



Disposal and resource utilization of waste masks: a review

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Abstract

Waste masks pose a serious threat to the environment, including marine plastic pollution and soil pollution risks caused by landfills since the outbreak of COVID-19. Currently, numerous effective methods regarding disposal and resource utilization of waste masks have been reported, containing physical, thermochemical, and solvent-based technologies. As for physical technologies, the mechanical properties of the mask-based materials could be enhanced and the conductivity or antibacterial activity was endowed by adding natural fibers or inorganic nanoparticles. Regarding thermochemical technologies, catalytic pyrolysis could yield considerable hydrogen, which is an eco-friendly resource, and would mitigate the energy crisis. Noticeably, the solvent-based technology, as a more convenient and efficient method, was also considered in this paper. In this way, soaking the mask directly in a specific chemical reagent changes the original structure of polypropylene and obtains multi-functional materials. The solvent-based technology is promising in the future with the researches of sustainable and universally applicable reagents. This review could provide guidance for utilizing resources of waste masks and address the issues of plastic pollution.

Keywords Waste mask · Disposal · COVID-19 · Resource utilization · Physical technology · Thermochemical technology · Solvent-based technology

Introduction

COVID-19 is a global issue that mankind is facing recently, so amounts of single-used masks are worn to cut off the transmission of novel coronavirus. Statistics show that 3.4 billion waste masks are produced and discarded every day around the world (Benson et al. 2021). With the extensive use of disposable medical masks, the related waste has brought severe problems. The used disposable masks can become mediums for the propagation of the infectious disease, which leads to uncontrollable spread of coronavirus. Meanwhile, a substantial number of disposable masks have been discarded to the environment, posing adverse physiological and ecotoxicological effects to wildlife (Silva

et al. 2021). Additionally, soil erosion and microbial action may result in the progressive breakdown of the disposable masks into microplastics, which can easily go into the food chain via crops and animals, threatening the health of human beings (Zhou et al. 2020). Disposable masks are mainly composed of spunbond non-woven fabric, melt-blown non-woven fabric, ear loop, and nose wire. Polypropylene (PP) non-woven microfiber is the main material of masks (Xiang et al. 2021), so it indicates that plastic pollution is the major challenge. The accumulation of polypropylene will cause incalculable damage to the ecological environment (Dharmaraj et al. 2021). At the same time, many discarded masks will also lead to a significant waste of resources (Park et al. 2021). Therefore, it is urgent to seek productive and eco-friendly solutions for the treatment or utilization of waste masks.

Generally, physical, thermochemical, and solvent-based technologies have been widely used for disposal and resource utilization of waste masks. The first two methods are regarded as traditional disposals of waste plastics. When physical technologies are used, masks are mixed with traditional construction materials such as asphalt to boost concrete strength (Saberian et al. 2021) after soaking

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masks with graphene oxide suspension. Besides, masks are directly melted and applied as raw plastic materials with low mechanical strength. Thermochemical technology refers to a process of pyrolyzing masks after being separated, crushed, and dried. In this kind of method, the most valuable pyrolysis product is liquid oil which has a calorific value and components similar to those of diesel (Sun et al. 2022). In this way, multiple carbon materials can also be prepared, which could serve as new conductive or charge storage materials (Hu and Lin 2021) through catalysts or sulfuric acid treatment. Recently, some breakthroughs have also been made in traditional technologies. For instance, novel physical technology intends to enhance the strength and functionality of mask PP and modify the material by mixing natural fibers (Pulikkalparambil et al. 2022) and inorganic nanoparticles (Irez et al. 2022). By adding reinforcing fillers, novel physical technology is more environmental-friendly and can produce novel properties, such as tensile property, compressive property, and antimicrobial property. The use of catalysts such as the zeolite and biochar in the thermochemical technologies is confirmed to increase the yield of H_2 . Thus, thermochemical technologies may become a favorable way of energy supplement.

Noticeably, it is promising that the solvent-based technology is focusing on the inherent characteristics (e.g., hydrophobicity and hydrophilicity) of masks. The waste masks can be prepared into highly value-added materials, such as battery separators and catalytically active substances, according to the properties of different components. Besides, this method can be conducted in more extensive experimental conditions without high-temperature and complex pretreatment process. Other than that, the novel solvent-based technology is more convenient to separate target products from by-products and solution than conventional technologies. Hence, novel solvent-based technology is desirable to solve the problem of waste mask pollution during the epidemic (Sangkham 2020). The most existing reviews are about the feasibility of the secondary use of waste masks after disinfection (Gir et al. 2021) and

the introduction of physical and chemical valorization (Asim et al. 2021; Torres and De-la-Torre 2021). However, the innovations of traditional technologies as well as the novel solvent-based technology have not been considered in previous reviews. Therefore, this review summarizes not only the latest development of the two traditional technologies along with the novel solvent-based technology for waste mask disposal, but also the mechanism of each technology. The aim is to provide inspiration and reference to obtain the ideal products. A more comprehensive and systematic utilization method of waste masks can be formed with some comparisons. Under the goals of carbon peaking and carbon neutrality, this review helps to better control the waste mask pollution and utilize waste energy.

Physical recovery technology

Traditional physical recovery

Direct melting and thermoforming

The main component of the mask is the thermoplastic polymer that can be melted. Direct melting and thermoforming refer to the process of directly melting in the extruder, extruding, and hot compressing disinfected masks to prepare regenerated materials. Due to the low molecular weight of mask PP, the regenerated material possessed low viscosity but equivalent stiffness and strength to the typical PP copolymer (Battezzore et al. 2020).

The PP fiber of the masks was heated and melted at 190 °C. The fiber structure of masks was transformed into a continuous matrix of PP, in which calcium carbonate particles were dispersed uniformly (Fig. 1a). Thermogravimetric analysis showed that it was the most suitable condition when the heating reaction was under 190 °C, for 2 min. It would lead to excessive degradation of PP under a higher heating temperature or a longer heating time. If ear loops were recycled together, the processing temperature of 230 °C would

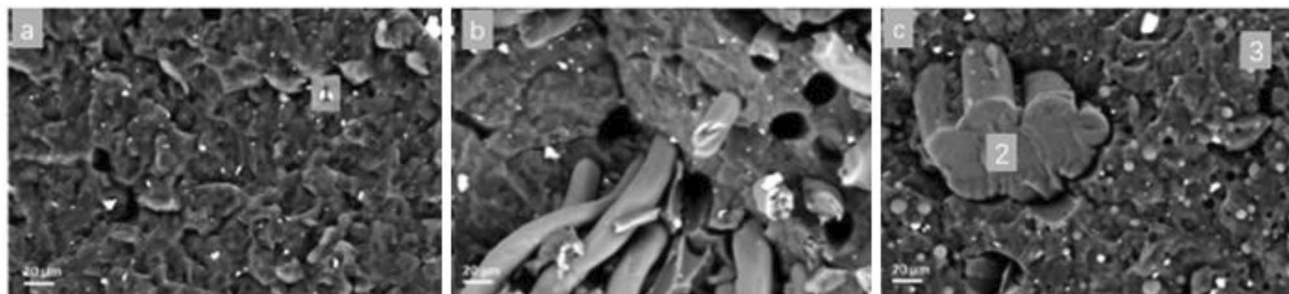


Fig. 1 SEM images of **a** masks without ear loops processed at 190 °C, **b** masks with ear loops processed at 190 °C, and **c** masks with ear loops processed at 230 °C. Figure 2 is taken from Battezzore et al. (2020) with copyright permission

be not sufficient. Unmelted fibers of ear loops existed in the PP matrix as fillers (Fig. 1b, c), and the adhesion between matrices and fibers was poor. Because ear loops in the market show great variability in materials and shapes, different kinds of ear loops have various effects on the properties of final products. In addition, the high local concentration of ear loop fibers may alter the viscosity and yield stress of the final materials due to heterogeneity (Crespo et al. 2021). Thus, mechanical or artificial separation and classification of the components are suggested in the recycling process of waste masks. The possible influence on the heterogeneity of masks could be eliminated and the efficiency of upgrading and reconstruction would be improved (Irez et al. 2022).

In short, the process of direct melting and thermoforming is simple and economical with a short procedure, which can be used to recycle waste masks. However, regenerated materials can only be used in situations requiring low mechanical properties, such as flowerpots, storage tanks, or transport pallets that are not critical to technical specifications (Crespo et al. 2021). Other fillers or polymers can be added to further improve the performance of regenerated materials to meet the requirements of more industrial applications. For example, fillers such as montmorillonite, SiO₂, and carbon nanomaterials can be added to mask PP to prepare composites or polymers such as polyethylene (PE) and polyamide (PA) can be added to prepare polymer alloys.

Modification of building materials

Waste masks can be treated by physical processing directly after strict medical disinfection and sterilization. Waste masks after physical processing can serve as a modifier for building materials to realize the recycling of waste masks, as illustrated in Table 1. Adding a low percentage (0–5%, according to soil weight) of the broken masks in road materials could strengthen the ductility and flexibility of pavement foundation and underlying foundation layer (Rehman and Khalid 2021; Saberian et al. 2021; Zhang et al. 2022). For example, waste masks were used as an asphalt modifier for the first time. The modification process of waste masks to asphalt was a physical modification, and no chemical reaction occurred to generate new functional groups. The fragmented mask was dispersed in the asphalt to form a partial network structure, and the asphalt had good compatibility with the mask under this process. Thus, the softening point, viscosity, rate of elastic recovery, high-temperature deformation resistance, rutting resistance, and freeze–thaw splitting strength of asphalt were improved (Yalcin et al. 2022; Zhao et al. 2022).

Concrete is one of the most widely used building materials in the construction process. Concrete is a quasi-brittle material. Internal stress in hardened concrete can lead to the

formation of microcracks. Studies have added small amounts of crushed masks to cement paste, cement mortar, or concrete (Kilmartin-Lynch et al. 2021). Waste masks bear part of load before any microcracking is initiated and reduce the number of microcracks (Nili and Afroughsabet 2010; Shen et al. 2020a). And, waste masks bridge cracks and transfer stress across the cracks after initial cracking of the specimen (Afroughsabet et al. 2016; Mohammadhosseini et al. 2017). Therefore, waste masks can improve the crack resistance and durability of concrete.

The effects of masks as fillers on the mechanical strength and durability of concrete were studied in terms of the shape, percentage, and pretreatment of the masks. Fibrosing the mask and cutting the masks into pieces of squares could modify the shape of masks (Idrees et al. 2022). Fibrous masks which were produced in the first approach offered better tensile strength of concrete than mask fragments. Additionally, the penetrability of the final material should be taken into consideration as lower permeability means better endurance. The permeability of the sample added with mask fragments was greatly reduced since square mask fragments were impermeable, not allowing water or ions to pass through. However, the fibrous masks did not reduce the penetrability of concrete significantly as the square fragments did. Therefore, specific mechanical properties and durability can be improved by changing the shape of the masks to meet engineering requirements.

Furthermore, the percentage of adding masks had a significant effect on the performance of concrete. It would be hardly possible for excessive fibrous or fragmented fillers to distribute evenly in concrete, creating too many voids instead. As a result, compressive and tensile strength declined and penetrability improved. The optimum percentage of fibrous masks was found to be 1% to enhance the mechanical and durable properties of concrete (Idrees et al. 2022). The optimum percentage of waste masks added to concrete in the form of fragments remains to be studied.

The drawback of waste masks in application in concrete is the weak bonding with cement matrix. The pretreatment of masks can improve the interface transition zone between the mask fibers and cement slurry matrix in order to further enhance the strength of concrete. Nano-active powders or chemical treatments can be used to the surface modification of the masks. For example, a high-range water reducer (HRWR, MasterGlenium7920, BASF) was used to disperse the masks into microfibers with a length range of about 5–30 mm and a diameter range of 20–40 μm. Microfibers were pretreated with graphene oxide (GO, 0.05 wt%) suspension (Li et al. 2022b). GO raised the degree of polymerization of hydration products in the interfacial transition zone between mask fibers and cement slurry matrix through its superior nano-nucleation and interlocking effect, resulting in tighter bonding between mask fibers and cement slurry

Table 1 Application of waste masks through physical treatment

Processing method	Processed object	Added material	Condition	Modulus (MPa)	Tensile strength (MPa)	Elongation at break (%)	Use	Reference
Direct melting and thermoforming	Face mask	–	Extrude: $T = 190\text{ }^{\circ}\text{C}$	825	22	7	For scenarios that do not require high mechanical properties	(Battagazzore et al. 2020)
	Face mask, ear loop	–	Extrude: $T = 190\text{ }^{\circ}\text{C}$	921	13	2		
	Face mask, ear loop	–	Extrude: $T = 230\text{ }^{\circ}\text{C}$	1049	13	2		
Face mask	Recycled PP (75 wt%)	–	Extrude: $T = 190\text{ }^{\circ}\text{C}$, $P = 5\text{ MPa}$, time = 5 min	660	18	5.8	For scenarios that do not require high mechanical properties	(Battagazzore et al. 2022)
			Extrude: $T = 190\text{ }^{\circ}\text{C}$, $P = 5\text{ MPa}$, time = 5 min	850	15	4.0		
Polymer alloy	N95	NBR, MA (compatibilizer)	Mix: ratio of PP to acrylonitrile butadiene rubber = 7:3 (g), $T = 180\text{ }^{\circ}\text{C}$	–	17	4	Can be used as an engineering product with higher thermal stability and barrier property	(Varghese et al. 2022)
			Mix: ratio of face masks to multi-walled carbon nanotubes = 49:1 (g)	750	34.03	250		
Composite modification with fillers	Face mask	Multi-walled carbon nanotubes	Extrude: $T = 180\text{ }^{\circ}\text{C}$, time = 5 min	–	–	–	Produce mixed material with improved mechanical properties, electrical properties, and thermal stability	(Xiang et al. 2022)

Table 1 (continued)

Processing method	Processed object	Added material	Condition	Modulus (MPa)	Tensile strength (MPa)	Elongation at break (%)	Use	Reference
Composite modification with fillers	Used mask, N95	OBC and GnPs	Nitric acid surface treatment: $C=65\%$, $T=60\text{ }^\circ\text{C}$ Add: ratio of OBC to GnPs = 25:1 (g), 50:3 (g), 25:2 (g); $T=135\text{ }^\circ\text{C}$ Extrude: $T=175\text{ }^\circ\text{C}$, $P=12\text{ bar}$	807.41	21.75	0.44	Produce material with self-healing characteristic, higher Charpy impact resistance and fracture toughness, which can be used in automotive industry, such as bumper material	(Irez et al. 2022)
				801.48	21.49	0.45		
	Face mask	Sisal fiber Hemp fiber	Extrude: $T=170\text{ }^\circ\text{C}$, $P=2.5\text{ MPa}$	–	40.5 55.1	20.9 8.1	Produce material with antimicrobial properties against <i>Staphylococcus aureus</i> , which can be used as food contact cutlery and packaging materials	(Pulikkalparambil et al. 2022)
	Face mask	Loofah sponge (12 wt%)	Extrude: $T=180\text{ }^\circ\text{C}$, time = 5 min	–	13	62	Sustainable railway sleepers, 3-dimensional (3D) printing feedstock material, and low-value building material	(Xiang et al. 2021)
Modification of building materials	Face mask	Asphalt	Mix: ratio of mask to asphalt = 1:24 (g), $T=170\text{ }^\circ\text{C}$, time = 5 min	–	3	3.8	High-temperature anti-rutting performance and low-temperature anti-cracking performance have been improved	(Zhao et al. 2022)

Table 1 (continued)

Processing method	Processed object	Added material	Condition	Modulus (MPa)	Tensile strength (MPa)	Elongation at break (%)	Use	Reference
Modification of building materials	Face mask	Granular soil, waste mask chips (0.5 wt%)	Mix: $P = 25$ kPa	1.1×10^{-3}	–	Void ratio = 0.558	Can be used in the embankment construction of road and railway, backfill, or reclamation construction	(Zhang et al. 2022)
	Face mask	Recycled concrete aggregate	Ratio of face mask to the recycled concrete aggregate = 1:49 (g)	304.78	–	–	Can be used as pavements base or sub-base	(Saberian et al. 2021)
	Face mask	Concrete	Ratio of water to cement = 1:2, ratio of fiber to concrete = 1:99	–	30	Compressive strength = 4.0	Produce green concrete with higher durability property and corrosion resistance	(Idrees et al. 2022)
	Face mask	Cement	Ratio of water to cement = 2:5, ratio of mask to concrete = 1:19	–	Flexural strength = 7.5	Compressive strength = 38	Can be used as cementitious material	(Castellote et al. 2022)
	Face mask	Concrete mixtures	Process: $T = 190$ °C, $P = 130$ bar, time = 10 min	–	7.80	Compressive strength = 75.9	Produce concrete whose durability has not been affected	(Konioreczyk et al. 2022)
	Face mask	Cement, graphene oxide (0.05 wt%)	Ratio of water to cement = 2:5	–	47% higher than that in the blank group	Compressive strength is 3% lower than that in the blank group	Can be used in the concrete industry	(Li et al. 2022b)
	Face mask	Silica fume (cementitious agent), selected soil	Ratio of silica fume to face mask = 40:3	–	3.5×10^{-3}	7	Can be used as subgrade material or impermeable layer	(Rehman and Khalid 2021)

GnP's graphene nanosheets

(Luo et al. 2021a). In the cement slurry with the water/cement ratio of 0.40, the GO-treated mask fibers at 0.1 vol% showed great growth on the splitting tensile strength (by 47% at 28 days), even though the compressive strength of paste decreased slightly (by 3% at 28 days).

In general, it is of a good prospect for waste masks to make building materials produce with better strength and endurance. As we expect, sustainability, circular economy, and effective waste management are gradually coming true.

Novel physical recovery

The relative molecular mass of melt-blown PP is small and the distribution is narrow, and it is easy to control the process of modifying the mask PP (Chadwick et al. 2004). Introducing common and inexpensive inorganic nanoparticles and natural fibers or blending mask PP with other polymers to obtain polymer alloys can convert waste masks into highly value-added products during mechanical recycling (Fig. 2).

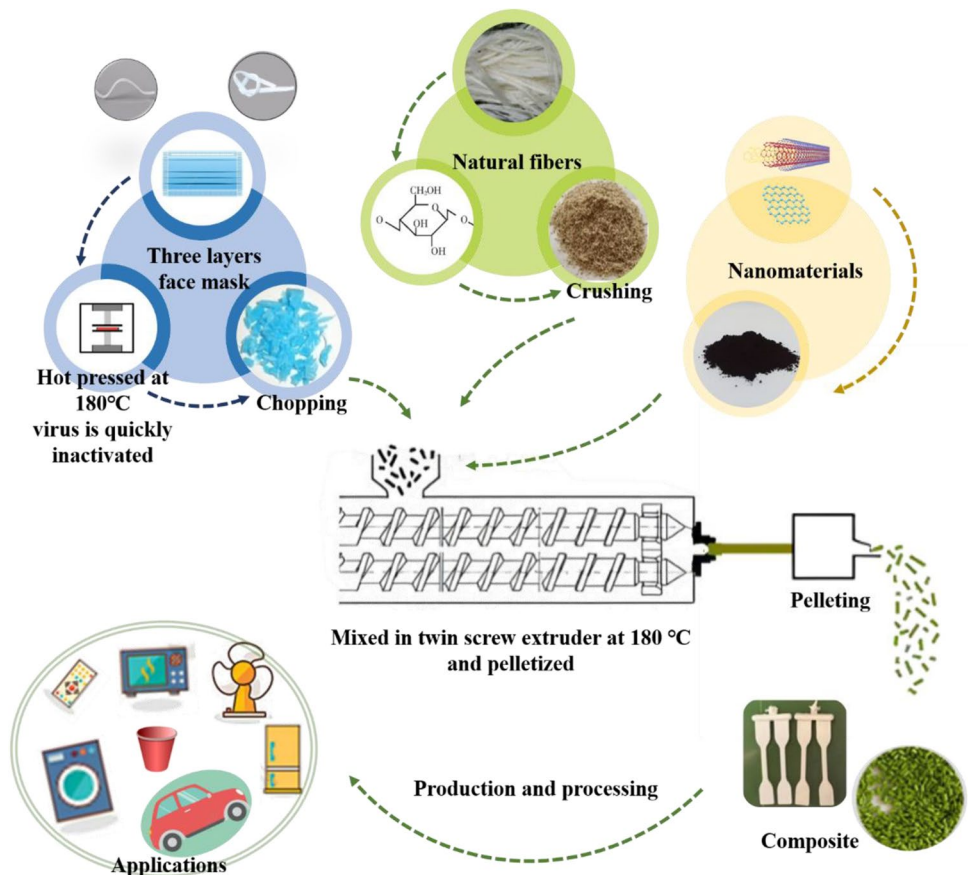
Composite modification with fillers

Nanomaterials have strong volume, surface, size, and macroscopic quantum effect, so they can affect the mechanical,

optical, electrical, and thermal properties of the final materials. Natural fibers have the significant properties of easy availability, low density, low cost, high mechanical strength, renewability, lower environmental impact, lower abrasive damage, and good insulation properties (Pulikkalparambil et al. 2017). Without any coupling agent or additive, nanomaterials and natural fibers can be used as reinforcing fillers to improve the mechanical strength of mask PP, and even allow mask PP to obtain special features, such as conductivity and antibacterial property. Composites can be utilized for specific industrial applications, as shown in Table 1.

Uniformly dispersed fillers act as the skeleton in the matrix. The physical or chemical interactions between filler and PP matrix restrict the movement of the matrix and consequently improve the mechanical properties of the composites such as stiffness, toughness, and strength (Liang et al. 2016). Graphene nanosheets (GnPs) were employed as reinforcement material to blend with mask PP. The elastic modulus of the composites was increased due to the high elastic modulus of GnPs when GnPs were uniformly distributed (Irez et al. 2022). Moreover, conductive polymer composites were fabricated by simply melting and blending mask PP and multi-walled carbon nanotubes (MWNTs) at 180 °C. PP matrix was locked in the network of MWNTs to avoid rupture under strong external force. The tensile strength of

Fig. 2 The process of novel physical recovery



the composites increased and was higher than that of common commercial grade polypropylene (Xiang et al. 2022). Loofah sponge (LS) containing a unique micron-channel structure was used as an enhancer to melt and blend with mask fragments at 180 °C (Xiang et al. 2021). Mask PP with high fluidity overcame the capillary effect of microchannels of LS. That micron channels of LS fiber were filled with the PP matrix led to the transformation of LS fibers from hollow fibers to solid ones, so a reinforcement network was formed. The LS/mask PP composites exhibited better tensile strength and toughness.

In addition to the basic mechanical properties, the introduction of inorganic nanoparticles and natural fibers can also functionalize PP and expand the range of use. For example, GnPs can absorb microwaves owing to such two-dimensional honeycomb microstructure (Chen et al. 2010; Hassan et al. 2009; Li et al. 2010). The composites with enhanced impact resistance and microwave self-healing function were produced by blending GnPs with mask PP, to provide beneficial outcomes for the maintenance planning and lifetime improvement of the bumpers in the automotive industry (Irez et al. 2022). In the microstructure of the MWNTs/mask PP composites, MWNT fibers interpenetrated with each other in the PP matrix to form a conducting network. Thus, more conducting paths were constructed to transport carriers, leading to the improved electrical property of the composites. And, good thermal conductivity of MWNTs transferred the heat needed by the thermal decomposition of the composite in time, leading to the improved thermal property of the composites. Besides, the enhanced thermal stability of the composites came from the good thermal stability of the MWNTs themselves (Xiang et al. 2021).

The uniform dispersion of nanomaterials and natural fibers as fillers melting in PP is the key to preparing composites by melt blending. High molecular weight of neat PP leads to high melt viscosity in the preparation of the composites. Fillers would be more difficult to uniformly disperse in the neat PP matrix, leading to a poor increase of mechanical property of the composites. Compared with neat PP, the molecular weight of mask PP decreases, leading to the lower melt viscosity in the preparation of the composites. Fillers would be easier to uniformly disperse in the mask PP matrix, leading to a higher increase of mechanical property of the composites (Xiang et al. 2021).

Nevertheless, excessive nanomaterials and natural fibers are prone to agglomerate. The aggregation of nanomaterials and natural fibers leads to stress concentration, resulting in microcracks around these nanoparticle clusters, and prevents effective stress transfer and reduces the toughening effects of nanoparticles (Irez et al. 2022). The aggregation of nanomaterials and natural fibers not only reduces the mechanical properties, but other functional properties also are negatively affected. Scientists investigate the influence of surface

bioactive treatment on the dispersion of fillers. For example, the surface of GnPs was treated with 65% nitric acid and distributed uniformly in the PP matrix, so the stiffness and toughness of the composites were boosted (Irez et al. 2022). On the other hand, starting from the processing machinery and technology, the uniform dispersion of nanoparticles in the PP matrix can be realized by changing the shear field and tensile flow field in the mixing process (Ferras et al. 2020; Grace 2007; Rwei et al. 1990, 1991; Sun et al. 2019).

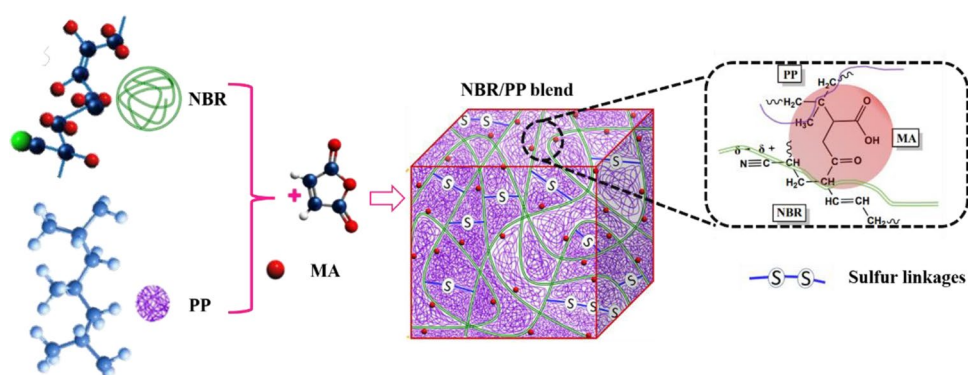
Recently, researchers have carried out a lot of researches on modifying polymers with nanoparticles and natural fibers and have been familiar with surface modification of nanoparticles or natural fibers. However, the study of these surface modification methods for mask PP modification is deficient. Other nanoparticles or natural fibers can also be used to modify mask PP to better enhance the mechanical properties of regenerated materials, or develop other special characteristics of regenerated materials, such as permeability, flame retardancy, thermal stability, and so on.

Polymer alloy

Polymer alloy is a polymer blend obtained by blending two or more polymers and additives in the molten state. Blending with the polymer can further improve the strength and impact resistance and toughness of mask PP. However, many polymers with complementary properties have obvious phase separation in their blends as their poor thermodynamic compatibility leads to the instability and deterioration of their properties. Compatibilizers can increase the compatibility between components. The interfacial adhesion between polymers can be strengthened, and a macroscopic non-separation and microscopic heterogeneous system can be formed. Consequently, the well-developed interface can transfer stress and enhance the mechanical properties of materials.

Nowadays, a reactive compatibilizer is exploited in PP blending technology. Grafted or block copolymers (Andreopoulos et al. 1999; Bertin and Robin 2002; Eagan et al. 2017; Radonjic and Gubeljak 2002; Yang et al. 2003) and maleic anhydride grafted polyethylene (Fang et al. 2013) are typical compatibilizers. For instance, the nonpolar PP fibers of the mask were mixed with polar acrylonitrile butadiene rubber (NBR) using maleic anhydride (MA) as the compatibilizer (Varghese et al. 2022). The reaction mechanism of PP-NBR blends is shown in Fig. 3. Dicumyl peroxide (DCP) acted as the free radical initiator in the overall reactions. MA reacted with PP first, and MA-modified PP molecules further reacted with NBR (George et al. 1995, 1999). As an interfacial agent, MA fixed PP and NBR together via chemical bonds to form a three-dimensional elastic network in the blends. Additionally, there was sulfur cross-linking within the NBR matrix, which

Fig. 3 Reaction mechanism of PP-NBR blends (Varghese et al. 2022)



resulted from the vulcanization process that again increased the strength of the blend. Meanwhile, islands of PP were formed in the network structures and the phase separation was prevented. The interface between PP and NBR in the blends has superior adhesion and stability compared with that between pure PP and NBR. It is obviously shown that PP-NBR blends present better mechanical and barrier properties.

The issue of poor compatibility between the fillers and the matrix also exists in the method of composite modification with fillers. The surface energy of nanoparticles is high, while the surface tension of PP melt is low. Natural fibers are usually strongly hydrophilic because of many hydroxyl groups contained while PP is hydrophobic. Therefore, the mixture of fillers and PP lacks thermodynamic driving force, resulting in obvious phase separation, thus destroying the modifying effects. The properties of composites can also be improved by using compatibilizers. For example, PP was grafted with MA (PP-*g*-MAH). Moreover, MWNTs were covalently attached with hydroxyl groups (MWNT-OH) using KOH and further transformed into MWNT-NH₂ by a silane coupling agent. The subsequent reaction between the amino groups on MWNTs and the MAH groups on PP resulted in the grafting of PP chains onto the MWNT, and the target product PP-*g*-MWNTs was obtained. Remarkable improvements in the mechanical, thermal, and electrical properties of the obtained composites were achieved due to the improved interfacial conditions (Wang et al. 2019).

The properties and applications of materials derived from different physical recovery technologies are summarized in Table 1. Traditional physical processing for recycled materials can be obtained economically. Recycled materials can be applied to industries with less stringent mechanical ownership requirements. Novel physical treatment can enhance the added value of recycled PP. Recycled PP composites can often be used as associated components for important equipment and decorations. However, the application of mechanical blending is limited since PP is a nonpolar polymer and its interaction with other polar compounds is weak (Chen

et al., 2020a). Furthermore, repeated mechanical treatment may cause side reactions in the molecular chain and reduce the performance of recycled PP.

Thermochemical technology

Thermal cracking

Thermal cracking is a widespread method to eliminate plastic waste. Polyolefins are degraded via the free radical random cleavage pathway in nitrogen or air without catalysts at 300–900 °C. The pyrolytic products of masks can be mainly gaseous or liquid with slight solid residues, as shown in Table 2. The pyrolysis gas is mainly composed of small molecules, including methane and hydrogen, which have the potential to become syngas. Meanwhile, no harmful gases will be released during pyrolysis because of the low content of N and S in masks (Schwartz et al. 2020). Liquid oil is mainly composed of hydrocarbon from C₆ to C₃₅, and the calorific value is similar to gasoline (44 MJ/kg). Thus, the effective usage of liquid oil as an energy resource can alleviate the energy crisis (Li et al. 2022a). In addition, the novel coronavirus could be inactivated at 100 °C (Rubio-Romero et al. 2020). Therefore, treating waste masks via thermal cracking was a relatively sustainable, efficient, and eco-friendly technology as opposed to incineration and landfilling.

Figure 4a depicts the mechanism based on the mask pyrolysis mass curve. The mask began to decompose at 130 °C with evaporating of moisture. The friction-mechanical bonds between the fabrics of masks were destroyed and existed in the form of individual microparticles as the temperature increased to about 280 °C (Yousef et al. 2021a). A high temperature (420 °C) would cause the van der Waals, hydrogen, and β-1,4-glycosidic bonds of cellulose, lignin, and hemicellulose destroyed, following the generation of small molecules and amorphous regions. Low-carbon

Table 2 Application summary of thermochemical treatment of waste masks

Method	Catalyst	Experimental conditions	Main products	Yield	Reference
Thermal cracking	–	$T=440\text{ }^{\circ}\text{C}$, time = 20 min	Liquid oil	42.1 wt%	(Sun et al. 2022)
Thermal cracking	–	$T=550\text{ }^{\circ}\text{C}$, time = 30 min	Liquid oil	80.7 wt%	(Lee et al. 2021)
Thermal cracking	–	$T=700\text{ }^{\circ}\text{C}$	Diesel	34.1 wt%	(Park et al. 2021)
Thermal cracking	–	$T=900\text{ }^{\circ}\text{C}$, heating rate = $5\text{ }^{\circ}\text{C}/\text{min}$	2,4-Dimethyl-1-heptene	32.1 vol%	(Yousef et al. 2021a)
Thermal cracking	–	$T=2700\text{ }^{\circ}\text{C}$, time = 8 s, carbon foam microwave plasma	H_2 and CH_4	52.0 vol%	(Xu et al. 2021)
Co-pyrolysis	–	$T=400\text{ }^{\circ}\text{C}$, time = 1 h, co-pyrolysis with surgical gloves	Bio-crude oil	75.0 wt%	(Aragaw and Mekonnen 2021)
Co-pyrolysis	–	$T=700\text{ }^{\circ}\text{C}$, ratio of food waste to masks = 3:1 (g)	H_2 and $\text{C}_1\text{--C}_3$ gas	13.0 vol%	(Park et al. 2021)
Co-pyrolysis	–	$T=300\text{ }^{\circ}\text{C}$, ratio of <i>Spirulina platensis</i> to masks = 3:1 (g)	Bio-oil	23.0 wt%	(Li et al. 2021)
Co-pyrolysis	–	$T=900\text{ }^{\circ}\text{C}$, ratio of bio-oil to masks = 10:1 (g)	Biochar, bio-oil, and graphene films	–	(Luo et al. 2021a, b)
Catalytic cracking	Nb-CeO ₂	$T=550\text{ }^{\circ}\text{C}$, time = 4 h	$\text{C}_3\text{--C}_{16}$	86.5 wt%	(Ali et al. 2022)
Catalytic cracking	$\beta(60\text{H})$	$T=580\text{ }^{\circ}\text{C}$	Butene	30.9 wt%	(Sun et al. 2022)
Catalytic cracking	ZSM-5	$T=900\text{ }^{\circ}\text{C}$, heating rate = $5\text{ }^{\circ}\text{C}/\text{min}$, ratio of ZSM-5 to masks = 1:4 (g)	1-Butanol	28.7 vol%	(Yousef et al. 2022)
Catalytic cracking	Ni/SiO ₂	$T=450\text{ }^{\circ}\text{C}$, heating rate = $10\text{ }^{\circ}\text{C}/\text{min}$, N_2 environment	H_2	55.1 mol%	(Jung et al. 2021)
Catalytic cracking	Biochar	$T=650\text{ }^{\circ}\text{C}$, ratio of biochar to masks = 4:1 (g)	H_2	65.7 vol%	(Wang et al. 2022)
Catalytic cracking	HBeta	$T=450\text{ }^{\circ}\text{C}$	H_2	19.5 wt%	(Lee et al. 2021)
Catalytic cracking	Biochar	$T=800\text{ }^{\circ}\text{C}$, ratio of biochar to masks = 2:1 (g)	H_2	37.0 vol%	(Jiang et al. 2022)
Catalytic cracking	Ni/ZSM-5	$T=550\text{ }^{\circ}\text{C}$, time = 3 h, ratio of Ni to ZSM-5 = 1:4	H_2	45.0 vol%	(Farooq et al., 2021)
Carbonization	–	$T=800\text{ }^{\circ}\text{C}$, time = 1 h	Activated carbons	–	(Serafin et al. 2022)
Carbonization	–	Sulfonation: $T=155\text{ }^{\circ}\text{C}$, time = 12 h Carbonization: $T=800\text{ }^{\circ}\text{C}$, time = 3 h Activation: $T=700\text{ }^{\circ}\text{C}$, time = 1 h, ratio of KOH to carbon = 2:1 (g)	Multifunctional carbon fiber	58.0 wt%	(Robertson et al. 2022)
Carbonization	–	Sulfonation: $T=110\text{ }^{\circ}\text{C}$, time = 12 h Carbonization: $T=750\text{ }^{\circ}\text{C}$, time = 2 h, ratio of KOH to carbon = 3:1 (g)	S-doped porous carbon	40.0 wt%	(Hu and Lin 2021)
Carbonization	–	Sulfonation: $T=120\text{ }^{\circ}\text{C}$, time = 6 h Carbonization: $T=2400\text{ }^{\circ}\text{C}$	Non-graphitizable carbon powders	50.0 wt%	(Lee et al. 2022)
Carbonization	NiO ₂ /NiCl ₂	$T=700\text{ }^{\circ}\text{C}$	CNTs/Ni hybrids	64.4 wt%	(Yu et al. 2021)
Carbonization	Ni-Fe-Al ₂ O ₃	$T=800\text{ }^{\circ}\text{C}$, time = 3 h, ratio of Ni to Fe = 4:1 (mol), ratio of catalysts to masks = 1:9 (g)	CNTs	26.8 wt%	(Yang et al. 2022)

hydrocarbon molecules were decomposed into gaseous and liquid products at $510\text{ }^{\circ}\text{C}$, and almost no solid existed at $700\text{ }^{\circ}\text{C}$.

The transformation of masks into fuel has been studied by pyrolysis. The temperature and feed composition are factors affecting the yield and distribution of liquid oil. Several

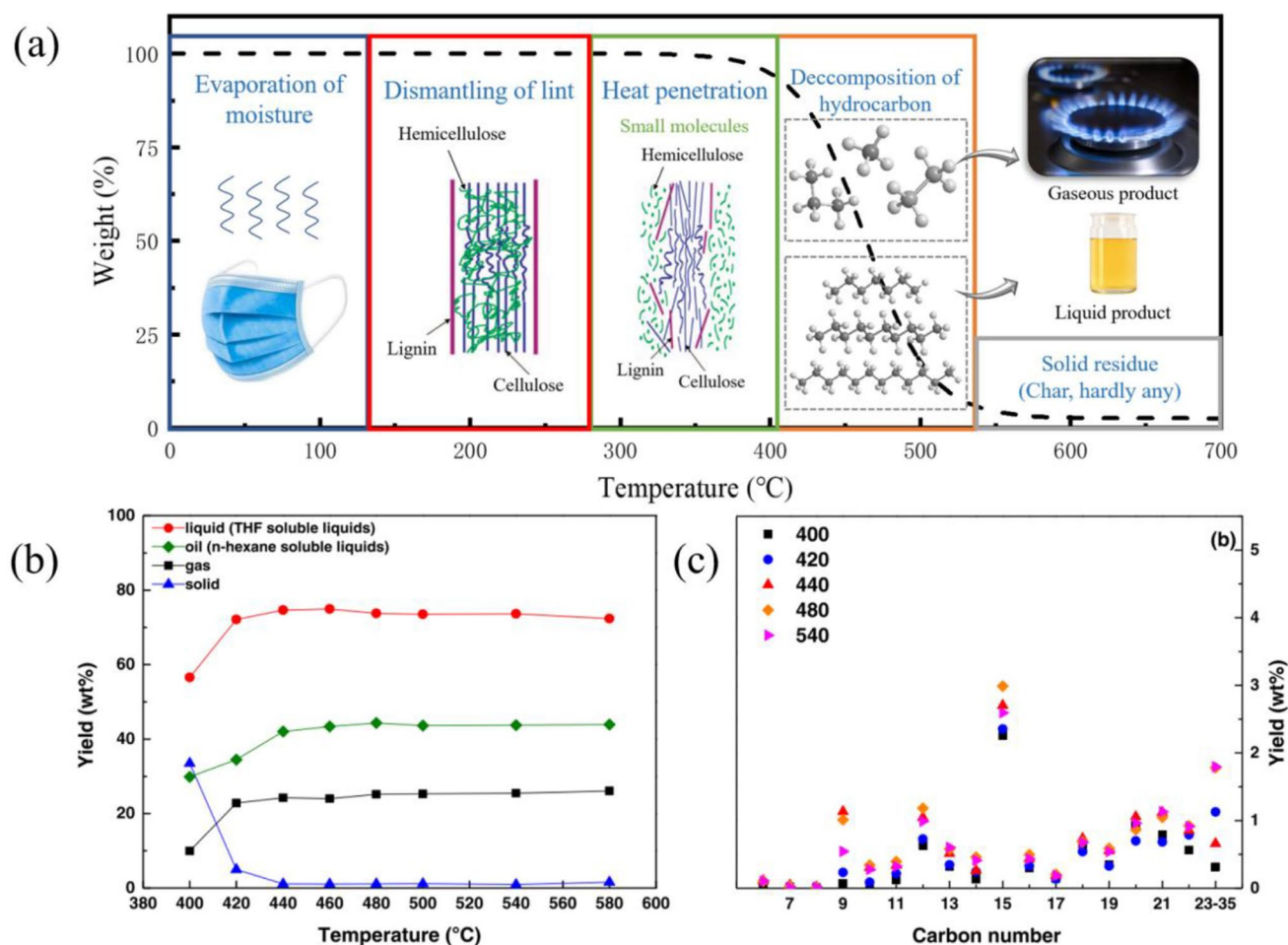


Fig. 4 a The mechanism diagram based on the mask pyrolysis mass curve (Aragaw and Mekonnen 2021; Kumar et al. 2009; Yousef et al. 2021a, 2021b). b Composition of pyrolysis products at different tem-

peratures. c Composition of oil products at different temperatures. Panels b and c are taken from Sun et al. (2022) with copyright permission

studies have investigated the effect of pyrolysis temperature on products. Figure 4b is the compositions of pyrolysis products at different temperatures. The yield of oil was 29.9 wt% at 400 °C, and it was up to 42.1 wt% at 440 °C. After 440 °C, the liquid product decreased slightly, while the gas and solid products increased marginally. The pyrolysis process was completed at 440 °C. The result of liquid oil quantified by gas chromatography is shown in Fig. 4c. Obviously, the oil product was dominated by C₁₅ alkene (accounting for about 3.0 wt% at 480 °C), followed by C₉, C₁₂, and C₁₈–C₂₃ compounds, which was similar to diesel components (Sun et al. 2022). Park et al. (2021) also pointed out that the pyrolysis process was completed at 500 °C. The yields of gasoline-range, jet fuel-range, diesel-range, and motor oil-range hydrocarbons were the highest at 700 °C, which were 14.7 wt%, 18.4 wt%, 34.0 wt%, and 18.1 wt%, respectively. The decrease or increase in temperature would both cause reduction in the oil yield (Park et al. 2021). A similar conclusion was drawn that the oil yield was up to 80.7 wt% at 550 °C

(Lee et al. 2021). In a word, high temperature is efficient to raise the yield of oil products, but negligible after 600 °C. The liquid yield may be reduced at an extremely high temperature. Both insufficient and excessive pyrolysis will have an effect on the product during the heating process. Hence, it is critical to find the appropriate temperature for synthesis of ideal target products.

The co-pyrolysis effects on different feeds and waste masks have been studied, as shown in Table 2. The quality and quantity of bio-oil obtained by co-pyrolysis of waste biomass were better than those obtained by pyrolysis of single raw material (Abnisa and Daud 2014; Gouws et al. 2021; Uzoejinwa et al. 2018). Li et al. (2021) used *Spirulina platensis* for co-hydrothermal liquefaction with waste masks at a relatively low temperature compared to simple pyrolysis. The yield of oil was up to 23.0% at 300 °C, which was much higher than the yield (7.0%) of hydrothermal liquefaction of individual waste masks. The yield of hydrocarbons within the diesel range increased in favor of heavy oil and

gasoline by blending masks with *Spirulina platensis* (Li et al. 2021). Luo et al. (2021b) co-pyrolyzed mask with the heavy fraction of bio-oil to obtain a series of biochar, bio-oil, and graphene films. The bio-oil contained some aromatics compounds, such as 1,2-dimethylbenzene and 2-methylnaphthalene, which were widely applied in the chemical and pharmaceutical industries (Luo et al. 2021b). However, no aromatic compounds were found in the single pyrolysis of masks (Lee et al. 2021). Food waste had higher contents of O and N compared with other co-feed. Therefore, co-pyrolysis of masks with food waste could obtain the high yields of liquid products containing oxygenates and nitrogenous compounds. The proportions of phenolic compounds and polycyclic aromatic hydrocarbons (PAHs) also increased. The high temperature was beneficial for the conversion of lignin to phenolic compounds and PAHs (Sharma and Hajaligol 2003). These components of liquid products were not compatible with fuels but suitable for the chemical and pharmaceutical industries (Park et al. 2021). In conclusion, adding biomass in the pyrolysis process would influence the properties of liquid products significantly. Suitable catalysts may be considered to be added in the co-pyrolysis process to realize the directional conversion products in the future. Co-pyrolysis of masks with other biomass is also a desirable route to obtain higher-quality target products.

The possible pyrolysis mechanism of PP is shown in Fig. 5. Firstly, the primary and secondary free radicals are mainly generated after the main PP backbone braking. Methyl radicals were formed with the 1–3-end-hydrogen transfer and β -scission of the primary free radicals. Then, methyl radicals captured hydrogen ones to form methane

(Fig. 5a). Meanwhile, 1–3-end-hydrogen and 1–4-end-hydrogen transfer may occur to generate secondary free radicals. Ethyl and propyl free radicals were generated following the β -scission. These free radicals may be transferred into corresponding alkanes and olefins by capturing or losing hydrogen free radicals (Fig. 5b, c). In addition, the random chain scission, 1–2-end-hydrogen transfer, and the capture of hydrogen radicals occurred in the secondary free radicals to form butene (Fig. 5d). It is a possible transformation pathway of micromolecular pyrolysis products. Although the thermal cracking of waste masks was simple to operate, the composition of products was complex and the direct use value was relatively low.

Catalytic cracking

Catalysts could reduce the activation energy, increase the reaction rate, and orient the product to transformation during pyrolysis. Some reports related to catalytic cracking are summarized in Table 2. The main process is divided into two steps, including thermal and catalytic cracking (Fig. 6). In the primary stage, PP in mask decomposes into relatively long-chain radicals through the free radical random cleavage pathway. Subsequently, the radicals can be converted into low-chain hydrocarbons through β -scission and hydrogen transfer. Then, aromatization of these hydrocarbons is conducted to form carbon nanotubes (CNTs) under a high temperature in the second stage. At the same time, the formation of aromatic hydrocarbons promotes the yield of H_2 sharply, which could replace traditional fossil fuels. Hence, the conversion of waste masks to H_2 is an ideal approach to

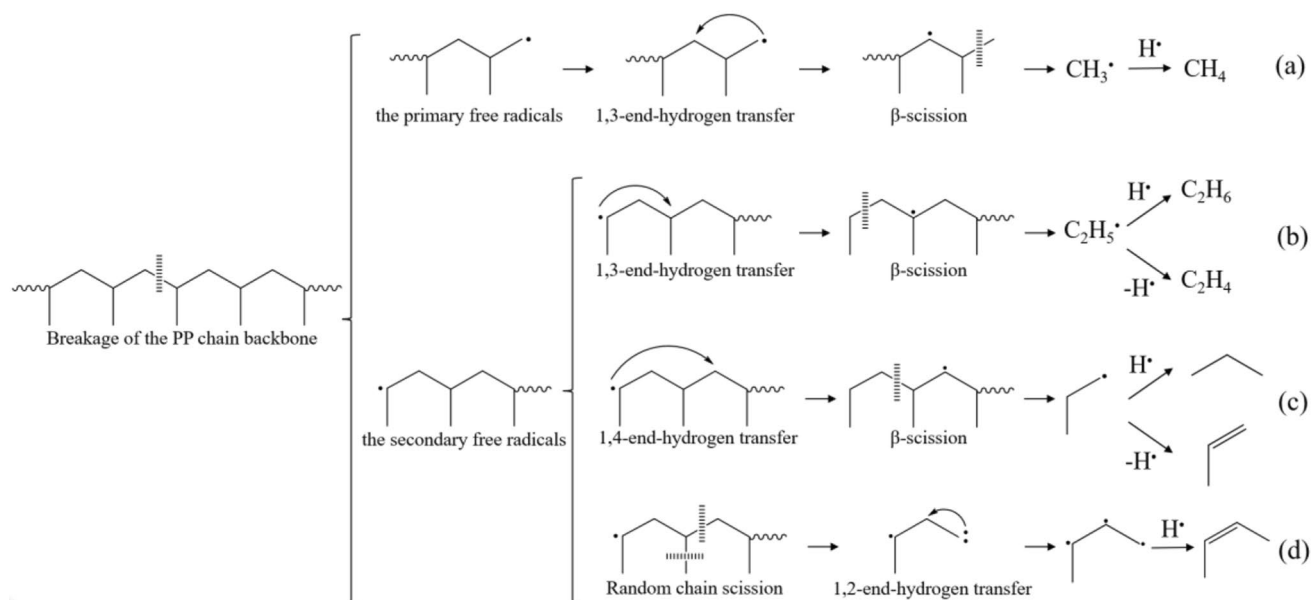


Fig. 5 The transfer of PP (the main component of waste masks) during pyrolysis (Yan et al. 2015; Sun et al. 2021)

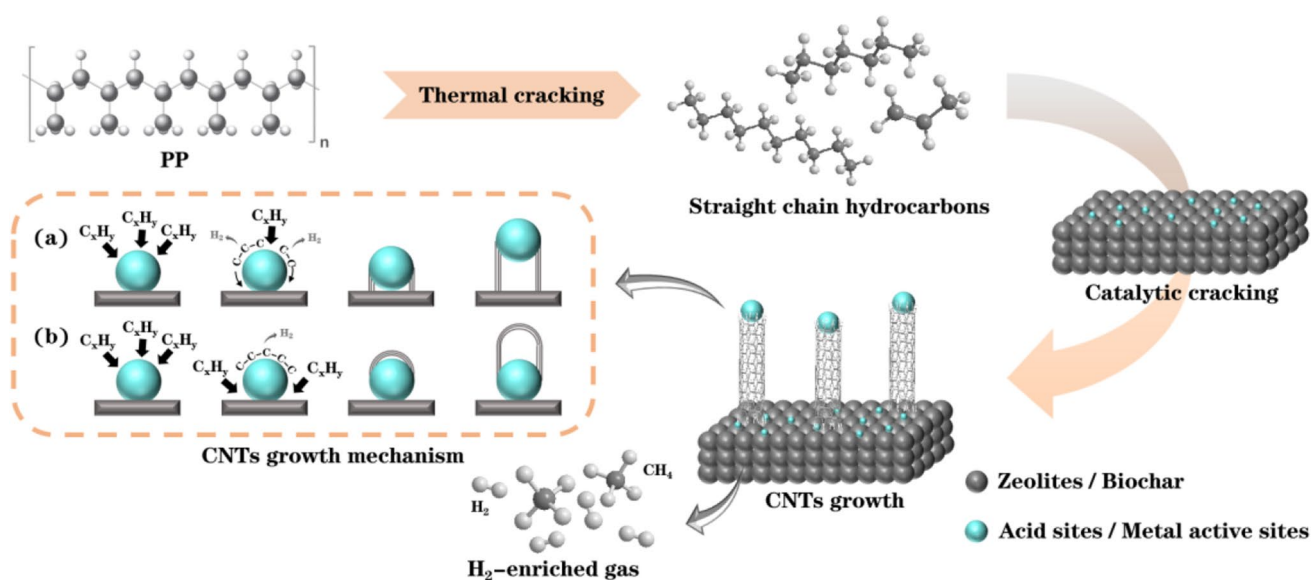


Fig. 6 Schematic diagram of catalytic cracking. **a** Base-growth of CNTs. **b** Tip-growth of CNTs

solve plastic pollution and produce clean energy. Currently, zeolite molecular sieves and biochar are commonly used as catalysts in the process of H_2 production.

Catalytic cracking of masks with zeolite molecular sieves has been investigated. The main factor affecting the catalytic performance of zeolites is the density of acid sites (Lopez et al. 2017). The amount of acid sites carried by zeolite exerts a great influence on the production of aromatics and light olefins as well as the formation of H_2 (Lin et al. 2010). Additionally, the porous structure and pore shape of the catalyst also play an important role in the proximity of macromolecules formed by polyolefin degradation to the acidic site of the catalyst (Park et al. 2002). Lee et al. (2021) studied the effect of different types of zeolites (HZSM-5, HBeta, and HY) on the pyrolysis product of waste mask. The results showed that HBeta had the best performance on the enhancement of H_2 yield (from ~0.5 wt% without the catalyst to ~19.5 wt%). The relative excellent nature of HBeta was ascribed to larger pore volume and more acid sites than those of others (Lee et al. 2021). Farooq et al. (2022) used ZSM-5 with different ratios of SiO_2 to Al_2O_3 as the catalyst to pyrolyze mask. The yield of H_2 would decrease with the increase of the ratio. Additionally, the m-ZSM-5 with 25% Ni loading would enhance the H_2 yield from ~3.10 to 45.04 vol% significantly. The reduced reaction ($NiO \rightarrow Ni^0$) would increase the PP conversion efficiently with the production of H_2 during pyrolysis (Farooq et al. 2022). However, the excessive content of Ni may cover the acid site on the catalyst surface, which will decrease the H_2 yield.

Several papers reported the influence of catalytic cracking of masks using biochar. Compared to activated carbon and carbon black, biochar had abundant surface functional

groups, nanostructures, and porosity that contribute to the enhancement of H_2 yield. Biochar had high electron affinity due to rich sp^2 hybrid orbitals so that the alkali and alkaline earth metallic species (e.g., Na and K) in biochar would be separated from their charges. These metal ions provided additional electron fields, inducing the olefination of alkane to produce H_2 (Liu et al. 2019). Wang et al. (2022) prepared corn stover-based biochar via microwave pyrolysis during catalyst cracking of masks. The yield of H_2 was 15.8 vol% in gas products at 550 °C without biochar while H_2 output soared to 56.8 vol% at the same temperature after adding biochar. Temperature was also a critical ingredient of the H_2 yield. The output of H_2 increased from 15.8 to ~31 vol% with temperature rising from 550 to 650 °C (Wang et al. 2022). High temperature was favorable for the conversion of aromatic hydrocarbons (Lin et al. 2021). Ni-loaded biochar exhibited the best performance on yield (34.2 vol%) of H_2 in comparison to individual, Zn-loaded, and Fe-loaded biochar at 800 °C (Jiang et al. 2022; Farooq et al. 2022). As the temperature increased to 800 °C, the pyrolysis gas was mainly decomposed into small molecules including H_2 and CH_4 . The C–H of small molecules (e.g., CH_4) could be cleaved by Ni nanoparticles, and the central carbon atoms of CH_4 were dissolved onto metal active sites, while the separated H diffused in the form of H_2 (Zhou et al. 2017).

In short, the yield of H_2 can be notably enhanced during catalytic pyrolysis adjusted by acid and metal active sites. Ni loading on the catalyst is also a considerable method that can further increase the output of H_2 . Nevertheless, catalytic cracking of mask is still waiting for further development due to lacking an action role of acid sites. The equilibrium

point of co-function between nickel and acidic sites should be found to maximize a catalytic effect. Subsequently, other types of catalysts could be tried to apply in the production of H_2 . For example, pyrolyzing masks with metallic oxide may be a desirable way in the future.

Carbonization

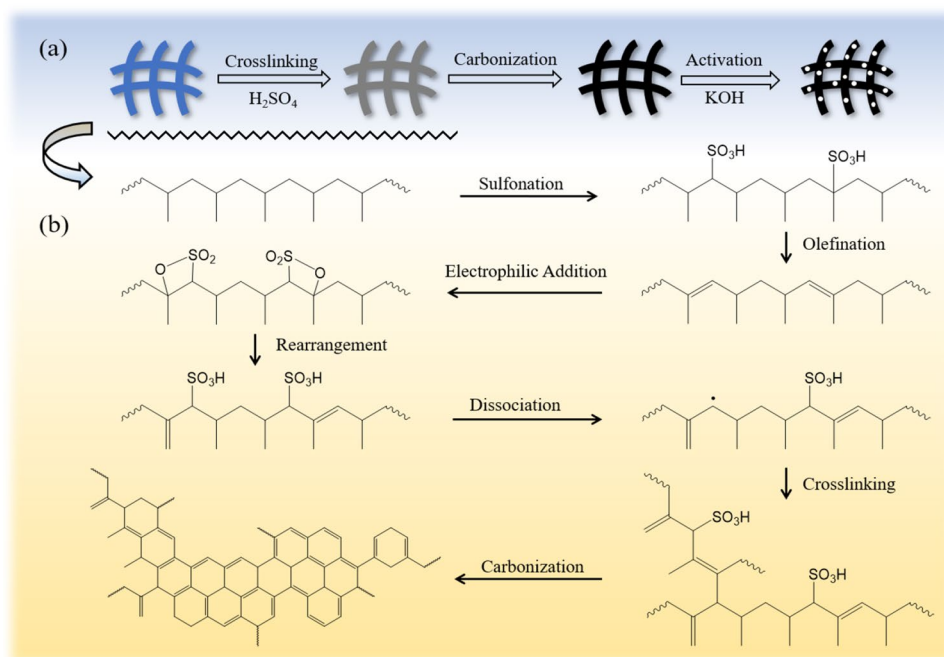
Carbonization is also applied for disposal and treatment of waste masks. Carbon with added value (e.g., graphite, carbon nanomaterials, activated carbon) can be formed via the carbonization of polymer compounds, which could be applied as electrode or absorption materials (Bazargan and McKay 2012; Shen 2020b). The high content of polyolefin contributes to the high carbon content of the mask (85.7%) (Gong et al. 2014a, 2014b). Additionally, masks have a high porosity framework which contributes to ion exchange or molecular adsorption to filter air. Therefore, mask as carbon sources to prepare high value-added carbon materials is a promising recycling strategy. However, the yield of solid products is fairly low by pyrolyzing masks directly at 500 °C. Therefore, some special methods need to be adopted to improve the carbon yield. Sulfonated modification and the introduction of catalysts are applied to the carbonization of masks.

Sulfuric acid can destroy and carbonize some complex plastic at high temperatures. And, sulfonation promotes efficient cyclization and oxidation to form dense carbon fiber structure (Xie et al. 2016). The waste mask can be heated in concentrated sulfuric acid before carbonization based on the porosity of PP so that the PP carbon chain can be

cross-linked. The mechanism of cross-linking is shown in Fig. 7b. First, sulfonyl groups bind to secondary or tertiary carbon atoms along the carbon chain, followed by the homolytic dissociation of the hydroxysulfonyl radicals ($\bullet HOSO_2$) to generate an unsaturated bond. The transformed polyolefin macromolecules react with $\bullet SO_3$ in sulfuric acid through electrophilic addition to produce β -sultones. Then, the rearranged β -sultones will further crack to form olefin PP containing free radicals which cross-link in sulfuric acid. This process is repeated until a highly cross-linked polymer network is formed (Lee et al. 2022).

Sulfonation pretreatment technology can cross-link a PP fiber structure and has been widely used in waste mask treatment. Lee et al. (2022) treated waste masks with sulfuric acid at 120 °C for 6 h and then pyrolyzed at 2400 °C directly. The remained carbon was up to 50 wt% and made into carbon materials that can be used as anodes for sodium-ion batteries. NMR analysis showed that sulfonation could not only induce simple cross-linking but also prompt the formation of PAHs (Lee et al. 2022). Nevertheless, the pyrolysis temperature of the above method was relatively high. Yuwen et al. (2022) completed the overall sulfonation and oxidation of the waste mask within 8 min by microwave solvothermal method based on the excellent microwave absorption capacity of concentrated sulfuric acid. The sulfonated sample was made into porous carbon with a high surface area, and the carbon yield was up to 54 wt% after self-activated pyrolysis in low-flow argon at 900 °C (Yuwen et al. 2022). Figure 7a shows the diagram of cross-linking, carbonization, and activation of PP fiber. Researchers introduced KOH activation into carbonization to obtain carbon materials with the

Fig. 7 **a** The diagram of cross-linking, carbonization, and activation of PP fiber (Robertson et al. 2022). **b** The schematic diagram of sulfonation cross-linking mechanism of PP. Panel **b** is taken from Lee et al. (2022) with copyright permission



high surface porosity. Thereby, the surface area and adsorption effect were enhanced. Regardless of activation before (Robertson et al. 2022) or after (Hu and Lin 2021) pyrolysis, sulfonated PP would be made into multi-functional fibers with porous structure, and carbon yield was not less than 40 wt%. Overall, mask treatment by sulfonation can produce high yield and high value-added carbon materials, although the procedure is slightly sophisticated.

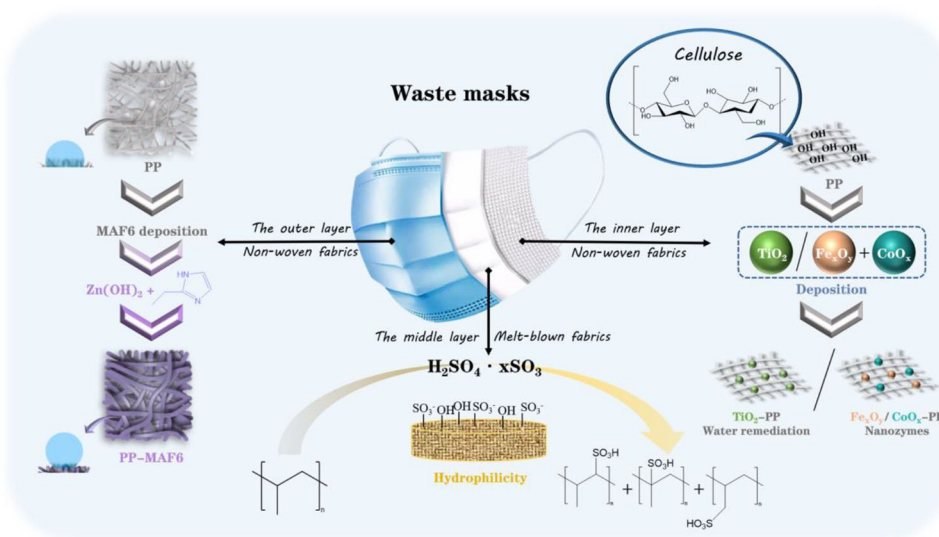
The introduction of catalysts can also enhance carbon yield. As mentioned in the previous section, Ni-based catalysts are commonly used in synthesis and conversion. The catalyst can promote the cracking of PP and convert PP into aromatic compounds selectively, followed by dehydrogenation and synthesis of CNTs, thereby increasing carbon yield. Yang et al. (2022) used Ni-Fe-Al₂O₃ as the catalyst in the process of carbonization. The catalyst not only promoted the growth of carbon nanotubes, but also divided them into multiple cavities, which had excellent electrochemical performance. In addition, the highest carbon yield was realized (26.75%) when the molar ratio of Ni to Fe was 4. The yield would decrease regardless of the increasing or decreasing of the ratio since synergies between Ni and Fe played a significant role (Yang et al. 2022). Carbon grows along the C/Ni interface. However, the growth would stop when the surface of Ni particles was wrapped completely by graphene layer (Helveg et al. 2004). In this process, Fe could promote the production of H₂ to prevent Ni surface from being covered by graphene layer, thus prolonging catalyst activity (Yao et al. 2017). Therefore, a suitable ratio of Ni/Fe would promote the formation of CNTs. The mechanism was similar to that in the section “Catalytic cracking”. When the C atom in the metal active sites was saturated, the dissolved C framework would further form CNTs. The growth process consisted of “base-growth” (Fig. 6a) and “tip-growth” (Fig. 6b) depending on the catalyst nanometric dimension

(Gohier et al. 2008). Yu et al. (2021) increased the carbon yield (up to 64.4 wt%) using NiCl₂·6H₂O as the catalyst. Unlike NaCl, NiCl could be decomposed into Ni and •Cl, which are effective components of the catalyst. The presence of Ni could fix most of the carbon in the condensed phase, while •Cl could control the degradation of polyolefin chains and promote dehydrogenation and aromatization reactions. The microwave absorption performance of the carbonized product was superior than that of most C/Ni hybrid materials due to synergies between Ni and CNTs (Yu et al. 2021). Overall, carbonization of mask via sulfonated modification or catalyst is an effective and low-cost method. And, the porosity of masks is used reasonably, which presents rosy application prospects in the fields of electrochemistry and adsorption.

Solvent-based technology

The solvent-based technology is used to obtain the certain carbon materials. The process of solvent-based technology is presented in Fig. 8. The waste mask should be soaked in an appropriate chemical solvent directly, and its original structure of the surface has been modified. The solvent-based technology pays more attention to the instinctive framework characters of masks compared with physical and thermochemical technologies. The medical mask consists of three layers commonly. The outer non-woven fabrics is hydrophobic, blocking splashing liquids and droplets. The inner layer is also made of non-woven fabrics but hydrophilic after modifying, which makes it possible to absorb moisture released from the noses and mouths. The middle melt-blown fabrics is the core functional area, filtering microorganisms and viruses with a diameter of 0.3–1.0 μm (Wibisono et al. 2020).

Fig. 8 Disposal of three-layer masks via solvent-based technology



The outer non-woven fabrics of the PP mask has low water absorption ability. Waste masks become an ideal material for the recycling of oil pollutants due to hydrophobicity (Wei et al. 2003). Non-woven PP shows fiber properties based on a single fiber network containing small pores, which helps liquid enter into the adsorbent and remain after being adsorbed. However, the original PP lacks high adsorption capacity and selective oil interception function. Therefore, the surface of the mask should be modified to remove oil pollutions. Fluorine-free ethyl-imidazole-based frameworks (MAF-6) with large pores and related hydrophobicity may provide additional adsorption sites (He et al. 2015). The MAF-6 was deposited on the PP mask in an organic solvent by optimizing the in situ method, obtaining the PP-MAF-6 with super hydrophobicity and strong adsorption capacity towards oil (Guselnikova et al. 2022). The adsorption capacity of PP-MAF-6 for diesel oil could reach 24,000 mg/g with the removal of pollutants in water with less than \$5 per square meter. Thus, the PP-MAF-6 has the potential for large-scale preparation. Park et al. (2022) found that the surface of the mask could also be modified by organic solvents, including *n*-hexane, *n*-heptane, and *n*-decane. The swollen macromolecular recrystallization formed a submicron protrusion on the surface of the mask after immersion (Zhu et al. 2015). The protrusion could maintain the original structure of PP. The surface roughness of both outer and inner layers increased, forming a superhydrophobic surface. The mask modified with heptane for 60 min at 90 °C has a better oil adsorption capacity (g/g), reaching 8–21 times the mass of its weight. The oil-saturated mask could be converted into crude oil via pyrolysis, filling the energy gap.

Unlike the outer, the surface of the inner non-woven fiber layer of the mask is rich in –OH, which endows the layer with super hydrophilicity. The –OH groups also provide strong, sustainable, and recyclable support for the deposition of metal/metal oxide nanoparticles (Mousli et al. 2020; Tang et al. 2020). The inner layer of the mask was immersed in the precursor solution containing TiO₂, CoO_x, and Fe_xO_y catalytic nanoparticles (Reguera et al. 2022). Then, the nanoparticles were embedded in the three-dimensional porous structure of the cellulose membrane successfully to attain catalytic activity. The dye in polluted water could be adsorbed onto catalytic nanoparticles with the non-woven PP as the carrier. The cellulose mask/TiO₂ system worked effectively in the decomposition of methylene blue under UV light, while the cellulose mask/Fe_xO_y/CoO_x system showed a good peroxidase-type activity, which could be used in advanced applications such as hydrogen peroxide electrochemical sensors. The advantage was to avoid the medium pollution caused by the aggregation and release of nanoparticles in the catalytic reaction process compared to previous studies concerning dispersed nanoparticles.

As for the main functional area of the mask, the ideal treatment of the middle layer has not been found, originating from mediocre performance and requirement for strict disinfection. The economical treatment could be realized by mixing the melt-blown fabrics with asphalt to manufacture high-performance roadbed materials (as mentioned in the section “[Modification of building materials](#)”) or modifying forcibly by chemical reagents. Fuming sulfuric acid (FSA) was used to react with the middle filter (MF) layer of the mask, obtaining optimized sulfonated MF (S-MF) layer (Kim et al. 2022). The S-MF layer is expected to play a role in many fields such as environmental catalysts and rechargeable battery separators, accounting for higher mechanical properties, excellent three-dimensional structure, satisfactory electrolyte wettability, and abundant polar functional groups. Kaneko studied the contact angle and O/C ratio during the reaction of FSA and PP (Kaneko and Sato 2005). The sulfonation proceeded rapidly in the initial stage of treatment, and the surface changed from hydrophobic to hydrophilic. The function is achieved because the rich •OH and •SO₃H are formed by the reactions between FSA and PP (Fig. 7). Unlike modified carbonization, no subsequent high-temperature treatment was performed, and ideal products can be produced in only a few minutes. The main operation of solvent-based technology is solution immersion. At present, the solvent-based approach is still in the experimental stage without being applied in large-scale industrial production.

In order to provide an intuitive comparison of different waste mask treatment technologies, we have listed the advantages and disadvantages of technologies in Table 3. Although the solvent-based technology has significant features such as high value-added products, operational simplicity, and low energy cost compared with the physical and thermochemical technology, its application in practical production is resistant. Pyrolysis is still the most promising technology for industrialization, and numerous environmental protection enterprises have already invested in the construction of pyrolysis recycling plants. In the process of pyrolysis, the experimental conditions such as pyrolytic temperature can modify significantly on the yield of liquid and gas products. Therefore, upcycling enterprises should concentrate on the influence factors of different technologies and define the appropriate conditions before the upcycling processing to obtain the optimal output.

Conclusion

This review summarizes the various technologies for the disposal and energy utilization of waste masks comprehensively. Some conclusions are put forward in the following:

Table 3 Comparison of the differences between various technologies

Method	Main treatment	Strengths	Weaknesses	Influencing factor
Traditional physical technology	Adding the mask fragments to the building materials or direct melting and thermoforming	<ul style="list-style-type: none"> • Simple steps • Larger processing capacity • High recovery rate 	<ul style="list-style-type: none"> • Low-added value of the product 	<ul style="list-style-type: none"> • The shape of the mask • The percentage of mask • Whether to preprocess
Novel physical technology	Blending modification by adding polymers, organic fillers, or inorganic fillers at 100–300 °C	<ul style="list-style-type: none"> • Improvement of mechanical properties of raw materials • Access to new materials with functions such as electricity or magnetism • Cheap and easy to obtain raw materials • Wide range of product applications 	<ul style="list-style-type: none"> • Reduced performance with multiple processing • Requirements for the interaction forces between the filler and mask 	<ul style="list-style-type: none"> • Nature of filler • Dispersion state of the filler • Interaction of fillers and masks
Thermal cracking	Degrading at 300–900 °C in air or nitrogen	<ul style="list-style-type: none"> • Easy to operate • High recovery rate of pyrolysis oil • Liquid product with a calorific value close to that of diesel 	<ul style="list-style-type: none"> • Complex product composition • Poor quality pyrolysis oil • High energy consumption 	<ul style="list-style-type: none"> • Pyrolysis temperature • Reaction time • Heating rate • Feed composition
Catalytic cracking	Addition of catalyst to the pyrolysis process	<ul style="list-style-type: none"> • High product selectivity • High calorific value of gas products • Lower pyrolysis temperature • Low energy consumption but high speed 	<ul style="list-style-type: none"> • The mechanism of cleavage has not yet been explored • Poor catalyst circulation 	<ul style="list-style-type: none"> • Catalyst acidity and porosity • Pyrolysis temperature • Pyrolysis ambient
Carbonization	Sulfuric acid or catalyst prior to pyrolysis pre-treatment	<ul style="list-style-type: none"> • Low running costs • Access to functional carbon materials 	<ul style="list-style-type: none"> • Complex operational processes • Risk of ignition and explosion 	<ul style="list-style-type: none"> • Sulfonation temperature • Sulfonation treatment method • Type of catalysts
Solvent-based technology	Soaking masks with chemical solvent	<ul style="list-style-type: none"> • Simple process • High economic and energy efficiency • Rational use of the structure of the mask 	<ul style="list-style-type: none"> • Difficulties with industrialization • The requirement for separation of 3-layer mask 	<ul style="list-style-type: none"> • Type of solvent • Processing time

1. Traditional physical technology such as mechanical compression can convert masks directly into stereotyped materials, which have comparatively low strength and can be applied to industries without strict mechanical property requirements. Another traditional physical technology used to mix sterilized and crushed masks into traditional construction materials can lead to a decline of cracks and a rise in tensile capacity. However, the hydrophobic mask fibers lead to a decrease of the permeability of building materials. Notably, the interfacial transition zone can be amplified between the mask fibers and the building material such as the cement paste matrix to improve the permeability via graphene oxide aqueous solution soaking. Novel physical technology indicates that the mechanical properties of materials can be modified and enhanced to some extent by blending fillers such as inorganic nanoparticles and natural fibers with polymers. Nevertheless, this process suffers from poor compatibility and weak interaction forces between masks and some fillers, requiring the addition of additives for surface modification.
2. Thermal cracking of masks could generate high-value liquid products with performance approaching diesel, but require high temperature and long processing time. Moreover, the low purity of liquid oil results in bare feasibility to get a large-scale promotion. Comparably, copyrolysis of waste masks with biomass is a considerable way to obtaining bio-oil with high quality and quantity. The composition of products could be modified by the addition of catalysts. The desirable yield of H₂ could be obtained by pyrolysis with biochar or zeolites, which was further improved with Ni loading. Furthermore, the yield of solid char soars up with additional Ni-based catalysts and pretreatment of sulfonation during pyrolysis. The solid char with inherent high porosity could serve as high-performance carbon material precursors, which was

applied to electrodes and adsorbent materials. However, thermochemical technology still has dilemmas such as strict requirements on pyrolysis temperature and time, complicated processes, and optimal catalyst selection.

3. The appropriate chemical solvent is chosen in solvent-based technology to soak the mask directly for modification based on different specific structures of three layers of the mask. The outer layer is hydrophobic which can be applied to oil spill clean-up while the inner is hydrophilic and can serve as a catalytic carrier. The middle layer has a relatively low reuse value. However, the middle layer can be modified forcibly by a suitable solvent. Solvent-based technology has simple operations and requires short time, showing a good prospect but the whole technology is still at the experimental stage.

The following challenges remain to be overcome in order to better realize the disposal of waste masks and resource utilization:

1. Modifying mask PP by nanoparticles or natural fibers may better strengthen the mechanical properties or improve permeability, flame retardancy, and thermal stability. Nanoparticles such as ceramic particles with high dielectric constant and boron nitride particles with high thermal conductivity, which were once used to modify other plastic, also have feasibility to be applied into the modification of mask PP. However, the maximization of modified effect can be realized only after considering the dispersion of nanoparticles and interfacial bonding strength between nanoparticles and PP matrix.
2. Considering the serious periodic energy shortage in the global energy market, catalytic pyrolysis, which can increase the H₂ output, is a favorable disposal. However, catalyst deactivation will occur after a long operation time, leading to deteriorated biochar performance in extracting hydrogen. Zeolite with heat resistance is a more desirable choice, and the mechanisms of zeolite catalysis should be further studied, especially for acid sites. Also, new catalysts with synergistic catalytic activity, excellent stability, and recyclability should be developed. In addition, the influence of ear loops and nose clips on the products should be paid attention for industrialization.
3. Prolonging the life cycle of mask PP via solvent-based technology avoids large energy consumption and recycled mask PP are applied successfully into sewage treatment. However, a large quantity of solvent would be consumed and the solvent like concentrated sulfuric acid belongs to hazardous chemicals, urging the appearance of recyclable and green solvents. Additionally, universally applicable reagents that can be applied to three different layers are expected to be developed to omit the mask separation step.

4. Advanced oxidation process has a desirable prospect for the disposal and resource utilization of waste masks. Using Fenton, photocatalytic, and persulfate oxidation, renewable energy such as alcohol-based fuels can be generated from waste masks. However, the practical application of advanced oxidation process for mask treatment is relatively immature with many problems to be solved. For example, the development of new catalysts with synergistic catalytic activity, excellent stability, and high efficiency is necessary. Besides, metal-free catalysts should be developed to avoid the secondary pollution caused by metal leaching. Additionally, ear loops, nose wires, by-products, and other impurities should be also taken into account due to the scavenging of reactive radicals.
5. At present, a great quantity of civil masks is directly mixed with domestic garbage and discarded in ordinary places of society, or even discarded at will. The treatments of waste masks in professional medical institutions refer to the disposal standard of medical waste. Due to the small volume and light weight, sorting waste masks is an arduous task. After mixing, masks are easy to be polluted, which also increases the difficulty of recycling and processing. Furthermore, masks have risks of exposure to viruses and different requirements for disinfection. Common disinfection, such as alcohol and ultraviolet light, can only achieve surface disinfection of masks. Therefore, disinfection methods with low cost, high efficiency, and large safety factors are desperately in need.

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