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# Upcycling face mask wastes generated during COVID-19 into value-added engineering materials: A review

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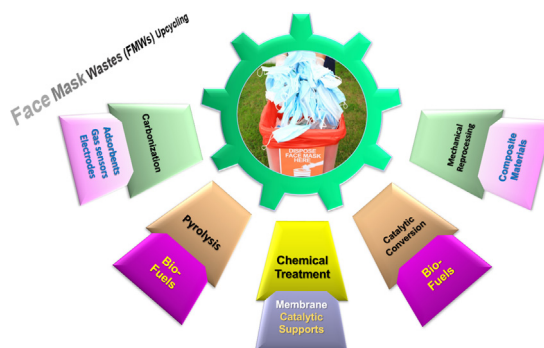
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## HIGHLIGHTS

- PP-based FMWs can be upcycled to value-added engineering materials.
- Carbonization is the main FMWs upcycling method.
- FMWs are converted to the carbon-based electrode used in batteries & supercapacitors.
- FMWs are suitable substrates for embedding catalytically active nanoparticles.
- FMWs fibers reinforce the construction materials to a notable extent.

## GRAPHICAL ABSTRACT



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## ABSTRACT

Billions of disposable face masks (i.e., single-use masks) are used and discarded worldwide monthly due to the COVID-19 outbreak. The immethodical disposal of these polymer-based wastes containing non-biodegradable constituents (e.g., polypropylene) has provoked marked and severe damage to the ecosystem. Meanwhile, their ever-growing usage significantly strains the present-day waste management measures such as landfilling and incineration, resulting in large quantities of used face-covering masks landing in the environment as importunate contaminants. Hence, alternative waste management strategies are crucially demanded to decrease the negative impacts of face mask contamination. In this venue, developing high-yield, effective, and green routes toward recycling or upcycling face mask wastes (FMWs) into value-added materials is of great importance. While existing recycling processes assist the traditional waste management, they typically end up in materials with downgraded physicochemical, structural, mechanical, and thermal characteristics with reduced values. Therefore, pursuing potential economic upcycling processes would be more beneficial than waste disposal and/or recycling processes. This paper reviews recent advances in the FMWs upcycling methods. In particular, we focus on producing value-added materials via various waste conversion methods, including carbonization (i.e., extreme pyrolysis), pyrolysis (i.e., rapid carbonization), catalytic conversion, chemical treatment, and mechanical reprocessing. Generally, the upcycling methods are promising, firming the vital role of managing FMWs' fate and shedding light on the road of state-of-the-art materials design and synthesis.

## 1. Introduction

Although the globe has noticed some favorable environmental impacts of occasionally long-term worldwide lockdowns caused by spreading severe acute respiratory syndrome coronavirus 2 (SARS-CoV-2 or COVID-19), such as cleaner water resources and more transparent skies, the same

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scenario is not concerning solid waste management (Sharma et al., 2020; Kulkarni and Anantharama, 2020). Countless medical and biohazardous wastes, such as infected face masks, gloves, and other single-use personal protective equipment (PPE), have been produced during this crisis. In particular, the global pandemic of COVID-19 has forced individuals to wear polymer-based face masks as one of the most crucial PPE for medical care procedures and routine activities of daily life (Forouzandeh et al., 2021). Of the diverse types of commercially available face masks, the polypropylene (PP)-based surgical (or medical) masks are the most commonly used for personal safety (Torres and De-la-Torre, 2021). It has been estimated that up to 3000 tons/week of PP-based face mask wastes (FMWs) have been only produced in India, the USA, and Australia. A substantial amount of these PP-based FMWs has been entering the environment, directly endangering wildlife and ecosystems (Silva et al., 2021).

Surgical face masks are often composed of three main layers of non-woven fabrics. The first external layer controls fluid transport, the middle layer captures microorganisms (e.g., viruses and bacteria) and micropollutants (e.g., aerosol particles), and the third internal layer uptakes fluids from the individual (Fadare and Okoffo, 2020). Despite altering the composition in some cases, the filter layer (i.e., the middle layer) is commonly made of cellulosic materials (Babaahmadi et al., 2021). In contrast, the external layers are mainly created of non-woven polypropylene or, in some cases, cellulose fabrics, offering, in the latter, a more skin-friendly surface. In the meantime, similar to other polymer-based wastes, PP-based FMWs are typically chemically inactive; assessments indicate that current materials require up to 500 years to degrade thoroughly (Ali et al., 2021; Sousa et al., 2021).

Consequently, the components of PP-based FMWs can easily find their way into the human food chain via crops and animals (Zhou et al., 2020). Such observations demonstrate that PP-based FMWs will negatively affect the sustainability of the environment. Certainly, practical solutions are urgently sought-after to manage the worldwide challenge of face masks pollution toward developing a sustainable environment and community. Several disposal procedures have been thus suggested to lower this contamination, among which thermal treatments (e.g., incineration) are the predominant methods (Das et al., 2021). However, such methods suffer notorious drawbacks such as expensive processes (i.e., the expenses of building the infrastructure and operating the incineration plants are usually high) (Dong et al., 2018). Besides, the smoke generated during the burning process contains harmful acidic gases (e.g., CO<sub>2</sub>, H<sub>2</sub>S, etc.), carbon monoxide (CO), carcinogens (e.g., polycyclic aromatic hydrocarbons), atmospheric aerosol particles, heavy metal species (e.g., arsenic, chromium, cadmium, etc.), sulfur oxides (SO<sub>x</sub>), and nitrogen oxides (NO<sub>x</sub>) (Ojha et al., 2022; Huiying, 2021). These chemical compounds are highly toxic to the total environment (Pourebrahimi et al., 2022).

Waste recycling usually faces major challenges as post-consumer plastic wastes (e.g., PP-based FMWs) often contain mixed plastics of unrevealed composition and diverse organic (e.g., food remains), inorganic (e.g., heavy metals), and biological pollutants (e.g., viruses and bacteria) (Manickavelan et al., 2022). Instead, upcycling is a more viable approach through which the highest possible value is exploited from the waste resources at hand, and the materials can be developed into new products with enhanced properties (Jehanno et al., 2022). In this respect, several environmentally benign and economically affordable processes, including (catalytic) pyrolysis (Peng et al., 2022), (catalytic) carbonization (Choi et al., 2022), surface deposition/modification (Guo et al., 2022), solvent-assisted extraction of valuable ingredients (Cabanes et al., 2020), thermochemical treatments (Das et al., 2021), hybridization with nanoparticles (Min et al., 2022), photocatalysis (Chu et al., 2022), alternating magnetic field (AMF)-assisted deconstruction (Luo et al., 2022), mechanical blending (Gaduan et al., 2022), and hydrothermal methods (Shen, 2020) have been widely adopted as promising PP-based FMWs upcycling approaches.

It should be noted that FMWs cannot be held for more than 1 day per their storage policies and should be incinerated or disinfected on the same collection day (Selvaranjan et al., 2021). Thus, most FMWs are sent for incineration, typically occurring at temperatures higher than 1100 °C. The microwave-assisted disinfection method is usually utilized

in accompanying autoclaving in the case of FMWs (Selvaranjan et al., 2021). Accordingly, FMWs are sterilized employing steam (commonly treated at 93–177 °C). Moreover, the chemical disinfection method is typically utilized with preliminary mechanical shredding to pre-treat FMWs. Reprocessing/decontamination methods mainly employ moist heat, dry heat, UV treatment, and hydrogen peroxide (H<sub>2</sub>O<sub>2</sub>) vaporization (Webb et al., 2012).

This paper reviews contemporary methods for upcycling PP-based FMWs into value-added engineering products. In the meantime, the benefits and restrictions of each method in practice are also discussed in detail. Ultimately, challenges and recommendations for focusing on future research and development are provided. This review aspires to understand upcycling methods of FMWs generated in bulk during the prolonged COVID-19 outbreak by analyzing the recently reported research. To the best of the author's knowledge, it is worth mentioning that this is the first report reviewing the original research papers recently published regarding upcycling FMWs to various value-added engineering materials.

## 2. Upcycling FMWs into value-added engineering products

### 2.1. The preparation methods for FMWs-derived carbon-based materials

The carbon-rich PP-based FMWs can be utilized as the precursor for synthesizing various value-added carbon-based materials. For instance, these PP-containing wastes can be upcycled to a broad range of carbon materials, including graphene (Vieira et al., 2022), carbon nanotubes (CNTs) (Modewe et al., 2021), hard carbons (Lee et al., 2022), and porous carbons (Hussin et al., 2021). The main PP-to-carbon conversion processes are pyrolysis (Harussani et al., 2022), catalytic carbonization (Chen et al., 2020), hydrothermal carbonization (Shen, 2020), flash Joule heating (Chen et al., 2021), and microwave heating (Vieira et al., 2022). Each method has its pros and cons.

Pyrolysis is simple, relatively low-cost, requires low equipment, and applies to almost all plastic wastes. Nonetheless, low carbon yield, particularly for polystyrene (PS) and polyolefins (e.g., PP), and rather high energy consumption are disadvantages of this method. Catalytic carbonization enables generating graphitic carbons, however, at the cost of using expensive catalysts and high energy consumption. Hydrothermal carbonization is a conversion method for transforming organic compounds into carbon materials. This exothermic process would be beneficial in which the carbon content is convertible without further oxidation of the waste polymer, leading to a reduction in CO<sub>2</sub> production. The significant issue of this method is tar formation. Flash Joule heating is considered a simple, economic, and fast conversion method that can be applied to most waste plastics. However, its shortcomings include managing volatile products, high current requirements, and the need for conductive materials. Microwave conversion, on the other hand, is a simple and fast method that has limited carbon yields and consumes high electrical energy.

It is vital to control the synthetic conditions to develop PP waste-derived carbons with desired properties such as high porosity, considerable specific surface area, functional surfaces featuring various functionalities and dopants, excellent conductivity, and adequate thermal/chemical stability (Pourebrahimi et al., 2018). The general characteristics of various carbonization techniques for preparing carbon-based materials from PP-based FMWs have been presented in Table 1. Accordingly, PP-containing FMWs have been recently utilized in applications associated with green energy (e.g., batteries and supercapacitors) and sustainable environmental approaches (e.g., pollutant removal, separation, and CO<sub>2</sub> capture). FMWs can offer substantial economic and environmental advantages while decreasing the expenses of plastic waste management. For example, Yu et al. developed a green and high-yield conversion procedure (carbon yield of about 64.4 wt%) to upcycle FMWs into CNTs/Ni hybrids through catalytic carbonization for microwave absorption application (Fig. 1) (Yu et al., 2021).

**Table 1**  
Summary of various carbonization methods for preparing carbon-based materials from PP-based FMWs.

Method	Conditions	Carbon materials	Advantages	Disadvantages
Pyrolysis carbonization	Temperature range: 500–1000 °C Atmosphere: Inert gas or molten salt Further stabilization and activation, if needed Time: From seconds to a few minutes	Amorphous carbons, e.g., activated carbons, mesoporous carbons, and carbon fibers	Simple, low equipment, relatively low cost, applicable for most plastics	Low carbon yield, relatively high energy consumption,
Catalytic carbonization	Temperature range: 400–900 °C Atmosphere: Inert gas Metal-based catalysts	Graphitic carbons, e.g., CNTs, graphene, carbon spheres, carbon fibers, carbon nanosheets	Applicable to most plastics, production of graphitic carbons	Needs catalyst, relatively high energy consumption
Hydrothermal carbonization	Temperature range: 180–250 °C Autogenous pressure Teflon-lined hydrothermal reactors Electrical heating (e.g., 5 kW h <sup>-1</sup> for a couple of hours)	Activated carbons, carbon dots, carbon spheres	High carbon yield, no further oxidation	Relatively high energy consumption, tar formation
Flash Joule heating	vacuum reactors High electrical currents for a short period (e.g., several seconds) Conductive materials (e.g., carbon black)	Graphene	Simple, low energy consumption, fast preparation, applicable to most plastic wastes	Difficult management of volatile products, high electrical current involved, needs electrically conductive materials
Microwave heating	Microwave reactors Microwave irradiation (e.g., 1 kW h <sup>-1</sup> for a couple of minutes) Catalyst, if needed	CNTs, char	Simple and fast preparation	Relatively high energy consumption, limited carbon yields

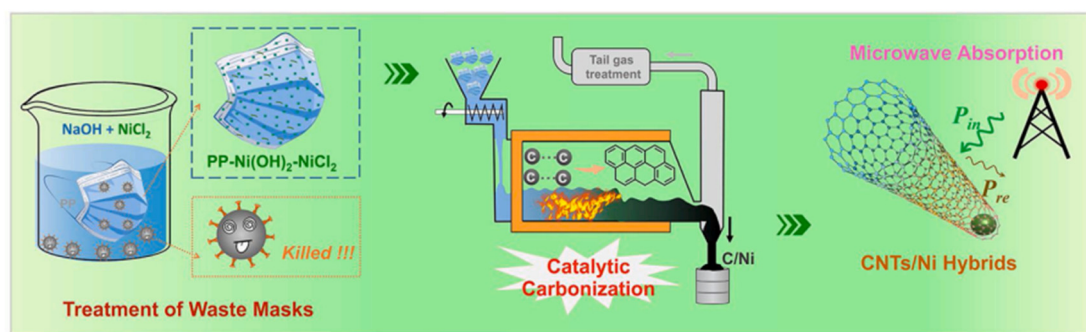
## 2.2. FMWs-derived adsorbents and gas sensors

As a carbon source with high carbon content (~75–80 wt%), FMWs can be utilized as precursors for preparing activated carbon (AC) adsorbents (Yuwen et al., 2022a). The first report on using FMWs as starting materials for the synthesis of ACs was published by Serafin et al. (Serafin et al., 2022). They devised an effective carbonization process combined with chemical activation to convert FMWs into valuable carbon materials. In this regard, several AC samples derived from FMWs were prepared using the KOH activation method at temperatures ranging from 600 to 800 °C. Surprisingly, the AC samples synthesized from FMWs possessed high specific surface areas (up to 969 m<sup>2</sup> g<sup>-1</sup>) and narrow pore size distribution, making them suitable candidates for CO<sub>2</sub> adsorption (Pourebrahimi et al., 2017; Pourebrahimi et al., 2015). The AC sample produced at 800 °C showed the maximum CO<sub>2</sub> adsorption capacities of 3.91, 3.23, and 2.61 mmol g<sup>-1</sup> at 0 °C, 10 °C, and 20 °C, respectively, all measured at 1 bar.

Employing sulfonation chemistry (i.e., using concentrated sulfuric acid or sulfur trioxide as activating agents to introduce sulfonic acid, SO<sub>3</sub>H, to the structure) accompanied by thermal treatment of PP-based FMWs

could be a promising method to prepare carbon nanofibers (Choi et al., 2019). The thermal stabilization process introduces further functionalities into the fibers via sulfur doping the carbon structure and developing micropores during carbonization. In this regard, Robertson et al. synthesized carbon nanofibers from FMWs with a relatively high carbon yield (greater than 50 %) (Fig. 2) (Robertson et al., 2022). They investigated the applicability of resultant carbon fibers in various real-world applications, such as oil adsorption, nanofillers for enhancing electrical conductivity, enhancing Joule heating behaviors of composites, and materials for removing organic pollutants from aqueous solutions (see Fig. 2).

It has been shown that ACs have the potential to be functionalized/doped with various functional groups/heteroatoms to expand their applications as well as adjust their physicochemical, textural, and structural properties (Abuelnoor et al., 2021). For instance, FMWs can be used as heteroatom-doping substrates to prepare AC adsorbents via thermal carbonization using activating agents such as K<sub>2</sub>CO<sub>3</sub>. In this respect, Bumajdad et al. utilized a readily available wild plant biomass (*Cyperus papyrus*, CP) as the N- and O-containing co-precursor for fabricating functionalized FMW-based AC adsorbents (Fig. 3) (Bumajdad and Khan, 2021). After blending



**Fig. 1.** Schematic representation of face mask wastes (FMWs) catalytic carbonization into high-value CNTs/Ni hybrids. Reprinted with permission from Ref. Yu et al. (2021). (Copyright 2021, Elsevier).



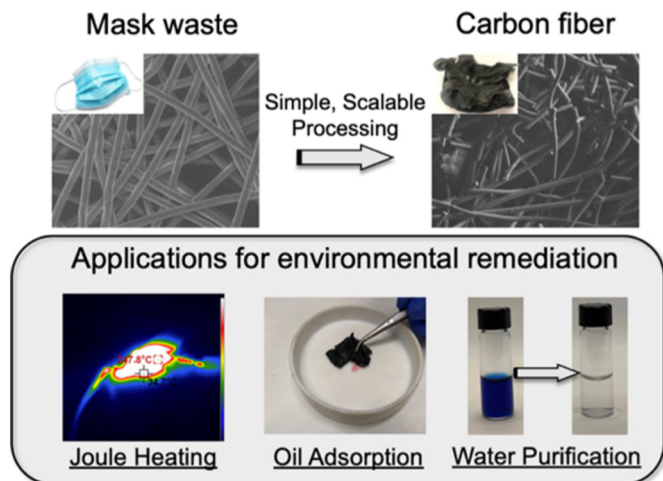


Fig. 2. Chemical upcycling face mask wastes (FMWs) to produce multifunctional carbon nanofibers. Reprinted with permission from Ref. Robertson et al. (2022).

FMWs with CP at a 1:1 weight ratio, the specific surface area of the resulting AC was enhanced significantly. At the same time, various functionalities (e.g., amino and carbonyl) were introduced to adsorbent surfaces, suitable for capturing environmental pollutants such as heavy metals from aqueous solutions (Pourebrahimi and Pirooz, 2022a).

The inherent characteristics of non-woven PP-based fabrics, e.g., low water adsorption capacity, make them attractive alternatives for removing oil pollution (Zaro et al., 2021). In fact, adsorbents fabricated by non-polar PP are ideal candidates for eliminating non-polar petroleum derivatives (e.g., gasoline and kerosene) from the environment. A proper adsorbent for oil spill clean-up must show hydrophobicity, oleophilicity, and high oil uptake capacity at the same time. Untreated (i.e., pristine) non-woven PP-based fabrics, however, have not shown notable adsorption capacity and applicability for selective elimination of oil spills. Meanwhile, the high price of starting materials is another major shortcoming of non-woven PP materials. As a promising alternative, PP-based FMWs may replace the expensive non-woven PP and act as promising oil adsorbents.

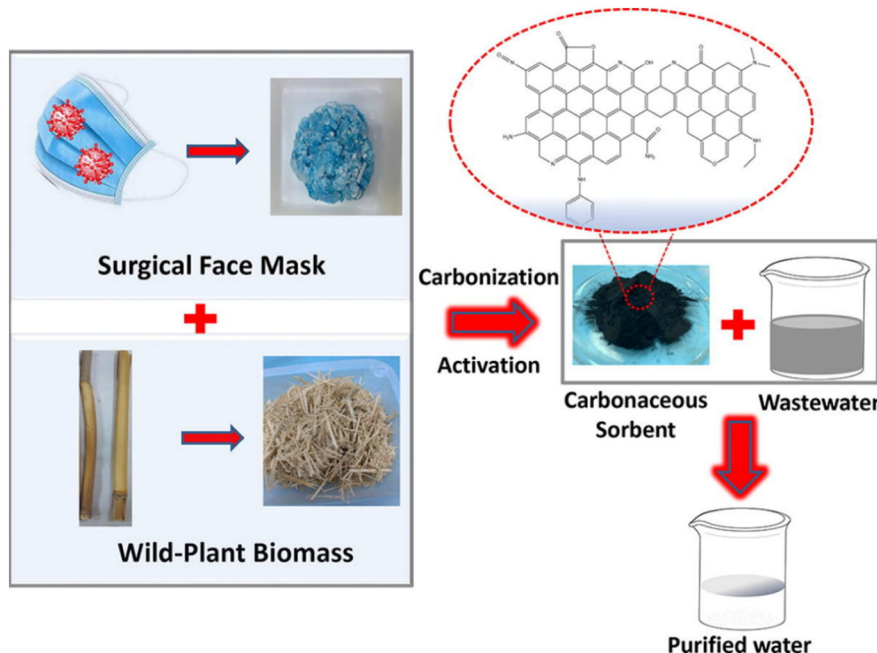


Fig. 3. Carbonization of FMWs and CP blends activated by  $K_2CO_3$  to prepare N- and O-functionalized AC adsorbents for heavy metal removal from wastewaters. Reprinted with permission from Ref. Bumajdad and Khan (2021).

The FMWs' hydrophobicity can also be improved by soaking in inexpensive solvents (i.e., employing chemical modification), increasing their oil adsorption capacity to a high extent. The alkane solvents may cause the surface of the FMWs to swell, raising surface roughness and thus resulting in superhydrophobic surfaces (Pavon et al., 2021).

In this venue, Park et al. developed a superhydrophobic face mask prepared by facile chemical modification with alkane solvents (e.g., n-hexane, n-heptane, and n-decane) and used it as an efficient adsorbent for oil spill cleanup (Fig. 4) (Park et al., 2022). All employed alkane solvents enhanced the surface roughness of FMWs and increased the face mask hydrophobicity noticeably. For instance, the n-heptane-treated FMW (treated at 90 °C for 1 h) can eliminate Arabian light crude oil spill up to 21 times its weight from the water surface. Moreover, other organic spills such as chloroform, toluene, gasoline, and diesel could be removed efficiently. More impressively, the oil-containing face mask can be subsequently refined into crude oil via the pyrolysis process, enabling sustainable development.

Surface embedding using hydrophobic additives is another technique typically used to enhance a surface's hydrophobicity (Seyfi et al., 2016). This idea motivated Guselnikova et al. to offer a practical upcycling method for FMWs by embedding the superhydrophobic fluorine-free metal-azolate framework (MAF-6) metal-organic framework nanoparticles within the pores of FMWs blended with disposable medical sheets to prepare oil pollution cleanup adsorbents (Fig. 5) (Guselnikova et al., 2022). MAF-6 particles' deposition on the FMW surfaces significantly improved dichloromethane, hexane, decane, dodecane, cyclohexene, toluene, and straight-run diesel adsorption capacity. The synthesized PP-MAF-6 hybrid adsorbent showed augmented mechanical robustness after UV irradiation, reusability, and scalability. Additionally, the pertinence of PP-MAF-6 has been demonstrated in treating realistic spill-containing solid pollutants.

PP is non-polar, semicrystalline, lightweight, commercially available, and easy to process, with many other fascinating features and possible applications (Yang et al., 2021). One plausible application of PP is in gas sensing (Geng et al., 2017). In gas sensing, the most significant factors are designing an easy-to-handle surface with a suitable, accurate, fast response and low cost. To discover the applicability of FMWs as potential substrates typically used in sensing applications, Wang et al. developed an FMW/ZnS gas sensor by depositing a layer of ZnS nanoparticles on FMW surfaces through a one-step hydrothermal method (Wang et al., 2022a). The FMW/ZnS hybrid sensor exhibited high sensitivity and reusability to mark vapors at ambient

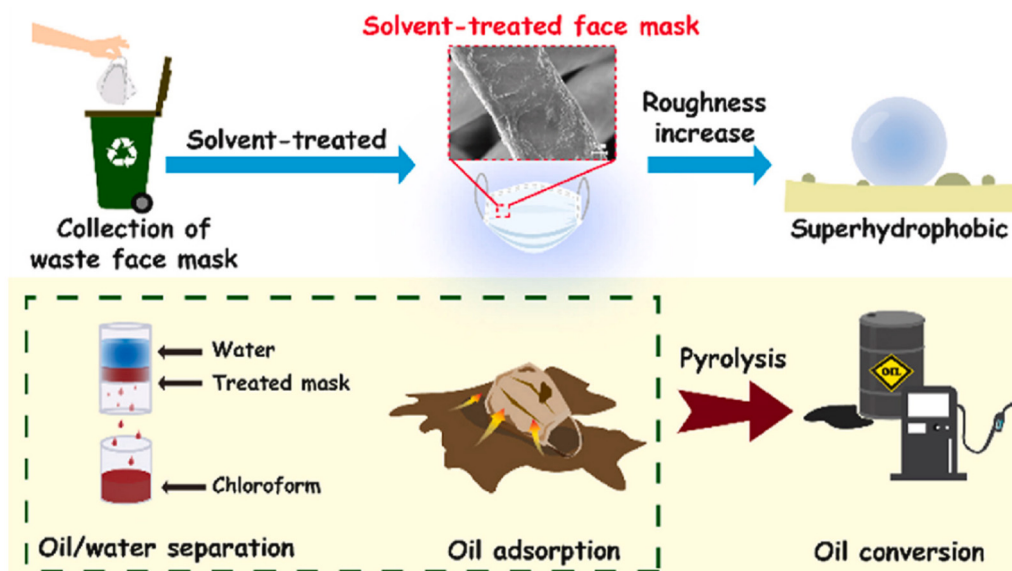


Fig. 4. Preparation of a superhydrophobic adsorbent by chemical treatment of FMWs using various alkane solvents for oil spill cleanup. Reprinted with permission from Ref. Park et al. (2022). (Copyright 2022, Elsevier).

temperature. Compared to ceramic-supported ZnS nanoparticles, the FMW/ZnS hybrid responses to analytes improved significantly. Moreover, the time needed for the FMW/ZnS hybrid sensor to conduct one response–recovery cycle was less than 30 s. The high sensitivity of FMW/ZnS can be ascribed to the increased gas permeability of the FMW substrate, making the deposited ZnS nanoparticles more accessible to contact with the target gas species efficiently.

### 2.3. FMWs-derived membranes

A polymeric membrane is a thin, semipermeable barrier between two media (Pourebrahimi and Pirooz, 2022b). Due to their hydrophobic nature resulting from their pure hydrocarbon structures (i.e., PP is a non-polar polyolefin), PP-based membranes have been widely utilized in industrial processes such as gas separation (Petukhov et al., 2022). Hence, it would be an intriguing idea to retrieve PP from FMWs and subsequently upcycle it into other value-added engineering materials such as membranes. In this venue, Cavalcante et al. developed nanofiltration membranes using green solvents (e.g., *p*-cymene) as PP extractants through the casting method (Fig. 6) (Cavalcante et al., 2022). The membranes were suitable for organic solvent nanofiltration owing to their superior chemical stability. The prepared membranes showed tunable molecular weight cut-off values ranging from 665 to 964 g mol<sup>-1</sup> by changing the coagulation bath temperature from 20 to 60 °C. Moreover, the nanofiltration membranes exhibited

long-run stability up to 5 days of nonstop operation at 30 bars, with rejection values higher than 98 % for roxithromycin and rose Bengal.

A separator is a porous membrane between electrodes of opposite polarity (i.e., anode and cathode electrodes), permeable to ionic flow (i.e., electrolyte) while suppressing the electrical contact between electrodes (Huang et al., 2020). Many sorts of separators have been utilized in batteries over the past decades. Porous polypropylene (PP) has been broadly employed as a commercial separator for lithium-sulfur (Li-S) batteries; in which organic electrolytes are used; to separate the anode and cathode electrodes, avoiding the inner short (Xiao et al., 2021). The non-polar and polyporous features of PP enclose influential benefits in chemical stability, electrical insulation, and mechanical strength of the resultant separator.

Meanwhile, as traditional separators, glass fiber (GF)-based microporous separators have been extensively utilized in most aqueous rechargeable batteries (ARBs) due to their superior wettability when contacting aqueous electrolytes (e.g., aqueous KCl solution) (Zhu et al., 2016). Nevertheless, GF separators' high cost and high thickness (about 380 μm) may restrict their real-world applications on a large scale. Thus, discovering a functional substitute for GF separators is critical for commercializing ARBs. To address this issue sustainably, Kim et al. prepared a high-value-added material through upcycling FMWs into an admirably efficient separator for ARBs (Kim et al., 2022). In this respect, the PP-based separator was prepared by a facile reaction between PP and fuming sulfuric acid (FSA), enhancing the hydrophilicity (i.e., wettability) of FMWs by introducing

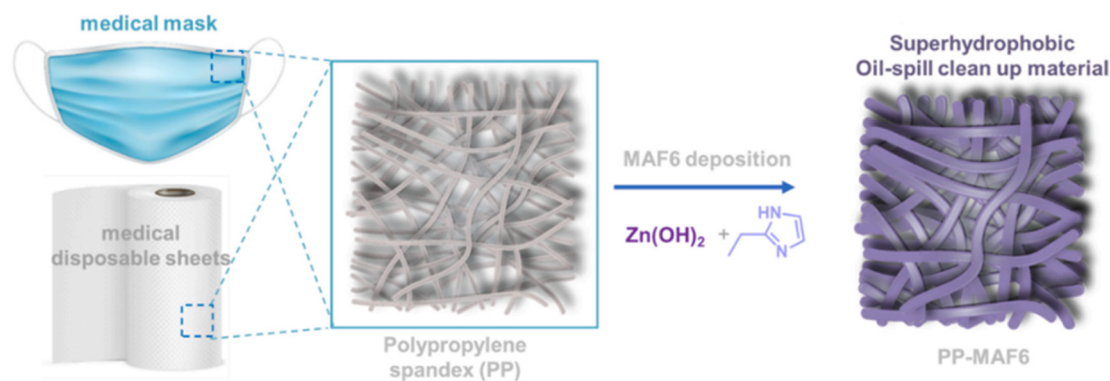


Fig. 5. Schematic representation of PP-MAF6 superhydrophobic adsorbent. Reprinted with permission from Ref. Gusebnikova et al. (2022). (Copyright 2021, Elsevier).

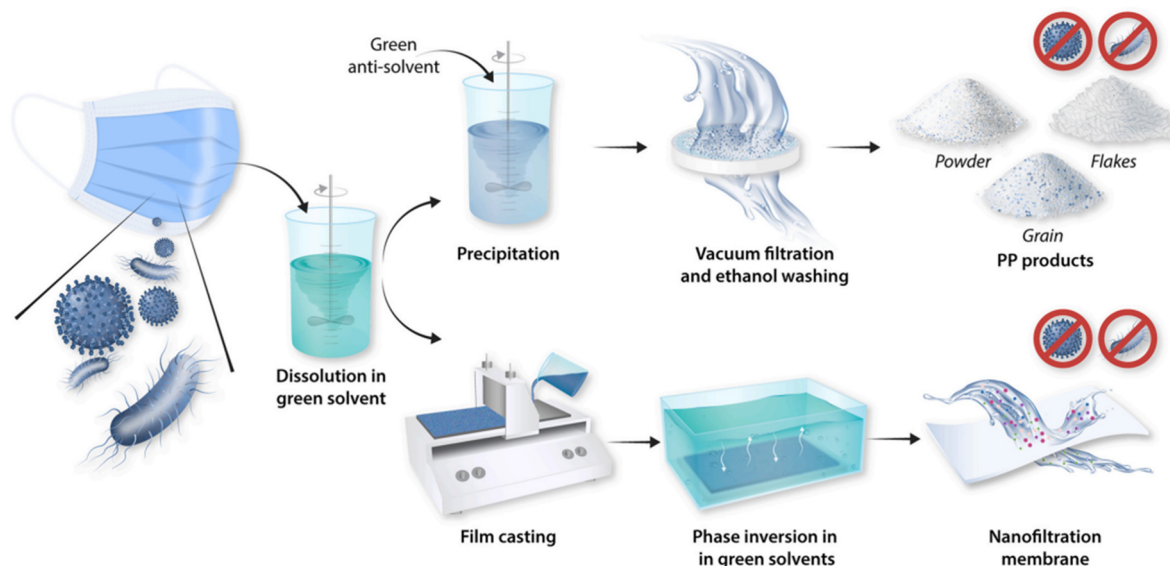


Fig. 6. Schematic representation of FMW-derived nanofiltration membrane. Reprinted with permission from Ref. Cavalcante et al. (2022). (Copyright 2022, Elsevier).

abundant hydroxyl and sulfonic acid (i.e., —OH and —SO<sub>3</sub>H, respectively) hydrophilic functionalities supplied by FSA. This approach enables the upcycling of used face masks into high-value-added functional materials.

#### 2.4. FMWs as catalytic supports

Cellulose-based materials with hydroxyl (—OH) functionalities in their structures can be utilized as reusable and environmentally friendly catalytic supports for the controlled immobilizing of catalytically active metal/metal-oxide nanoparticles (Kamel and Khattab, 2021). In this framework, Reguera et al. exploited cellulosic fabrics from FMWs as free-standing catalytic support for the deposition of titanium dioxide (TiO<sub>2</sub>), iron oxide (Fe<sub>x</sub>O<sub>y</sub>), and cobalt oxide (CoO<sub>x</sub>) metal oxide nanoparticles (Reguera et al., 2022). Notably, the considerable porosity and hydrophilicity of the structure of the cellulose-based non-woven catalytic supports provide the pollutants/reactants with higher accessibility to the active centers. Consequently, adequate catalytic activities, along with prolonged stability and recyclability, are attained. Furthermore, the free-standing catalytic supports can bypass disfavored reaction media pollution provoked by the leaching of nanoparticles.

A novel synthetic route has recently emerged exploiting waste organic compounds, mostly from waste biomass, as ideal precursors for developing electrocatalysts for typical electrochemical conversion reactions (Sekhon et al., 2022). Current studies confirmed the potential of this approach for preparing oxygen reduction reaction (ORR) and hydrogen evolution reaction (HER) electrocatalysts (Sekhon et al., 2022). For example, waste plastics can be converted to carbon-based electrocatalysts. More importantly, this pathway results in the valorization of waste carbon-containing sources converted to conductive char. Char can be functionalized with the proper metal–nitrogen moieties, producing a suitable electrocatalyst. Inspired by this, Muhyuddin et al. converted FMWs to platinum group electrocatalysts for ORR, HER, and crude oil (Muhyuddin et al., 2022). In this respect, FMWs were firstly pyrolyzed under controlled temperature and atmosphere, and the obtained char was then transformed into electrocatalysts by functionalizing it with the metal phthalocyanine of interest. The electrocatalytic performance characterization of ORR and HER highlighted favorable activity and durability.

#### 2.5. FMWs-derived electrodes for batteries and supercapacitors

One promising way of converting PP-based FMWs with complex structures into functionalized porous carbons with high specific surface area

is the microwave-assisted solvothermal method accompanied by self-activating pyrolysis using sulfuric acid, which enables the cost-effective preparation of functionalized carbon-based materials on large scales (Vignesh et al., 2022). Benefiting from this innovative idea, Yuwen et al. utilized FMWs as the carbon source and prepared a series of oxygen and sulfur co-doped porous carbons with high specific surface areas up to 830.9 m<sup>2</sup> g<sup>-1</sup> and improved thermal stability (Fig. 7) (Yuwen et al., 2022a). They used the synthesized porous carbons as the cathode electrode in lithium-sulfur (Li-S) batteries. Due to the synergistic effect of oxygen and sulfur co-doping along with their porous conductive structures, the prepared porous carbons showed promising electrochemical performance.

Similarly, this fast microwave-assisted method is used by Yuwen et al. for simultaneous sulfonation, nitrification, and oxidation of FMWs in the presence of concentrated sulfuric acid and urea (acting as both crosslinking agents and heteroatoms sources) to produce an aromatic carbon precursor with adequate thermal stability (Yuwen et al., 2022b). The obtained sulfur, nitrogen, and oxygen multi-doped carbon material impressively preserved 51 wt% of its initial weight at 1000 °C. Porous carbon obtained from FMWs was prepared through the self-activation pyrolysis elucidated earlier. Low pyrolysis temperature, however, would not produce sufficiently in-situ generated surface self-activating agents such as H<sub>2</sub> and H<sub>2</sub>O, hindering obtaining a high specific surface area. Benefiting from the synergistic effect of sulfur, nitrogen, and oxygen heteroatoms co-doping and hierarchical porous conductive structure with high specific surface areas up to 890 m<sup>2</sup> g<sup>-1</sup>, the first discharge-specific capacity of the sample pyrolyzed at 900 °C was 1459.8 mAh g<sup>-1</sup> at 0.1C. The discharge-specific capacity retention at 0.5C after 400 cycles was 52.3 % when used as the cathode electrode in lithium-sulfur batteries.

Hard carbons (HCs), synthesized by carbonization of chemically pre-treated synthetic polymers, cellulose-based materials, and proteins, are among the most appealing anode materials for sodium-ion batteries (SIBs) (Tyagi and Puravankara, 2022). Taking advantage of the high PP content of FMWs, Lee et al. synthesized a series of HCs through sulfuric acid treatment and subsequent carbonization and graphitization (also known as the solid-to-solid conversion approach) of disposable masks at temperatures up to 2400 °C (Fig. 8) (Lee et al., 2022). More impressively, they carbonized the PP-based FMWs without utilizing any catalyst or gasification method, the typical procedures for preparing PP-based carbons. The optimal HC sample showed a remarkable reversible capacity of about 340 mAh g<sup>-1</sup> at a current rate of 0.01 A g<sup>-1</sup>, along with excellent rate performance.

The supercapacitors (SCs) constructed with carbon materials are modern, hands-on energy storage systems drawing the scientific community's



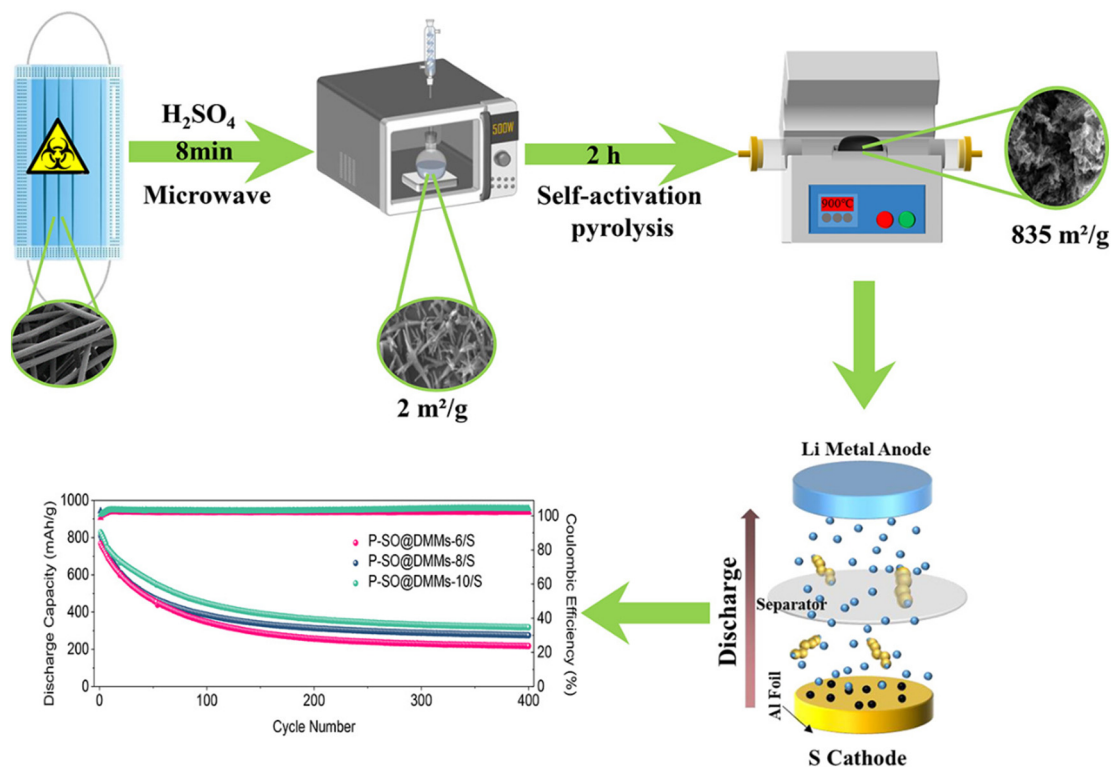


Fig. 7. Schematic representation of solvothermal microwave-assisted preparation of O- and S-doped FMWs-derived porous carbons as cathode electrodes for Li-S batteries. Reprinted with permission from Ref. Yuwen et al. (2022a). (Copyright 2022, Elsevier).

attention. To assemble SCs from massive waste sources and lower the environmental pollution provoked by FMWs (whose usage has unexpectedly risen because of the COVID-19 outbreak, as elucidated earlier), Mendoza et al. designed an innovative composite electrode utilizing FMWs (Mendoza et al., 2022). They coated the pristine (i.e., non-carbonized) surgical face masks with a thin layer of graphene ink to disinfect them, make them conductive simultaneously, and employed them directly as SC electrodes. The evaluation of the electrochemical performance of the FMW-based SCs revealed maximum capacitance/energy density values of 816.8 F g<sup>-1</sup>/99.7 Wh kg<sup>-1</sup>, respectively.

As mentioned, combining sulfonation and carbonization techniques can successfully develop new carbon-based materials with porous structures. To address prevalent issues of carbon electrodes such as low carbon yield, low porosity, and low specific capacitance typically occurring in the carbonization step, one might exploit the porous features of non-woven

PP-based FMWs to design high-performance porous carbon materials. Hu et al. devised a novel strategy for safely preparing value-added carbon electrode materials (CMS) using PP-based FMWs based on modified carbonization of the porous polymer (Hu and Lin, 2021). In this respect, they used the solvothermal method to prepare sulfonated FMWs (i.e., sulfuric acid-loaded FMW) before heat treatment. The resultant carbon electrode materials could attain an increased specific capacitance with 328.9 F g<sup>-1</sup> at 1A g<sup>-1</sup>. Because of the synergistic effects induced by sulfonic acid groups (—SO<sub>3</sub>H) and KOH, the carbon surface possessed a compact porous structure, enabling the fast diffusion of ions.

Generally, transforming polymers into CNTs can be split into two stages. The polymer is decomposed to light hydrocarbons as the carbon source at the first step. Then, the obtained light hydrocarbons are dehydrogenated and aromatized (i.e., carbonized) over a specific catalyst to yield CNTs. For instance, the light hydrocarbons and aromatic chemicals generated



Fig. 8. Schematic representation of HC synthesis from FMWs for anodes in Na-ion batteries. Reprinted with permission from Ref. Lee et al. (2022). (Copyright 2021, Elsevier).



via fast pyrolysis of PP-based polymers could act as carbon sources. It has been demonstrated that the Ni-Fe bimetallic catalysts are capable of rendering high-quality CNTs with desired morphology and physicochemical properties (Fadillah et al., 2021). Motivated by this idea, Yang et al. upcycled PP-based FMWs into CNTs through an environmentally benign process and utilized them as supercapacitor electrodes for energy storage (Yang et al., 2022). The production yield of CNTs could reach up to 26.11 wt% with high purity and a remarkable extent of graphitic ordering. The optimal CNT sample indicated a specific capacitance of  $56.04 \text{ F g}^{-1}$  (1 A/g) and delivered superior cyclic stability, with the material's capacitance retention rate of 85.41 % after 10,000 cycles.

## 2.6. FMWs-derived fuels

Compared with lignocellulosic materials, polymer-based feedstocks such as PP-based FMWs have been demonstrated to possess superior features such as low moisture and ash content and high volatile content (Tang et al., 2021). Therefore, FMWs can be directly utilized as promising feedstocks (or co-feedstocks) in thermochemical conversion (i.e., pyrolysis) processes to produce bio-based products such as bio-oil, bio-char, and non-condensable gases (i.e., permanent gases).

Park et al. developed a co-pyrolysis of disposable face masks and food wastes simultaneously for energy and resource valorization of the waste materials (Fig. 9) (Park et al., 2021). The non-condensable gases comprised mainly  $\text{CH}_4$ ,  $\text{C}_2\text{H}_6$ ,  $\text{C}_3\text{H}_8$ ,  $\text{C}_2\text{H}_4$ , and  $\text{C}_3\text{H}_6$  with no char. Moreover, hydrocarbons with a wide range of carbon numbers (e.g., gasoline-, jet fuel-, diesel- and motor oil-range hydrocarbons) were obtained by pyrolysis of FMWs. In the meantime, co-feeding food waste dramatically influenced the products of the FMWs pyrolysis. The char production in the co-pyrolysis process was mainly due to the food wastes. Meanwhile, the co-pyrolysis of FMWs with food wastes yielded more  $\text{H}_2$  gas and fewer hydrocarbons, elucidating the food waste's complicated heterogeneous texture and high oxygen content.

A novel technique for upcycling FMWs is to convert them into valorized materials through a catalytic oxidation-reduction reaction, improving the yield of methylated aromatic compounds (e.g., 1-methyl-naphthalene), essential chemical compounds in preparing transportation fuels and petrochemical products (Talibi et al., 2018). In this venue, Ali et al. developed niobium (Nb)-containing cerium oxide ( $\text{CeO}_2$ )-based catalyst (Nb- $\text{CeO}_2$ ) featuring increased capability for handling oxidation-reduction reactions evolving FMWs as the feedstock with high capacity, suitable over-oxidation inhibition properties, and high selectivity (Ali et al., 2022). They showed that the products obtained through catalytic oxidation are superior precursors for preparing synthetic lubricants compared to the pyrolysis products, which mostly contain long-chain hydrocarbons. Furthermore, Nb- $\text{CeO}_2$  could improve the selectivity toward producing gaseous methylated benzene hydrocarbons from FMWs, which are valuable in the petrochemical industry.

In another study, Ardila-Suarez et al. investigated the possibility of co-processing FMWs with used motor oil and woody biomass (e.g., a mixture

of fir and spruce) to decrease the consequences of the fast-growing environmental pollution (Ardila-Suárez et al., 2022). They examined its influence on the production of value-added fuel-grade mixtures of compounds. Strikingly, utilizing zeolite CBV 100 as the catalyst, they achieved the production yield of oily products up to 89.58 % with large hydrocarbon content, enabling its usage as green diesel. Additionally, even though the used waste motor oil contained a high sulfur content, the oily products exhibited a negligible sulfur content, possibly due to the distribution of sulfur mainly in the solid and gas phases. Similarly, Li et al. employed pyrolysis of various layers of FMW to evaluate its possible valorization as waste-to-energy feedstocks (Li et al., 2022a). Not surprisingly, the main pyrolysis products were carbon- and hydrogen-rich and oxygen-deficient oily products with a higher heating value (HHV) of 43.5 MJ/kg. Thermal degradation is a useful means of polymer-based waste upcycling, particularly PP-based FMWs, due to their thermoplastic nature. In this regard, Aragaw et al. converted FMWs to fuel energy through pyrolysis (Aragaw and Mekonnen, 2021). The FMWs were pyrolyzed in a closed reactor at 400 °C for 1 h. They achieved a liquid and wax fuel with a percentage of 75 %, char of 10 %, and non-condensable gases in a lab-scale process (Fig. 10).

Luo et al. proposed a low-cost and eco-friendly co-pyrolysis coupled chemical vapor deposition (CVD) approach to effectively transform FMWs and the heavy fractions of bio-oil (HB) into biochar, bio-oil, and high-quality three-dimensional graphene films (3DGFs) simultaneously (Fig. 11) (Luo et al., 2021). The obtained biochar showed high HHV (33.22–33.75 MJ/kg) and low ash content (2.34 %), superior to the walnut shell and anthracite coal. The produced aromatic-enriched bio-oil included 1,2-dimethyl benzene and 2-methylnaphthalene, suitable chemical feedstocks for producing insecticide. Also, the as-synthesized 3DGF can be used in oil spill cleanup and oil/water separation because of its fascinating features such as excellent hydrophobicity, fire resistance, high adsorption capacity (40–89  $\text{g g}^{-1}$ ), considerable porosity, and extended cyclic stability. The HHV of biochar, the chemical composition of bio-oil, and the thickness of 3DGFs can be readily adjusted by regulating the pyrolysis temperature.

Biochar is a carbon-rich porous material with various surface functionalities, endowing it with catalytic activity. In this respect, Wang et al. performed the biochar-assisted catalytic upcycling of FMWs to obtain fuel chemicals (Wang et al., 2022b). They investigated the retrieving of FMWs via catalytic pyrolysis over corn stover-derived biochar catalyst to produce hydrogen gas, light, and mono-aromatic hydrocarbons. However, the type and yield of products obtained through this catalytic pyrolysis method are highly sensitive to the amount of catalyst (i.e., biochar) used. For instance, At the biochar/FMWs ratio of 2, most products were liquid oils (e.g., mono-aromatic compounds such as toluene, xylene, and ethylbenzene) without wax formation. In the meantime, the hydrogen content in the gas phase increased significantly along with the production of light hydrocarbons, e.g., methane and  $\text{C}_2\text{--C}_4$ , when the biochar/FMWs ratio rose to 3.

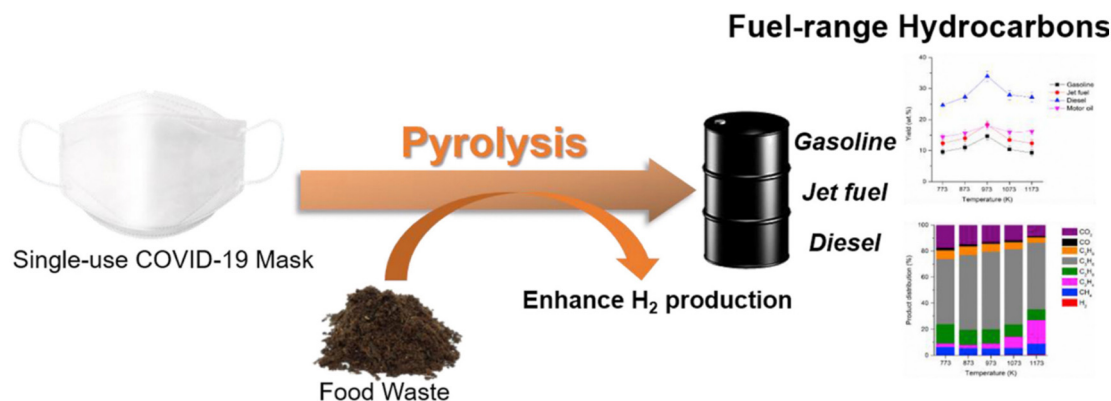


Fig. 9. Co-pyrolysis of FMWs with food wastes to produce fuel-range hydrocarbons. Reprinted with permission from Ref. Park et al. (2021). (Copyright 2021, Elsevier).

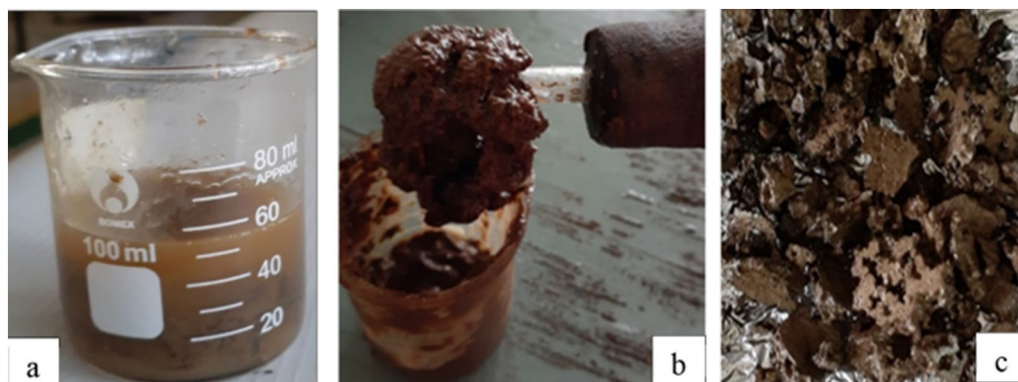


Fig. 10. (a) Pyrolysis products of FMWs, (b) bio-crude oil, and (c) char. Reprinted with permission from Ref. Aragaw and Mekonnen (2021).

### 2.7. FMWs-derived composite construction materials

Using waste materials in constructing cementitious composites is another useful waste upcycling approach. It has been proven that incorporating PP fibers as additives into the cement improves the characteristics of the resultant composite material, such as enhancing the cementitious matrix's tensile/bending strengths and crack resistance (Gupta et al., 2019). On the other hand, the interfacial transition zone (ITZ) between additives and cement paste matrix is another factor affecting the final quality of the resulting composite (Wang et al., 2019). Considering these criteria, Li et al. utilized graphene oxide (GO)-pretreated microfibers of FMWs in fabricating cementitious composites with improved ITZ and tensile strength (Li et al., 2022b). In the meantime, polymer wastes can also be partly utilized as additives in diverse construction materials such as brick, concrete, bitumen, and soil to enhance their physicochemical and rheological characteristics. In this venue, Yalcin et al. used tiny pieces of disposable FMWs as an additive in the bitumen binder (Yalcin et al., 2022). They prepared bitumen samples with different contents of FMWs and one sample containing styrene-butadiene (SBS) for comparison purposes. The results revealed that adding FMWs and SBS to bitumen increased the binders' softening point and viscosity while reducing the penetration value. Besides, bitumen modified with FMWs could preserve its elastic characteristics at low and high-stress levels with temperature increments. The bitumen samples with more than 2 % FMWs showed superior physicochemical and rheological characteristics compared to their counterparts containing 3 % SBS.

As a prevalent issue in the construction sector, rutting, the permanent deformation in the bituminous pavements, drives significant pavement

structure damage. Using polymer-based additives as binders can enhance the flexible pavements' mechanical and structural characteristics (Shin et al., 2022). In this respect, polymers such as polyethylene, polypropylene, and polystyrene, have shown a great tendency to form a coating layer around the asphalt aggregates, resulting in more suitable raw materials for building flexible pavements with enhanced properties (Ma et al., 2021). A creative method is designed by Wang et al. by utilizing the shredded FMW fibers as an additive to hot mix asphalt (HMA) to improve rutting resistance and reduce pollution provoked by FMWs abandoned in the environment simultaneously (Fig. 12) (Wang et al., 2022c). Since the PP-based face mask acts as a semi-liquid material in the temperature range of 115.5 and 160 °C, falling in the HMA mixing and paving temperature, it can be a good binding agent for gluing the asphalt aggregates. This study demonstrated that the mixtures with different contents of PP-based face mask fibers induced decent resistance against rutting. At the same time, the result was remarkable for the mixture comprising 1.5 % FMW fibers.

The PP fibers have also been used as an additive to concrete to hinder its plastic shrinkage or enhance its performance in the case of fire (Latifi et al., 2022). One promising way of upcycling FMWs has been recently proposed by Koniorczyk et al. through which the FMWs are processed at high temperature and pressure, shaped into fibers, and subsequently added into a concrete mixture (Koniorczyk et al., 2022). The upcycling process conditions (190 °C, 130 bars) resulted in full inactivation of the virus and the conversion of FMWs into homogeneous PP fibers. Regarding capillary behavior, the PP fibers-containing concrete exhibited a more rapid water absorption than the virgin concrete sample, indicating increased porosity of concrete resulting from the raised contact area between the cement matrix and PP fibers.

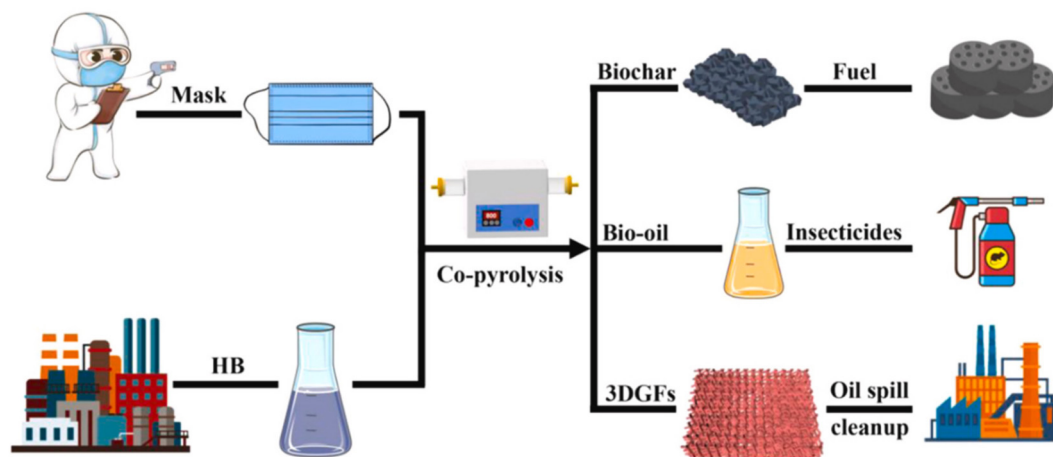


Fig. 11. Simultaneous co-pyrolysis of FMWs and HB to produce biochar, bio-oil, and high-quality 3DGFs. Reprinted with permission from Ref. Luo et al. (2021). (Copyright 2021, Elsevier).

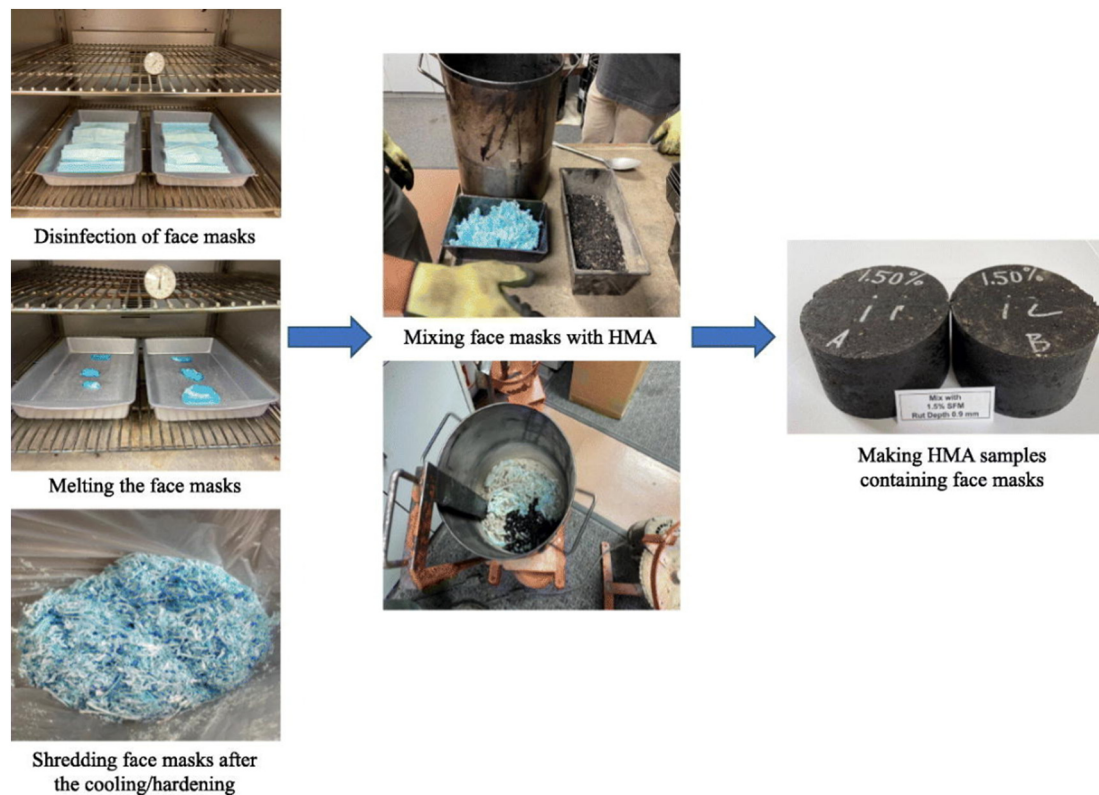


Fig. 12. Utilizing FMWs as an additive to HMA to improve rutting resistance. Reprinted with permission from Ref. Wang et al. (2022c). (Copyright 2022, Elsevier).

Incorporating PP-based FMWs can enhance the complex modulus, rotational viscosity, and tensile elongation, along with lowering the phase angle of base asphalt, leading to a better performance in a wide range of temperatures (Zhao et al., 2022). For instance, Zhao et al. used FMWs as an efficient additive to prepare modified asphalt with notable longevity (Zhao et al., 2022). The modification effect introduced by PP-based FMWs to asphalt is predominantly a physical mix. Besides, adding FMWs to asphalt enhances the moisture vulnerability, rutting resistance, and cracking resistance of the asphalt blend.

Abdullah et al. explored a novel method to reduce FMWs pollution by utilizing them in road construction (Abdullah and Abd El Aal, 2021). In this respect, various mixtures containing shredded FMWs (0, 0.5, 1, and 2 %) were prepared using silty sand (SM) soil for road construction. The modified compaction experiment results demonstrated an increment in the optimal moisture content by increasing the FMW fibers contents from 0.5 % to 1 % and 2 %. Nevertheless, a decrease in the maximum dry density was marked. Such observations might be because of the low density and water absorption capability of FMW fibers. Moreover, the soil-FMWs mixture showed outstanding performance when employed as a subbase layer and decreased vertical displacement by 11 % compared to the regular subbase material. The modified compaction experiment results also revealed an optimal moisture content increment by increasing the PP-based FMW fibers contents from 0.5 % to 1 % and 2 %. The transformation of stress to PP-based FMW fibers improved the strength and immobility when added up to 0.5 % compared to the standard soil. The soil-FMWs subbase layer can improve the performance of the total pavement structure and decrease the rutting and fatigue failure distresses through the bridge-reinforcement action.

The applicability of FMW chips for soil reinforcement has also been investigated by Xu et al. via triaxial examinations on mixed samples possessing complete decomposed granite (CDG) and FMW chips at different mixture contents (Xu et al., 2022). The results revealed that introducing a moderate volumetric quantity of FMW chips (0.3 %–1 %) to the soil sample will enhance its strength, particularly under high encompassing pressure. However, when the content of FMW chips surpassed the optimal value,

the peak shear strength lowered consequently. On the one hand, a controlled portion of FMW chips raised the elastic modulus and slowed the volumetric response. On the other hand, excessive FMW chips formed extra voids, redirecting the robust soil-FMWs contacts to ineffective and unconsolidated chips-chips contacts.

Saberian et al. designed experiments of modified compaction, unconfined compression strength, and resilient modulus tests performed on different blends of shredded FMWs incorporated into the recycled concrete aggregate (RCA) at various composition contents (Saberian et al., 2021). They investigated the applicability of the resultant blends as road base and subbase materials. Incorporating the shredded FMWs augmented strength and stiffness and enhanced the ductility and flexibility of RCA/FMWs blends. In particular, the incorporation of 1 % FMWs to RCA led to the most elevated values of unconfined compressive strength and the most increased resilient modulus. Nevertheless, when exceeding 2 %, raising the content of FMWs reduced strength and stiffness. These observations might be due to the shortness and discontinuousness of the PP-based FMW fibers. FMW fibers can act as reinforcement agents, binding the RCA particles. Besides, the bridging effect of the fibers in RCA could inhibit the evolution of tension cracks. Nonetheless, above 2 %, increasing FMWs content lowered strength and stiffness, which can be ascribed to the fact that the excessive fibers content generates a high portion of voids.

In another study, Varghese et al. adopted a low-cost composite fabrication method comprising the non-woven PP fibers obtained from FMWs blended with acrylonitrile butadiene rubber (NBR) compatibilized by maleic anhydride, resulting in PP-NBR blends (Varghese et al., 2022). The PP – NBR blends displayed improved thermomechanical characteristics, among which the sample containing 70 wt% PP exhibited outstanding features compared with other composites with lower contents of PP.

### 3. Challenges of FMWs upcycling and some possible solutions

The major challenge in FMWs upcycling is to deal with the negative opinions that relate waste upcycling to the concept of low-quality products.



In contrast, an upcycled material (e.g., carbon-based electrodes) can be considerably more useful than the initial material (i.e., FMWs). The simple solution is to develop a product that speaks for itself. Upcycling enterprises should concentrate on designing high-quality materials that are among the best in the market, competing with their first-hand counterparts.

Another challenge for FMWs upcycling industry is merely collecting recycled and disposed FMWs. Particular businesses collect waste materials for upcycling enterprises. However, filtering and checking the receiving materials might be difficult for quality consistency. Upcycling becomes a real challenge if the waste materials are not high-quality or similar. Once waste materials are upcycled, the quality of all the raw materials is important. The foremost solution is to screen the material providers carefully. The process can ensure that incoming FMWs are high-quality by establishing a strong relationship with a trustworthy FMWs supplier.

Furthermore, when receiving FMWs, the upcycling operators must conduct careful quality assessments. Analyzing the chemical, mechanical, and structural properties of FMWs is necessary. It is crucial to realize how much time is needed for FMWs upcycling through each method. Producing a standard product is challenging enough, but upcycling industries might encounter many other hindrances. Most processes require operating quality checks at almost every phase. These quality checks are essential from when the FMWs are received to once the value-added material exits the factory.

Moreover, driving an FMWs upcycling operation on an industrial scale requires a large space. As elucidated, there are extra quality inspections, the probable demand for a recycling place, and storing bulk raw FMWs. Hence, FMWs upcycling businesses can extend and scale up more efficiently with the less costly property, lowering the final price of the value-added product.

One more challenge in upcycling FMWs is to efficiently and safely disinfect the FMWs before being processed. Some upcycling methods, e.g., thermochemical treatments, can disinfect FMWs at high temperatures and/or using chemicals. For those methods unable to do so, a proper disinfection procedure should be defined in the upcycling roster.

#### 4. Future recommendations

- (i) The environmental consequences must be considered by following the principles of green chemistry and green engineering as much as feasible. Particularly, the ultimate upcycling yield should be maximized. At the same time, the usage or generating of biotoxic or hazardous by-products/chemical compounds should be suppressed.
- (ii) The negative outcomes of the FMWs' upcycling strategies on the environment must be investigated. In this venue, valid and reliable evaluation methods should be employed to quantify the across-the-board environmental consequences of the used FMWs' upcycling processes and compare them to the present plastics production industry to estimate their positive effects on the supply chain. For instance, the circular economy for FMWs toward greenhouse gas emission and resource shortage (e.g., petrochemical industry resources) can be considered in this regard.
- (iii) The total expenses needed for upcycling FMWs, including but not limited to collection, disinfection, organizing, deconstruction, and final purification, must be offset by the typical price of the value-added upcycled material for truthfully earning a payoff from the resultant upcycled material.
- (iv) The desired value-added material made due to the upcycling strategy for FMWs must be a profitable alternative for a specific application or prove performance-advantaged properties.
- (v) Eventually, the FMWs' upcycling strategies should involve technologies with the potential of scaling up for execution on industrial scales.

#### 5. Conclusions

Upcycling FMWs into value-added engineering materials is a fortunate effort toward a sustainable economy and society. FMWs can be converted into materials of higher value via pyrolysis, carbonization, catalytic conversion,

mechanical reprocessing, and chemical modification. FMWs have been successfully used in green energy devices (e.g., batteries and supercapacitors) and sustainable environment-related processes (e.g., pollutant removal, separation, and CO<sub>2</sub> capture). Besides, using FMWs as additives/modifiers in construction materials is another practical waste upcycling approach. The performance of FMWs can be enhanced by adjusting their nanostructure (particularly porosity) and surface chemistry (e.g., by using dopants or incorporating functional groups into their structures).

#### CRediT authorship contribution statement

Sina Pourebrahimi: Conceptualization, Methodology, Writing – Original Draft, Writing – Review & Editing.

#### Data availability

No data was used for the research described in the article.

#### Declaration of competing interest

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

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