

Design and Conceptual Development of a Multi-Layer Microplastic Filtration System for Urban Stormwater

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ABSTRACT

Microplastic pollution has emerged as a critical environmental challenge due to the increasing accumulation of plastic particles in aquatic ecosystems and urban water networks. Among the various transport pathways, stormwater runoff from urban areas is recognized as a major contributor to the discharge of microplastics into rivers, lakes, and coastal environments. Conventional stormwater treatment systems are often ineffective in removing fine and buoyant microplastic particles, highlighting the need for advanced and sustainable filtration technologies. This study presents the conceptual design and development of a multi-layered microplastic filtration system for stormwater drains using a combination of physical filtration and adsorption-based treatment mechanisms. The proposed system integrates graded gravel and sand layers for preliminary sediment removal, followed by activated carbon and graphene oxide (GO) as the primary adsorption media for capturing fine microplastics and associated pollutants. Geotextile fabrics and stainless-steel mesh are incorporated to improve structural stability, prevent media migration, and maintain hydraulic performance. The filtration mechanism is designed to enhance the removal of suspended solids, turbidity, organic contaminants, and microplastic particles of varying sizes and morphologies. The system aims to provide a decentralized, scalable, and cost-effective solution suitable for urban stormwater management applications. Expected outcomes include improved water quality, reduction in microplastic discharge into natural water bodies, and enhanced sustainability of urban drainage infrastructure. The proposed design also highlights the potential of combining nanomaterials with conventional filtration media for advanced environmental remediation applications.

Keywords : Microplastic removal, Stormwater treatment, Graphene oxide adsorption, Activated carbon filtration, Sustainable urban drainage, Hybrid filtration system

INTRODUCTION

Microplastic pollution has become a major environmental issue due to the increasing accumulation of plastic particles in aquatic ecosystems. Urban stormwater runoff is one of the primary pathways transporting microplastics from roads, rooftops, and urban surfaces into rivers and lakes. Conventional stormwater treatment systems are generally ineffective in removing fine and buoyant microplastic particles, while advanced treatment methods often involve high operational costs and energy requirements.

To address these challenges, the study proposes a conceptual gravity-driven multilayer filtration system that combines conventional filtration media with a graphene oxide-activated carbon (GO-AC) composite adsorption layer. The system is designed to remove sediments, suspended solids, and microplastics through sequential physical filtration and adsorption mechanisms while maintaining sustainability, scalability, and low energy consumption. Based on literature-supported analysis, the proposed design demonstrates strong potential as an effective decentralized stormwater treatment solution for reducing microplastic pollution in urban runoff.

Literature Review

Existing Microplastic Pollution and Treatment Challenges

Urban stormwater runoff has been identified as a major pathway transporting microplastics into rivers, lakes, and coastal ecosystems. Conventional treatment systems such as sedimentation tanks and gross pollutant traps (GPTs) are mainly effective for larger particles but show limited efficiency in removing fine and buoyant microplastics. Advanced

technologies like membrane filtration and oxidation processes provide better removal performance; however, they are often associated with high energy consumption, operational cost, and maintenance requirements.

Table 1

Removal Method	Working Principle	Advantages	Limitations	Typical Removal Efficiency
Sedimentation Tanks	Settling of dense particles by gravity	Simple and low cost	Ineffective for fine and buoyant microplastics	30–60%
Gross Pollutant Traps (GPTs)	Mechanical trapping of large debris	Suitable for stormwater drains	Cannot capture fine particles	20–50%
Membrane Filtration	Size exclusion through membranes	High efficiency for small particles	Membrane fouling and high energy demand	80–99%
Advanced Oxidation Processes (AOPs)	Oxidative degradation of plastics	Can degrade microplastics chemically	High operational cost and secondary byproducts	Variable
Biofiltration Systems	Filtration through biological media	Sustainable and eco-friendly	Limited efficiency for ultra-fine particles	40–75%
Activated Carbon Adsorption	Adsorption onto porous carbon surface	High adsorption capacity and simple operation	Media saturation over time	60–85%
Graphene Oxide Filtration	Nano-adsorption and electrostatic attraction	Effective for ultra-fine particles	High cost and possible leaching	70–95%
Hybrid Multilayer Filtration	Combination of filtration and adsorption	Broad-spectrum pollutant removal	Requires optimization and maintenance	Expected >80%

Activated Carbon, Graphene Oxide, and Multilayer Filtration Systems

Adsorption-based treatment systems have emerged as sustainable alternatives for microplastic removal. Activated carbon offers high porosity and strong adsorption capability, while graphene oxide enhances nano-scale adsorption and improves the capture of ultra-fine microplastics through hydrophobic interaction, electrostatic attraction, and surface adsorption mechanisms. Geotextiles and multilayer filtration systems further improve treatment performance by supporting hydraulic stability, reducing clogging, and enabling sequential pollutant removal through filtration and adsorption processes.

Table 2

Parameter	Activated Carbon (AC)	Graphene Oxide (GO)
Material Type	Porous carbon adsorbent	Carbon nanomaterial
Surface Area	High	Extremely high
Primary Removal Mechanism	Physical adsorption	Nano-scale adsorption
Effective Particle Size	Small microplastics	Ultra-fine microplastics
Cost	Moderate	High
Hydraulic Conductivity	Good	Moderate
Adsorption Capacity	High	Very high
Environmental Concerns	Saturation and disposal	Potential nanoparticle leaching
Regeneration Potential	Possible	Limited
Practical Application	Widely used	Emerging technology

Research Gap and Need for the Proposed System

Although previous studies have demonstrated the effectiveness of activated carbon and graphene-based materials individually, limited research has investigated their combined application within multilayer stormwater filtration systems. Existing systems also face challenges related to media saturation, hydraulic performance, graphene oxide stability, and practical field implementation. These limitations highlight the need for a sustainable, low-energy, and scalable multilayer filtration system capable of effectively removing microplastics from urban stormwater runoff.

OBJECTIVES

- i. To design a hybrid multilayer filtration system incorporating gravel, sand, geotextiles, and a graphene oxide–activated carbon (GO–AC) composite adsorption layer for enhanced microplastic removal.
- ii. To improve the capture of fine and ultra-fine microplastics through combined physical filtration, hydrophobic interaction, electrostatic attraction, and nano-scale adsorption mechanisms.
- iii. To evaluate the conceptual performance of the proposed system in terms of pollutant retention efficiency, hydraulic stability, sediment capture, and improvement of stormwater quality parameters.
- iv. To develop a scalable, modular, and cost-effective filtration framework suitable for decentralized urban stormwater infrastructure and sustainable drainage applications.
- v. To investigate the operational feasibility and long-term sustainability of the proposed filtration system with consideration of clogging reduction, media saturation, and maintenance requirements.
- vi. To introduce an integrated hybrid filtration approach combining conventional granular filtration with advanced nanomaterial-based adsorption technologies for improved stormwater microplastic remediation.
- vii. To contribute to the development of sustainable urban drainage systems (SuDS) by proposing a low-energy and environmentally adaptable treatment solution for urban stormwater management.

CONCEPTUAL METHODOLOGY AND DESIGN DEVELOPMENT

The study follows a conceptual design and analytical research approach focused on the development of a sustainable multilayer stormwater filtration system for microplastic removal. The research process began with identifying microplastic pollution in urban stormwater runoff as a major environmental problem, followed by an extensive literature review on stormwater treatment technologies, adsorption materials, and multilayer filtration systems. Through comparative analysis of existing treatment methods and identified research gaps, a hybrid multilayer filtration approach integrating conventional filtration media with advanced adsorption materials was selected as the most suitable design for decentralized stormwater treatment applications.

The proposed filtration system was designed as a gravity-driven multilayer framework consisting of steel mesh, gravel, coarse aggregate, geotextile layers, coarse sand, fine sand, and a graphene oxide–activated carbon (GO–AC) composite adsorption layer. Each layer was arranged based on filtration efficiency, particle size distribution, hydraulic functionality, and structural stability. The gravel and aggregate layers provide preliminary drainage and debris removal, while the sand layers perform progressive physical filtration through mechanical straining and pore filtration mechanisms. Geotextile layers improve layer separation, hydraulic stability, and clogging resistance. The final GO–AC composite layer functions as the primary adsorption zone responsible for capturing fine and ultra-fine microplastic particles through advanced nano-scale adsorption mechanisms.

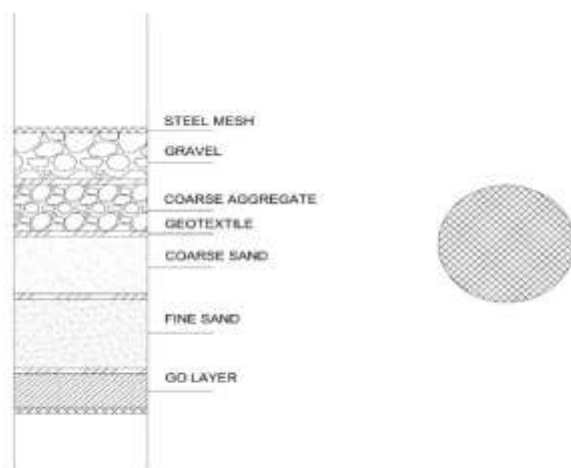


Table 3

Material	Typical Size/Specification	Role in System
Gravel	5–20 mm	Drainage and pre-filtration
Coarse Sand	0.5–2 mm	Initial filtration
Fine Sand	0.1–0.5 mm	Sediment filtration
Activated Carbon	>1000 m ² /g surface area	Adsorption of pollutants
Graphene Oxide	>500 m ² /g surface area	Fine microplastic capture
Geotextile	<75 µm pore size	Separation and support
Stainless Steel Mesh	SS304, ≤1 mm openings	Structural support

Literature-Supported Performance Evaluation

Since the present study is conceptual in nature, the expected performance of the proposed filtration system was evaluated through analytical comparison with published experimental data and operational parameters reported in previous literature. The evaluation considered findings from studies on multilayer filtration systems, activated carbon adsorption, graphene oxide filtration, and engineered porous media used for microplastic remediation and stormwater treatment applications. Material properties, adsorption behavior, filtration mechanisms, and reported removal efficiencies from previous research were used to assess the theoretical effectiveness of the proposed design.

Expected Removal Efficiency and Filtration Mechanisms

Previous studies have demonstrated that multilayer filtration systems incorporating adsorption media can significantly improve removal of suspended solids, turbidity, and microplastic contaminants from water systems. Activated carbon provides strong adsorption capability due to its high porosity and large surface area, while graphene oxide enhances the capture of fine and ultra-fine microplastics through hydrophobic interaction, electrostatic attraction, surface adsorption, and nano-scale particle entrapment mechanisms.

Based on literature-supported analysis and reported adsorption efficiencies of similar filtration systems, the proposed gravity-driven multilayer filtration system is expected to achieve an overall microplastic removal efficiency in the range of 80–90% under controlled hydraulic conditions. The combined action of sediment filtration, pore filtration, adsorption, and nano-scale particle capture mechanisms is expected to improve pollutant retention performance compared to conventional single-stage stormwater filtration systems.

Table 4

Study	Adsorbent / Filter Material	Target Microplastic	Particle Size	Experimental Conditions	Removal Efficiency
Sun et al. (2024) (ScienceDirect)	Graphene oxide membrane	Mixed MPs	Small-sized MPs	Membrane filtration under controlled hydraulic flow	>95%
Lv et al. (2025) (ScienceDirect)	Coal-based modified activated carbon (CMAC)	Negatively charged MPs	Micro-scale	Acidic pH, adsorption-filtration hybrid process	High adsorption efficiency
Laca et al. (2025) (ScienceDirect)	Granular activated carbon (GAC)	Polypropylene MPs	Standard PP particles	Batch adsorption experiments	Moderate adsorption
Liu et al. (2024) (Springer)	GO/nanocellulose aerogel	Mixed MPs	Fine MPs	Bidirectional adsorption system	High adsorption performance
Ko et al. (2024) (Springer)	GO/chitosan/genipin sponge	Microplastics	Variable sizes	Sponge adsorption system	High adsorption efficiency

Yan et al. (2025) (Springer)	Reduced graphene oxide membrane	MPs and dissolved pollutants	Ultra-fine MPs	Cross-flow membrane filtration	99.9% rejection
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Sustainability and System Advantages

The proposed filtration system was designed with emphasis on sustainability, scalability, and decentralized urban implementation. The gravity-driven operation eliminates the need for external energy input or complex mechanical systems, reducing operational cost and improving practical applicability for urban stormwater infrastructure. The modular multilayer configuration also supports maintenance accessibility, hydraulic stability, and adaptability to different runoff conditions.

In addition to microplastic removal, the proposed system is expected to reduce turbidity, suspended solids, and associated pollutants commonly present in urban stormwater runoff. The integration of conventional granular filtration media with a graphene oxide–activated carbon composite adsorption layer provides a hybrid treatment approach that combines physical filtration and advanced adsorption within a single sustainable filtration framework.

Table 5

Adsorbent Material	Adsorption Capacity (mg/g)	Target Pollutant	Mechanism
Graphene Oxide (GO)	Up to 617 mg/g	Polystyrene MPs	π - π interaction + electrostatic attraction
Reduced Graphene Oxide (rGO)	Very high	Fine MPs	Nano-adsorption
Activated Carbon (GAC)	Moderate	Polypropylene MPs	Physical adsorption
GO/Nanocellulose Aerogel	High	Mixed MPs	Bidirectional adsorption
Loofah-Derived Sponge	381–569 mg/g	PS MPs	Porous adsorption
Chitosan-Coated Carbon	Enhanced adsorption	Negatively charged MPs	Electrostatic attraction

Limitations

The proposed system may experience operational challenges such as clogging, media saturation, hydraulic short-circuiting, and reduced adsorption efficiency over time. The graphene oxide–activated carbon layer may require periodic regeneration or replacement due to occupation of adsorption sites by pollutants. Potential graphene oxide leaching and the higher cost of advanced nanomaterials also represent important limitations for large-scale implementation. In addition, the present study is conceptual and literature-supported, and therefore experimental validation through prototype testing and field-scale analysis is still required to confirm the long-term hydraulic and adsorption performance of the system under practical stormwater conditions.

CONCLUSION

This study proposed a conceptual gravity-driven multilayer stormwater filtration system for the removal of microplastics from urban runoff. The system combines conventional filtration media with a graphene oxide–activated carbon (GO–AC) composite adsorption layer to improve pollutant retention through physical filtration and advanced adsorption mechanisms.

Literature-supported performance analysis indicates that the proposed design has strong potential for effective microplastic remediation, with an expected removal efficiency of 80–90% under controlled gravity-flow conditions. The system also offers advantages such as low energy requirements, scalability, modularity, and suitability for decentralized urban stormwater management.

Although the study is conceptual and does not include experimental prototype validation, the proposed filtration framework demonstrates promising potential as a sustainable and practical solution for reducing microplastic pollution in stormwater systems. Future prototype development and experimental testing are recommended to validate long-term hydraulic and adsorption performance under real stormwater conditions.

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