Nr 6 (365–XX) CZERWIEC 2025 Tom LXX

POLIMERY

Plastic waste carbonization – a review. Part II. Thermal properties

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DOI: https://doi.org/10.14314/polimery.2025.6.1

Abstract: This article presents a literature review on the carbonization of plastic waste as a modern approach to waste recycling and a source of renewable energy. The second part of the review discusses the thermal stability of carbonized products, including PE, PP, PS, and PET. This paper also provides potential future applications of carbonized plastic waste.

Keywords: plastic waste, thermal stability, carbonization, char, degradation.

Karbonizacja odpadów polimerowych – przegląd literaturowy. Część II. Właściwości termiczne

Streszczenie: W artykule przedstawiono przegląd literatury na temat karbonizacji odpadów z tworzyw sztucznych jako nowoczesnego podejścia do recyklingu odpadów i źródła energii odnawialnej. W drugiej części przeglądu omówiono właściwości termiczne karbonizowanych materiałów polimerowych m.in. PE, PP, PS i PET.

Słowa kluczowe: odpady tworzyw polimerowych, stabilność termiczna, karbonizacja, węgiel, degradacja.

The management of plastic waste presents a major environmental issue globally, with plastic pollution threatening both ecosystems and human health. Traditional methods for handling plastic waste, such as landfilling and incineration, are often inadequate or potentially detrimental to the environment. To address this challenge, researchers have been investigating innovative techniques, including the carbonization of plastic waste. Carbonization entails the thermal breakdown of organic materials like plastic waste in an oxygen-free setting, yielding a carbon-rich byproduct such as charcoal or biochar. The carbonization of plastic waste is becoming a promising technique for transforming plastic waste into valuable carbon materials applicable in energy and environmental sectors [1, 2]. Different thermal treatment techniques, such as pyrolysis, catalytic carbonization, and hydrothermal carbonization (HTC), can be used to convert plastics into carbon-rich materials [2, 3]. HTC specifically functions at comparatively low temperatures (180-250°C) and pressures (2-10 MPa), rendering it ideal for handling various plastic waste types [4]. The hydrochar obtained can serve as solid fuel, material for supercapacitors, a catalyst, or an adsorbent [3, 4].

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In Malaysia, converting plastic waste into energy through carbonization seems to be an effective approach. Research on various types of plastics found that high-density polyethylene (HDPE) is the most favorable choice for energy recovery due to its high calorific value and low activation energy [5]. A pilot-scale flue gas pyrolysis system for organic and plastic waste demonstrated improved liquid properties by employing a non-thermal plasma reactor, which could reduce operating costs and carbon emissions [6]. Electronic plastic waste has been analyzed as a potential energy source, featuring an average heat value of 30,872. 42 kJ/kg and emission levels that adhere to environmental standards [7]. The catalytic pyrolysis of plastic waste using calcinated raw dolomite and zeolite catalysts has been studied, producing a liquid oil like conventional diesel [8].

The thermal stability properties of carbonizing plastic waste have been researched thoroughly. The pyrolysis of packaging plastics takes place at temperatures ranging 300–500°C, whereas PVC breaks down in three phases within the range 200–800°C [9]. HTC can transform plastics into valuable hydrochar at temperatures between 180–250°C, with elevated temperatures enhancing energy densification [4]. Catalytic pyrolysis requires temperatures over 700°C for carbon nanotube formation, and 800°C yields high-quality nanotubes when employing FeNi catalysts [10]. Co-pyrolysis of biomass and plastic waste at temperatures of 673K and higher produces chars that have greater carbon content and enhanced uniformity compared to separate pyrolysis while maintaining char yield [11]. Figure 1 shows a visual schematic diagram of hydrothermal carbonization of polyethylene terephthalate (PET) and polystyrene (PS) waste plastic and their hydrochar product.

HTC is a novel process for producing valuable carbon products from plastic waste at low pressures and temperatures [4]. It alters the chemical composition of the plastics by increasing both carbonyl and hydroxyl groups while maintaining their aromatic structures [12]. The hydrochar produced has enhanced energy characteristics, with polyethylene terephthalate (PET) exhibiting superior energy densification compared to polystyrene (PS) [12]. Carbon products derived from plastic waste (PWCMs) have extensive applications in environmental cleanup, manufacturing, and green energy storage [2]. By employing various thermal treatment techniques, including catalytic carbonization and pyrolysis, PWCMs can be prepared [2]. The thermal stability of these materials is essential for their practical applications, as demonstrated in asphalt binder scenarios where waste plastic pyrolytic char (PPC) modified binders exhibited enhanced stability with the incorporation of sulfur [13].

The thermal breakdown of plastics can produce various by-products, including hydrocarbons, gaseous emissions such as methane, ethylene, and carbon dioxide, along with solid carbon remnants like biochar. These by-products are crucial for assessing the efficiency of plastic waste carbonization in different applications. The temperature plays a crucial role in the thermal stability and quality of carbonized products derived from plastic waste, with varying optimal ranges based on the process and intended results. Understanding the thermal stability characteristics of plastic waste during carbonization is crucial for optimizing the process and yielding desirable products, such as carbon black, activated carbon, or even materials suitable for energy storage. These products can exhibit outstanding thermal, mechanical, and chemical

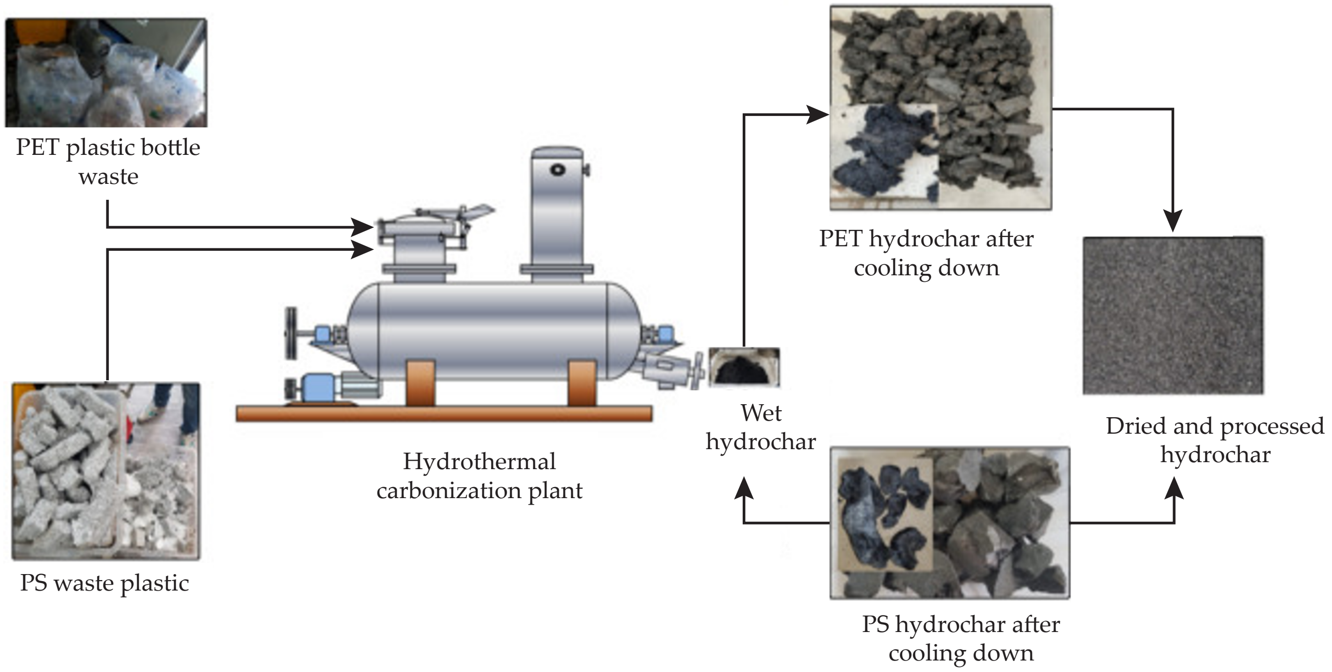

Fig. 1. Schematic diagram of PET and PS plastic waste hydrothermal carbonization and their hydrochar product. Reprinted from [12]

properties, making them valuable for various applications.

EFFECT OF CARBONIZATION ON THERMAL STABILITY CHARACTERISTICS

The thermal stability properties of plastic waste are altered significantly as it goes through the carbonization process. This procedure changes the chemical makeup of plastic waste and impacts its thermal stability, which can be measured using parameters like decomposition temperature and heat resistance. The thermal stability properties of plastic waste differ based on the type of plastic. Packaging plastics break down at temperatures ranging from 300°C to 500°C, whereas PVC breaks down in three stages within the 200-800°C temperature range [9]. The thermal stability of the final product is significantly influenced by the degree of carbonization, temperature, and duration of the process.

The thermal stability of carbon obtained from plastic waste has been widely researched. Amorphous hard carbon films created through cathodic arc deposition show significant thermal stability, retaining their characteristics up to 700°C [14]. In the case of carbon nanotubes produced from polypropylene (PP), effective growth requires temperatures exceeding 700°C, where increased temperatures primarily influence yield instead of thermal stability [10]. Thermal oxidation can be used as a pretreatment to convert uncarbonized PE into structural carbon, which can then be graphitized to produce a highly conductive material [15].

Temperature plays a crucial role in both the carbonization process and the quality of the final product. Temperatures exceeding 700°C are required to create premium carbon nanotubes from PP with Fe-Ni catalysts you. The carbon materials produced could be used in storing energy, protecting the environment, and as solid fuels according to [4, 16]. Comprehending these thermal stability traits is essential for improving the carbonization procedure and enhancing the value of recycling plastic waste. The process also enhances the plastic's thermal resistance and decomposition temperature, while converting it into a more stable, carbon-rich product suitable for different uses. Carbonization is an appealing option for managing plastic waste due to its ability to enhance the material's thermal characteristics and allow it to be used in industries with demanding heat requirements.

Carbon fillers derived from plastic waste can enhance the thermal stability and mechanical properties of polymer composites. For instance, carbon obtained from pyrolyzed PET waste increased the thermal stability of PP composites from 300°C to 370°C with a loading of 20 wt% [17]. Similarly, coal-plastic composites demonstrated improved thermal stability and lower flammability compared to wood-plastic composites, as the amount of coal increased, resulting in a reduction of the burning rate by 19.9-27.6% [18]. Research has explored the use of biochar produced from food waste as an additive in biodegradable and recycled plastics, showing promise for improving compostability, although it encounters issues with thermal stability and particle distribution [19]. According to Kumar *et* al. [20], the thermal stability of carbonized plastic waste is essential for its real-world uses. For example, in asphalt binders, sufficient thermal storage stability guarantees consistency and uniform characteristics throughout storage, handling, and transport. The thermal stability of carbonized plastic waste is vital for its uses, with research indicating that minor quantities of additives such as sulfur can improve stability.

DECOMPOSITION TEMPERATURE

Before carbonization, plastics such as PE, PP, and PS decompose at lower temperatures (200-500°C) which emitting toxic gases like CO, methane (CH_4), hydrogen sulfide (H_2S), and polycyclic aromatic hydrocarbons (PAH). Following carbonization, the breakdown temperature of plastic waste rises, resulting in solid carbon (char) that is more stable than its original form. This carbonized substance is resistant to decomposition at lower temperatures, typically maintaining its structure even when heated above 500°C [21]. The decomposition temperature for various plastics ranges from 400°C to 550°C, influenced by the type of plastic and whether it is mixed with other waste materials [22]. PE degrades at 419°C, with a rapid increase in reaction rate at 420°C [23]. PP degrades around 400°C and fully decomposes at 500°C [21]. PVC decomposes between 200°C to 300°C, while polytetrafluoroethylene (PTFE) decomposes from 500–540°C [24].

For PS, thermal degradation was examined at temperatures between 500°C to 1000°C [25]. Thermolysis conducted at 1200-1500°C produces solid carbon (36–53 wt%), and elevated temperatures lead to reduced particle sizes and enhanced surface area [26]. The degradation temperatures of various plastics rank as PS > PET > PP > HDPE, while blended plastics exhibit two separate degradation phases [22]. Higher temperatures result in greater pro-

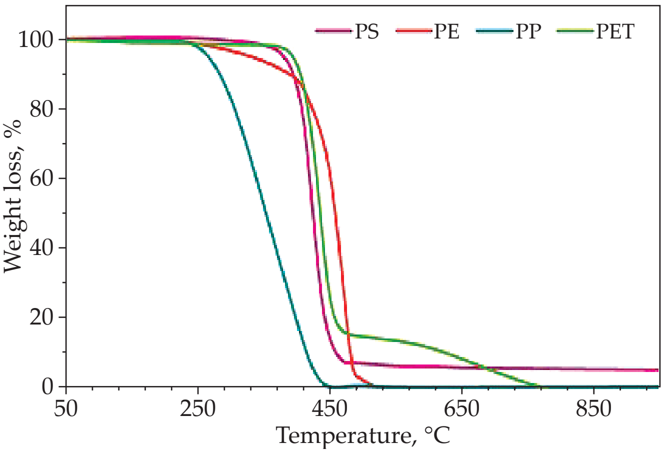

Fig. 2. TGA curves of PS, PE, PP, and PET plastic waste. Reprinted from [27]

duction of carbon and hydrogen gases during pyrolysis processes. Research by Singh *et* al. [22] stated temperature of 500°C were identified as the ideal condition for achieving the highest liquid yield in the non-catalytic thermal pyrolysis of different plastics. The mechanisms of decomposition differ, as PE and PP experience random chain scission, PS degrades via side elimination or end chain scission, while mixed plastics follow random chain scission and β-scission processes. Figure 2 shows the behavior of degradation with quick weight loss of hydrocarbons between 150°C and 250°C temperature range using TGA.

HEAT RESISTANCE

The ability of carbonized plastic waste to withstand heat is determined by the plastic type and carbonization method employed [28]. Plastics tend to have poor resistance to heat and tend to deteriorate rapidly when they are subjected to high temperatures, leading to a loss of characteristics like flexibility, strength, and integrity. The process of carbonization creates char which possesses strong heat resistance because of its steadfast carbon structure. This material is more resistant to melting or breaking down when exposed to high temperatures, making it more stable than the original plastic waste. The carbonized material produced can tolerate elevated temperatures, making it appropriate for applications that need thermal durability, such as insulation or in high-temperature settings. Exposing waste PET bottle flakes to carbon dioxide at 800 psi can enhance their tolerance to heat [28]. PET hydrochar decomposes at lower temperatures (150–270°C) compared to PS hydrochar but reaches higher peak temperatures (420–585°C). Hydrochar types reach the same burnout temperatures of 650-800°C [12].

Studies on the heat resistance of carbon from plastic waste show various applications and characteristics. The pyrolysis of plastic waste at elevated temperatures (400-1550°C) generates chars with differing carbon content, surface area, and structural arrangement, making them suitable for iron carburization [29, 30]. Integrating plastic waste into high-strength concrete can reduce heat-related spalling and enhance mechanical properties following exposure to elevated temperatures [31]. The plastic waste, consisting of various polymers, breaks down at temperatures ranging from 250°C to 500°C, forming irregular reservoirs that assist in alleviating internal pressure. In aromatic polyamide-based graphite plastics, the incorporation of graphite boosts heat resistance by 2% to 22% and lowers the energy activation for thermal degradation, improving production parameters [32]. These innovations aid in the creation of high-performance materials suitable for extreme temperature uses.

Carbon fiber reinforced plastics (CFRPs) demonstrate exceptional heat resistance, rendering them ideal for high temperature uses. CFRP materials using thermally cured polyimide binders exhibit glass transition temperatures ranging from 364°C to 367°C and retain 86–97% of their strength properties at 300°C [33]. Incorporating copper-coated carbon fibers into carbon plastics can improve heat resistance by 20-255°C relative to the base polymer, with an ideal content of 17 wt% [3]. For applications involving even greater temperatures, composites that integrate elastomeric matrices, phenol-formaldehyde resin, and carbon fiber fabric can be enhanced further by adding inorganic additives such as SiC, ZrB_2, and glass microspheres [2]. These materials demonstrate potential for applications in heat shielding. The advancement of carbon plastics that possess improved heat resistance is vital across numerous engineering disciplines since extended exposure to elevated temperatures may cause material deterioration via thermal and chemical mechanisms [3].

POTENTIAL OF PLASTIC WASTE VALORIZATION

Carbonization of plastic waste is becoming a hopeful method for sustainable management and recovery of resources. The process of hydrothermal carbonization can convert plastic waste into valuable items such as solid recovered fuels, catalysts, and materials for energy storage purposes [34]. Different techniques such as anoxic pyrolysis, catalytic methods, and flash Joule heating can transform plastic waste into carbon-based functional materials [35]. The carbon materials derived from plastic waste have promises for use in green energy storage, pollution cleanup, and capturing CO_2, according to Chen *et* al. [35]. Nevertheless, challenges persist such as variability in feedstock, contamination, and scalability [34]. More studies and partnerships are necessary to enhance existing technologies and set up beneficial regulatory systems for sustainable plastic waste management [36].

Recycling plastic waste carbon has numerous potential applications, as highlighted in a recent study by Pereira *et* al. [37], which demonstrated that activated carbons could be produced from plastic waste materials like PET, PS, PE, and polyacrylonitrile (PAN) for use in wastewater treatment. Plastic waste pollution is a growing global concern that significantly impacts ecosystems and human health, leading to severe consequences such as wildlife destruction and health risks for communities relying on contaminated water sources [38]. The potential for using plastic waste to create activated carbon offers a promising solution for effective wastewater treatment, addressing both the reduction of landfill overflow and ocean pollution. This approach not only mitigates an environmental crisis but also contributes to a circular economy by transforming waste materials into valuable resources, endorsing sustainability, and reducing reliance on virgin materials. Efficient treatment of industrial wastewater is crucial for eliminating dangerous pollutants prior to discharging the treated water into natural water bodies or repurposing it for industrial applications. Insufficient treatment can result in considerable environmental harm and health risks. Utilizing plastic waste to produce activated carbon presents a viable

T a b l e 1. Results of adsorption experiments in liquid effluents containing CECs

Material	CEC	pH	T, °C	Adsorbent dose, g/L	q_{max}, mg/g
PET	MCPA	3	–	–	341
PET/PAN	MCPA	3	–	–	200
PET	Ibuprofen	4	30	0.67	206
PET	Bisphenol A	6	25	0.4	2.3
PET	Cephalexin	NA	30	0.4	21.3
PS	Tetrabromobisphenol A	8	25	0.03	117
PET bottle waste	p-nitrophenol	NA	25	4	659
PET bottle	4-chlorophenol	NA	Room temperature	1	625
PE-lined paper coffee cup	Ibuprofen	–	–	3.33	36
	acetaminophen	–	–	3.33	36

solution for efficient wastewater treatment [39], tackling the issues of landfill overflow and marine pollution. This method not only alleviates an environmental emergency but also supports a circular economy by converting waste into valuable resources, promoting sustainability while decreasing dependence on new materials.

Heavy metals accumulate in living organisms, do not break down naturally, and are toxic, presenting significant health hazards to both humans and ecosystems. Common sources of pollution consist of industrial emissions, mining operations, and inadequate waste management practices [40]. Contaminants of Emerging Concern (CECs) encompass a variety of chemicals like pharmaceuticals, hormones, flame retardants, surfactants, and disinfectants, which are increasingly detected in wastewater and pose a rising worry for regulators and public health authorities. Conventional techniques like chemical precipitation and membrane filtration can be ineffective and produce environmentally damaging sludges. As a result, adsorption is commonly favored because of its affordability and effectiveness in eliminating pollutants, particularly when using advanced materials like activated carbon derived from various waste materials [41]. Studies show that activated carbons demonstrate varying effectiveness in eliminating heavy metals and CECs, with peak observed capacities typically occurring for contaminant pairings and operational settings. Recent research emphasizes outstanding removal efficiency for pollutants like p-nitrophenol, highlighting a competitive edge of activated carbon sourced from plastic waste [42]. Activated carbons produced from plastic waste may possess a surface area varying between 0.1 to 2152 m^2/g, influenced by the activation technique employed. Potassium hydroxide (KOH) has been recognized as the most efficient activation agent for improving the textural characteristics of the product. Adsorption capacities frequently attain values below 300 mg/g [43]. The adsorption displays considerable variation, with observed rates ranging from 2 to 659 mg/g, this fluctuation suggests that superior kinetic rates may be attained for the uptake of CECs, enhancing their elimination from wastewater flows [42]. Table 1 shows the results of adsorption experiments in liquid effluents containing CECs [37].

Activation techniques increase the surface area and porosity of chars, which are essential for effective adsorption. Chemical activation utilizes agents like sodium hydroxide (NaOH) or potassium hydroxide (KOH) to enhance microporosity in the activated carbons, while physical activation begins with a carbonization step followed by treatment with oxidizing gases at elevated temperatures. Although physical activation has a lower environmental impact, it typically demands greater energy consumption [39]. According in Pereira *et* al. [37] study, various elements impact the effectiveness of adsorption processes, including pH levels, initial concentration, temperature, and duration of contact. The most effective adsorption takes place in mildly acidic environments, which improves the interaction between contaminants and the surfaces of activated carbon. Initially, higher concentrations of pollutants can enhance adsorption until the saturation point is achieved. Changes in temperature can affect adsorption efficiency by modifying molecular interactions. Extended contact periods typically enable greater pollutant absorption, although a plateau effect may occur after a certain interaction duration.

Plastic valorization is a transformative technique that changes waste plastics into valuable chemical goods, thus prolonging the life of plastic materials and reducing their environmental impact. Recent research by Colelli *et* al. [44] stated formic acid (HCOOH) an essential substance in various chemical production methods, can be generated from plastic waste. This is in accordance with circular economy principles that encourage resource efficiency and sustainability. The production of formic acid depends on fossil fuels and chemical processes, leading to greenhouse gas emissions and the depletion of resources. This study illustrates the potential for sustainable alternatives by using plastic waste as a feedstock for producing formic acid, which could significantly decrease dependence on conventional fossil fuel resources.

An important use of plastic valorization is the creation of formic acid, a multifunctional chemical employed in numerous industries [45, 46]. Its significant reactivity and solubility in water renders it crucial in areas like agriculture, pharmaceuticals, textiles, and chemical production.

Historically, formic acid has been generated via energy-demanding chemical synthesis techniques dependent on fossil fuels, leading to greenhouse gas emissions. Due to rising worries regarding fossil resource exhaustion and their environmental impacts, the demand for sustainable alternatives has intensified [47]. To investigate the formation of concentrated aqueous solutions of formic acid, three processes are analyzed which are the electrolysis process, the hydrogenation process, and the traditional process. The process based on electrolysis converts electric energy into chemical energy by electrochemically reducing CO_2 within a designated cell system. The process involves multiple phases, starting with the incineration of plastic waste to generate electricity, then exhaust gas cleaning, an electrolyzer segment to produce formic acid, and finally a distillation process to obtain a concentrated formic acid solution. [48]. This process captures energy from the burning of plastic waste and electrochemical processes, detailing specific reactions that result in the creation of formic acid.

The process based on hydrogenation focuses on the catalytic hydrogenation of CO_2 to generate formic acid, utilizing a $Cu/CuCr_2O_4$ catalyst [49]. CO_2 can be transformed through hydrogenation into various chemicals, including methanol, methane, hydrocarbons, and formic acid [50]. This process involves the gasification of plastic waste to produce syngas, which is subsequently processed to attain ideal reaction conditions. The series involves gasifying plastic waste to improve CO_2 usage, hydrogenating CO_2 to produce formic acid and performing separation processes to recover and purify the desired products particularly emphasizing the extraction of concentrated formic acid solutions. In the traditional process, formic acid is generated via the hydrolysis of methyl formate, which is sourced from the carbonylation of methanol and carbon monoxide. The operational strategy includes the recirculation of unreacted materials to enhance the process efficiency. The hydrogenation process showed greater efficiency than the conventional and electrolysis process, mainly because the latter requires a significant amount of electricity. Figure 3 shows the block diagram to produce aqueous formic acid solution in the hydrogenation-based process.

Comprehensive economic analyses emphasize key factors such as capital expenses, production costs, and anticipated revenues to determine the most efficient production method for formic acid [51]. According to Colelli *et* al. [44], the primary findings indicate that the electrolysis-based approach displayed poor returns in most financial evaluations, suggesting it is not economically viable when assessed against current technological limitations and operating expenditures. In contrast, both hydrogenation and conventional methods demonstrated positive NPVs and suitable payback periods, highlighting their greater economic viability and thus increased prospects for industrial application.

The research conducted by Tee *et* al. [52] investigates the potential of co-pyrolysis for valorization plastic waste of activated sludge (WAS) alongside PET, representing a significant advancement in methodologies for managing waste by converting harmful materials into valuable bioproducts. WAS generated during food production consisting of a variety of organic materials. Improper management of this waste can cause leachate to form, which has the potential to pollute freshwater streams and initiate eutrophication due to elevated concentrations of nutrients such as nitrogen and phosphorus [53]. The kinetic evaluation shows activation energies that exceed merely additive values, suggesting complex interactions occurring during the pyrolysis, potentially involving molecular transformations between WAS and PET. These findings provide a theoretical basis essential for implementing co-pyrolysis technology in practical applications aimed at converting hazardous waste into beneficial products [54].

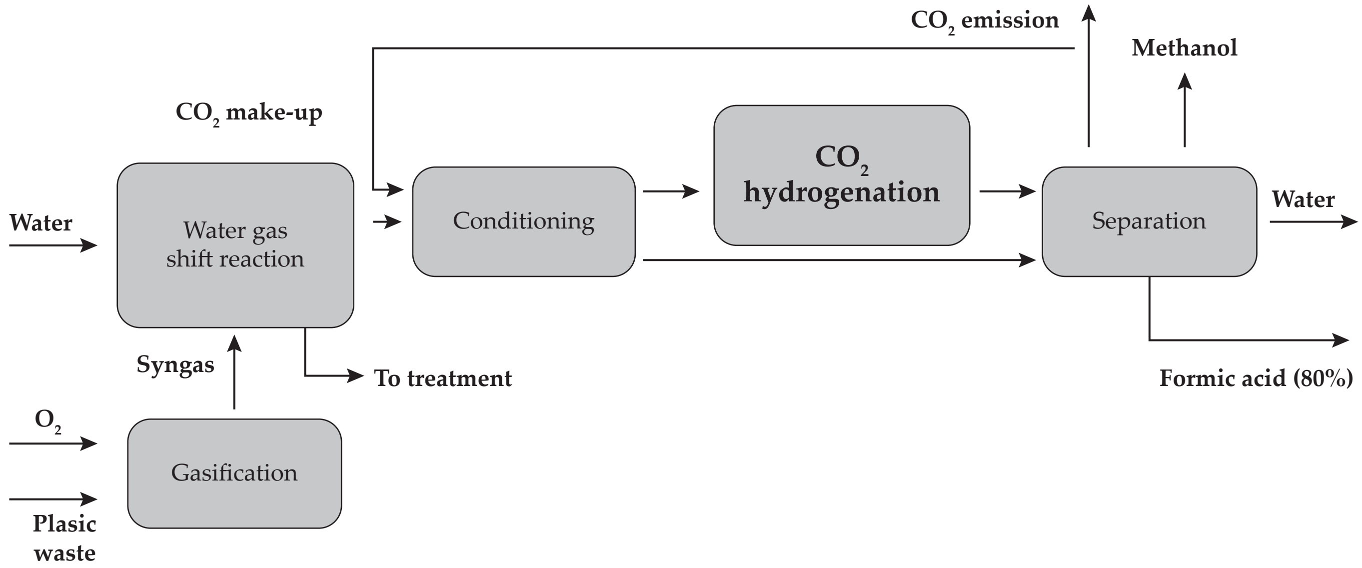

Fig. 3. Block diagram to produce aqueous formic acid solution in the hydrogenation-based process. based on ref. [44]

The research analyzes different blending ratios (3:1, 1:1, 1:3) of WAS and PET to evaluate thermal degradation characteristics and kinetic behaviors, highlighting enhanced decomposition with PET addition and differing impacts at elevated WAS levels [52]. The incorporation of PET not only facilitates WAS breakdown but also seems to prevent PET degradation when present in larger proportions of the mixture. WAS were first air-dried and subsequently dried in an oven at 110°C to efficiently decrease moisture content. The PET waste bottles were gathered and rinsed with running tap water to eliminate contaminants, after which they were air-dried and cut into smaller pieces (3´3 cm) also oven-dried to guarantee uniformity in the reaction process. An elemental analyzer was utilized for ultimate analysis to assess the composition of feedstocks, including metrics like the effective hydrogen index (EHI), which is crucial for comprehending the energy content. While PET has a marginally lower hydrogen content (3.96%) compared to WAS (6.31%), it maintains a superior EHI value (− 0.07) in relation to WAS (− 0.11), suggesting that adding PET can enhance the production of pyrolytic volatiles throughout the conversion process [55].

Co-pyrolysis of WAS combined with PET and biomass presents a promising method for waste valorization and energy generation. This method can enhance pyrolysis efficiency, product quality, and yield relative to conventional pyrolysis [56]. Co-pyrolysis of biomass and PET yields char with improved energy properties, achieving heating values as high as 32.17 MJ/kg [57]. Collaborative effects among feedstocks in co-pyrolysis may lower activation energies and enhance degradation rates [58]. The thermal breakdown of WAS takes place in the temperature range of 190-550°C, generating useful volatile substances and light gases moreover, the kinetic analysis indicates that activation energies for WAS pyrolysis vary between 68.9 and 693.1 kJ/mol, based on conversion levels [59]. These findings offer theoretical backing for reactor design and the industrial implementation of co-pyrolysis technologies [58, 56].

Co-pyrolysis can generate useful biofuels and chemicals, offering environmentally friendly options for waste management and sustainability [60]. Moreover, the inclusion of substances such as clay in sewage sludge pyrolysis can catalyze the process, boost the gasification of carbon remnants, and enhance the properties of the solid byproducts for vitrification and immobilization of heavy metals [61]. The co-pyrolysis of WAS and PET results in synergistic effects that enhance the thermal decomposition of WAS. At higher proportions of WAS, there is a potential inhibition of PET degradation, which may assist in managing product yield. The process of co-pyrolysis displays lower activation energies than the separate pyrolysis of WAS and PET, thereby improving efficiency. Additionally, co-pyrolysis generates fewer CO_2 emissions compared to the conventional individual pyrolysis methods, suggesting a more sustainable approach to bio-product production.

IMPLEMENTATION OF PLASTIC WASTE CARBONIZATION

The carbonization of plastic waste offers a promising strategy for recycling and upcycling, addressing environmental challenges while producing valuable carbon materials. Various methods have been explored, such as a hybrid template approach utilizing magnesium oxide and iron(III) acetylacetonate, which leads to the creation of 3D porous carbon structures suitable for lithium-ion

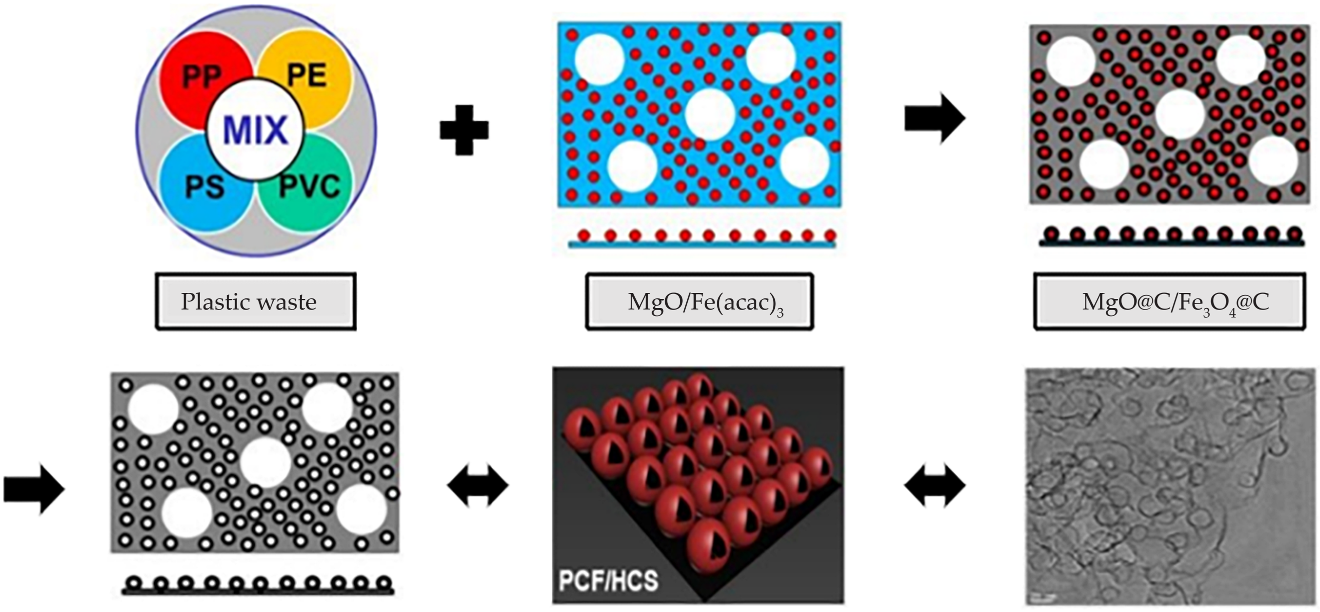

Fig. 4. Schematic diagram illustrating the production process of three-dimensional porous PCF/HCS nanomaterials. Reprinted from [62]

batteries [62]. The carbonization processes differ among various plastic types, indicating potential applications in energy storage and environmental preservation [1]. Real-world mixed waste plastics can be converted into porous carbon nanosheets through carbonization on modified montmorillonite and KOH activation, producing materials with high adsorption capacity for organic dyes in wastewater treatment [63]. Hydrothermal carbonization emerges as a promising technique for transforming plastic waste into hydrochar, useful in diverse fields such as solid recovered fuels, catalysts, and supercapacitors [34]. However, challenges remained regarding material properties and environmental considerations for widespread implementation. Figure 4 shows the schematic diagram demonstrating the process for producing 3D porous PCF/HCS nanomaterials.

CHALLENGES AND LIMITATIONS OF CARBONIZATION

The carbonization of plastic waste provides encouraging options for waste management and energy generation but encounters various challenges and constraints. Variability in feedstock and contamination challenges can influence the quality and uniformity of carbonized products [34]. The procedure necessitates efficient synthesis techniques to guarantee reliable performance and enduring sustainability [1]. Different plastics, including polyethylene, polypropylene, polystyrene, and PVC, are characterized by unique chemical compositions. Variations in feedstock can lead to inconsistencies in the quality of the carbonized product. The carbonization process demands a significant amount of energy. Achieving the required temperatures for heating plastic waste consumes a considerable energy quantity, which could offset the environmental benefits of recycling plastics if the energy comes from non-renewable sources.

Carbonization and pyrolysis represent effective methods for recycling plastic waste, converting it into useful carbon products and oils while tackling environmental issues [1, 64]. The yield and quality of carbonized materials are influenced by various factors, including temperature, heating rate, reactor design, residence time, pressure, and the composition of the feedstock [65, 66]. Adjusting these parameters to achieve the desired traits (like high-quality carbon black, energy-rich gas, or biochar) is complex and often requires careful experimentation and precise modifications for different types of plastics. Combining pyrolysis with biomass can enhance biochar yield, and the choice of catalyst can improve the quality of carbon nanomaterials [65, 66].

Despite the potential uses, there are challenges such as the impact of pollutants, methods for quality evaluation, and economic viability that require more research to refine these processes for industrial application [64, 66]. Although carbonization can help reduce the amount of plastic waste and produce useful by-products, poor management may result in the release of greenhouse gases (GHGs) such as carbon dioxide (CO_2) and methane (CH_4), particularly when the pyrolysis method is not carried out efficiently or lacks proper regulation. If these gases are not adequately captured and neutralized during the carbonization process, they can create hazards for both human health and the environment. The pyrolysis of mixed engineering plastics presents financial challenges, as the minimum sales prices required to break even vary depending on the capacity of the plant [67]. Large-scale operations struggle with issues regarding the availability, quality, and cost of feedstock, which may require additional revenue streams or subsidies to ensure economic viability [67]. Carbonization and similar techniques provide promising alternatives for recycling plastic waste but optimizing these processes and addressing economic limitations are crucial for wider implementation [1, 67].

SOLUTIONS TO MEET THE CHALLENGES

Research into advanced catalysts, reaction mechanisms, and pyrolysis methods can enhance the carbonization process, increasing energy efficiency, reducing harmful by-products, and elevating the quality of the end products. Recent research on the catalytic pyrolysis of plastic waste has shown promising advancements in refining processes and creating catalysts. Carbon-metal oxide hybrid nanocomposites have proven to improve the generation of char, oil, and syngas when compared to traditional ZSM-5 catalysts [68]. Variables such as temperature, reaction time, and catalyst concentration significantly influence the outcomes [68]. The use of biochar derived from biomass waste in a two-stage catalytic pyrolysis process has shown promise for increasing gas yield and hydrogen production [69].

These innovations contribute to the circular polymer economy by improving the recovery of energy and materials from plastic waste [70]. Establishing systems to capture and utilize the heat and gases produced during carbonization can help reduce the energy needed for the process while improving overall sustainability. Investing in efficient sorting and pre-treatment methods for plastic waste can ensure that only suitable plastics are processed, reducing contamination and increasing the quality of the carbonized output. Governments can introduce clearer and more supportive regulatory frameworks to encourage safe and effective carbonization practices. This could include incentives for using carbonized products in various industries, such as construction, energy, or agriculture.

Increasing understanding of the benefits of carbonizing plastic waste, while openly discussing safety and environmental concerns, will promote public support and acceptance of this technology. Raising public awareness and promoting education is vital for addressing the challenges associated with plastic waste management and carbonization. Research shows that many individuals continue to use plastic bags and containers, even though they are aware of their harmful effects [71]. There is a correlation between education levels and awareness, with many people showing a tendency to reduce their plastic use and opt for eco-friendly alternatives [71].

Carbonization has been proposed as a viable method for converting plastic waste into useful carbon materials for various applications [1]. Awareness of waste management strategies and standard procedures for disposing of plastic waste significantly aids in decreasing carbon footprints [72]. To improve waste management practices and decrease reliance on single-use plastics, it is recommended to develop initiatives that are community-oriented, foster partnerships between the public and private sectors, and create innovative solutions such as waste-to-energy facilities [73]. Enhanced public education and responsible management are essential for achieving sustainable waste management and reducing pollution in urban areas.

CONCLUSIONS

The carbonization of plastic waste presents an innovative and sustainable solution to the growing environmental crisis caused by plastic pollution. This process not only offers an effective waste management strategy but also converts plastic waste into valuable carbon-rich materials with enhanced thermal stability and durability. Carbonized products, including biochar, activated carbon, and carbon nanotubes, have diverse applications across multiple industries, such as energy, water treatment, agriculture, construction, and electronics. This transformation aligns with the principles of a circular economy by maximizing material value and minimizing waste, thereby promoting sustainability. Carbonization enhances the thermal and chemical resilience of plastics, yielding products with improved heat resistance, thermal conductivity, and chemical stability—making them suitable for high-performance applications. Additionally, the process generates by-products such as liquid fuels and gases, which can be utilized for energy production, reducing reliance on fossil fuels and mitigating environmental impact. This dual benefit—plastic waste recycling and energy recovery—positions carbonization as a highly sustainable approach to waste management. However, challenges remain in optimizing the process to manage harmful emissions from certain plastics, improve economic viability, and accommodate variations in plastic composition. Further research and development are crucial to enhancing efficiency, reducing costs, and scaling the technology for widespread adoption. As global demand for plastic recycling and effective waste management grows, carbonization offers a promising opportunity to reduce plastic pollution while enabling resource recovery. Continued innovation and investment in this technology can drive significant progress, contributing to a cleaner and more sustainable future.

Authors contribution

A.H.M.P.N. – investigation, validation, visualization, writing; M.N.N. – research concept, writing, methodology, investigation, validation, visualization; N.I.S. – visualization; S.M.– validation, visualization.

Funding

No funding/no source of financing.

Conflict of 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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Received 28 XII 2024.
Accepted 2 IV 2025.