
POLIMERY

Plastic waste carbonization – a review. Part I. Morphology and characteristics of carbonization products

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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 first part of the review discusses the structure and properties of carbonized products, including PE, PP, PS, and PET.

Keywords: plastic waste, carbonization, morphology, particles size, mechanical properties.

Karbonizacja odpadów polimerowych – przegląd literaturowy. Część I. Struktura i charakterystyka produktów karbonizacji

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

Słowa kluczowe: odpady tworzyw polimerowych, karbonizacja, morfologia, wielkość cząstek, właściwości mechaniczne.

The notable increase in plastic use and waste production, along with the urgent demand for sustainable energy options, has initiated groundbreaking research

aimed at transforming plastic waste into useful resources. From 1950 onwards, over 8 billion tons of plastic have been produced, showing an average yearly growth rate of 8.4% [1]. Across the globe, 370 million tons of plastic waste are generated annually, but only 9% of this amount is recycled [2]. The presence of plastic waste poses serious threats to both the environment and public health, with microplastic pollution affecting ecosystems and human health [3]. Plastics offer various conveniences and flexibility, yet they also create major environmental problems [4]. The rising consumption of plastics has resulted in significant waste production, requiring efficient management approaches. Recycling is an essential strategy for minimizing environmental effects, saving energy, and lowering greenhouse gas emissions [5]. Various methods

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for managing plastic waste have been explored, including mechanical and chemical recycling, pyrolysis, gasification, and biodegradation. However, carbonization has appeared as an additional viable method for dealing with plastic waste. Carbonization, which transforms plastics into useful carbon products [4], and incorporating plastic waste in the construction of roads and the manufacturing of concrete [6]. Recycling methods have progressed considerably, generating fresh possibilities to redirect plastic waste away from landfills [7]. Nonetheless, difficulties remain, including the non-biodegradable characteristics of plastics and the energy demands of specific processing techniques [6]. In spite of these challenges, recycling serves an essential and active function in the plastics sector, providing possible remedies for the ecological problems linked to plastic waste [7].

The findings of Dokl *et al.* [8] indicate that worldwide plastic consumption is projected to rise from 464 million tones (Mt) in 2020 to 884 Mt by 2050, potentially reaching 4725 Mt of plastic accumulation by 2050 (since the year 2000). In comparison to other existing forecasts, a marginally reduced level of plastic consumption and supply is achieved. The analysis projects global plastics consumption from 594 Mt to 1018 Mt by 2050, considering various growth rates (from -1% to 2.65%). In the packaging industry, setting plastic reduction goals (15% decrease by 2040 comparing to 2018) could result in a 27.3% decline in its consumption by 2050 relative to 2018, whereas meeting recycling objectives (55% by 2030) would enable the recycling of over 75% of plastic packaging by 2050.

Studies by Ebai *et al.* [9] and Shaibur *et al.* [10] shows that LDPE is to be the most common form of waste, representing 39.51% of the plastic waste in Bamenda, Cameroon, and 40.75% in Jashore, Bangladesh. Other waste materials include polyethylene terephthalate (PET), high-density polyethylene (HDPE), and PP. In Russia, plastic

waste makes over 25% of the municipal solid waste [11]. In developing nations, widespread disposal methods feature open dumping and incineration, which are inadequate practices [10]. In certain European nations, recycling rates reach approx. 50%, whereas in other places, such as Russia, they are significantly lower (4%) [11]. In Malaysia, polymeric materials make up a large part of residential solid waste, causing difficulties in managing plastic waste [12].

The predominant forms of plastic waste in Malaysia include HDPE, PET, LDPE, and PP [12, 13]. These materials are common because of their collection ease and increased density [12]. Malaysian beaches are heavily polluted with plastic waste, where recreational areas gather polymeric films, foams, and pieces, while fish-landing spots collect fishing lines and foams [14]. The issue of plastic waste in the country has been worsened by its position as the leading importer of plastic waste since 2017 [15]. Solving this problem needs enhancing waste management systems, raising recycling rates, and applying uniform policies among state governments [12, 15].

The majority of monomers for plastic production are hydrocarbons including ethylene and propylene, which are extracted from fossil fuels such as petroleum and coal. All of these mass-produced plastics cannot be decomposed [4]. The majority of plastics are thrown away after their initial use. It is estimated that about 20% of global plastic waste (4–12 Mt) has infiltrated aquatic environments, such as rivers and oceans [16]. Since the majority of polymers are produced in large quantities and are inexpensive, they are easily discarded after use. The disposal of plastic waste is essential to lessen pollution and mitigate its environmental effects. Plastic waste comes in numerous forms and sizes, and their proper disposal has emerged as a widespread problem globally [17]. Zong [18] discovered a correlation between worldwide plastic

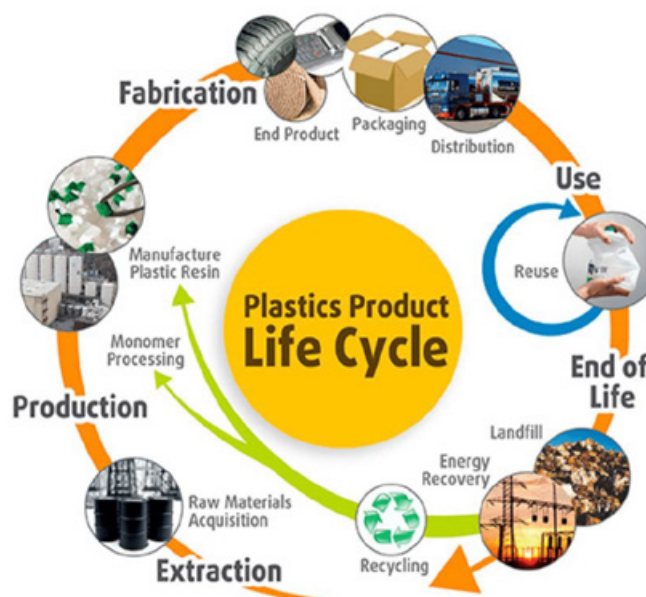


Fig. 1. Schematic diagram of carbon cycle during the production and disposal of plastics. Reprinted from [20]

production and the quantity of macro- and micro-plastic debris in the ocean, concluding that increasing recycling and creating alternatives to plastic are essential for significantly decreasing ocean plastic waste [19].

One way to convert and enhance the worth of plastic waste, in addition to recycling, is carbonization. Besides that, as shown in Figure 1, traditional techniques used for plastic waste disposal involve recycling, landfilling, combustion or incineration, and polymerization. Carbonization serves as an effective technique for transforming polymer precursors into valuable carbon materials suitable for energy conversion and storage, along with environmental protection and restoration.

The carbonization of plastic waste presents a promising strategy for reducing environmental pollution while producing valuable carbon-rich materials with diverse applications. This article offers a comprehensive review of the carbonization process of plastic waste, with a focus on analyzing its morphological and proximate characteristics of carbonized plastic waste. Understanding these characteristics is crucial for optimizing the carbonization process and improving the quality and functionality of the final product. This knowledge can expand the potential applications of carbonized plastic waste in energy production, industrial materials, and environmental remediation.

EFFECT OF CARBONIZATION ON MORPHOLOGICAL CHARACTERISTICS

Pyrolysis was widely recognized as a suitable method for recycling waste streams with various plastics and materials when mechanical recycling is not practicable [21]. As an illustration, waste streams from facilities that process municipal solid waste through mechanical and biological methods typically contain over 40 wt% of plastics [22]. The study of the carbonization effects on plastic waste requires careful examination of morphology. The emphasis is on the materials' physical structure and surface characteristics, which undergo significant changes during carbonization. This can offer important perspectives on the alterations in material qualities and effectiveness. During carbonization, different methods such as Scanning Electron Microscopy (SEM), Transmission Electron Microscopy (TEM), Atomic Force Microscopy (AFM), and X-ray Diffraction (XRD) can be used for examining morphological properties.

The morphological features of carbonized plastic waste have been thoroughly examined through a range of methods. During carbonization, plastics experience several phases such as melting, decomposition accompanied by bubble formation, and the accumulation of ash [22]. The bubble ratio and pixel area can act as morphological indicators to define these stages [22, 23]. Diverse plastics produce distinct carbon nanomaterials, as non-charring plastics generally create graphite while charring plastics result in amorphous carbon [24]. Elements like mono-

mer type, temperature, and heating rate affect the resultant carbon morphology [23, 24]. Pyrolyzing elastomers at low temperatures can give cellular carbons featuring turbostratic structures and increased surface areas, along with non-porous lamellar structures that possess distinct characteristics [25]. For PET, carbonization occurs *via* decarbonylation and decarboxylation, resulting in the production of char and wax, respectively [26]. The study by Ren *et al.* [24] stated, that inherent structure of plastics affects pyrolysis intermediates, as non-charring plastics are likely to produce light hydrocarbons, while charring plastics typically generate aromatics. Elements like catalysts, temperature, and processing time influence the morphology of the produced carbon nanomaterials.

The generation of black carbon from the pyrolysis of gaseous hydrocarbons is thought to involve intermediate droplets composed of complex hydrocarbons, a suggestion supported by studies using electron microscopy and diffraction techniques [27]. The parallels observed between the carbonization of solid polymers and the deposition of carbon in gas-phase processes indicate a shared fundamental mechanism for carbon formation across different methods [27]. Recent computational models that integrate phase field frameworks have been created to forecast morphological changes that occur during pyrolysis for the purposes of micro or nanofabrication [28]. Carbonized plastic waste can be transformed into various nanostructures, including core or shell carbon nanoparticles and three-dimensional porous carbon frameworks. These structures show unique morphologies, such as turbostratic arrangements and granular forms, which are influenced by the conditions of carbonization and the presence of additives like carbon black [29, 30]. Activating carbonized plastics, often through the use of chemical agents like KOH, can enhance the porosity and surface area of the resulting carbon materials. This enhancement is crucial for applications in gas adsorption and energy storage, as it increases the material's ability to interact with other substances [31].

Waste PET can be transformed into microporous and hierarchical porous carbon (HPC). High CO₂ absorption, favorable selectivity for N₂ and CO, straightforward regeneration, remarkable cyclic stability, and rapid kinetics for CO₂ adsorption and desorption make them a cost-efficient option for CO₂ capture. The excellent selectivity and adsorption ability of these materials can aid in reducing greenhouse gas emissions [31]. In addition, they show significant specific surface area and substantial mesopore or macropore volume, providing potential for energy density capacitive storage applications [32]. The structure of carbonized products can differ, with certain methods leading to spherical microparticles or turbostratic formations. Methods such as SEM-EDS and FT-IR are used to examine these structures [33]. Carbon materials obtained from plastic waste have demonstrated potential in energy storage uses, including lithium-ion batteries. The distinct nanostructures and elevated surface areas enhance per-

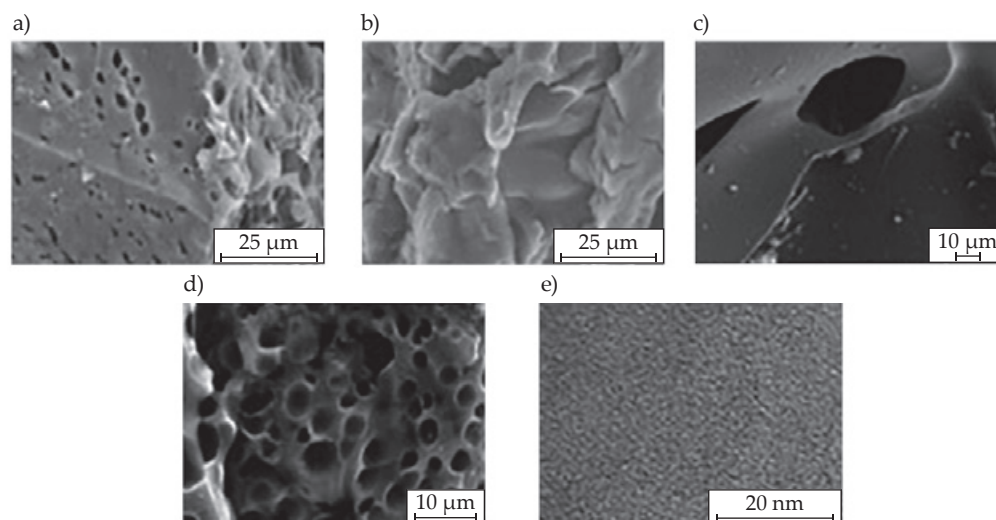


Fig. 2. SEM and corresponding TEM images: a) PET-AC treated with KOH at 700°C, b) modified PET-AC with KOH at 1000°C, c) carbonized PET-AC at 700°C, d, e) modified PET-AC treated with KOH at 700°C. Reprinted from [34]

formance and stability in these uses but the existence of different polymers, such as halogenated plastics, creates difficulties in the carbonization process. Creating universal techniques that can manage various waste streams is crucial for wider usage [29]. Figure 2 presents SEM and TEM images of modified PET-AC treated with KOH at different temperatures.

The transformation of plastic waste into carbon materials represents a promising strategy to combat environmental pollution while generating useful products for energy storage applications. This method involves the conversion of waste plastics into porous carbon structures, which can be used in supercapacitors and various energy storage systems. Carbonization results in alterations to the surface composition of plastic materials. The heat used in the carbonization process breaks down polymer chains in plastic, leading to the creation of pores, cracks, and rough textures on the surface. Factors such as the polymer type, temperature, and carbonization duration can influence the size and distribution of pores, which can be unveiled through the process. Elevated temperatures lead to the material losing volatile components, which causes shrinkage and the creation of a porous structure. The release of these gases can result in surface erosion, causing the formation of craters or cavities on the surface, this can be seen in Figure 3.

The carbonization of plastic waste encompasses multiple mechanisms to give porous carbon structures. One widely used technique is the catalytic carbonization process, which employs catalysts such as ferrocene and sulfur to turn waste plastics into carbon nanosheets that have a high carbon yield and minimal thickness [35]. Another technique involves the use of templates, like CaCO_3 , to aid in creating nanoporous carbon spheres, where factors such as carbonization temperature and material ratios play a crucial role in determining pore structures

[36]. Porous Carbon Nanosheets (PCNS) are created from a mix of waste plastics via catalytic carbonization and KOH activation, resulting in a structure that is microporous or mesoporous with a high specific surface area and substantial pore volume. This structure is advantageous for supercapacitor applications because of its excellent specific capacitance and rate performance [37, 38]. The co-etching effect of sp^2/sp^3 hybridized carbon is also leveraged to generate hierarchical porous structures characterized by micropores and meso-/macropores [32].

The catalytic carbonization method employs catalysts such as organically modified montmorillonite or magnesium oxide to aid in the transformation of waste plastics into carbon structures. These catalysts play a role in developing the desired porous forms by affecting the carbonization process [29, 38, 39]. The surface characteristics of carbonized plastic waste are defined by its unique surface area and pore volume, both of which are essential for its use in energy storage. Hierarchical porous carbon obtained from waste PET, for instance, shows a considerable specific surface area of $2238 \text{ m}^2/\text{g}$ and a substantial pore volume of $0.51 \text{ cm}^3/\text{g}$, improving its electrochemical properties [32]. Likewise, carbon nanosheets derived from a blend of waste plastics have a specific surface area of $2198 \text{ m}^2/\text{g}$ and a pore volume of $3.026 \text{ cm}^3/\text{g}$, enhancing their excellent performance in supercapacitors [38].

Morphological parameters such as bubble ratio and pixel area can be used to characterize dechlorination behavior in PVC [24]. These materials are likely to develop more porous formations because they decompose further during pyrolysis. PVC specifically, might produce a higher amount of inorganic waste as a result of its chlorine content, impacting its surface characteristics. Hydrothermal carbonization is a promising technique for converting plastic waste into valuable hydrochar pro-

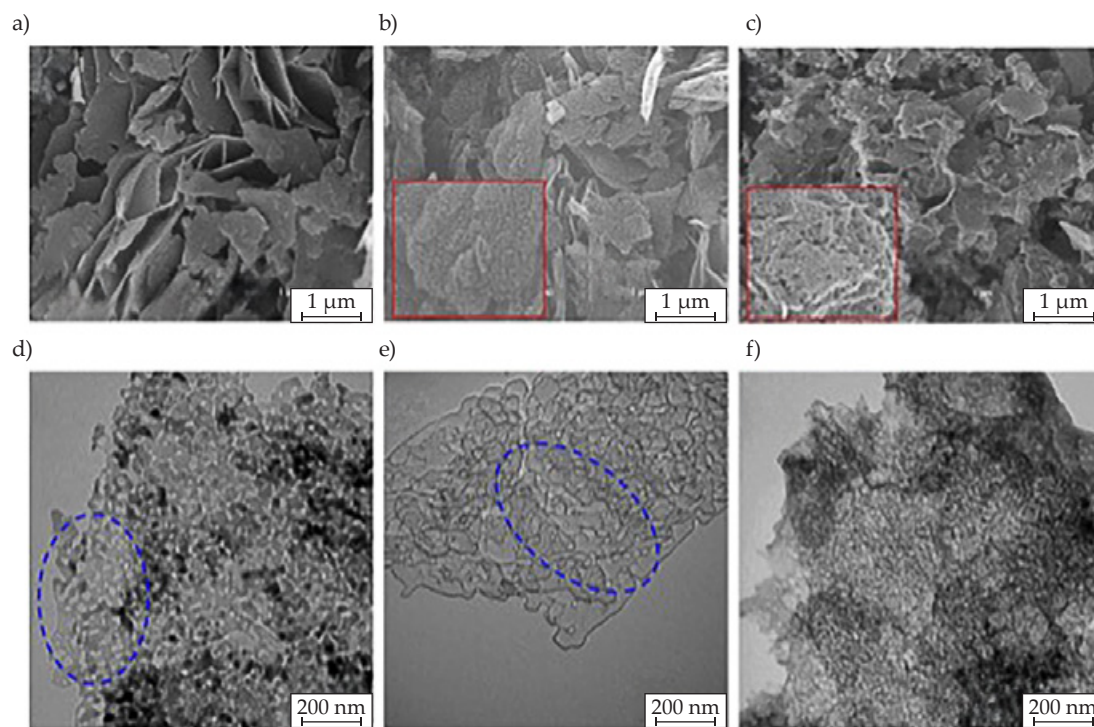


Fig. 3. SEM and corresponding TEM images; a, d) MgO; b, e) CNS; c, f) ACNS-800. Reprinted from [42]

ducts, with reaction pathways affected by temperature and plastic composition [40]. The pyrolysis intermediates produced by plastics are influenced by their inherent structure, leading non-charring plastics to create light hydrocarbons and graphite, while charring plastics result in aromatics and amorphous carbon [25].

The pores size and distribution depend on the kind of plastic being carbonized and the particular conditions applied throughout the procedure. Certain polymers, like PE and PP, have a tendency to develop a graphite structure with fewer pores, whereas others like PVC may have more disordered or highly porous formations. These layers of graphite enhance the materials electrical conductivity and enable the carbonized material to be beneficial in different applications like batteries and supercapacitors. Co-pyrolysis of biomass and plastic waste results in superior char quality and yield when compared to separate pyrolysis processes [41]. Understanding and optimizing the production of carbon nanomaterials from plastic waste relies on the importance of structure changes during heat conversion processes. Figures 3a and 3b show that both the MgO template and resulting carbon nanosheets (CNS) exhibit a thin nanoflake structure based on SEM findings. TEM analysis also shows that CNS has numerous mesopores resembling those of magnesium oxide (MgO) template (as shown in blue circles in Figures 3d and 3e). After treating with KOH at 800°C, ACNS-800 develops numerous micropores and small mesopores on its surface, creating a hierarchical porous structure (Figure 3f and inset in Figure 3c).

Carbon materials obtained from plastic waste demonstrate potential uses in energy storage, especially in supercapacitors. These materials demonstrate elevated specific capacitance and energy density, making them ideal for applications in supercapacitors. For example, carbon sheets with a hierarchical porous structure derived from polystyrene waste have a specific capacitance of 323 F/g and an energy density of 44.1 Wh/kg [42]. Likewise, carbon nanosheets derived from PP waste display a specific capacitance of 349 F/g, emphasizing their possibility in energy storage uses [35].

Even with the encouraging outcomes, obstacles persist in the mass production and utilization of carbonized plastic waste. The presence of diverse polymers, including those containing halogens, adds complexity to the carbonization process. Creating universal methods capable of processing mixed and complex plastic waste presents a notable challenge [29]. Future studies should concentrate on creating more efficient and scalable techniques for transforming various plastic waste into high-quality carbon materials, while also investigating additional applications beyond energy storage [43]. While the conversion of plastic waste into carbon materials provides a solution to pollution problems, the environmental consequences of the carbonization and activation process themselves also must be considered. It is crucial to adopt sustainable and eco-friendly methods to ensure the successful long-term viability of this approach [32]. Although processes tested in laboratories have shown potential, the transition to industrial-scale applications poses a significant obstacle. There is a need

for effective catalysts and processes that can be implemented at a larger scale to make this approach practical for general use [35].

EFFECT OF CARBONIZATION ON PARTICLE SIZE CHARACTERISTICS

The dimensions and form of particles in substances, like those generated from plastic waste *via* carbonization, play a significant role in determining their properties and potential applications. The composition of plastic waste is changed through carbonization, which affects the size and shape of the particles produced. Understanding these effects is essential for assessing the viability of carbonized products across various applications, including energy production, absorbent materials, and soil quality enhancement. Carbonization is increasingly recognized as a promising approach for converting plastic waste into valuable carbon materials. The carbon materials that are made could be used in energy conversion, storage, and environmental preservation [4].

According to a study by Sawant *et al.* [44], using plastics like PE and PP, this method can produce carbon microspheres with sizes varying from 1 to 8 μm . Plastics undergo degradation when they are carbonized. This heat-induced degradation results in the material breaking into smaller pieces or particles. The decrease in size is mainly caused by the evaporation of tiny molecules and the degradation of the long polymer chains found in the plastic. The amount of shrinkage varies, depending on the type of plastic, temperature, and duration of the carbonization process. Increased temperatures typically result in more significant deterioration, and thus, reduced particle dimensions. Research has indicated that PE and PS materials tend to degrade into finer particles at elevated temperatures because of their simplistic chemical compositions and limited resistance.

The carbonization process of plastic waste can generate a range of carbon nanomaterials (CNMs) exhibiting diverse structures and characteristics. The inherent structure of plastics affects pyrolysis intermediates, where non-charring plastics promote graphite generation and charring plastics lean towards amorphous carbon [25]. Studies on the particle size of carbonized plastic waste have revealed its influence on multiple applications. The size of particles is essential in the carbonization process, as larger particles demonstrate improved combustion efficiency in pyrolysis residues [45]. Smaller particle sizes lead to bigger gas yields and elevated levels of H_2 and CO in the gas, along with a higher carbon concentration in the char. This effect is more noticeable in materials that have higher levels of fixed carbon and ash [46]. Different techniques have been created to generate carbon nanomaterials from plastic waste, such as hydrothermal treatment for the size-controllable synthesis of photoluminescent carbon nanoparticles [47].

A sustainable synthesis for carbon nanoparticles (CNPs) derived from discarded plastic bags uses hydrothermal processing in H_2O_2 solutions. The size of photoluminescent CNPs can be regulated by varying the concentration of H_2O_2 , where increased concentrations result in smaller particle sizes. This method is straightforward and eliminates the need for harmful chemicals, thus being eco-friendly [47]. The dimensions of metal particles in catalysts greatly influence the generation of CNTs from discarded plastics. Bigger metal particles generally generate larger amounts of hydrogen and carbon, whereas smaller particles lead to the formation of more amorphous carbon, which is not as favorable for CNTs manufacturing [48, 49]. The pyrolytic treatment of electronic waste, such as plastic enclosures, produces particulate matter with particular size distributions. Finer particles are more common, and their emission factors are considerably elevated in relation to other sources, underscoring the environmental implications of processing waste plastics [4].

The size of particles is essential in influencing the microstructure and characteristics of composites made from carbon. Particles of carbon within the 20 to 75 μm size range lead to enhanced dispersion and better mechanical characteristics [50]. The size of metal particles affects the mechanisms of graphitization, where particles are smaller than approx. 25 nm radius creates closed carbon structures, whereas larger particles lead to the formation of nanotubes and ribbons [51]. Incorporating biochar into composting can enhance the process, speed up organic matter breakdown, and lower greenhouse gas emissions. Composting with biochar leads to reduced particle sizes and bigger looseness in the end product [48]. In the combustion of plastic pyrolysis, larger particle sizes showed improved performance, with oil-carbon coupling enhancing the reaction [45]. An optimal particle size of 80 mesh was identified for briquette production utilizing palm shell waste and LDPE, resulting in the best physical properties [52].

The study by Dai *et al.* [53] stated that the conversion of waste plastics into carbon materials is attracting interest influenced by aspects like reactor design, types of catalysts, and pyrolysis temperature, which impact the quality of the resulting carbon nanomaterials. Additionally, the quality of carbon materials is affected by factors including reactor design, types of catalysts, and pyrolysis temperature. Although advancements have occurred in this area, there are also obstacles, such as the impact of impurities and the assessment of quality on a large scale. Transforming plastic waste into carbon materials appears to be a viable and eco-friendly recycling method. The temperature influences the size and structure of soot particles generated during the pyrolysis of waste plastics. Elevated temperatures result in smaller, more uniform soot particles, featuring improved graphite structures and higher carbon content. This indicates that managing temperature is vital for enhancing the particle size and quality of carbon materials derived from plastic waste

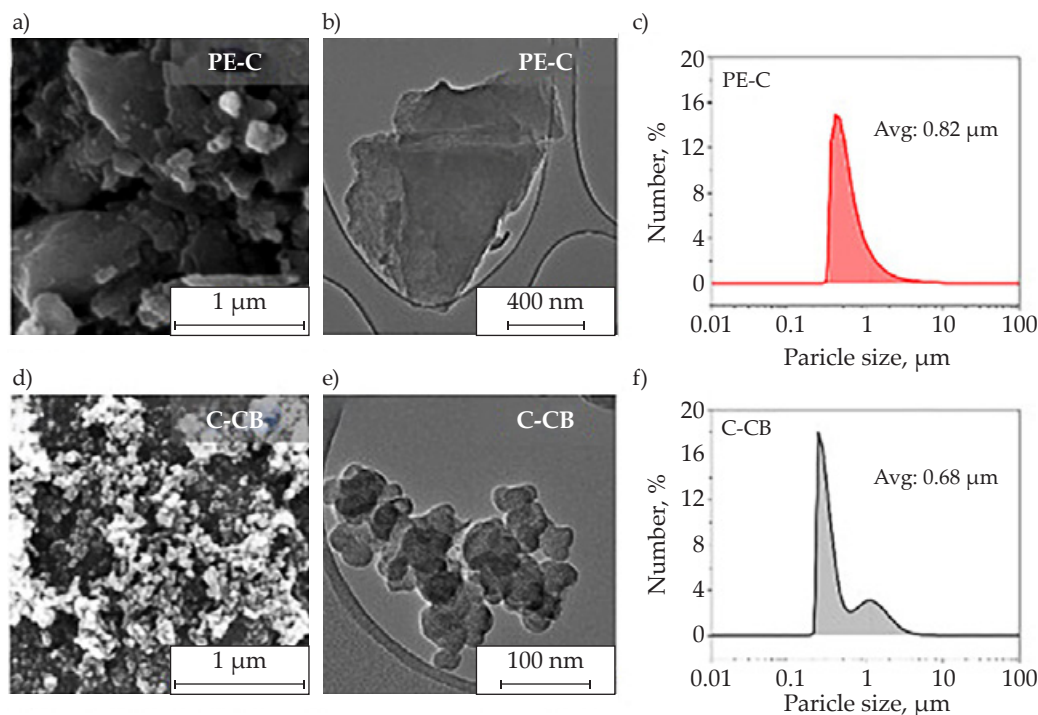


Fig. 4. FESEM and TEM images with particle size distribution: a-c) PE-C, d-f) C-CB. Reprinted from [56]

[54]. Carbon nanoparticles and polymer carbon dots obtained from plastic waste demonstrate significant photoluminescence and optical durability. These substances have potential uses in cellular imaging, photocatalysis, and optoelectronic sensors, presenting the adaptability of carbonized plastic waste in advanced material applications [47, 55]. Figure 4 presents the field emission scanning electron microscope (FESEM) and TEM images,

along with particle size distribution data for carbon material derived from polyethylene (PE-C) in Fig. 4a-c, and for commercial carbon black (C-CB) in Fig. 4d-f. PE-C has a positively skewed distribution with an average particle size of 0.82 μm, while C-CB shows two peaks, one between 0.2–0.5 μm for aggregates and another from 0.5–7 μm representing agglomerates, resulting in an average particle size of 0.68 μm.

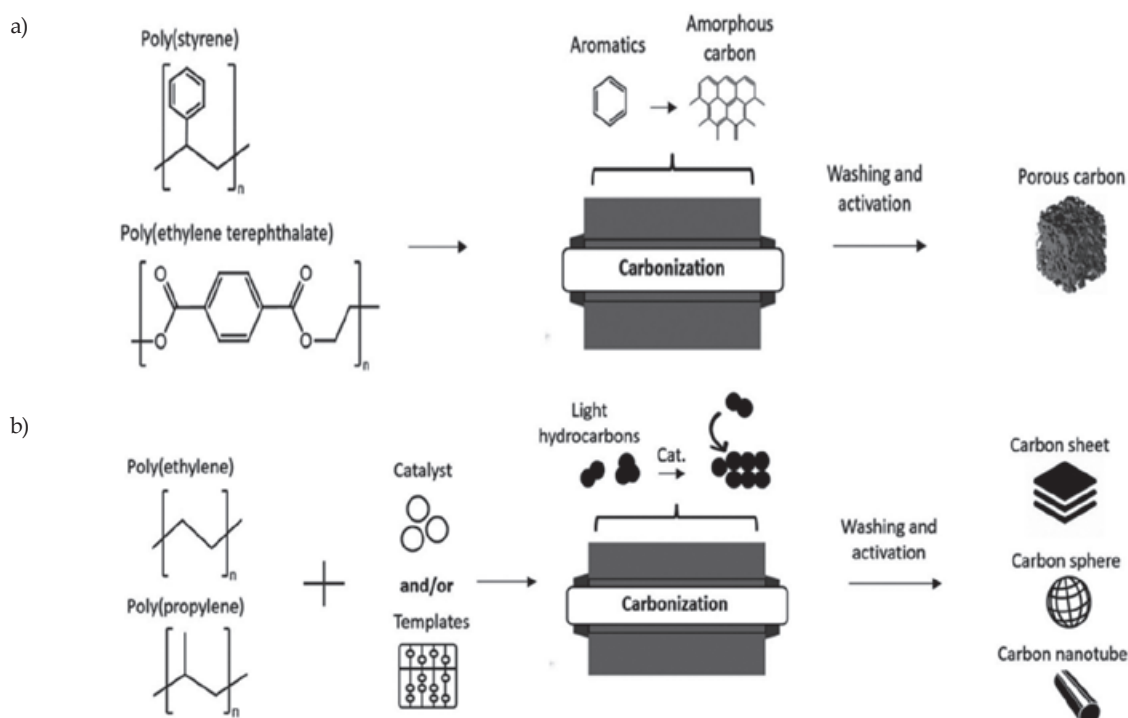


Fig. 5. Schematic diagram of plastic waste carbonization: a) PS and PET, b) PE and PP. Reprinted from [57]

The size of carbonized plastic waste particles affects combustion performance with larger particles usually having better combustion characteristics. Even though the overall combustion behavior as indicated by multiple weight loss peaks were not notably impacted by particle size. Plastic pyrolysis waste has low combustion activation energy, making them an excellent fuel option with a lower combustion point than coal. The presence of oil and carbon elements in the plastic pyrolysis waste enhanced the combustion process [45]. Various carbon nanomaterials such as carbon filaments, graphene, carbon nanosheets, carbon spheres, and porous carbon can be produced from waste plastics. The fundamental composition of the plastic (whether it chars or not) affects the pyrolysis byproducts, leading to the production of either graphite or amorphous carbon nanomaterials [25]. Even with progress made, there are still challenges such as understanding impurities effects and increasing production on a larger scale [53]. Overall, carbonization offers a viable and environmentally sustainable approach for repurposing plastic waste, highlighting the importance of further studies and progress [4, 53]. Figure 5 shows the carbonization of charring plastics to produce porous carbon and the carbonization of non-charring plastics to produce carbon sheets, carbon spheres, and carbon nanotubes.

Ningsih *et al.* [58] discovered, that carbonized plastic waste from PP with a finer particle size (40 mesh) enhances the quality of briquettes making in contrast to larger particle sizes in terms of moisture content, ash content, volatile matter, fixed carbon content, and calorific value when compared to those made with a 100 mesh particle size. Carbonization differs from pyrolysis by focusing on creating solid materials with a high carbon content rather than liquid and gas products. Different carbon-based materials, such as activated carbon, carbon fibers, carbon spheres, carbon nanotubes, and graphene can be created by adjusting the carbonization process to achieve various structures and properties [57]. Transforming plastic waste into carbon-based materials shows great potential as a valuable recycling method that can be used in various practical ways [59]. However, the low carbon yield associated with current methods may make the production of porous carbons from plastic waste impractical. To meet this challenge, it is essential to propose an integrated approach in which porous carbons are gener-

ated as a byproduct during the conversion of plastics into other products [60].

EFFECT OF CARBONIZATION ON PROXIMATE ANALYSIS

Proximate analysis is used for identifying the composition of a substance, usually focusing on its moisture content, volatile matter, fixed carbon, and ash content. Proximate analysis offers valuable information on the change of plastic during carbonization of plastic waste. Grammelis *et al.* [61] proved that different temperature levels are used to determine moisture, volatile matter, and ash content. Loss of weight at specific high temperatures can be used to detect moisture and volatile matter. Ash is the term used for the leftover substance after burning has ceased and reached its final temperature. The ASTM 2009 standards are commonly used for conducting proximate analysis [62].

The fixed-carbon parameter is what sets apart moisture, volatiles, and ash parameters from each other. The fixed carbon value in low volatile materials is equivalent to the elemental carbon content of the sample. The volatile matter content, measured without moisture and ash, varies from 2 to around 50%. With abundant volatile matter easily ignited in household stoves and furnaces or small industrial appliances but, with increased volatile matter contents tend to have decreased heating values. The carbonization of plastic waste is a successful technique for recycling and generating energy. Pyrolyzing HDPE quickly at temperatures between 400–450°C results in char with a high volatile matter percentage of 51.40% and fixed carbon content of 46.03% along with minimal moisture (2.41%) and ash content (0.16%) [63].

Comparable findings were noted for char derived from mixed HDPE and PP waste, which also showed promise as an adsorbent for the removal of arsenic and organic matter chemical oxygen demand (COD) from water solutions [64]. The process of pyrolyzing plastic waste for oil production has attracted interest due to the advantageous chemical properties and the plentiful availability of plastic waste as feedstock [65]. The attributes of plastic waste, such as proximate and ultimate analyses, heating value, and degradation temperature, affect its suitability as feedstock for pyrolysis. Moreover, the chemical activation and carbonization of plastic waste can produce activated

T a b l e 1. Results of proximate and final analysis

Proximate analysis	Weight, wt%	Element analysis	Ash free basis, wt%
Moisture content	0.41	Carbon (C)	83.93
Volatile matter	96.88	Hydrogen (H)	12.84
Fixed carbon	0.28	Nitrogen (N)	-
Ash content	2.43	Oxygen (O)	0.80
		Sulfur (S)	-
		C/H ratio	6.53

carbon for a variety of applications involving functional materials [57], thereby broadening the opportunities for the valorization of plastic waste. Different waste streams, such as municipal solid waste and polymer waste, were examined for their carbon content, revealing values of 28.2 ± 8.0 wt%, 80.1 ± 2.3 wt%, and 50.3 ± 2.3 wt%, respectively. These values emphasize the ability of these wastes to transform into secondary carbon-derived compounds via methods such as oxidative liquefaction [66].

The elemental composition including carbon, hydrogen, nitrogen, oxygen, and sulfur (CHNOS) is determined through ultimate analysis. CHNOS content in the chosen material is crucial for their pyrolysis conversion and ultimately affects the quality of the pyrolysis products. The examination was conducted using an EA 1108 Elemental Analyzer following the test protocols outlined in the ASTM D3176-84 standard [67]. Table 1 shows the test outcomes of the proximate and elemental analysis. It should be noted that only C, H, N, O and S are identified in elemental compositional analysis [67].

The carbonization of plastic waste presents a viable method for recycling and generating valuable carbon-based materials. The pyrolysis of plastic waste produces char residue that can be processed further into activated carbon [68]. The produced char usually has elevated amounts of volatile matter and fixed carbon, with low levels of moisture and ash [63]. Activated carbons produced from plastic waste char have the potential for CO₂ adsorption, with KOH chemical activation demonstrating superior results compared to physical activation [68]. The carbonization process can be improved by modifying variables like temperature and activation methods to make better the characteristics of the resulting carbon materials [4]. Furthermore, plastic waste can be mixed with various substances to create briquettes, which can be examined for proximate composition to verify their accordance to quality standards [69]. This method of handling plastic waste aids in conserving energy and reducing emissions.

EFFECT OF CARBONIZATION ON MOISTURE CONTENT ANALYSIS

The moisture level of carbonized plastic waste is an essential element affecting its processing and possible uses. Counting the moisture content aids in evaluating the appropriateness of plastic waste for different recycling and energy recovery methods. Moisture content is initially high for plastic waste [70] but can decrease during carbonization due to the removal of moisture. Plastic waste taken from landfills had a notably higher average moisture level of 19.96% prior to manual washing and cleaning. The elevated moisture levels can create obstacles for recycling methods since it might need extra drying stages to prepare the waste for mechanical or chemical recycling.

The level of moisture in plastic waste influences its ability to be recycled. Elevated moisture levels, charac-

teristic of plastics obtained from landfills, can hinder both mechanical recycling and chemical methods such as pyrolysis and gasification. Different techniques are employed to assess moisture content in polymers, such as weight loss during drying, thermogravimetric analysis (TGA), differential scanning calorimetry (DSC), and Karl Fischer titration (KFT). KFT is recognized for measuring total water content, but it does not identify the kind of water that is present. It is advised to use complementary methods for a thorough analysis [71].

HDPE is known to have minimal moisture content, making it a great option for converting energy from plastic waste [13]. The moisture content in plastic waste briquettes mixture of HDPE and PP were 5.47%, which met The Indonesian National Standard (SNI) as stated by Ningsih and Udyani [69]. Pyrolyzing HDPE plastic waste quickly at 400-450°C produced char with a moisture content of only 2.41%, as reported by Jamradloedluk and Lertsatitthanakorn [63]. The moisture level of activated carbon derived from PET waste was determined to be 2.2%. Such a low moisture level benefits processes such as adsorption, which help lower pollutants in leachate [72]. Another research found that during a comparison of PET and PP, PET based briquettes showed better qualities with a moisture content of 4.98%, lower than PP [73].

In carbon fiber-reinforced plastics (CFRP), initial moisture saturation does not decrease mechanical properties, yet extended high temperature and moisture exposure can significantly diminish flexural strength. This degradation is studied through dynamic mechanical analysis (DMA) and various other advanced methods [74]. The ideal moisture level is essential for attaining an elevated degree of carbonation. For example, in the carbonation process of incineration bottom ash, a moisture level of 15% were identified as ideal for attaining substantial carbonation quickly [75]. This indicates that managing moisture levels is essential for effective carbonization of plastic waste. Moisture presence can change the mechanical characteristics of biodegradable polyesters. Higher moisture levels prior to processing and mechanical testing lead to bigger elongation at break, along with a minor decrease in elastic modulus and tensile strength. This is due to hydrolytic degradation and the plasticizing influence of absorbed moisture [76].

The amount of moisture significantly impacts the carbonization process of polymeric materials. When PVC is added during the co-hydrothermal carbonization of PVC and coal, it prevents moisture from being re-absorbed by the resulting hydrochar because of its hydrophobic properties [77]. The moisture level additionally affects emissions when waste is burned openly. For example, vegetation with elevated moisture levels (50%) lead to significantly increased emissions of carbon monoxide and particulate matter when compared to those with reduced moisture levels (0% and 20%) [78]. This emphasizes the significance of taking moisture content into account in waste management strategies to reduce environmental and health effects.

EFFECT OF CARBONIZATION ON VOLATILE MATTER ANALYSIS

Volatile matter is often characterized as the portion of waste converted into gaseous or liquid fuel during combustion. It refers to the constituents of the material that vaporize upon heating [79]. Plastics, which are composed of hydrocarbons, possess elevated levels of volatile matter. During the carbonization process, these volatile components are emitted as gases, which results in a reduction of volatile matter and an increase in the fixed carbon content. Elevated levels of volatile matter facilitate the creation of liquids and gases [80]. The breakdown of plastics such as polycarbonate (PC) and polysulfone (PSU) generates a range of volatile compounds, including methane, carbon dioxide, and carbon monoxide. These volatiles make up a considerable part of the plastic's mass, and PSU also emits sulfur dioxide [81].

The recycling of plastics needs to focus on eliminating volatile contaminants to enhance the quality of recyclables. Methods like solvent and heat desorption have been created to quantify and diminish these pollutants, though they should be completely eliminated [82]. The co-pyrolysis of plastic waste and biomass can enhance the yield of volatile matter, with the most significant difference noted in mixtures of beech sawdust and polystyrene [83]. Briquettes produced from PET plastic waste had higher calorific value (10.129 cal/gram) and volatile matter content (65.31%) than those made from PP [73]. Char obtained from the pyrolysis of blended HDPE and PP showed substantial volatile matter (46.5–48.0%) and carbon (41.3–84.7%) content [64].

The creation of techniques to transform plastic waste into useful products, like multi-walled carbon nanotubes and porous carbons for CO₂ absorption appears promising. Carbon materials produced from plastic waste, like N-doped microporous carbon, have demonstrated potential in absorbing CO₂. These substances can be used for CO₂ capture from exhaust gases, providing a dual advantage of waste handling and helping in reduction of climate change [31, 84]. The carbonization of plastics helps to decrease waste while generating valuable substances such as carbon nanotubes and syngas. These items are used in energy storage, environmental conservation, and as electrocatalytic substances [43, 85].

EFFECT OF CARBONIZATION ON FIXED CARBON CONTENT ANALYSIS

Fixed carbon refers to the solid carbon that remains after the volatile components have been removed. It represents the solid carbon fraction of the material, which experiences a significant increase after the carbonization process. A higher fixed carbon content indicates a bigger potential for the material to be utilized as a solid fuel or in carbon-based applications, such as activated carbon [86] additionally, to achieve higher biochar production

[87]. Nonetheless, the low carbon yield could restrict the feasibility of generating porous carbons from plastic waste [60]. Although energy recovery through incineration is prevalent in Northern Europe, its environmental effects differ based on variables like efficiency and the ratios of electricity to heat. In certain instances, incineration may produce greater greenhouse gas emissions compared to landfill disposal, highlighting the importance of enhanced recycling initiatives and thoughtful evaluation of waste management practices [88].

The burning of plastic waste demonstrates significant energy content (34 MJ/kg) and reduced CO₂ emissions (~75 g CO₂/MJ) relative to light, showing its potential as a fuel source [89]. The fixed carbon content in LDPE waste plastic varies between 0.051% and 0.68% [90], PET waste – 11% [91], HDPE – 0.02% [92], and PS – 0.99% [93]. The carbonization temperature significantly affects the yield of fixed carbon, with elevated temperatures typically leading to a higher fixed carbon content [94]. The study from Samal *et al.* [95] stated that co-pyrolyzing plastic waste alongside biomass like eucalyptus wood can yield char that has a high energy density and fuel value, making it suitable for multiple uses. The characteristics of the resulting char, such as fixed carbon content, fuel ratio, and elemental makeup, differ markedly depending on pyrolysis temperature, residence time, and feedstock ratio.

In composites of coal gangue and polyethylene (PE), a rise in fixed carbon content boosts density, hardness, and bending characteristics, yet diminishes tensile strength [96]. To produce biochar, pyrolysis carried out at 300°C optimizes the fixed carbon content, resulting in a gravimetric yield factor of 0.22672 C/biochar. In CO₂ environments, PP and PC show distinct carbon fixation behaviors when undergoing pyrolysis. At 750°C for 30 minutes, PP and PC achieve carbon conversion efficiencies of 45.1% and 32%, respectively. PP can sequester carbon at 600°C, with the impacts of temperature growing over time. Significantly, only plastics that possess extremely low oxygen levels are capable of fixing CO₂ during pyrolysis [77].

EFFECT OF CARBONIZATION ON ASH CONTENT ANALYSIS

Ash content is an important parameter that measures the quantity of inorganic matter remaining after the incineration of the material [97]. The presence of ash signifies the level of non-combustible components, including fillers, additives, or minerals, within the plastic. In certain plastics such as PVC which contain chlorine and various additives, the ash content may be elevated. Conversely, in carbonized plastic, the ash content typically decreases due to the carbonization process, which effectively removes many inorganic substances. A high-quality hydrochar should contain less ash, as ash is a substance that cannot be dissolved and may prevent combustion [62].

Research has indicated that various categories of plastic waste display distinct features. The ash levels in packaging plastics and PVC are 2.36% and 27.24%, respectively, with ideal pyrolysis temperature ranges 300–500°C and 200–800°C [98]. A blend of plastic waste from municipal solid waste demonstrated around 5% of ash content [89]. Briquettes produced from PET and PP plastics have demonstrated favorable calorific values, accompanied by ash content ranging from 0.27 to 3.90% [73, 99]. The pyrolysis of assorted plastic waste (PP, PS, and PE) generates char with distinct characteristics that vary depending on the temperature. Elevated pyrolysis temperatures lead to a reduction in solid product yield, but an increase in ash content and enhanced adsorption capacity [100]. Co-gasification of plastic waste with biomass containing high ash (>10% ash) can enhance the quality of producer gas and decrease clinker formation [101]. The stabilization of thermoplastics through the use of resins such as high-density PE and PS can efficiently encapsulate ash particles municipal solid waste combustion, resulting in robust cylinders that comply with regulatory leaching limits for toxicity [102]. The results indicate that burning plastic waste might be a viable method for both waste disposal and energy generation, especially for types of plastics that are difficult to recycle, as long as harmful emissions can be controlled [89].

CONCLUSIONS

The carbonization of plastic waste presents a promising and effective method for converting plastic waste into valuable porous carbon-based materials with increased surface area. SEM analysis reveals significant morphological transformations, including the development of porous structures that improve adsorptive properties. These features make carbonized materials suitable for applications in air and water purification, soil enhancement, and catalysis. Additionally, the formation of porous networks enhances their potential for energy storage applications, such as in batteries and supercapacitors, where surface area and porosity are critical for conductivity and charge retention. Carbonization also reduces volatile components in plastics while increasing fixed carbon content, resulting in more stable, energy-dense products that can serve as alternative fuels. The lower volatile content suggests reduced emissions of harmful pollutants, making carbonized materials a cleaner option compared to conventional fossil fuels. This waste-to-resource approach is in accordance with global sustainability efforts by reducing plastic pollution and promoting a circular economy. Despite its potential, further research is needed to optimize the carbonization process for bigger efficiency and scalability. Understanding the influence of plastic type, carbonization temperature, and processing duration will enable tailored product development for specific applications. Additionally, assessing the economic feasibility of large-scale plastic waste car-

bonization—considering processing costs, market value, and potential revenue will be crucial for its broader adoption and industrial implementation.

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Authors contribution

A.H.M.P.N. – investigation, validation, visualization, writing; M.N.N. – research concept, writing, methodology, investigation, validation, visualization; M.N.F.N. – research concept, writing, methodology, investigation, validation, visualization; N.I.S. – visualization; S.M. – validation, visualization; V.F.K. – manage the article processing charge; M.N.F.N. – manage the article processing charge.

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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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