance and fatigue resistance of asphalt materials, but usually encounters other problems such as poor rheology and low storage stability [161]. By incorporating organic waste plastics into asphalt not only consumes a lot of domestic or industrial waste but also optimizes the rigidity, rheological properties, and other engineering properties [162–164]. Leng et al. [165] used the products obtained by chemical ammonia decomposition of waste PET as functional additives for CR-based asphalt. The results show that the functionalized asphalt has greatly improved in storage stability, rheological properties, and chemical properties. This study opened up a new value-added recycling method for waste plastics to produce high-performance asphalt paving mixtures. Hu et al. [166] used polyethylene waste packing tape (WPT) material as the performance-enhancing binder of asphalt and conducted a comprehensive rheological characterization of modified asphalt with different WPT dosages. Figure 9 shows that the failure temperatures, phase angle, loss modulus, and storage modulus of modified binder all exhibited higher failure temperatures than the corresponding liquid phase, which demonstrated that adding WPT improves the rheological properties of asphalt.

India was the first country to use a mixture of waste plastic debris and hot mix asphalt to pave roads and has been successfully used to build more than 100,000 km of roads in 11

Table 4 High heating values of liquid oils in megajoules per kilogram produced from catalytic pyrolysis with natural and synthetic zeolite catalysts [119]. Reproduced with permission Copyright © 2017, Elsevier Ltd.

Waste plastic type	High heating values (MJ/kg) Natural zeolite	High heating values (MJ/kg) Synthetic zeolite
PS	41.9	40.6
PE	45.0	41.0
PP	41.7	42.2
PS/PP	40.2	41.6
PS/PE	41.7	41.2
PE/PP	40.8	41.8
PS/PE/PP	41.7	42.9

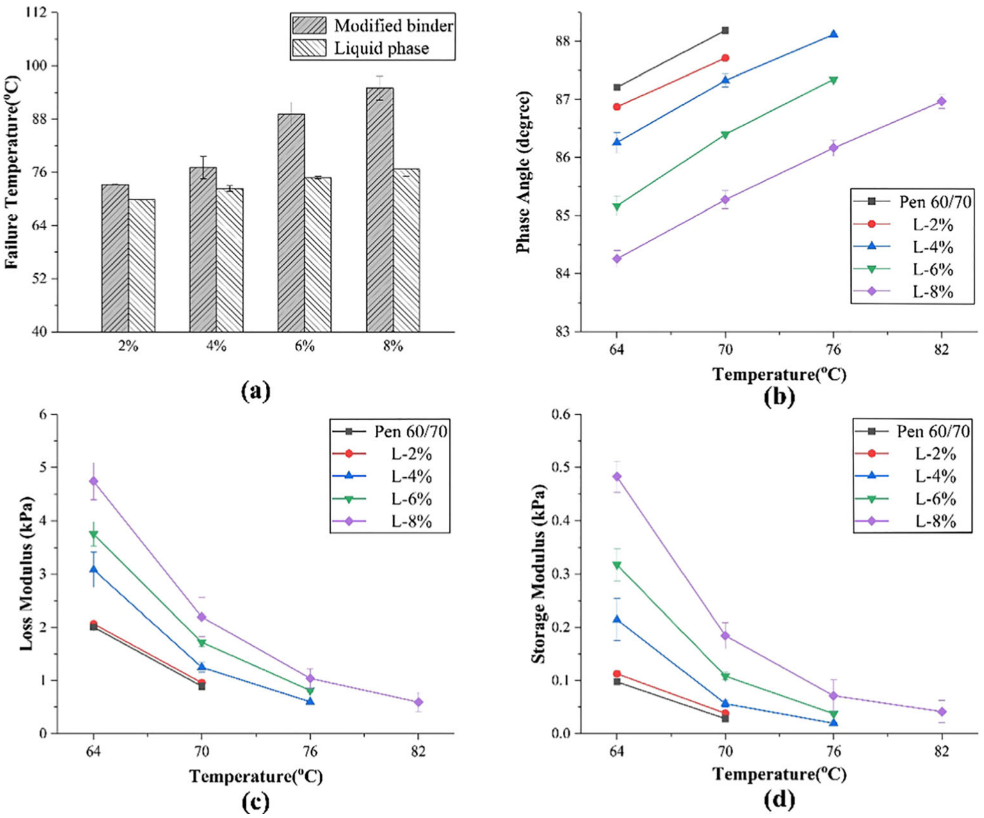
Fig. 8 Values of flame speed factor (**a**) and combustion potential (**b**) for the individual gases as compared with NG and propane. Reproduced with permission [155] copyright © 2016 Elsevier Ltd.



states (Fig. 10a). Compared with traditional roads, the plastic road not only is stronger and heat resistant but also has a cost reduction of 8–9%. Coincidentally, Dutch construction company VolkerWessels (KWS) has developed a new hollow road-building solution by replacing traditional asphalt and stones with waste plastic (Fig. 10b). This novel road has the advantages of being light, easy to assemble, and maintain.

The recycled waste plastics that undergo further processing not only add value to the modification and construction of road materials but also have high value in the application of wall building materials. Mansour et al. [167] used plastic mortar to casting waste plastic bottles filled with saturated sand and air in a fixed mold to obtain plastic bottle masonry blocks (the specific production process is shown in Fig. 11). This masonry block could be used as suitable construction units for partition walls or as bearing walls for one roof slab and showed better thermal insulation than the tradition block construction. Japan is gradually promoting a foam house DOME HOUSE built with polystyrene foam as the main material. The foundation of DOME HOUSE is directly fused with concrete and each flame-retardant foam board can withstand the weight of 10 people, so it also plays a good role in resisting typhoons and earthquakes.

Fig. 9 Rheological properties of liquid phase unaged. **a** Failure temperature. **b** Phase angle. **c** Loss modulus. **d** Storage modulus. Reproduced with permission [166] Copyright © 2018 Elsevier Ltd.



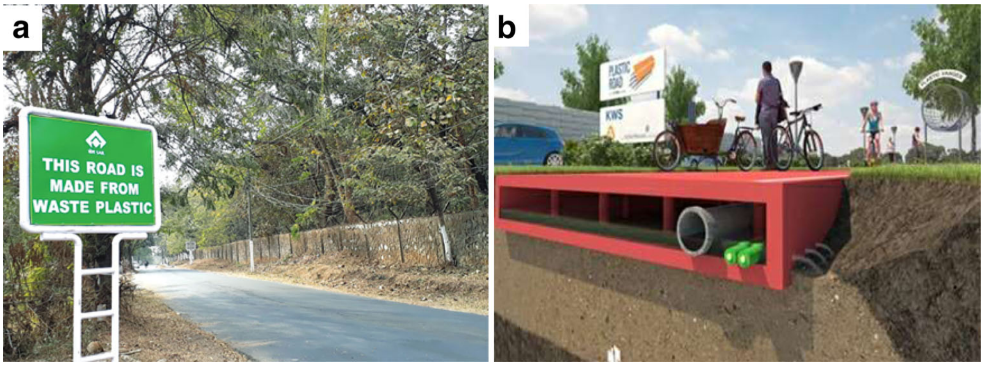


Fig. 10 **a** Plastic roads in India. **b** Schematic diagram of the novel hollow road in the Netherlands

In addition, the use of waste plastics as aggregate in concrete can produce lightweight concrete in an economical way [168]. Corinaldesi et al. [169] used waste PET particles and powdered glass fiber–reinforced plastic (GFRP) waste to replace the natural sand and limestone filler in the traditional concrete, lime and hydraulic lime to replace cement, wood waste (WW), and industrial by-product silica powder particles as functional additive and adjuvant and finally got a concrete containing 100% waste particles, which showed low thermal conductivity and lightweight characteristics, as well as can be employed also in ancient masonry for restoration.

Combined with the current research situation at home and abroad, the application of waste plastics to building materials can not only meet the corresponding building standards but also show good ductility which can restrain the generation and development of internal cracks in concrete [170]. In addition, some waste plastics such as foamed plastics have strong high-temperature stability, so the resulting building materials have obvious thermal insulation effects. However, how to strengthen the adhesion between waste plastic particles and cement slurry still needs further research.

3.3 Applied in the synthesis of carbon nanomaterials

It is well known that the main component of waste plastics is polyolefin, whose carbon content accounts for about 86% of the weight of polyolefin [171, 172]. Therefore, the use of waste plastics to synthesize high value-added carbon nanomaterials is undoubtedly an innovative method for recycling waste plastics [173–175]. Oh et al. [176] pioneered a method for quickly synthesizing vertically aligned carbon nanotube (CNT) forests using waste plastic bottles. The obtained carbon nanotubes have an average outer diameter of 20–30 nm (Fig. 12), and the wall graphitization is slightly higher than that of commercially available multiwall carbon nanotubes (MWCNT). More importantly, this method can be

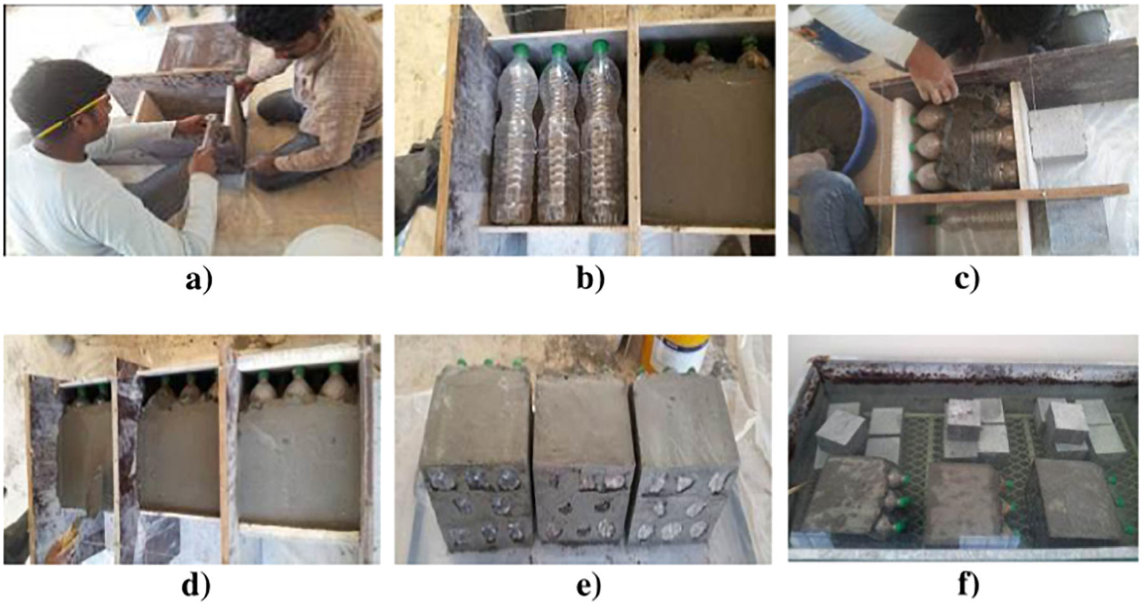


Fig. 11 The specific production process for plastic bottle masonry blocks. Reproduced with permission [167] Copyright © 2014 Elsevier Ltd. **a** Mold preparation. **b** Array of bottles in molds. **c** Casting the cement mortar in molds. **d** Finalizing the molds. **e** Samples ready for curing/testing. **f** Samples curing for 28 days

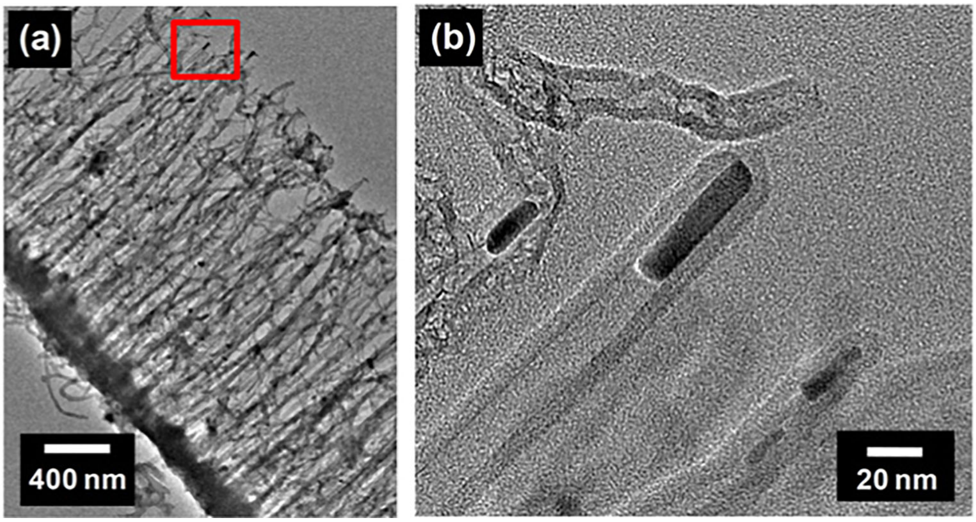


Fig. 12 **a** TEM image of CNT forest. **b** Enlarged TEM image taken from the area marked by the square in **a**. Reproduced with permission [176] Copyright © 2012 National Institute for Materials Science

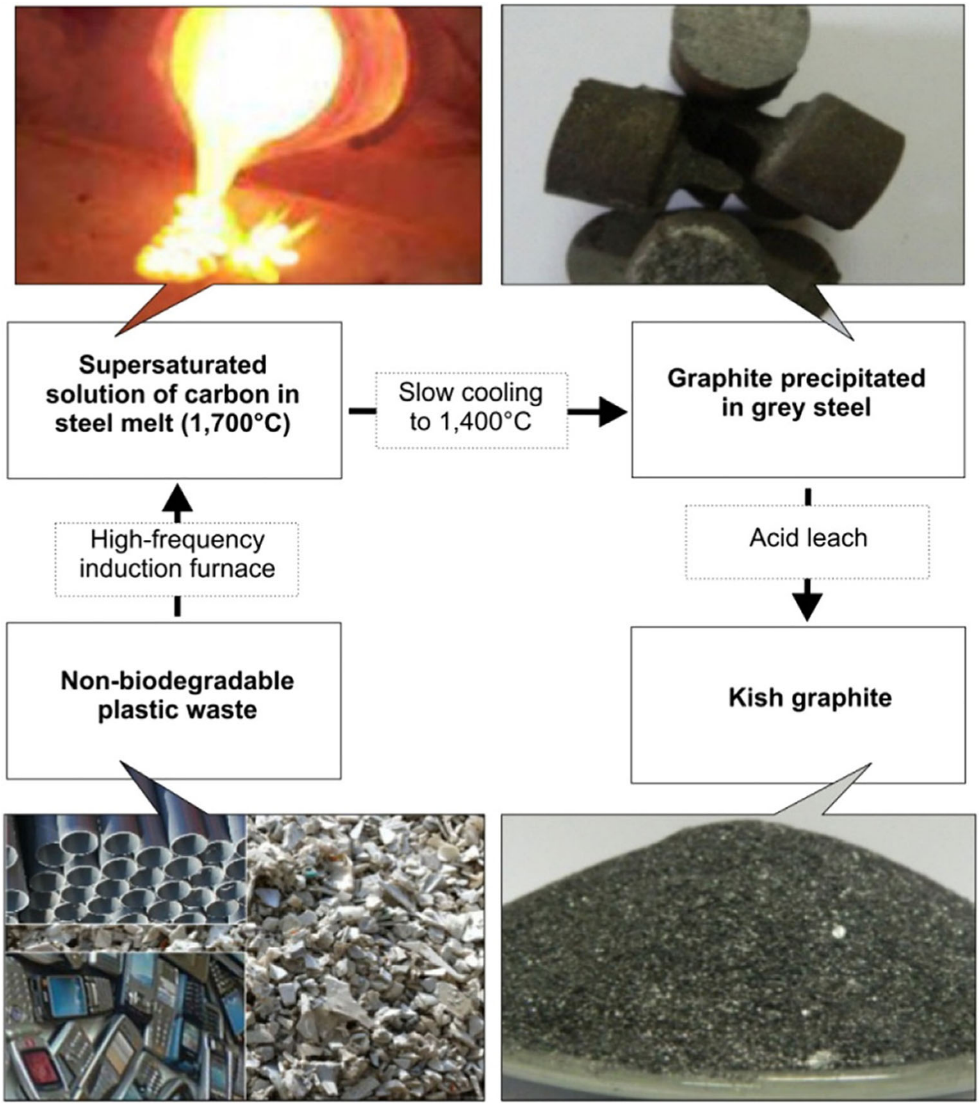


Fig. 13 Procedure for the generation of kish graphite. Reproduced with permission [183] Copyright © 2019 Springer-Verlag GmbH Germany

applied to industrial mass production of CNTs. Several studies [177–179] have also confirmed the potential value of using waste plastics to synthesize carbon nanotubes.

Graphite carbon nanomaterials can also be obtained from waste plastics, which can be used as electrode materials in lithium ion batteries [180, 181]. Kumari et al. [182] carbonized the crushed waste PVC plastic in a high-temperature iron melt to deposit Kish graphite material (Fig. 13) and used PVC-derived kish graphite as a anode electrode for lithium ion batteries. The new electrode material exhibits a first-cycle reversible capacity of 444 mAh/g and is more thermally stable than commercial lithium battery graphite. This research provides a novel way to synthesize high value-added nanocarbon materials for lithium-ion batteries by reutilization of waste plastics. Similarly, Wei et al. [183] proposed an economical and practical strategy to preparation of silicon/carbon nanofibers/carbon (Si/CNF/C) composite for lithium-ion batteries using self-prepared micron-sized silicon and waste high-density polyethylene (HDPE) as raw materials. The obtained Si/CNF/C electrode material possesses high initial coulombic efficiency of 82.2% and a steady reversible capacity of 937 mAh/g after 100 cycles.

The current research on the conversion of waste plastics into high value carbon nanomaterials is somewhat effective, but it still takes a long way to go to obtain relatively pure and single carbon materials. In addition, the current research focuses on carbon materials and ignores another important product, hydrogen.

3.4 Applied in polyester textile industry

Waste plastics can be processed into polyester textile after washing and sterilization, high-temperature melting, spinning, and weaving [184, 185]. Recently, the research and development team of Anta group has broken through many technical barriers to achieve efficient regeneration from waste plastic bottles to polyester fiber. In this research, recycling 11,550-mL waste plastic bottles can make a single energy technology clothing, so the overall cost is 30–50% lower than international brands. The process of making carpets in China by using recycled waste plastics is quite mature. A carpet company in Shandong Province consumed nearly 2.6 billion waste plastic bottles a year to produce 6 million blankets, which not only created economic benefits but also effectively solved the problem of waste plastics. A typical example is that the red carpet used in China's 2019 military parade was made of 400,000 waste plastic bottles, which is spectacular and environmentally friendly.

Compared with animal fiber and plant fiber, the textile such as clothing and carpets obtained by this technology has the advantages of insect resistance, mildew resistance, good elasticity, and abrasion resistance [186, 187]. However, there are two difficulties in this field. On the one hand, the recycling mechanism is not perfect (the traditional recycling mode is no longer applicable to the current market economic development); on the other hand, it is restricted by technical conditions [188]. For example, melt-spun fabrics produced from recycled waste plastics still have some problems in color adjustment and performance control after mixing different waste plastics.

4 Concluding remarks and future works

The development of the plastic industry plays a huge role in promoting the progress of human science and technology civilization and the improvement of people's living standards. But every coin has two sides, most of the discarded plastic products are not biodegradable, which poses a huge threat to the environment and human health. At present, the amount of waste plastic recycled is very small and traditional management methods such as landfill and incineration not only cause secondary pollution but also waste a lot of natural resources. In order to realize the concept of green, environmental protection, and sustainable development, various countries are actively exploring the use of waste plastics to obtain economic and environmentally friendly value-added products. This review provides a high-level overview of the different commonly used waste plastics management methods and their advantages and disadvantages. More importantly, the article lists the value-added fields in which waste plastics have been successfully applied, which has important reference value and significance.

Although the world's research on waste plastics is already in a hot stage, the current technical treatment is still at the primary level, and there is still a long way to go and still face enormous challenges [189, 190]. The further tasks are:

i. In the face of the technical management and recycling problems of waste plastics, it may be caused by human beings' lack of environmental awareness and imperfect environmental management. In order to solve the problem from the source, the society should vigorously publicize the harm of "white pollution" and continuously improve people's environmental awareness, so that more and more waste materials will be on the road of recycling.
ii. Nowadays, most of the management of waste plastics uses landfill and incineration methods; the next step is to promote the use of the management methods such as thermal decomposition and modification reuse. Rapid and accurate classification and identification of hard-to-separate waste plastic mixtures will be one of the important factors to promote the development of this field. Furthermore, the development of mild catalyst and new production process will become the important ways to

improve the recycle rate and economic benefit of waste plastics.

iii. The most of the current value-added applications are in the primary stage, it needs to further explore new technical means and develop new value-added products, so as to achieve both environmental protection and economic benefits on the basis of reducing waste plastic recycling costs.

iv. The recycling treatment and utilization of waste plastics not only is a waste disposal problem but also closely related to resources and the global environment. Countries should strengthen communication, enhance understanding, and make joint efforts to optimize the environment and benefit future generations.

Compliance with ethical standards

Conflict of interest The authors declare that they have no conflict of interest.

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