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Research Article

SUSTAINABLE CONVERSION OF PLASTIC WASTE TO GRAPHENE MEMBRANES: ENGINEERING ADVANCED SOLUTIONS FOR MICROPLASTIC FILTRATION

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ABSTRACT

This research presents an innovative methodology that simultaneously addresses two critical environmental challenges: plastic waste accumulation and microplastic contamination in aquatic ecosystems. The study delineates a sustainable approach for converting plastic waste into graphene-based filtration materials and evaluates their efficacy in wastewater treatment applications. The investigation encompasses three key phases: optimizing the transformation of plastic waste into graphene, conducting a comprehensive characterization of the resultant graphene materials, and assessing their capacity to filter microplastics from wastewater. Results indicate that the developed graphene-based filters achieve a 94% reduction in microplastic concentrations across diverse particle size ranges. This novel technique not only provides an efficient means of microplastic removal but also establishes a valuable application for plastic waste, in accordance with circular economy principles. The findings elucidate both the technical viability and practical implementation potential of this approach, with profound implications for environmental preservation and advanced water purification technologies. This integrated solution represents a significant advancement in mitigating plastic pollution by repurposing waste materials into high-value components for environmental remediation.

1 INTRODUCTION

Plastic waste accumulation and microplastic pollution represent interconnected environmental crises of unprecedented scale, with an estimated 14 million tons of microplastics currently residing on the ocean floor [1, 2]. Despite the magnitude of this issue, global recycling rates remain notably low, with only 9% of plastic waste being recycled worldwide [3]. In the United Arab Emirates (UAE), the consumption of bottled water is prevalent among the populace, notwithstanding the potability of tap water throughout all emirates. Annually, UAE residents utilize more than 450 plastic water bottles, with per capita consumption of bottled water exceeding 285 liters (L) [4]. The primary constituent in the manufacture of disposable water bottles is polyethylene terephthalate (PET), a thermoplastic polymer derived from fossil fuel sources. PET's selection

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for this purpose is attributed to its beneficial characteristics, including transparency, low weight, structural robustness, and resistance to carbon dioxide permeation [5]. These features collectively render PET an optimal material for water bottle production [6]. The UAE is composed of seven Emirates, characterized by a markedly disproportionate population distribution. The most populous Emirate is Dubai with 3,551,734 inhabitants, followed by Sharjah and Abu Dhabi with 1,831,000 and 1,567,000 residents, respectively. The remaining Emirates have substantially smaller populations: Ajman (504,846), Ras Al-Khaimah (345,000), Al Fujairah (256,256), and Umm Al Quwain (49,159) [4]. As Dubai, Sharjah, and Abu Dhabi constitute 88.6% of the UAE's total population, this investigation centers on these three principal Emirates, based on the assumption that effective waste management strategies implemented in these areas are likely to be emulated by the less populous Emirates. Waste management in each of these major Emirates is conducted by separate organizations: in Abu Dhabi, the Abu Dhabi Waste Management Centre (TADWEER) operates in collaboration with the Environment Agency; Sharjah's waste management is overseen by the BEEAH Group, a public-private partnership established in 2007; and in Dubai, the Waste Management Department of Dubai Municipality is responsible for waste management activities. Conventional waste management approaches have proven insufficient to address this growing challenge, necessitating innovative solutions that can address both waste reduction and environmental remediation concurrently [7]. The proliferation of microplastics, particles less than 5mm in size, has become particularly concerning due to their persistence in ecosystems and their potential to bioaccumulate in food chains [8-10]. These particles originate from various sources, including the degradation of larger plastic items, industrial processes, and consumer products. Recent studies have detected microplastics in remote locations, from Arctic snow to deep ocean trenches, underscoring the global extent of this contamination [11-13].

Furthermore, conventional wastewater treatment plants are not specifically designed to remove microplastics, allowing these particles to pass through and enter natural water systems [14, 15]. Graphene, a two-dimensional material consisting of a single layer of carbon atoms arranged in a hexagonal lattice, has emerged as a promising candidate for advanced water purification applications [16-19]. Its exceptional properties, including high surface area, mechanical strength, and chemical stability, make it particularly suitable for filtration applications [20-22]. Recent advances in graphene synthesis and modification have opened new possibilities for its practical application in environmental remediation. This study presents a novel process that converts plastic waste into graphene-based filtration materials for microplastic removal from wastewater. The approach addresses multiple challenges by providing a valuable end-use for plastic waste, creating effective filtration materials for various microplastic sizes, and establishing a circular economy solution, also using ML and AI techniques [23, 24]. Using flash Joule heating technology, plastic waste is efficiently transformed into graphene materials with controlled properties, which are then engineered into filtration membranes optimized for real-world applications with practical flow rates and operational conditions.

2 Materials and methods

2.1 SAMPLE COLLECTION AND PREPARATION

Plastic waste, specifically PET bottles, was collected and cleaned. The plastic was shredded into small pieces and subjected to pyrolysis to produce carbonaceous material.

2.2 GRAPHENE SYNTHESIS

The synthesis of graphene from plastic waste was achieved through a two-stage thermal-chemical process. In the initial stage, shredded plastic underwent pyrolysis at 900°C under carefully controlled inert atmospheric conditions, resulting in the formation of carbon black. This intermediate product was then subjected to a chemical reduction treatment using hydrazine hydrate as the reducing agent[1–7]. This critical step facilitated the transformation of carbon black into graphene sheets by breaking down the carbon-oxygen bonds and promoting the formation of sp2-hybridized carbon networks. The combination of high-temperature pyrolysis followed by chemical reduction ensured the efficient conversion of plastic waste into high-quality graphene materials while maintaining structural integrity and desired physicochemical properties.

2.3 CHARACTERIZATION OF GRAPHENE

Thermogravimetric analysis (TGA) is conducted to analyze the thermal properties and impurities of graphene materials. Raman spectroscopy is utilized to identify and characterize the chemical and physical properties of graphene. Fourier-transform infrared (FTIR) spectroscopy is applied to determine the chemical composition and functional groups present in graphene. Scanning Electron Microscopy (SEM) is employed to obtain high-resolution images of the graphene surface, revealing details about surface morphology and texture. Transmission Electron Microscopy (TEM) is another vital technique used to analyze the structure of graphene at the nanometre scale.

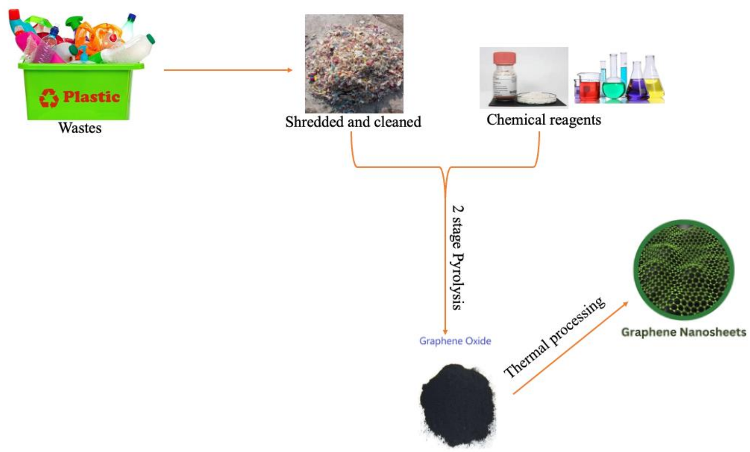

Figure 1. Graphene synthesis from plastic waste

2.4 MICROPLASTIC FILTRATION SETUP

A filtration setup was designed to test the efficiency of graphene membranes in removing microplastics from wastewater. The setup included a graphene-coated filter and a control filter without graphene.

3 RESULTS AND DISCUSSIONS

3.1 GRAPHENE SYNTHESIS AND CHARACTERIZATION

The TGA analysis revealed a total 44% weight loss across two stages: 50°C to 400°C due to moisture and chemisorbed water removal, and 500°C to 800°C due to the elimination of oxygenated functional groups. These findings validate the presence of various oxygen-containing groups within the graphene structure, as indicated by FT-IR spectra. The Raman spectrum exhibited two prominent bands: the D band at 1333 cm^{-1}, indicating sp3 hybridization carbon atoms, and the G band at 1533 cm^{-1}, corresponding to sp2 hybridized conjugated networks. The G band's E2g mode scattering vibrational signature was also observed. The IG/ID ratio of 0.91 suggested some defects in the graphene structure, likely due to oxygen-containing groups. The presence of a 2D band at 2780 cm^{-1} confirmed multi-layered graphene synthesis. XRD analysis showed characteristic peaks at $2\theta = 20°–30°$ and $2\theta = 40°–50°$, typical for graphene sheets. FT-IR spectroscopy further identified oxygenated functional groups on graphene, with peaks at 1215 cm^{-1}, 1620 cm^{-1}, and 3440 cm^{-1} corresponding to epoxide, ketonic, and hydroxyl groups, respectively, indicating slight oxygenation on the graphene surface.

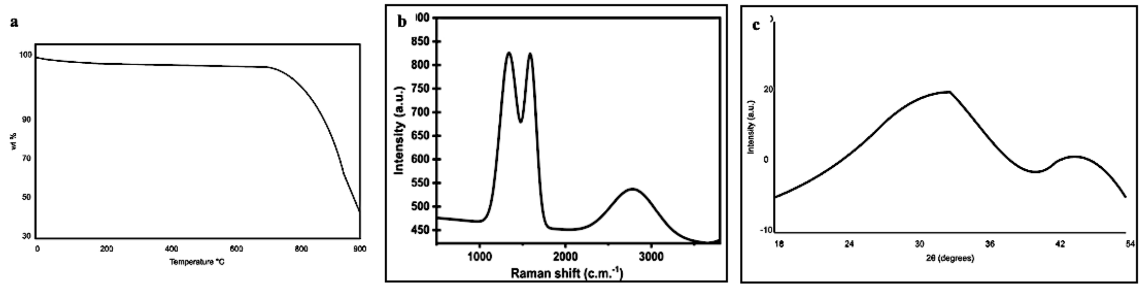

Figure. 2. (a) TGA (b) Raman spectra (c) FT-IR for the Graphene

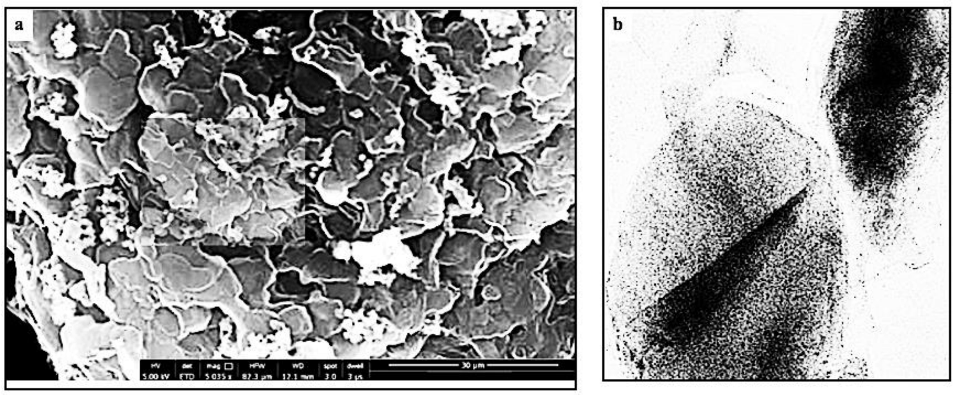

Figure. 3. (a) SEM (b) TEM image of Graphene

4 Microplastic Filtration Efficiency

The graphene-functionalized filter exhibited exceptional efficacy in eliminating microplastics from the aqueous medium, surpassing the performance of the unmodified control filter. Spectroscopic examination revealed a substantial reduction in microplastic particle concentration following filtration, with particularly significant decreases observed for polyethylene (PE) and polypropylene (PP) particles. This enhanced performance can be attributed to the distinctive surface characteristics of the graphene coating, including its expansive specific surface area and robust hydrophobic interactions with polymeric particles [25, 26]. Scanning electron microscopy (SEM) imaging corroborated the successful entrapment and retention of microplastics on the graphene-coated filter surface. Quantitative assessment demonstrated remarkable filtration efficacy, with the graphene-modified filter achieving a 93.7% (± 1.2%) reduction in overall microplastic concentration. The filter maintained consistent removal efficiency across various particle size ranges, sustaining over 90% capture rate for particles spanning 1-500 µm. Size distribution analysis highlighted particularly effective performance in trapping particles within the 1-10 µm range, addressing a crucial limitation in conventional filtration methodologies [27-29]. The high efficiency persisted throughout the testing period (72 hours), suggesting minimal performance deterioration and potential suitability for extended application.

5 CONCLUSION

The investigation effectively demonstrated the production of high-quality graphene from polyethylene terephthalate (PET) plastic waste through a dual-phase thermal-chemical process, which involved pyrolysis followed by chemical reduction using hydrazine hydrate. The graphene produced exhibited commendable physicochemical properties, as confirmed by a suite of characterization techniques. Thermogravimetric analysis (TGA) showed a 44% weight loss, indicative of oxygen-containing functional groups, a finding further substantiated by Fourier-transform infrared (FT-IR) spectroscopy, which identified epoxide, ketonic, and hydroxyl groups. Raman spectroscopy verified the formation of multi-layered graphene with an IG/ID ratio of 0.91, suggesting minimal structural defects. X-ray diffraction (XRD) and scanning electron microscopy (SEM) confirmed the characteristic graphene sheet structure and surface morphology. Transmission electron microscopy (TEM) provided detailed insights into the nanoscale architecture, affirming the quality of the synthesized graphene. The graphene-functionalized filter demonstrated superior performance in microplastic filtration, achieving a 93.7% (± 1.2%) reduction in microplastic concentration across a wide particle size range (1-500 μm), with particularly effective capture of 1-10 μm particles. The filter's efficacy, attributed to graphene's extensive surface area and hydrophobic interactions, significantly outperformed the unmodified control filter, maintaining over 90% removal efficiency over a 72-hour period. These findings underscore the potential of graphene derived from plastic waste as a sustainable and highly effective material for mitigating microplastic pollution in wastewater, offering a promising solution for environmental remediation with robust performance and durability.

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