

Research Article

# Engineering of Coffee Waste Based Drainage Filtration Media on Polyester Fabric for Green Infrastructure Applications

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**Abstract:** The growing pressure on urban drainage systems caused by blockages and environmental pollution highlights the importance of developing sustainable filtration materials. This study explores the use of coffee waste as an environmentally friendly filler integrated into polyester fabric (PE 24S) to create a green filtration medium for drainage applications. The research focuses on developing and characterizing the composite material through macro-photographic morphology analysis, tensile strength testing, and antibacterial evaluation. The findings demonstrate that polyester fabric modified with coffee waste shows a tensile strength of  $54.024 \pm 5.498$  MPa, elongation of  $111.128 \pm 6.915\%$ , and a Young's modulus of  $0.486 \pm 0.543$  MPa, indicating improved flexibility and sufficient mechanical durability for drainage system use. Additionally, antibacterial testing reveals that the composite material can inhibit microbial growth due to the presence of natural bioactive compounds found in coffee waste. Overall, the results suggest that coffee waste-enhanced polyester fabric offers a sustainable and mechanically reliable alternative for environmentally friendly drainage infrastructure while supporting circular economy practices.

**Keywords:** Coffee Waste; Drainage Systems; Mechanical Properties; Polyester; Sustainable Filtration.

## 1. Introduction

Urbanization and rapid infrastructure development have increased the burden on urban drainage systems, particularly in densely populated areas (Fletcher et al., 2015). Conventional drainage systems often experience clogging, reduced permeability, and environmental contamination due to sediment accumulation, organic waste deposition, and microbial growth, which collectively degrade system performance and contribute to urban flooding. These challenges have driven the need for sustainable drainage materials that integrate mechanical reliability with environmental functionality within green infrastructure frameworks (Ahiablame et al., 2012). The development of multifunctional drainage materials is therefore considered a critical component of sustainable urban development strategies (Fletcher et al., 2015).

The utilization of waste derived materials has emerged as a promising approach for enhancing the sustainability of drainage filtration systems. Agricultural and food wastes are widely studied due to their abundance, low cost, and functional potential, including adsorption capacity and antimicrobial activity. Among these materials, coffee waste has gained attention as a bio resource containing lignocellulosic structures and bioactive compounds that support environmental engineering applications (Skwierawska et al., 2022). Several studies have demonstrated that coffee waste exhibits adsorption and antibacterial properties, supporting its potential role as a functional material (Xia et al., 2023).

Previous investigations of coffee waste have primarily focused on its use as an adsorbent in wastewater treatment, particularly for removing synthetic dyes and heavy metals. These

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studies reported high adsorption efficiency and favorable sorption behavior, highlighting the environmental benefits of coffee waste based materials (Ardila-Leal et al., 2021). However, adsorption focused approaches do not adequately address mechanical durability or long term structural performance required for drainage filtration systems. While coffee waste has also been explored as a filler in polymer composites, most studies target packaging or industrial materials rather than filtration systems for infrastructure applications (Muhi et al., 2024). The mechanical behavior of particulate organic fillers is strongly influenced by interfacial interaction within the polymer matrix (Kuan et al., 2021).

Textile based filtration materials, particularly those fabricated from polyester, are widely used in civil engineering due to their tensile strength, durability, and chemical resistance. Polyester fabrics have demonstrated effective performance as filtration and separation media in drainage and geotechnical applications (Barman et al., 2024). Nevertheless, conventional polyester filtration media often lack environmental functionality and are susceptible to biofouling, limiting their sustainability (Liang et al., 2025). Existing research rarely explores coffee-waste functionalization of polyester textiles to impart antibacterial functionality while evaluating the resulting changes in surface morphology and tensile performance (Mohammed et al., 2022). To address this gap, this study proposes the engineering of a coffee waste based drainage filtration media integrated into polyester fabric, aiming to combine mechanical performance, filtration capability, and antibacterial functionality within a single sustainable material system (Wang et al., 2019).

## 2. Preliminaries and Related Work

### 2.1. Drainage Filtration Media in Green Infrastructure Systems

Green infrastructure promotes sustainable urban drainage systems that integrate hydraulic performance with environmental protection. Drainage filtration media function to control sediment transport, maintain permeability, and reduce pollutant accumulation within drainage networks (Ahiablame et al., 2012). In practice, textile-based materials such as geotextiles have been widely applied in drainage and infiltration systems due to their flexibility and ease of installation (Malinda et al., 2025).

National studies on geotextile applications demonstrate that nonwoven geotextiles can effectively support infiltration and drainage functions in urban water management systems (Malinda et al., 2025). Experimental investigations further show that geotextile thickness and flow orientation significantly influence filtration performance and permeability behavior (Ayuningtyas et al., 2013). However, these studies mainly focus on hydraulic behavior and structural performance, while environmental functionality and material sustainability remain largely unexplored.

### 2.2. Polyester Based Textiles for Engineering Applications

Polyester textiles are extensively used in civil and environmental engineering due to their high tensile strength, chemical resistance, and durability under wet conditions. Research on polyester textile processing indicates that polyester materials retain acceptable thermo-mechanical properties even after chemical treatments and recycling processes (Standing et al., 2025). These properties make polyester a reliable substrate for engineered filtration materials in drainage systems.

Studies on textile structures in civil engineering applications highlight the increasing role of textiles as functional components in load-bearing and filtration systems (Barman et al., 2024). Nevertheless, conventional polyester-based filtration media are generally inert and prone to biofouling, which limits their long-term filtration efficiency and environmental performance (Liang et al., 2025). This limitation motivates the integration of functional additives to enhance the environmental responsiveness of polyester textiles.

### 2.3. Coffee Waste as a Functional Filler Material and Filler

Coffee waste has gained attention as a sustainable bio-based resource due to its abundance and chemical composition, including lignocellulosic structures and phenolic compounds. Studies on sustainable recycling of coffee waste demonstrate that coffee waste can be converted into value-added materials with environmental and functional benefits (Xia et al., 2023). Research on coffee waste-based materials also reports adsorption capabilities and pollutant interaction mechanisms that support environmental engineering applications (Skwierawska et al., 2022).

The incorporation of coffee waste as a particulate filler in polymer systems has been shown to modify mechanical behavior and surface characteristics. Experimental studies indicate that coffee waste particles can enhance flexibility and structural performance when appropriately integrated into polymer matrices (Rizal et al., 2023). However, most existing investigations focus on adsorption applications, and the potential of coffee waste as a functional component in textile-based drainage filtration systems remains underexplored.

## 2.4. Interfacial Interaction, Antibacterial Functionality, and Research Gap

The performance of organic filler-reinforced materials is strongly governed by interfacial adhesion between the filler and the matrix. Reviews on natural fiber and particulate filler composites emphasize that effective interfacial bonding is essential for stress transfer and mechanical stability (Lee et al., 2021). These principles are critical when integrating coffee waste particles into polyester textiles to ensure structural reliability in drainage environments.

Drainage textiles are continuously exposed to moisture and organic matter, which promotes microbial growth and biofilm formation. Recent studies on antimicrobial textiles indicate that functional additives can inhibit bacterial activity; however, maintaining performance under environmental exposure remains challenging (Orasugh et al., 2025). From a mechanical perspective, incorporating particulates may alter tensile behavior depending on dispersion and interfacial adhesion, where poor bonding can reduce stress transfer and structural stability. Despite this, limited work has examined coffee-waste functionalization of polyester textiles by jointly assessing interfacial morphology, tensile response, and antibacterial activity (Arese et al., 2024). Therefore, this study investigates coffee-waste-modified polyester fabric through morphology observation, tensile testing, and antibacterial evaluation as initial indicators of multifunctional potential for drainage-related textile applications

## 3. Research Methodology



**Figure 1.** Flow diagram of the preparation and characterization of coffee waste–based polyester filtration media for drainage applications.

### 3.1. Materials Preparation and Fabrication Procedure

The research procedure began with the preparation of the primary materials, consisting of dried coffee waste and polyester fabric (Rizal et al., 2023). The polyester (PE) 24S (24 Ne, plain weave, 110 g/m<sup>2</sup>) commercial woven fabric provided by CV was the one under evaluation. Bandung, Indonesia's Karunia Textile. Used Robusta coffee waste was collected from coffee shops. Coffee bean wastes was washed with distilled water (aquades, pH 6.8), filtered, and sun-dried to reduce moisture content before being utilized as a functional filler (Franca & Oliveira, 2022).

The dried coffee waste was subsequently ground and sieved to obtain fine particles with a size of 200 mesh. The prepared coffee waste was then integrated into the polyester fabric through a controlled mixing process followed by thermal treatment using a heat press technique (Huynh et al., 2022). The resulting samples were categorized based on variations in coffee waste content to evaluate the influence of filler addition on material performance

(Mohan et al., 2025). This fabrication approach was designed to produce composite filtration media with consistent structure and mechanical integrity (Rizal et al., 2023).



**Figure 2.** Equipment used for the preparation and tensile testing of polyester samples modified with coffee waste.

### 3.2. Data Collection

Experimental data were obtained through a series of laboratory tests to evaluate the physical, mechanical, and functional characteristics of the fabricated filtration media (Barman et al., 2024). Surface morphology and the distribution of coffee waste within the polyester fibers were examined using macro photography analysis (Rizal et al., 2023). Mechanical performance was evaluated through tensile testing to determine tensile strength, elongation at break, and Young's modulus (Liang et al., 2025).

Tensile testing was conducted in accordance with ASTM D638 Type IV using a Universal Testing Machine (UTM) equipped with a 50 N load cell to ensure accurate force measurement during deformation. Prior to testing, all specimens were conditioned at a controlled temperature of 25 °C and relative humidity of 65% for 24 hours to achieve equilibrium moisture content and minimize environmental effects on mechanical response (Maulana et al., 2025). Two specimens were tested for each material variation to account for inherent variability in fabric structure, and the results were reported as mean values  $\pm$  standard deviation.

In addition to tensile testing, the resistance of tear properties of textile was evaluated based on standard ASTM D624 (Type B). To initiate tearing, a 1 mm-deep pre-cut notch was set up at the designated location. Specimens were tested on a universal testing machine at a crosshead speed of 500 mm/min  $\pm$  50 mm/min under controlled loading (Maulana et al., 2025). Until complete tear propagation got effect, the applied force was continually recorded. Equation (1) was used to get the tear strength (T).

$$T = \frac{F}{d} \quad (1)$$

where  $d$  is the specimen thickness (mm) and  $F$  is the maximal tearing force (N). The tear strength was expressed in N/mm, and at least three replicates were tested for each sample to ensure data reliability.

In addition, antibacterial testing was conducted to evaluate the ability of the filtration media to inhibit the growth of microorganisms, which is a critical factor for drainage applications exposed to humid environments.

### 3.3. Data Analysis

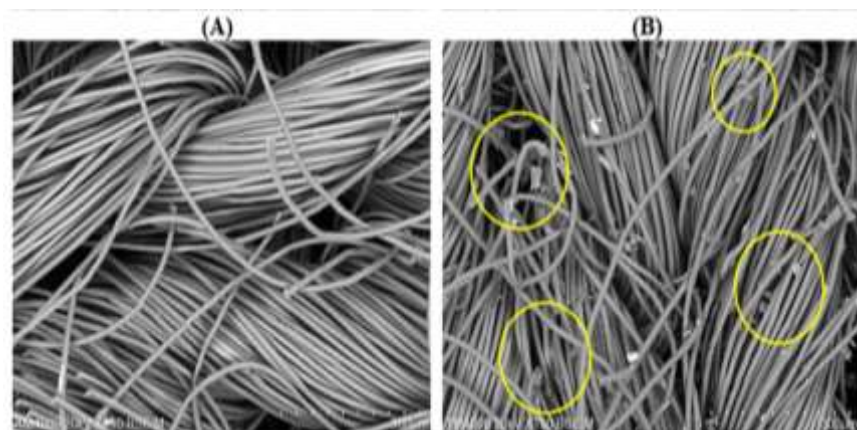
The experimental results were analyzed using a descriptive quantitative approach by comparing the performance of two material variations. Mean values and standard deviations were calculated to assess data consistency and reliability. The analysis focused on identifying the relationship between coffee waste content and mechanical strength, surface morphology, and antibacterial activity. The final interpretation was conducted to determine the feasibility of the proposed filtration media as a sustainable supporting material for green infrastructure applications.

## 4. Results and Discussion

The experimental results demonstrate that the incorporation of coffee waste into polyester fabric (PE 24S) significantly influences the morphological structure, mechanical behavior, and antibacterial performance of the drainage filtration media. The combined effects of these properties indicate that coffee waste addition provides multifunctional enhancement while maintaining structural integrity required for drainage applications.

### 4.1 Morphological Characteristics

Macro photographic analysis reveals that coffee waste particles are uniformly distributed across the surface of the polyester fibers, forming a more compact and porous surface layer compared to untreated polyester fabric. This uniform distribution suggests effective integration between the coffee waste filler and the polyester substrate, as evidenced by the consistent surface coverage observed in the treated samples (Fig. 3).



**Figure 3.** SEM Result of Textile Surface (A) Control, (B) PE with Addition Coffee Waste.

The formation of a denser porous structure contributes to increased surface roughness and expanded contact area between fibers. Such morphological changes are expected to enhance the ability of the filtration media to retain suspended solid particles and to regulate water flow during filtration processes. Compared to pristine polyester fabric, the modified surface shows higher structural complexity and roughness, which may increase fiber–particle interactions and suggests potential for improved interaction with suspended solids; however, hydraulic and filtration performance parameters were not evaluated in this study.

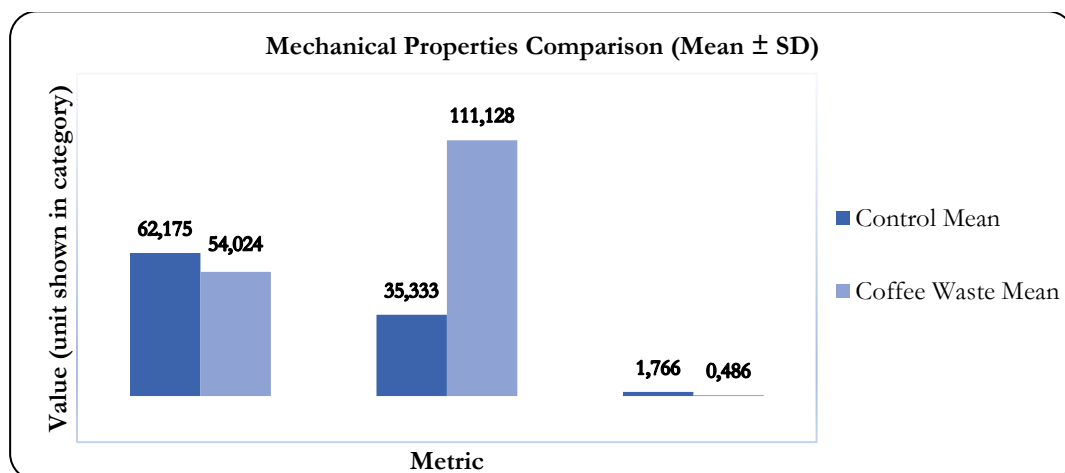
### 4.2 Mechanical Properties

The findings of the tensile test demonstrate the fact that the mechanical response of the polyester filtration media is changed when coffee waste is added. The coffee waste–modified samples exhibit a tensile strength of  $54.024 \pm 5.498$  MPa, an elongation at break of  $111.128 \pm 6.915\%$ , and a Young's modulus of  $0.486 \pm 0.543$  MPa, as summarized in Table 1. These values demonstrate that the material retains sufficient mechanical strength while exhibiting enhanced flexibility.

**Table 1.** The tensile properties of polyester filtration media (PE 24S) with and without the addition of coffee waste.

Sample	Tensile Strength (MPa)	Elongation at Break (%)	Young's Modulus (MPa)
Polyester (PE 24S)	$62.175 \pm 1.089$	$35.333 \pm 1.977$	$1.766 \pm 0.123$
Polyester (PE 24S) with Addition Coffee Waste	$54.024 \pm 5.498$	$111.128 \pm 6.915$	$0.486 \pm 0.543$

To improve readability and highlight relative changes between mechanical parameters, Figure 4 displays the data in Table 1 using a bar chart.

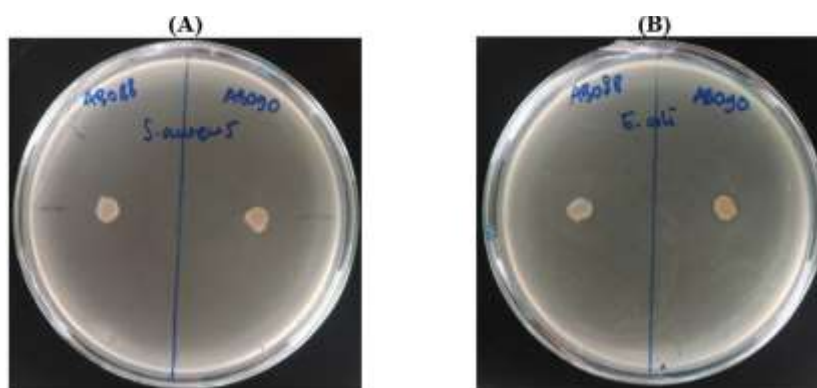


**Figure 4.** Comparison of tensile strength, elongation at break, and Young's modulus of PE 24S polyester fabric with and without coffee-waste addition (mean  $\pm$  SD).

Although a slight reduction in tensile strength is observed compared to untreated polyester fabric, the significant increase in elongation at break indicates improved ductility and resistance to tearing. This behavior is characteristic of polymer systems reinforced with organic fillers, where filler matrix interactions disrupt rigid molecular packing and promote energy dissipation during deformation. The increased flexibility is particularly beneficial for drainage filtration media, which must withstand continuous hydraulic loading and deformation without structural failure.

#### 4.3 Antibacterial Performance

Antibacterial testing shows the formation of clear inhibition zones surrounding the coffee waste-modified filtration media, indicating effective antibacterial activity (Fig. 4). This behavior suggests that bioactive compounds naturally present in coffee waste, such as chlorogenic acids and polyphenols, contribute to suppressing bacterial growth on the material surface.



**Figure 4.** Antibacterial activity comparison of Addition Coffee Waste in PE textile against *S. Aureus* (A) and *E. Coli* (B).

The antibacterial functionality represents an added advantage over conventional polyester filtration media, which are typically inert and susceptible to biofilm formation. In drainage environments characterized by high moisture and organic content, the presence of antibacterial properties is expected to reduce microbial colonization and mitigate clogging caused by biofilm development. Consequently, the integration of coffee waste enhances not only the mechanical and filtration performance but also the hygienic durability of the drainage system.

#### 4.4 Discussion and Implications for Green Infrastructure

The combined results of morphological, mechanical, and antibacterial evaluations demonstrate that coffee waste integration provides synergistic benefits for polyester-based drainage filtration media. Morphological modification enhances filtration efficiency through improved particle retention and flow regulation, while mechanical performance remains

adequate for structural demands in drainage applications. Simultaneously, the antibacterial properties contribute to long-term functionality by reducing biofouling risks.

From a sustainability perspective, the utilization of coffee waste as a functional filler aligns with green infrastructure principles by converting organic waste into value-added engineering materials. This approach supports waste reduction strategies while improving the environmental performance of drainage systems. However, it should be noted that this study was conducted at the laboratory scale, and long-term hydraulic performance under real environmental conditions was not evaluated. Future research should focus on field-scale testing, durability assessment under cyclic loading, and optimization of coffee waste content to further enhance performance.

## 5. Conclusions

This study demonstrates that integrating coffee waste into polyester (PE 24S) fabric modifies the surface morphology and introduces observable antibacterial activity, while also altering the tensile response of the material. Compared to pristine polyester, the coffee-waste-modified fabric exhibited a tensile strength of  $54.024 \pm 5.498$  MPa, an elongation at break of  $111.128 \pm 6.915\%$ , and a Young's modulus of  $0.486 \pm 0.543$  MPa, indicating a more flexible mechanical behavior accompanied by functional surface changes.

From a broader perspective, these findings support the potential of valorizing coffee waste as a waste-derived functional additive for polyester textiles relevant to drainage-related applications and green infrastructure principles. However, this study was limited to laboratory-scale morphology observation, tensile testing, and antibacterial evaluation; hydraulic/filtration performance, long-term durability under wet exposure, and practical feasibility were not assessed. Future work should address these aspects, including optimization of coffee-waste content and extended durability evaluation under realistic drainage conditions.

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**Data Availability Statement:** The data presented in this study are available on request from the corresponding author. The data are not publicly available due to privacy and ethical restrictions.

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