Application of Nanotechnology in Plastic Waste Management and Recycling: Bangladesh Perspective

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Abstract

Plastic waste is a major environmental threat globally, with profound impacts on ecosystems. Rapid urbanization and economic growth in Bangladesh have significantly increased plastic consumption and pollution. Between 2005 and 2020, the average annual per capita plastic usage surged from 3 kg to 9 kg, with an even more pronounced rise in Dhaka, where it grew from 9.2 kg to 22.25 kg per capita over the same period. This escalating plastic consumption is projected to continue generating substantial plastic waste, which, without proper management, contributes to severe environmental degradation. Consequently, Bangladesh ranks among the nations with the highest plastic pollution levels, emphasizing the urgent need for effective recycling and waste management strategies. Nanotechnology offers a promising approach for addressing this issue. Transforming plastic waste into valuable nanomaterials not only mitigates environmental and human health risks but also provides resources for diverse applications. However, no studies to date have specifically examined the use of nanotechnology in Bangladesh for plastic waste management. This study aims to bridge this gap by demonstrating the conversion of PET waste into high-value carbon-based nanomaterials through nanotechnological processes. Our findings highlight the potential of waste plastics to produce various nanomaterials, including carbon dots, graphene and graphene films, carbon nanocomposites, MoC_2 nanoparticles, photoluminescent carbon nanoparticles, carbon nanostructures, and carbon nanotubes (CNTs), thereby offering a sustainable solution for plastic waste reduction.

Keywords: Waste plastic, Recycle, Nanomaterials, Management, Carbon Nanotube, Graphene

Significance | This study provides critical insights into utilizing nanotechnology for sustainable plastic waste management in Bangladesh, promoting environmental and economic benefits.

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Introduction

Bangladesh, a rapidly developing nation with a population of approximately 174 million (World Population Prospects, 2024), has shown remarkable economic growth despite the challenges posed by its dense population. This growth has driven an increase in living standards, which in turn has led to a rise in plastic consumption. Currently, Bangladesh generates about 3,000 tons of plastic waste daily, accounting for roughly 8% of all waste produced in the country (Monjur et al., 2017; Mahmudul et al., 2019). The demand for plastic across various sectors, such as food packaging and electronics, can be attributed to its durability, lightweight nature, cost-effectiveness, and superior thermal and electrical insulation properties (Richard et al., 2009; Anthony, 2015). The plastics industry in Bangladesh supports approximately 1.2 million jobs across 5,000 manufacturing units (BIDA, 2021), reflecting the sector's significant role in the national economy.

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In Dhaka, the average annual plastic consumption rose from 9.2 kg per capita in 2005 to 22.25 kg in 2020, mirroring a broader trend of increasing plastic use nationwide (The World Bank, 2021). The Bangladesh plastics market, valued at $2.99 billion, primarily serves domestic demand (83.4%), with the remaining 16.6% of production targeted at international markets (The Business Standards, 2023). However, this expanding industry has led to a parallel rise in plastic waste, posing serious environmental threats. Improper disposal practices have made Bangladesh one of the most plastic-polluted countries globally, intensifying the need for effective recycling and waste management strategies.

Various approaches are being explored to tackle plastic waste management, focusing on sustainable practices and technological innovations. Recent research has concentrated on enhancing the plastic waste supply chain through Blockchain technology and other innovations to improve transparency and accountability in recycling efforts (Nesreen et al., 2023). Solutions aimed at reducing marine plastic pollution, such as plastics-to-value initiatives and designing products for recyclability or upcycling, are also under investigation (Chauhan, 2023). Additionally, advancements in plastic recycling processes are being made through technologies like compatibilizers, upcycled plastics, and selective deconstruction catalysts, which enhance the efficiency of converting plastic waste into reusable forms (Jack et al., 2023). Methods such as adsorption, coagulation, photocatalysis, and microbial degradation are being studied to assess their potential for plastic waste removal, with additional focus on reusing plastic waste in sectors like textiles and energy production (Pandey et al., 2023). Catalytic pyrolysis is another promising technique under exploration for converting waste plastics into value-added products like fuels and monomers (Rahul et al., 2023a).

Nanotechnology is emerging as a promising solution for addressing plastic waste. By converting plastic waste into valuable nanomaterials, nanotechnology not only offers a pathway to mitigate environmental and health hazards associated with plastic but also generates materials useful across various applications. The unique physical and chemical properties of nanomaterials, such as high surface area and reactivity, make them particularly advantageous for diverse uses (Islam et al., 2012; Makhlouf and Ali, 2012). Numerous studies have explored the potential of synthesizing nanoparticles from waste plastic, finding this approach to be both economically viable and environmentally beneficial (Makhlouf and Ali, 2012). Research has shown that different types of waste plastics can be converted into a variety of nanomaterials: for instance, carbon dots can be derived from plastic bags, MoC_2 nanoparticles from polyvinyl chloride (PVC), photoluminescent carbon nanoparticles from polypropylene, and carbon nanostructures from polyethylene terephthalate (PET) bottles. Other transformations include carbon nanotubes (CNTs) from general plastic waste and graphene films from various plastic sources (Mustofa, 2020; Deng et al., 2016).

However, despite these promising developments, no studies have specifically examined the application of nanotechnology in the recycling and management of plastic waste in Bangladesh. This article seeks to address this gap by presenting a detailed analysis of nanotechnology's role in converting plastic waste into high-value carbon-based nanomaterials, highlighting the potential applications of these materials. By reviewing the current state of plastic waste in Bangladesh, this work provides an overview of how nanotechnology could be applied to create sustainable solutions for waste management and recycling. The findings offer insights into the transformative potential of nanotechnology for plastic waste handling in Bangladesh, suggesting pathways for its effective integration into national waste management strategies.

Present scenario of plastic waste in Bangladesh

Improper plastic waste management in Bangladesh is significantly attributed to the country's plastic manufacturing sector. Plastic manufacturers produce a vast range of items, including household goods like toys, construction materials, sanitary products, lids, bottles, and kitchenware, along with accessories for electronics, textiles, and pharmaceuticals. Additionally, they produce items such as buttons, clear film, hangers, and various packaging materials (BIDA, 2021).

Single-use plastics, commonly used worldwide and prevalent in Bangladesh, are a major concern. These items, designed for one-time use, include plastic bags, clear wraps, coffee cups and lids, cutlery, straws, stirrers, caps, and bottles. These products are often discarded improperly, accumulating in landfills and river systems, thereby contributing to severe environmental pollution. In Bangladesh, PET bottles hold considerable market value and are widely collected by informal sector workers, even if contaminated. However, materials like polythene packaging, Low-Density Polyethylene (LDPE) items, and multilayer plastics (MLPs) are typically left behind by waste collectors due to their low market value, slow degradation rates, and high sorting effort. Recycling MLPs, which include snack packaging and similar wrappers, is particularly challenging due to inadequate infrastructure, leaving large quantities to accumulate in landfills (The World Bank, 2021).

Over the past few decades, the challenges Bangladesh faces in managing plastic waste have worsened. High population growth rates, increased economic activities in urban areas, and limited training in waste management methods continue to hinder Bangladesh's development efforts in environmental sustainability. Approximately 17,000 tons of soft plastics are dumped in landfills annually alongside other waste, while recyclable hard plastics are collected, processed into flakes, and redirected into manufacturing chains (Nadiruzzaman et al., 2022).

Bangladesh generates an estimated 800,000 tons of plastic waste each year, representing about 8% of the country's total waste.

Daily, this translates to roughly 3,000 tons of plastic waste and about 14 million polythene bags used just in Dhaka Metropolitan (Mahmudul et al., 2019; Fahmida et al., 2021). The Padma, Yamuna, and Meghna rivers alone contribute over 73,000 tons of plastic waste per year to the ocean, and Old Dhaka produces around 250 tons of non-recyclable items monthly, including disposable cutlery and straws. These single-use plastics typically have no residual value after disposal (Mahmudul et al., 2019; Fahmida et al., 2021).

A 2019 survey indicates that Bangladesh discards approximately 87,000 tons of single-use plastic annually, with consumer products comprising over 96% of this waste. Of this, nearly 33% consists of non-recyclable sachets (The World Bank, 2021). In the Dhaka metropolitan area alone, plastic waste makes up 10% of the total 6,646 tons of waste produced daily. Nationally, less than half of all plastic waste is recycled, with 48% ending up in landfills. The remainder is often discarded into sewers, other urban areas, or rivers (The World Bank, 2021).

Between 2005 and 2020, the average per capita annual plastic consumption in Bangladesh rose from 3 kg to 9 kg, with Dhaka experiencing an even sharper increase from 9.2 kg to 22.25 kg per capita over the same period (The World Bank, 2021). This trend underscores the escalating waste management challenge Bangladesh faces and highlights the urgency for enhanced recycling infrastructure and sustainable solutions.

In Bangladesh, per capita waste production is significantly higher in metropolitan areas compared to rural regions, reflecting the country's ongoing struggle with efficient plastic waste management. Bangladesh collects approximately 646,626 metric tons of plastic waste daily, yet only about 10% is recycled, while 37.2% requires proper disposal (Akter, 2024). The rapid rise in urban waste highlights serious environmental concerns similar to those observed globally (Abdullah & Abedin, 2024). Although a variety of recycling methods are implemented worldwide, Bangladesh aims to recycle 50% of its plastic waste by 2025. Six major Bangladeshi cities alone contribute 305,000 kg of plastic waste daily from municipal solid waste (Zakir et al., 2014). Figure 2 illustrates both the daily plastic waste generation and the average composition of plastic waste in these cities—Khulna, Dhaka, Chattogram, Rajshahi, Barisal, and Sylhet City Corporations. The persistent issue of plastic pollution underscores the urgent need for Bangladesh to adopt the "3 Rs" strategy—reduce, reuse, and recycle—to mitigate its waste management challenges effectively (Abdullah & Abedin, 2024).

Impacts of Plastic Wastes

Plastic pollution has become a prominent concern in Bangladesh, which ranks 10th globally among nations producing the highest levels of mismanaged plastic waste (Kibria, 2017). Rapid growth and urbanization have significantly increased plastic consumption, with single-use items like bags, packaging, and wrappers making up a large portion of mismanaged waste. Poor waste management has led to polluted rivers, canals, rural areas, and urban environments, often resulting in blocked sewers and urban flooding. As plastics break down slowly into microplastics, they present severe threats to human health, marine life, and ecosystems (Inspira Advisory & Consulting Limited, 2019).

The widespread use of plastic bottles and packaging has intensified environmental degradation. Plastics not only disrupt ecosystems but also endanger marine life and human health due to their release of hazardous chemicals. Plastics emit endocrine-disrupting, carcinogenic, and developmentally harmful chemicals, and microplastics have been linked to cellular stress, oxidative damage, inflammation, and genotoxic effects (Akter, 2021). During the processing and degradation of plastic waste, toxic substances such as organic compounds (furans, dioxins), heavy metals (lead, mercury), and acidic gases are released into air, water, and soil, exacerbating environmental and health risks. Toxins from emissions, ash, and slag can travel far, accumulate in plant and animal tissues, and eventually permeate human systems through bioaccumulation (James Gaunt, 2021).

Government Initiatives for Plastic Wastes Management

Bangladesh faces significant challenges in managing the increasing volume of plastic waste, primarily due to inadequate budgets, infrastructure, and waste disposal facilities (Ramírez, 2022). Despite these challenges, the nation has the potential to become a global leader in plastic recovery, provided that there are coordinated efforts from both public and private sectors (Mehnaz & Aditi, 2020). With appropriate institutional and governmental support, the plastic recycling industry could emerge as one of the most lucrative sectors in the country (Rahul et al., 2023b). Historically, the people of Bangladesh have employed traditional knowledge and methods to implement the principles of a circular economy (Monjur et al., 2017).

The Bangladeshi Constitution safeguards fundamental rights, including the right to a pollution-free environment as enshrined in Article 31, which guarantees the right to life (Mustofa, 2020). The primary legislation addressing environmental protection in Bangladesh is the Environment Protection Act of 1995, which requires environmental factors to be considered before establishing industrial projects. Section 12 mandates obtaining environmental clearance, while Section 16 prescribes fines of up to 50,000 Taka or a maximum of 10 years in prison for violations. The Act aims to preserve and reduce environmental pollution; however, technical assessments have identified shortcomings in its implementation (Mustofa, 2020).

While Bangladesh has made strides in combating plastic pollution, significant barriers remain, particularly the lack of recycling technology and effective waste segregation at the source (Fahmida

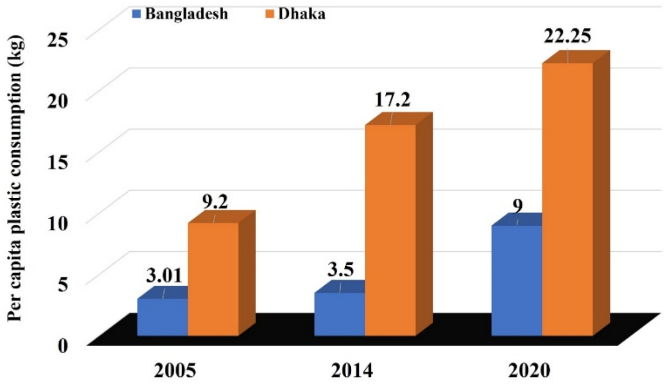

Figure 1. Average per capita consumption of plastic (kg) trends within 15 years

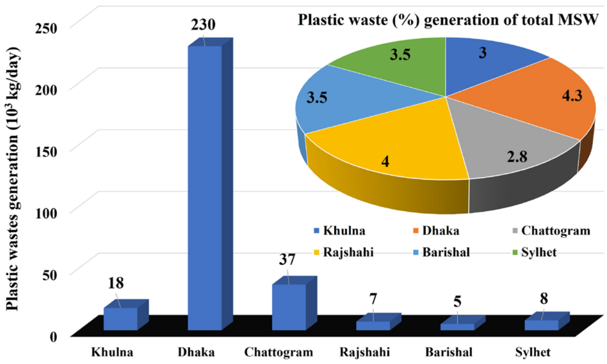

Figure 2. Daily municipal solid waste (MSW) plastic generation and average composition (%) of generated plastic waste (MSW) in six mega-cities of Bangladesh

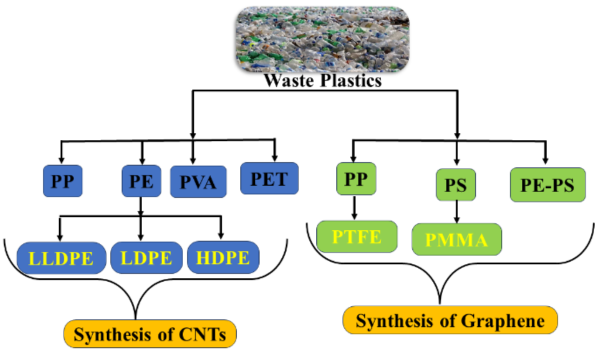

Figure 3. Schematic representation of the synthesis of CNTs and graphene from various plastic waste materials (reproduced from Deng et al., 2016)

Table 1. CNTs synthesis methods from waste plastic materials. In each specific catalyst, additives, main reactor types, and critical results are listed (reproduced from Deng et al., 2015).

		Catalysts & Additives	Main Reactors	Critical Results (yield%)	Ref.
Waste plastics	PP	Ni	Quartz tube	MWNTs (20%): high quality, high transmittance (85%),	(Gong et al., 2012)
	PP	ACs&Ni2O3	Quartz tube	CNTs: low structure defects, high purity (higher carbonization temp.), yield of carbon~ 50%	(Mishra et al., 2012)
	PE	CuBr&NiO	Quartz tube	LLPDE (56.5%): cup-stacked, longer length, smooth surface, straight shape; LDPE (36.8%) & HDPE (30.9%): shorter length, rough surface, curved shape	(Gong et al., 2014)
	HDPE	Stainless steel wire mesh	Quartz tube	MWNTs (10%): length 1~5μm, diameter 30~85nm	(Zhuo et al., 2010)
	PP	MA-PP&Ni	Autoclave	CNTs (80%): diameter~160nm, wall thickness~45nm	(Zhang et al., 2008)
	PP	Ni/Mo/MgO	Muffle furnace	Ni4Mo0.2MgO1: largest yield; ↑Mo%: larger diameter CNTs+ lower yield; ↓Mo%: smaller diameter CNTs + larger yield (45.8%)	(Bajad et al. 2015)
	PP	OMC&Ni	Crucible	MWNTs (41.6%): inner diameter~12 nm, outer diameter~33nm; ↑OMC%: yield increase	(Tang et al.,2005)
	PVA	FA	Quartz tube	CNTs (54%) grow along FA surface	(Nath et al., 2012), (Nath et al., 2011)
	PET	Catalysts free	Arc discharge	Higher temperature: nano-sized CNTs; lower temperature: solid carbon spheres; yield of carbon ~39%	(Berkmans et al., 2014)

Table 2. Graphene synthesis methods from waste plastic materials. In each specific catalyst, additives, main reactor types, and critical results are listed (reproduced from Deng et al., 2015).

		Catalysts & Additives	Main Reactors	Critical Results (yield%)	Ref.
Waste plastics	PP	OMMT & talcum	Crucible	GFs (yield~86.6%) with surface functional groups: C-OH, C=O and	(Gong et al., 2014)
	PS (grass blades, dog feces, cockroach legs, waste cookie and chocolate)	Cu foil	Quartz tube	Monolayer graphene: high quality, negligible defects, high transmittance	(Ruan et al., 2011)
	PE (86%)- PS (14%	Cu foil	Quartz tube	Lower rate of pyrolysis and injection: large hexagonal-shaped single graphene crystal;y higher rate of injection: bilayer or multilayer graphene	(Sharma et al., 2014)
	PTFE (SiC)	Catalysts free	Stainless steel reactor	Graphene sheets coated on porous carbon particles with large accessible surface area; yield of carbon ~28%	(Manukyan et al., 2013)
	PMMA	Cu thin layer	Not specified tube (CVD)	Thin graphene films	(Takami et al., 2014)

et al., 2021). In 2002, the country imposed a ban on plastic shopping bags in accordance with the 1995 Environment Act, but this ban has been ineffective due to poor enforcement and a lack of viable alternatives (MoEFCC, 1995). In a counterproductive move, the government lifted a five percent levy on plastic and polythene bags in FY2022, undermining efforts to foster a circular economy and exacerbating plastic pollution challenges (MoF, 2022).

In 2020, the High Court issued a directive to strictly enforce the nationwide ban on plastic bags, requiring regular market inspections, closure of polythene bag manufacturers, and confiscation of production equipment. The court also banned single-use items such as straws, cotton swabs, cutlery, bottles, food containers, and plastic plates in coastal hotels and restaurants (Writ Petition, 2020).

The National 3R Strategy for Waste Management, established in 2010, aims to reduce, reuse, and recycle waste to limit the disposal of rubbish in open areas and waterways (DoE, 2010). However, widespread non-segregation of waste due to insufficient institutional infrastructure complicates recycling efforts for waste pickers. The Department of Environment, in collaboration with Pro Blue, developed a report outlining short-, medium-, and long-term goals for sustainable plastic waste management (2022–2023 and 2027–2028). This initiative is linked to the Eighth Five-Year Plan and aims to promote circular plastic consumption based on the 3R framework.

The National Action Plan for Sustainable Plastics Management sets ambitious targets relative to a baseline of 2020/21: achieving 50% plastic recycling by 2025, eradicating 90% of single-use plastics by 2026, and reducing plastic waste generation by 30% by 2030 (Fahmida et al., 2021). To achieve these objectives, Bangladesh must focus on establishing robust infrastructure, effectively utilizing technology, and developing a comprehensive waste management system. Additionally, creating a value chain for collecting plastic waste is essential for fostering growth in the recycled plastic industry (Rahman et al., 2017). Embracing sustainable plastic waste management techniques has the potential to significantly benefit the national economy of Bangladesh.

Application of Nanotechnology in Plastic Waste Management and Recycling

Synthesis of Nanoparticles and nanocomposites using plastic waste materials

The predominant materials in used plastic bags include polypropylene, polyvinyl chloride (PVC), and polyvinylidene chloride (PP). Recently, there has been a significant focus on converting waste plastics with high carbon content into carbon nanomaterials (CNMs). Researchers have made substantial strides in transforming plastic waste into low-cost, highly effective nanoparticles for various applications (Mustofa, 2020). For instance, photoluminescent carbon nanoparticles were synthesized from used plastic bags (Hu et al., 2014), while PET waste has been utilized to produce unsaturated polyester nanocomposites (Drah et al., 2016). Asaad et al. (2014) also explored the depolymerization of PET waste into unsaturated polyester, leading to the creation of nanocomposites.

Various plastic waste polymers have served as precursors for nanocomposite synthesis. In an environmentally friendly process, sponge-like Fe/carbon nanotube nanocomposites were produced using a solvent-free autogenic method (Zhang et al., 2014). Recently, PVC waste was repurposed into valuable nanocomposites; for instance, Wang et al. (2019) developed a tantalum carbide/carbon nanocomposite from PVC via a one-step conversion process. Alhajri et al. (2013) also produced a carbon nanocomposite from hose PVC, autoclaving it for ten hours at 700 °C with metallic lithium and Ta2O5. Additionally, Fang et al. (2013) synthesized organic montmorillonite/PE nanocomposites using waste packaging polyethylene.

Recent studies have also combined waste polystyrene with titanium dioxide (TiO2)-reduced graphene oxide (rGO) and g-C3N4 to create nanocomposite photocatalysts (Das et al., 2019). These photoluminescent carbon nanoparticles have applications beyond photocatalysis, including optoelectronics, drug delivery, and bioimaging (Li et al., 2007; Hu et al., 2014). Moreover, magnetic nanoparticles encased in carbon serve numerous functions, including drug administration, ultra-high-density magnetic recording, and electromagnetic wave absorption (Zhang et al., 2014; Choi et al., 2013; Fan et al., 2013; Seo et al., 2006; Wei et al., 2006; Yang et al., 2013).

Synthesis of CNTs using plastic waste materials

Carbon nanotubes (CNTs) are a recently discovered form of carbon, consisting of coiled layers of hexagonally organized graphite that resemble smooth cylinders (Mustafa et al., 2021). These nanotubes can be synthesized by heating various waste polymers, such as polystyrene (PS), polyethylene (PE), and polypropylene (PP), to extremely high temperatures (700–900 °C) in an inert nitrogen atmosphere (Fig. 3). Several types of scrap plastics have been successfully converted into CNTs. For instance, carbon nanotubes were synthesized through the vacuum pyrolysis of PP in the presence of iron (Fe) nanoparticles, using a combination of PP, Fe catalyst, and p-xylene as the precursor (Chung and Jou, 2005). The synthesis of CNTs from waste polymers has been conducted in various reactor systems, including crucibles, autoclaves, quartz tubes, and muffle furnaces (Bazargan et al., 2012). Notably, plastics containing elements other than carbon and hydrogen, such as polyvinyl alcohol (PVA) and polyethylene terephthalate (PET), have also been utilized for the successful synthesis of CNTs (Gong et al., 2012). Zhang et al. (2011) employed the chemical vapor deposition method to create CNTs from heated waste PS, PE, and PP. In a two-step process, Liu et al. (2011)

converted waste vehicle bumper plastic and virgin PP into multi-walled carbon nanotubes and sustainable hydrogen, eliminating carbon dioxide emissions. Additionally, Bajad et al. (2017) described a method for producing fuel oil and CNTs from leftover plastics.

CNTs have diverse applications, including as components in thin-film transistors and substrates for neural development. They are also used as biomaterials in therapeutic settings and various biomedical procedures, as well as in metallurgical operations when combined with metals and in fuel cell electrodes (Bambagioni et al., 2009; Kocabas et al., 2005; Liao and Tan, 2011; Mattson et al., 2000; Saito et al., 2014; Yang et al., 2007). A summary of various discoveries of CNTs derived from different plastic wastes is provided in Table 1.

Synthesis of graphene using plastic waste materials

Graphene foil has been successfully produced from various types of plastic bottles, including those used for wraps, cleaning products, and mineral water (Qu et al., 2017). These plastic bottles, alongside plastic bags, valve bags, lunch boxes, and protective wraps, primarily consist of materials such as polystyrene (PS), polyvinyl chloride (PVC), polypropylene (PP), polyethylene terephthalate (PET), polymethyl methacrylate (PMMA), and polyethylene (PE). The solid-state chemical vapor deposition (CVD) method has been employed to synthesize graphene foil from these materials (Fig. 3). Recently, researchers utilized melted salt from PET waste bottles to create graphene nanostructures (Kamali et al., 2019). Gong et al. (2014) achieved high yields of graphene flakes (GFs) using waste paraffinic paraffin (PP) as the raw material, catalyzed by organically modified montmorillonite (OMMT).

A novel approach for converting waste polystyrene (PS) and other carbon-containing materials into high-quality single-layered graphene was introduced by Ruan et al. (2011). Sharma et al. (2014) conducted another CVD-based synthesis experiment using solid waste plastics comprising approximately 86% PE and 14% PS. Additionally, Manukyan et al. (2013) employed an energy-efficient combustion process through pyrolysis and injection to create graphene sheets from waste polytetrafluoroethylene (PTFE) and silicon carbide (SiC). In another study, Takami et al. (2014) utilized the CVD method to manufacture graphene films from PMMA.

Graphene, a two-dimensional semiconductor with a zero bandgap, possesses extraordinary physical properties, making it a subject of intense research across numerous scientific and engineering fields. Its exceptional mechanical strength and potential applications span photonics, mechanics, chemistry, biotechnology, optoelectronics, laser materials, biomedicine, hydrogen storage, batteries, and supercapacitors (Mustafa et al., 2021). An overview of various research findings on graphene derived from different types of plastic waste is summarized in Table 2.

Conclusion

In conclusion, Bangladesh faces significant challenges in managing plastic waste due to rapid urbanization and inadequate infrastructure. However, innovative approaches to recycling and waste utilization, such as converting plastic waste into valuable materials like carbon nanotubes and graphene, present promising solutions. Research highlights the potential of employing various waste polymers to produce nanoparticles and nanocomposites, which have applications in fields ranging from medicine to electronics. Despite existing environmental regulations, the enforcement remains lax, hindering efforts to mitigate plastic pollution. Nonetheless, with coordinated efforts from both public and private sectors, Bangladesh can establish a robust recycling industry, embrace the principles of the circular economy, and potentially position itself as a global leader in sustainable waste management. By leveraging its traditional practices and investing in advanced technologies, the country can address its plastic waste crisis while contributing to environmental sustainability.

Author contributions

M.S.I. conceptualized the study, designed the methodology, and drafted the manuscript. M.Z. and M.M.R.M. contributed to data collection and analysis. J.R. and A.K. were involved in data interpretation and provided critical revisions. G.M.S.R. supervised the study and reviewed the final manuscript. All authors reviewed and approved the final version of the manuscript.

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Competing financial interests

The authors have no conflict of interest.

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