

Transformation of Upcycle Plastic Waste into Carbonaceous Materials for Advanced Energy-Storage Applications

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Abstract

Recycling and depositing plastic waste materials into valuable carbonaceous materials is an important method for generating more sustainable machinery. This dynamic is further reinforced by the mounting industrial and societal demand for recycled materials and the crucial need to transition to a more sustainable and elegant route towards demand for recycled materials and the crucial need to transition to a more sustainable and elegant route towards greener synthesis approaches. More specifically, renovating waste plastic materials into upgraded forms for energy-storage devices like batteries and supercapacitors helps reduce pollution while also increasing sustainable resources for current energy systems. Moreover, the plastic waste containing a large quantity of carbon has emerged as a promising strategy to transform through combustion to produce for manufacturing carbonaceous materials with large specific surface area and high electric conductivity, showing great promise for sustainable applications in electrochemical energy-storage devices such as sodium-ion batteries, lithium-ion batteries, and also supercapacitors. The review is focused on the preparation of novel syntheses of active carbonaceous frameworks for energy storage applications from plastic waste and addressed how the use of plastic waste could enhance more sustainable, ecofriendly and highly efficient plastic upcycling technologies.

Keywords: *Applications; Carbon Materials; Carbonaceous Frameworks; Energy Storage; Plastic; Polymer Waste*

Introduction

The ongoing growth of society has led to the rapid accumulation of deposited plastic waste, which has emerged as a significant global environmental challenge, posing threats to ecosystems, social health, and economic stability. The continuous increase in plastic manufacture has become widely used by population and accelerated industrial development coupled with expanding worldwide productivity. One promising method includes renovating plastic waste into highly active carbonaceous frameworks and nanomaterials with high porosity, large surface area, abundant functional groups, and good conductivity, such as graphene, activated carbon, carbon nanotubes (CNTs), carbon quantum dots (CQDs), and porous carbon material. This review provides a wide-ranging overview of generally used plastics, describing their classifications, physicochemical characteristics, buildup pathways, and related environmental and health impacts. Furthermore, it focuses on various recycled waste synthetic approaches and highlights recent advances in the pathway of converting discarded plastics into carbonaceous materials through diverse synthesis methods and their application in energy-storage systems and supercapacitors, followed by insights into future research directions.

Moreover, solid waste, which involves various types of waste from various sources, such as plastic, agricultural, municipal, paper, polymeric wastage, and industrial waste, is predominantly contained in carbonaceous skeletal frameworks, which facilitates the advancement of nanoscience-based technologies. Moreover, especially carbon materials synthesized from waste polymer precursors have recently gathered considerable attention as eco-friendly and cost-effective alternatives for energy-related technologies (Dzikunu *et al.*, 2025; Tatrari *et al.*, 2021). The conversion of polymer waste into carbon frameworks through

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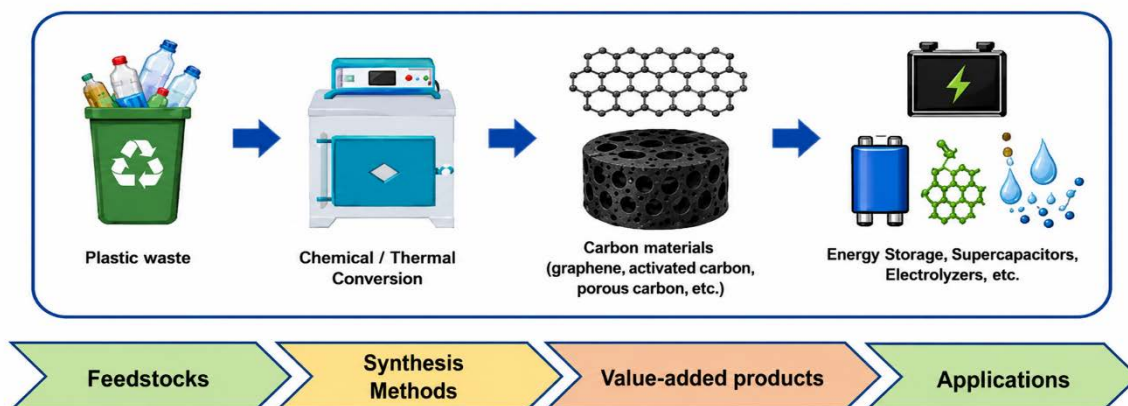


Figure1: Reusing And Advancement of Plastic Wastes to Carbonaceous Materials and Potential Applications

pyrolysis, activation, or templating systems mitigates environmental pollution and synthesizes materials with high surface area, sharp porosity, and excellent electrical conductivity (Ferdous *et al.*, 2024; Zhai *et al.*, 2022). These structural and electronic features show such carbon resources highly suitable for battery electrodes, facilitating higher ion diffusion, charge transport, and longstanding cycling stability (Ruan *et al.*, 2025). The supercapacitors, which have a hierarchical pore structure and large surface area, demonstrate superior capacitance and rapid charge-discharge capabilities (Okonye & Ren, 2024). Additionally, these carbonaceous materials have exposed promising potential in highly energy conversion and storage systems, with fuel cells, metal-air batteries, and electrocatalytic processes. Thus, carbonaceous materials synthesized from unwanted polymers represent a sustainable pathway toward sustainable energy machineries. In contrast, the activation process plays a vital role in tailoring the structural morphology and physicochemical features of the carbonaceous framework, with the final characteristics being basically dictated by the activation approach and processing conditions employed. The current global solid waste situation and its distribution highlight the urgent need for effective management. The current dispositions in solid waste generation and its widespread distribution highlight the urgent stipulation for sustainable waste government strategies. The specific emphasis is located on recent advances in waste-to-resource conversion skills, the synthesis of functionalized porous carbon materials, and their emerging applications like green energy, environmental protection, and also nanotechnologies. These developments expose the immense potential of solid waste as a renewable carbon resource, contributing promptly to waste valorization and eco-friendly sustainability.

Plastic Waste-to-Carbon Nanostructures: A Combustion-Based Approach

The different types of plastic raw materials oscillate in their conformation, molecular structure, and carbonization yield, which pointedly affect their carbonization process. For example, larger macromolecules like polyimides are closely governed by their structural features, such as strong thermal stability and resistance to carbonization, but low-molecular-weight polymers like polypropylene (PP) showed carbonization at elevated temperatures due to their molecular chain configuration. Since plastics are usually structured with high carbon content, converting waste plastics into high-value carbon nanomaterials shows a highly effective approach for both recycling and manufacturing functional carbon-based materials. Furthermore, the structural properties of the resulting carbonaceous nanomaterials depend principally on the type of plastic precursor used under carbonization.

The carbonization yield also fluctuates among raw materials; for example, the yield from waste PP can vary notably under specific processing conditions. Therefore, selecting suitable carbonization techniques and parameters according to the characteristics of the plastic feedstock is critical to maximizing the production of carbon materials. Accordingly, solid waste resources can be repurposed for the large-scale development

of diverse carbon-containing nanomaterials (CNMs). Among these, carbon quantum dots (CQDs), carbon nanotubes (CNTs), and graphene exhibit remarkable physicochemical characteristics, including high aspect ratios, outstanding electrical conductivity, excellent mechanical robustness, and superior thermal transport properties. Over the last decades, enormous efforts have been made to investigate transforming solid waste into carbon nanotube materials and applying their potential in various technological fields, like supercapacitors, fuel cells, solar energy conversion devices and targeted drug delivery (Lobato-Peralta *et al.*, 2025). In 2015, Gong and his teams. Gong and his teams developed a method to transform real-world waste polymers, specifically polyethylene (PE), polystyrene (PS), and polypropylene (PP), into porous carbon nanosheets (PCNSs) that can eliminate organic dyes from wastewater. The resulting PCNSs demonstrated outstanding adsorption performance, attributed to their substantial specific surface area, structural tunability, and multiple adsorption pathways, including pore filling, π - π stacking interactions, hydrogen bonding, and electrostatic interactions, which ease the effective appropriation of diverse contaminants (Gong *et al.*, 2015).

Some important plastic precursors for carbon material synthesis, polyethylene (PE), polystyrene (PS), and polypropylene (PP) are often favored due to their high carbon production. Polystyrene (PS) has been reported to generate aromatic hydrocarbons during pyrolysis, which can reduce its effectiveness as a carbon precursor (Riedewald *et al.*, 2022). Moreover, Veksha *et al.* (2017) explored the impact of various plastic feedstocks on carbon nanomaterial yield under catalytic chemical vapor deposition (CCVD), exploiting non-condensable gases resulting from plastic pyrolysis at 500°C and 800°C. At 500°C, a hybrid plastic mixture (MP) designed carbon nanocages and multi-walled carbon nanotubes along with a large graphitization level. Furthermore, they also examined how various plastic feedstocks influence the formation of carbon nanomaterials (CNMs), as examined by Yao *et al.* (2022) and Sharma & Batra (2020). Their verdicts revealed that polystyrene (PS) formed the highest CNM yield, which was accredited to its high carbon content, low hydrogen concentration, and increased formation of liquid-phase products. polypropylene (PP) and Polyethylene terephthalate (PET) containing approximately 33 wt% oxygen revealed low carbon yield because of its oxygen-rich structure helps carbon oxidation during pyrolysis, leading to excessive CO₂ generation. Therefore, PET was recognized as an unsuitable precursor for CNM synthesis. In addition to this, polystyrene (PS) is non-biodegradable and may persist in the environment for decades. During degradation time, polystyrene materials can release styrene and other harmful substances into the surroundings, potentially contaminating soil and water and posing risks to both humans and wildlife.

The conversion of waste plastics into high-value carbon nanomaterials presents a cost-effective and economically viable strategy for producing advanced functional materials. These carbon nanomaterials derived from plastic waste generally possess superior electrical conductivity and thermal stability, making them highly suitable for high-performance applications, including supercapacitors and conductive composites. Therefore, Hu *et al.* (2024) utilized a salt-assisted carbonization approach to transform waste poly(ϵ -caprolactone) (PCL) into graphene materials. It is seen that the resulting material demonstrated remarkable photothermal properties, including a 98% solar absorption rate, efficient light-to-heat conversion, strong water transport ability, low water evaporation enthalpy, and a thermal conductivity of 0.06 W·m⁻¹·K⁻¹. Its water evaporation rate reached 2.92 kg·m⁻²·h⁻¹, outperforming numerous state-of-the-art photothermal materials. This advancement enables the upcycling of waste plastics and offers a promising route for developing integrated systems for freshwater generation and power cogeneration. Moreover, under the vehicle scrapping, valuable metals and electronic components are typically recovered; however, up to 350 kg of plastic waste often ends up in landfills. In 2020, Algozeeb and colleagues introduced a technique for synthesizing graphene from mixed plastic waste. The process employs rapid thermal discharge to heat waste plastic resistors to exceptionally high temperatures, resulting in highly carbonized materials, which are suitable for graphene formation (Luong *et al.*, 2020).

Graphene material manufacturing from waste plastics signifies a promising strategy for environmental remediation and sustainable applications. Additionally, due to their outstanding electrical conductivity, high porosity, large surface area, and abundant surface groups, they have been widely used as anode materials in lithium-ion batteries, as substrates for photocatalysts, and also used as main components in various fields like supercapacitors, flexible electrodes, and biosensors. This strategy decreases environmental pollution brought about from waste plastics, endorsing the sustainability of our society. However, due to its high practical applicability and excellent performance, graphene derived from plastic waste has emerged as a major topic of research in recent years.

This is particularly evident in the area of catalyst recycling and reuse, where catalysts play a vital role across the chemical, energy, and environmental industries. In response to these demands, recent studies have introduced innovative strategies for recovering precious and critical metals from metal-rich waste sources. Within the sustainable chemistry framework, particular attention has been focused toward changing waste materials into high-performance catalysts capable of operating efficiently under mild reaction conditions. The chemical recycling methods like hydrogenolysis, catalytic cracking, pyrolysis and advanced oxidation help the transformation of plastic waste into good yields, including liquid fuels, carbon-containing constituents, syngas, and hydrogen-enriched gases. However, Cheng *et al.* (2024) investigated that pyrolysis and fluid catalytic cracking restored some part of the energy fixed in packing plastic waste and biomass materials and produced highly active carbon fibers.

The microwave-assisted pyrolysis catalytic process has shown promise in achieving both substantial carbon yields and enhanced hydrogen energy recovery (Yu *et al.*, 2024). Similarly, plasma gasification has gained considerable attention for solid waste processing, as it efficiently converts plastic residues into hydrogen-rich syngas without generating harmful emissions (Qin *et al.*, 2025). Among these technologies, catalytic conversion is particularly crucial, since the choice of catalyst profoundly affects the overall efficiency and selectivity of the plastic-to-carbon conversions. Various transition metal oxides, such as Fe_2O_3 , Co_3O_4 , NiO , $\text{Ni}_3\text{Co}_2\text{O}_x$ and FeAlO_x , have been widely explored owing to their widespread accessibility and cost-effectiveness (Qin *et al.*, 2025). For instance, in 2022, Shen *et al.* synthesized an FeAlO_x catalyst material for the catalytic conversion of plastic waste into carbon nanotubes (CNTs) and hydrogen.

As of now, the majority of reviews concentrate on recent advances in the catalytic transformation of waste plastics into carbon-based nanostructures for the practical applications of the resulting materials. The study specifically focuses on three major products—graphene, porous carbon, and carbon nanotubes—and their applications across various technological sectors.

Although several methodologies have been established for the conversion of plastic waste into functionalized carbon nanomaterials, restrictions in product efficiency and yield remain. For these reasons, continued research is needed to design and synthesize advanced catalytic pathways and improve reaction conditions to achieve superior structural characteristics and enhance production. It enhances conversion efficiency and develops the applicability of these materials in high-performance devices.

The conversion of waste-derived feedstocks into diverse carbon-based nanomaterials (CNMs) and subsequently their integration into polymeric nanocomposites, energy-storage and energy-conversion devices, bioactive systems, and aerospace technologies has significantly improved the value and relevance of waste-based CNMs. Due to the mounting importance of these waste resources as viable precursors for carbon-based nanomaterials synthesis, this review focused on recent strategies in the field. It outlines and hypothesizes various categories of waste materials that can be used to generate carbon-based nanomaterials with specific morphology, structure, and physicochemical properties, while also considering their sustainability and potential applications for environmental remediation. Despite several review articles

on waste utilization, this review also introduces the challenges of implementing carbon-based nanomaterial synthesis and contributes a clearer perspective on their increasing significance to human society.

Recently, extensive research has explored the biomass-resultant materials derived from nanofibers, cellulose, and melanin for application as binders, polymeric electrolytes, or active electrode apparatuses, applying high potential in supercapacitors and rechargeable battery systems (Olazabal *et al.*, 2022). A promising approach for addressing the abounded complications in the plastic residue material is upcycling, which involves converting secondary plastic resources from consumer and industrial feedstocks into high-value products for broader technological applications (Jehanno *et al.*, 2022; Jan *et al.*, 2026). These biomass-derived materials demonstrate noteworthy potential applications for rechargeable battery and supercapacitor systems for increasing the overall sustainability of energy-storage technologies.

Conclusion

The worldwide accumulation of waste plastics has risen to a serious global waste management challenge. Large volumes of mismanaged waste plastics are disposed of in landfills and natural ecosystems, causing environmental pollution and loss of valuable resources. Addressing the global waste crisis needs innovative and sustainable garbage disposal solutions with an environmentally friendly approach. By transforming waste plastics into functional carbon materials, including porous carbon, graphene-like materials, activated carbon, carbon nanotubes and carbon nanofibers obtained through co-pyrolysis of various types of biomass materials and plastics, it helps to generate valuable and sustainable yields for advanced energy-storage systems and also instantaneously reduce plastic pollution. Overall, the valorization of plastic waste into carbonaceous materials signifies a sustainable and green pathway for addressing both plastic waste management and the rising demand for advanced energy-storage technologies. This review approaches the green pathway over the transformation of plastic waste into functional carbonaceous materials, offering a co-friendly sustainable and environmental remediation to effectively reduce environmental pollution.

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