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Carbonaceous Materials from Plastic Waste: Synthesis and Water Remediation: A Review

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***Abstract*: The issue of plastic pollution has become a significant global environmental concern, driven by the rising accumulation of improperly discarded plastic waste. Although conventional waste management methods like recycling, incineration, and energy recovery provide some solutions, new and innovative strategies are being investigated to tackle the ongoing challenge. An auspicious approach entails transforming the carbon-rich structure of plastics into valuable carbonaceous materials, including carbon nanotubes, fullerenes, and activated carbon. This review examines the latest developments in converting waste plastics, particularly multilayer packaging (MLP), which poses significant recycling challenges, into char and then activated carbon via chemical treatment methods. The investigation highlights the importance of material characterization, encompassing the assessment of carbon content, char yield, and the surface properties of the resultant activated carbon product. Carbon-based materials show significant promise in environmental applications, particularly in the field of water purification, where they effectively adsorb contaminants and improve the quality of wastewater streams. This dual-purpose strategy effectively tackles the challenge of plastic waste management while simultaneously advancing the creation of sustainable water treatment technologies. This approach transforms plastic waste into functional carbon materials, offering an environmentally sustainable and resource-efficient method to reduce pollution and support circular economy efforts.**

***Keywords*: Plastic waste, waste management, carbonaceous materials, activated carbon, recycling, water purification application**

I. INTRODUCTION

Plastics are essential in contemporary society, attributed to their diverse characteristics, including durability, lightweight nature, affordability, and resistance to chemicals and moisture. The characteristics of these materials have resulted in their extensive application across various sectors such as packaging, electronics, automotive, construction, agriculture, and consumer goods (Verma & Choudhary, 2025b). Single-use plastics (SUPs), particularly multilayer flexible packaging materials, are notably common in the food and fast-moving consumer goods (FMCG) sectors. The materials are typically engineered to provide barrier properties that ensure freshness and protection. They often feature a composite structure comprising layers such as an aluminium-metallized film, a low-density polyethylene (LDPE) core, and a biaxially oriented polypropylene (BOPP) outer layer(Verma & Choudhary, 2025a).

While multilayer plastic films are useful, they pose a considerable challenge in the management of post-consumer waste. The intricate composition, which includes both polymeric and metallic elements, presents challenges for recycling through standard mechanical techniques. The connection of different materials in multilayer packaging makes it economically and technically impractical for separation and reprocessing in most conventional recycling facilities (Schmidt et al., 2022). Consequently, these plastics frequently find their way into landfills or become litter in both terrestrial and aquatic ecosystems, leading to persistent pollution because of their non-biodegradable characteristics (Nayanathara Thathsarani Pilapitiya and Ratnayake 2024a).

Improper management and accumulation of plastic waste have serious and long-term environmental impacts. The development of microplastics, tiny plastic particles produced when larger plastic objects break down due to sunlight, mechanical forces, and environmental exposure, is a major concern. These microplastics have been found in oceans, rivers, soil, and even the atmosphere, posing a significant threat to ecosystems and entering the food chain through consumption by both marine and terrestrial life. Once ingested, it can be physically harmful and contain toxins substances that can bioaccumulate, posing a health risk to humans and wildlife. Another major problem is the release of hazardous substances from plastic waste, especially in landfills, which contaminate the groundwater and the soil, threatening drinking water supplies and agriculture. Furthermore, wildlife is increasingly being injured, having reduced mobility, or even killed due to entanglement in plastic waste. Birds, marine mammals, and sea turtles are particularly at risk. Uncontrolled plastic pollution impacts ecosystems, causing long-term environmental damage.(Kumar et al. 2021). In response to these urgent environmental challenges, experts and decision-makers are actively pursuing innovative and sustainable strategies to enhance the management of plastic waste (Debnath et al. 2023).

The objective of this review is to examine the current challenges associated with plastic waste management and evaluate emerging technologies and strategies aimed at reducing its environmental impact. By exploring methods such as pyrolysis, mechanical recycling, and alternatives, this review aims to highlight both their potential and limitations. It also seeks to provide information on the economic and technological factors influencing the effectiveness of plastic waste solutions, which will ultimately help in making informed decisions for a more sustainable and circular plastic economy.

Worldwide Overview

The synthesis of nanomaterials derived from plastic waste presents a compelling area of study, as it encompasses significant environmental, economic, social, and technological implications that are likely to influence the future landscape (Firoozi et al., 2025). Additionally, the predictive analysis concerning the nanomaterials and plastic industries, as highlighted in reports such as the Nanomaterials Market (2021–2026), Global Engineering Plastic Recycling Market (2021–2026), and Global Carbon Nanotubes Market (2016–2030) by Mordor Intelligence, underscores the relevance of this field (Muñoz Meneses et al., 2022a).

The global engineering plastics market was valued at 10,262.45 kilotons in 2020 and is projected to reach 15,256.19 kilotons by 2026, reflecting a compound annual growth rate (CAGR) of 7.03% during the forecast period from 2021 to 2026(Muñoz Meneses et al., 2022a). The primary element propelling the expansion of the examined market is the increasing focus on sustainability among consumers and packaging products. Conversely, challenges in gathering and categorizing mixed plastic, coupled with the complexities of eliminating residues, are anticipated to impede the expansion of the market under examination (Rabiu & Jaeger-Erben, 2024).

This review aims to succinctly explore the significant effects of plastic waste on the environment and to pinpoint alternatives for its utilization through the application of circular economy principles. This process helps identify gaps that can lead to new insights and promotes advancements in producing carbonaceous materials from plastic waste.

Comprehensive analysis of the generation

The report presents a summary of the diverse waste types generated daily by individuals worldwide (Cayumil et al., 2021), as illustrated in Figure 1. Diverse types of waste are produced worldwide.

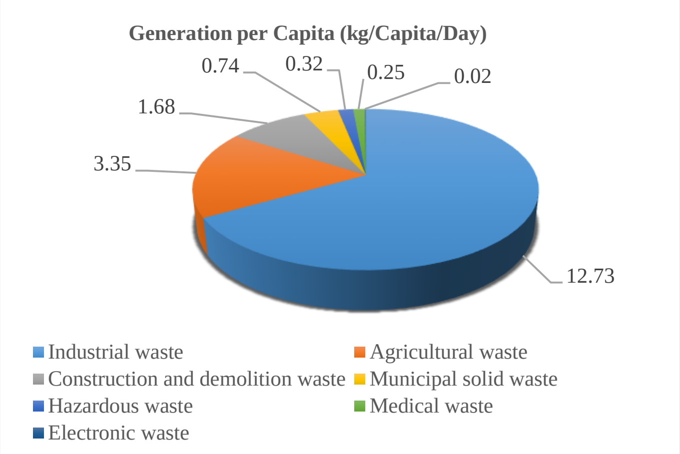
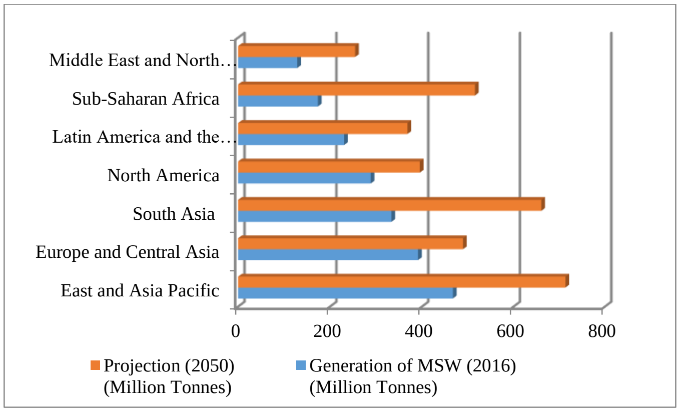


Figure 1: The quantity of various trash generated per capita each day globally

Generation of MSW by region (2016), and their projection by 2050 (Cayumil et al., 2021) are illustrated in Figure 2.



Challenges of Traditional Recycling Methods

Mechanical Recycling: The process of mechanical recycling, which is the predominant approach to plastic recycling, entails the collection, sorting, shredding, melting, and remolding of plastic waste. This process exhibits constraints in both scope and effectiveness, especially when addressing contaminated or multilayer plastics. Throughout the processing phase, contaminants present in the waste stream have the potential to compromise the mechanical characteristics of the recycled product, thereby restricting its range of applications. Moreover, mechanical recycling frequently produces secondary waste, such as wastewater and degraded plastic remnants, thereby not offering a genuinely sustainable solution (Kassab et al., 2023).

Chemical Recycling: Methods of chemical recycling, including depolymerization and solvolysis, focus on deconstructing plastics into monomers or other valuable chemicals. Although these methods show potential in certain situations, they continue to be costly and technologically intricate and have not yet achieved commercial viability on a large scale for multilayer packaging waste (Schade et al., 2024).

Pyrolysis as a Viable Option: Thermal recycling methods, especially pyrolysis, have attracted considerable interest as a more adaptable and efficient solution for managing mixed and multilayer plastic waste. Pyrolysis is a thermochemical decomposition process that occurs without oxygen, generally at temperatures between 300°C and 700°C (Li et al., 2022). In the process of pyrolysis, plastic waste undergoes decomposition, resulting in three main products: gaseous hydrocarbons, liquid oils, and solid carbonaceous char. The solid residue, referred to as pyrolytic char, is abundant in carbon and holds significant promise for subsequent transformation into activated carbon, a material characterized by its high porosity, extensive surface area, and robust adsorption capabilities. Activated carbon finds widespread application across numerous environmental and industrial sectors, such as in the purification of water, filtration of air, separation of gases, and catalytic processes (Bassey et al., 2023).

TABLE 1
Typical sources and compositions of MSW
(Cayumil et al., 2021)

Waste Sources	Waste Generators	Typical Wastes
Residential	Single and/or multi-family dwellings, apartment blocks, high-rise buildings.	Food waste, paper, cardboard, plastics, yard waste, furniture, glass, metals, bulky items, consumer electronics, white goods, batteries, and household hazardous waste
Commercial institutes, shopping malls, and organizations	Shops, stores, hotels, restaurants, markets, offices, schools, hospitals, government organizations	Paper, cardboard, plastics, food wastes, glass, wood, special wastes, metals, hazardous wastes
Municipal services	Street cleaning, landscaping, parks, other recreational areas, beaches, and wastewater treatment	General wastes from parks, street sweepings, landscape and tree trimmings, other recreational areas, beaches, and sludge.

Transforming Plastic Waste into Carbon Materials

The transformation of plastic waste into carbon-based materials is primarily accomplished via pyrolysis, which can be performed in either batch or continuous processing modes. This thermochemical process, conducted with minimal or no oxygen, is well-established and adaptable, currently emphasizing the optimization of operational conditions to suit particular plastic types and intended applications. Several studies and reviews of the techniques used to prepare carbon materials from plastic waste have been conducted(Saxena, 2025). The reviews emphasize that factors like pyrolysis temperature, heating rate, type of plastic, presence of catalysts, gas flow rate, and atmospheric conditions (such as inert gases like N_2 or CO_2) are essential in influencing the final properties of the produced carbonaceous materials(Roychand et al., 2025). showcased the process of synthesizing activated carbon from polyethylene terephthalate (PET) waste through pyrolysis in a nitrogen environment. processing of PET bottles under controlled inert conditions to achieve high-performance activated carbon. In addition to PET(Pham, 2023). Recent investigations have involved the pyrolytic transformation of polypropylene (PP), polystyrene (PS), polyvinyl chloride (PVC), and low-density polyethylene (LDPE) into valuable carbon materials. For example, LDPE demonstrates potential because of its elevated hydrocarbon content and produces a significant amount of char that is appropriate for subsequent activation. Similarly, PS and PP, frequently utilized in packaging and consumer products, have been effectively employed to create porous carbon materials with adjustable surface characteristics(Harussani et al., 2022; Lopez, 2023).

Operational parameters may be modified based on the type of plastic feedstock and the specific characteristics sought in the carbon product. Fast pyrolysis, slow pyrolysis, and flash pyrolysis yield distinct carbon structures, porosities, and surface functionalities, providing opportunities for tailoring materials for various applications, including adsorption, energy storage, or catalysis.

Transforming Plastic Waste into Activated Carbon

By the pyrolysis process, multilayer packaging (MLP) waste is used to produce char. The char undergoes chemical activation to improve its porosity and increase the presence of surface functional groups. The process of chemical activation generally entails the application of activating agents like phosphoric acid (H_3PO_4), potassium hydroxide (KOH), or zinc chloride ($ZnCl_2$) to the char, followed by heating at elevated temperatures under regulated conditions. This procedure establishes a network of micro- and mesopores within the carbon framework, greatly enhancing its adsorption potential (Verma & Choudhary, 2025a).

The activated carbon produced through this method undergoes characterization using a range of analytical techniques to assess essential parameters, including carbon content, char yield, surface area (determined through BET analysis), pore volume, and functional group composition (analyzed via FTIR and XPS methods). The evaluation of these parameters is essential for understanding the material's effectiveness as an adsorbent, particularly in environmental contexts such as wastewater treatment(Solís et al., 2022).

Approaches aligned with the principles of the circular economy for the plastic industry

The plastic industry is embracing circular economy principles by advancing past conventional recycling methods. This encompasses cutting-edge upcycling technologies. A noteworthy strategy involves transforming plastic waste into valuable carbon materials such as activated carbon, carbon nanotubes (CNTs), and graphene. These materials may subsequently be applied in innovative, high-performance applications. For instance, activated carbon obtained from plastic waste can be utilized for water filtration, whereas CNTs and graphene can act as reinforcing agents to develop stronger, lighter composite materials across various industries, thereby "closing the loop" and maintaining materials in circulation at their highest possible value (Haba et al., 2025).

Generation of carbon nanomaterials derived from plastic waste

Among the various valorization approaches accessible both internationally and nationally, the production of carbon nanomaterials stands out as having the most significant potential. This is due to two main factors: first, carbon nanomaterials alone constitute an expanding market segment, often marketed as raw material; second, they can be integrated into various products that cater to different markets, such as environment, energy, health, and aerospace, leading to an increase in demand. Plastic waste can serve as a carbon source for the production of carbon nanomaterials (Jović et al., 2020; Patrick et al., 2023).

Carbon Nanotubes (CNTs).

Carbon nanotube (CNT) is recognized as an important nanomaterial. Prior to 1991, the scientific community acknowledged merely two main allotropes of carbon. In 1991, a Japanese physicist named Sumio Lizima made significant advancements by developing CNT, an intriguing allotrope of carbon (Aqel et al., 2012). We will explore the definition of carbon nanotubes: A carbon nanotube is a cylindrical structure made entirely of carbon, featuring a diameter at the nanoscale level. In conclusion, it is referred to as CNTs. Carbon nanotubes are also known as buckytubes (Dubey et al., 2021).

Nanotubes are formed by the method of folding or rolling two-dimensional graphite into a cylindrical structure. Nanotubes feature a hollow interior. The nanotube demonstrates a diameter that falls within the range of roughly 1 to 3 nanometers (Kolahdouz et al., 2022). The carbon nanotube demonstrates a markedly larger length relative to its diameter. Nanotubes generally attain lengths of several micrometers (Sakurai et al., 2013).

Characteristics of Carbon Nanotube

Cylindrical structures composed of carbon atoms are organized in a hexagonal lattice, known as carbon nanotubes (CNTs) (Venkataraman et al., 2019). This distinctive structure imparts remarkable characteristics to them. These materials exhibit remarkable strength, boasting a tensile strength that can reach up to 100 times that of steel, while also demonstrating significant flexibility (Musa et al., 2025). These materials exhibit outstanding electrical conductivity and can function as semiconductors, contingent upon their structural characteristics, such as chirality. Furthermore, they exhibit outstanding thermal conductivity, surpassing that of diamond. Their nanoscale dimensions and elevated aspect ratio result in an extensive surface area (Jia et al., 2024).

Utilization of Carbon Nanotubes

Carbon nanotubes (CNTs) are employed in various domains owing to their outstanding characteristics, such as impressive strength, electrical conductivity, and thermal stability. In the field of electronics, applications include transistors, transparent conductive films utilized in touchscreens, and energy storage devices such as batteries and supercapacitors (Ali et al., 2024). Their exceptional strength positions them as outstanding reinforcing agents for composite materials utilized in aerospace, automotive, and sporting goods, resulting in components that are both lightweight and durable (Parveez et al., 2022). In the field of biomedicine, carbon nanotubes are being investigated for their potential applications in targeted drug delivery, the development of biosensors for disease detection, and advancements in tissue engineering. These materials find applications in environmental contexts, particularly in water filtration and as catalysts (Sonowal & Gautam, 2024).

Graphene

Graphene consists of a singular, two-dimensional layer of carbon atoms organized in a hexagonal lattice structure. The discovery occurred in 2004 via the adhesive tape peeling method (H. Singh et al., 2025). Graphene exhibits a strength that is 300 times greater than that of steel, positioning it among the strongest materials ever evaluated (Hussain et al., 2020). Graphene's remarkable properties enable its utilization across various fields, particularly in photonics, electronics, biomedical applications, and environmental pollution management, serving roles such as a biosensor, drug carrier, energy storage medium, nanocomposite polymer, and adsorbent (Goodrum et al., 2024). Over the past few years, the graphene industry has been expanding steadily, and in 2022, it is expected to generate an average of 380 million US dollars in revenue worldwide (with projections ranging from 50 million to 1.1 billion US dollars). Even though this is still far smaller than, say, the graphite market (22.5 billion US dollars in 2022) or the carbon black market (17 billion US dollars in 2021), it is still rather astounding given how recently it was discovered for practical application. The market is expected to increase significantly over the next few years, reaching a size of 1.5 billion US dollars in 2027 (estimates range from 0.34 to 5.5 billion US dollars)(Schmaltz et al., 2024).

Various strategies have been suggested employing the CVD method to synthesize different forms of graphene from plastic waste, including polyethylene terephthalate (PET), polyethylene (PE), polyvinylchloride (PVC), polypropylene

(PP), polystyrene (PS), and polymethylmethacrylate (PMMA) (Muñoz Meneses et al., 2022b).

Activated Carbon

Activated carbon is characterized as a microcrystalline material. The activated carbon demonstrates a remarkably elevated surface area and porosity. The properties of activated carbon reveal a notable degree of microporosity (K. Singh & Baheti, 2024). Activated carbon consists of tiny, solid, black porous sponges or black beads. This material is acknowledged for its exceptional environmental sustainability and economic efficiency as an adsorbent. Activated carbon, commonly known as charcoal, is a black solid material. Activated carbon is derived from biomass materials, including coconut husk, spent tea leaves, orange peel, wood, and other sources, employing particular temperature and atmospheric conditions (Tetteh et al., 2024). The surface area of activated carbon may vary depending on the particular raw materials utilized and the conditions present during the carbonization process (Lin et al., 2021). The characteristics of activated carbon, including pore size, surface area, and adsorption capacity, are greatly affected by various factors such as the choice of raw materials, temperature, and the specific activation method employed. The low temperature of carbonization offers benefits for the production of highly efficient activated carbon, as it promotes the formation of the porous structure (Karume et al., 2023).

Classification of Activated Carbon (Ganjoo et al., 2023)

1. Powdered activated carbon (PAC): Size range of 5 to 150 Å.
2. Granular Activated Carbon (GAC): Dimensions ranging from 0.2 mm to 5 mm
3. Extruded Activated Carbon (EAC): Size range of 1 mm to 5 mm

Characteristics of activated carbon

Activated carbon adsorbents possess a distinct porous carbon structure that resembles the structure of graphite. The IUPAC categorizes pore size into three distinct groups (Mopoung et al., 2015).

- Macropores, with a diameter exceeding 50 nm.
- Mesopores, with diameters ranging from 2 to 50 nm.
- Micropore, with a diameter of less than 2 nm [19]

Water Purification Application

Activated carbon is a highly porous material known for its remarkable adsorption capacity, rendering it essential in various environmental and industrial applications. The extensive surface area and unique surface chemistry allow it to capture and hold a diverse range of substances from both liquids and gases, making it a preferred material for applications in filtration, purification, and remediation processes (Kumar Mishra et al., 2024; Sharma et al., 2022).

Activated carbon derived from plastic waste has recently surfaced as a sustainable alternative to traditional sources of activated carbon, such as coal, wood, or coconut shells (Kundu et al., 2024). This method of converting waste into valuable resources tackles the problem of plastic pollution while simultaneously producing effective adsorbents for use in environmental applications (Kapoor et al., 2024). In the realm of wastewater treatment, activated carbon derived from plastic waste has demonstrated significant efficacy, particularly in the removal of pollutants from industrial effluents, municipal wastewater, and water utilized in the food and beverage industries (B. J. Singh et al., 2023).

A notable characteristic is its capacity to eliminate colorants, rendering it particularly beneficial for sectors where dyes and food colorings are common in wastewater. Activated carbon demonstrates the ability to adsorb a diverse array of organic and inorganic contaminants, encompassing pesticides and both basic and acidic residues, as well as heavy metals such as lead, mercury, and cadmium (Thakur & Kumar, 2024). The presence of these pollutants poses significant risks to both ecosystems and human health, which emphasizes the necessity of their removal for the safe discharge and reuse of water. Furthermore, activated carbon is extensively utilized in the pre-treatment of chlorinated water, particularly in the production of drinking water (Nishmitha et al., 2025). It plays a crucial role in removing residual chlorine and organic compounds that may lead to the formation of harmful by-products, such as trihalomethanes. The capacity to bind with and capture chemicals and impurities renders it exceptionally appropriate for application across various phases of water treatment, encompassing the initial stage (before the spread of contamination), mid-process, and in end-of-pipe treatment, which represents the concluding step before wastewater is discharged into the environment (Shamshad & Ur Rehman, 2025).

Among the more sophisticated applications and urgent-response scenarios for activated carbon are mobile carbon filtration systems, which are utilized to address contaminated sites in real time (Jaber et al., 2024). These hold significant relevance in scenarios like fuel spills, leaking petroleum pipelines, industrial fires, and chemical accidents. The mobile filters efficiently handle substantial amounts of contaminated water, effectively eliminating harmful substances directly at the source and safeguarding adjacent ecosystems and water supplies from potential contamination (Brown et al., 2017).

In summary, the remarkable adaptability and effectiveness of activated carbon, especially when sourced from waste plastics, position it as a crucial component in contemporary water purification methods. The ability to adsorb a wide range of contaminants makes it an essential element in both regular and emergency water treatment. The incorporation of activated carbon derived from plastic into industrial processes serves to reduce water pollution while simultaneously promoting a circular economy by transforming plastic waste into high-performance, reusable materials (AlAqad et al., 2025).

Advantages of Environmental Sustainability and Circular Economy

The transformation of plastic waste into activated carbon presents numerous ecological advantages. Initially, it offers a practical approach to redirect non-recyclable plastics away from landfills and natural settings, thereby reducing plastic pollution. Additionally, it enhances the utility of waste materials by converting them into high-performance, reusable products. This method is consistent with the principles of a circular economy, wherein waste is regarded as a resource and reintegrated into the economic cycle in an alternative form (Hasan et al., 2025; Nayanathara Thathsarani Pilapitiya & Ratnayake, 2024b).

Furthermore, employing waste-derived activated carbon in water purification systems can fulfill two objectives: mitigating environmental pollution and tackling worldwide issues related to the availability of clean water (Khan et al., 2025). The significant adsorption capacity of activated carbon makes it highly effective for removing various pollutants, including heavy metals, dyes, organic contaminants, and pathogens, from water sources (Akhtar, Ali, and Zaman 2024).

Demerits

Pyrolysis offers an attractive and complex approach to addressing the challenges of plastic waste and various organic materials. However, its widespread implementation faces several serious obstacles. The process requires significant energy investment and careful control of temperature and operating conditions, resulting in increased operating expenses and technical complexities. Setting up a pyrolysis facility requires substantial financial resources for specialized infrastructure and sophisticated monitoring systems, which are crucial to ensuring safety and maintaining product quality.

Furthermore, the variability of feedstocks, particularly in mixed plastic or municipal solid waste, adds complexity to the process and may lead to inconsistent product outputs. Harmful by-products like VOCs, dioxins, and ash containing heavy metals present further environmental and health challenges, making it imperative to implement rigorous emissions regulation and effective hazardous waste management. The refinement of end products such as bio-oil and syngas increases processing expenses and restricts commercial feasibility.

Increasing the scale of pyrolysis presents significant challenges stemming from various technical and economic limitations. The demands of regulatory compliance and the necessity for advanced control systems amplify the operational challenges.

II. CONCLUSION

Plastic waste poses a significant and enduring challenge to the environment due to its remarkable resistance to natural degradation. Discarded plastics accumulate in soils, water bodies, and ecosystems, causing significant ecological damage. A significant amount of household plastics is not disposed of correctly, often ending up in landfills or being thrown away in open areas after just one use. Conventional recycling initiatives have demonstrated a lack of economic sustainability and efficiency, particularly in the context of mixed or contaminated plastic waste streams.

Considering these constraints, it is crucial to devise innovative, value-enhancing approaches for more efficient management of plastic waste. A promising approach entails the integration of plastic waste into innovative production processes designed to develop advanced materials. Recently, the focus of scientific and technological inquiry has increasingly been on transforming plastic waste into nanoparticles and carbonaceous materials, which hold significant potential in essential areas like energy, environmental protection, and healthcare.

These developments indicate a transition from perceiving plastic merely as waste to acknowledging its potential as a valuable raw material. Carbon-based nanomaterials derived from plastic, including carbon nanotubes, graphene, and activated carbon, have applications in wastewater treatment, energy storage and conversion, as well as in technologies for capturing and converting carbon dioxide (CO_2). The emerging applications offer solutions for pollution and energy challenges while adhering to circular economy principles by reintegrating waste into the value chain in a novel, functional manner.

This review emphasizes that repurposing plastic waste for the creation of high-value carbon materials presents a sustainable and effective alternative to traditional disposal methods. Transforming waste into functional materials can effectively reduce environmental pollution.

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