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Bio-Based Substitutes for Geotextile Barriers in Permeable Brick Paving Systems

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Abstract

Conventional permeable brick paving systems rely heavily on petroleum-derived, synthetic non-woven polypropylene geotextiles to separate subgrade native soils from clean aggregate reservoirs. However, these synthetic barriers pose severe ecological liabilities, including the long-term leaching of microplastics into urban groundwater tables, carbon-intensive manufacturing footprints, and a susceptibility to premature mechanical "blinding" - where fine clay particles plug synthetic fibers and trigger systemic waterlogging. To mitigate these environmental pitfalls, this paper presents a comprehensive comparative assessment of organic, bio-based alternatives (Coconut Coir, Jute, Hemp, and Sisal) against traditional synthetic geotextiles and plastic geogrids. Utilizing technical design data and performance metrics, we evaluate each material across critical parameters, including tensile strength, water permeability, service life durability, and structural use-case suitability.

The major assessment reveals that natural fiber geotextiles provide a viable "temporary support" mechanism. Among the bio-based candidates, heavy woven Coconut Coir matting (700 - 900 GSM) represents an optimal biomaterial substitute due to its high lignin content, which extends biological durability to 3 - 5 years. This window provides a stabilized transition, allowing the native subgrade soil to achieve natural compaction equilibrium before organic degradation safely concludes. To supplement shorter functional lifespans—such as Jute (1 - 2 years), Hemp (2 - 4 years), and Sisal (3 - 4 years) this paper examines the integration of the "No - Fabric" engineering method based on Terzaghi's Filter Criteria. By leveraging precision particle size distribution and geometric stone interlocking, the system establishes a permanent subgrade transition zone that outlasts organic decomposition without risking subbase contamination. Ultimately, this research demonstrates that substituting synthetic geotextiles with bio-based barriers, backed by graded aggregate physics, achieves zero-plastic stormwater infiltration, eliminates groundwater microplastic accumulation, and transitions civil infrastructure toward high-performance, carbon-negative life cycles.

Keywords: Permeable Brick Paving, Bio-Based Geotextiles, Coconut Coir, Sustainable Drainage Systems (SuDS), Microplastic Mitigation, Terzaghi's Filter Criteria.

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Chapter 1: Introduction

1.1 Background of the Study

Rapid urbanization has drastically increased impervious surfaces globally, fundamentally altering natural hydrological regimes and escalating the risks of urban flash flooding and microclimate heat island effects. Permeable brick paving systems have emerged as a critical instrument within Sustainable Drainage Systems (SuDS) and low-impact development (LID) frameworks. These systems mitigate stormwater runoff by facilitating direct infiltration into localized subsurface storage zones. Traditionally, these assemblies rely on a synthetic geotextile membrane placed at the subgrade interface to prevent the vertical migration of fine subgrade soil particulates into the clean, open-graded stone aggregate reservoirs. Despite their widespread acceptance, the long-term ecological consequences of embedded synthetic polymers represent a significant paradox within sustainable architecture and civil engineering design.

1.2 Statement of the Problem

The standard engineering reliance on petroleum-derived, non-woven geotextiles introduces multi-tiered environmental liabilities. Over operational horizons, these synthetic barriers undergo macro- and micro-degradation due to shifting subbase pressures and localized chemical interactions, shedding microplastics directly into vulnerable groundwater tables. Mechanically, synthetic geotextiles are prone to "blinding" - a phenomenon where fine silt and clay particulates plug the synthetic pore matrix, forming an absolute hydrological block that triggers premature pavement waterlogging and structural failure. Furthermore, the high embodied carbon of plastic - derived geotextiles undermines the net-zero objectives of modern sustainable infrastructure.

1.3 Research Objectives

This study aims to resolve these issues through the following structural objectives:

- To evaluate the performance, longevity, and structural suitability of organic, bio-based alternatives (Coconut Coir, Jute, Hemp, and Sisal) as temporary subgrade separators in permeable paver systems.
- To analyze the degradation timelines of bio-based materials relative to subgrade soil stabilization windows.
- To model a "No-Fabric" engineering solution utilizing Terzaghi's Filter Criteria to establish permanent stone-on-stone filtration that functions seamlessly post-biodegradation.

1.4 Scope and Significance

The scope of this research is confined to low-to-medium traffic applications, including pedestrian plazas, residential walkways, public courtyards, and light vehicular driveways. The significance lies in establishing a zero-plastic technical framework for stormwater management, showing that high-performance drainage infrastructure can be achieved without synthetic additions by leveraging regional, carbon-negative agricultural byproducts.

1.5 Limitations of the Study

This study acknowledges specific operational limitations: bio-based barriers possess inherent structural lifespans limited by natural biological decay (ranging from 6 months to 5 years). Consequently, they cannot provide permanent standalone physical separation under heavy, continuous municipal highway traffic or highly fluid, unconsolidated subgrade conditions without precision-engineered graded stone aggregate transitions.

Chapter 2: Literature Review

2.1 Environmental Impacts of Synthetic Geotextiles

Existing literature establishes that conventional non-woven geotextiles break down under deep subsurface friction and localized biochemical action, releasing microplastics directly into local aquifers. Additionally, mechanical "blinding" caused by cohesive clay interaction results in a significant reduction in hydraulic conductivity, shifting subbase behavior from a permeable medium to an artificial aquitard, which induces systemic waterlogging.

2.2 Performance Metrics of Bio-Based Alternatives

Natural lignocellulosic fibers offer varied mechanical profiles. Coconut Coir features an exceptionally high lignin content (exceeding 40%), which reinforces its cell walls against rapid microbial decomposition under continuous subgrade moisture. Hemp and Sisal present high initial tensile strength and excellent structural stretching resistance, making them ideal for initial bridging phases. Jute and Rice Straw offer short-term, highly porous filtration profiles suited for rapid vegetation routing and rapid initial soil consolidation.

2.3 Terzaghi's Filter Criteria and the "No-Fabric" Method

To address the eventual biodegradation of natural fibers, researchers have looked to classical geotechnical filters. Karl Terzaghi's geometric filter criteria provide a mathematical method to prevent intermixing without using a fabric sheet. By enforcing specific grain-size relationships between the subgrade soil and the overlying base aggregate—specifically where the 15% passing size (D_{15}) of the filter stone is less than or equal to 4 to 5 times the 85% passing size (D_{85}) of the native subgrade—the aggregate matrix forms a stable, permanent geometric stone interlock that prevents pipage and subbase contamination across geological timeframes.

2.4 Identified Research Gaps

While standard geotextile data focus on synthetic durability, there is a clear gap in tracking the dual-phase interaction between biological degradation and progressive soil self-compaction equilibrium. Limited research explores the exact mathematical transition zone dynamics when a bio-mat degrades while a Terzaghi-graded aggregate filter layer takes over long-term mechanical separation.

Chapter 3: Methodology

3.1 Research Design

This study employs a comparative analytical evaluation framework. Technical property profiles extracted from agricultural and civil engineering database baselines were normalized to evaluate performance across durability, hydraulic conductivity, tensile capacity, and life-cycle sustainability.

3.2 Material Selection and Properties

Five natural biomaterials (Coconut Coir, Jute Burlap, Hemp Geotextile, Sisal Mats, Rice Straw Fiber) were selected and benchmarked against standard commercial industrial non-woven polypropylene and recycled plastic geogrids to map absolute physical boundaries.

3.3 Experimental Parameters & Mathematical Modeling

The mathematical criteria utilized to assess subgrade filtration safety without permanent fabrics follow Terzaghi's classical constraints:

Constraint 1 (Piping Resistance): D15 (Filter Aggregate) ≤ 4 to 5 × D85 (Native Subgrade Soil)
Constraint 2 (Permeability Requirement): D15 (Filter Aggregate) ≥ 4 to 5 × D15 (Native Subgrade Soil)
These criteria ensure that the void spaces within the primary stone subbase aggregate are small enough to retain the native soil fines, while remaining open enough to allow unrestricted water movement, eliminating hydrostatic pressure accumulation.

Chapter 4: Analysis, Comparative Evaluation & Discussion

4.1 Comprehensive Subgrade Barrier Alternatives Matrix

The following table provides a comprehensive summary of the technical performance trade-offs evaluated across the seven material configurations:

Material	Longevity & Durability	Permeability & Water Flow	Tensile Strength & Stabilization	Best Structural Use Case	Eco-Footprint & Sustainability
Coconut Coir	3–5 Years; high lignin content slows down natural decomposition.	Excellent; open weave allows rapid drainage while retaining aggregates.	Medium; reliable for pedestrian loads and light slope stabilization.	Temporary paths, eco-friendly public plazas, and residential walkways.	Very Low; completely biodegradable, renewable byproduct.

Jute (Burlap)	1–2 Years; degrades rapidly when continuously exposed to moisture.	High permeability; excellent initial filtration of fine soil particles.	Low-Medium; drops significantly as fibers begin to decompose.	Short-term pedestrian paths, landscaping, and quick vegetation routing.	Very Low; fully compostable and leaves zero synthetic residues.
Hemp Geotextile	2–4 Years; superior natural rot and UV resistance compared to jute.	Excellent; highly porous structure maintains continuous drainage.	Medium-High; exceptionally strong natural tensile strength.	Medium-duty natural paths, parks, and high-moisture landscape zones.	Very Low; carbon-negative crop that enriches the subgrade upon degrading.
Sisal Mats	3–4 Years; robust, coarse fibers offer strong	High; coarse weave provides uniform water	High (for natural fiber); excellent structural	Light vehicular driveways, courtyard paths, and	Very Low; derived from agave plants with highly
Material	**Longevity & Durability**	**Permeability & Water Flow**	**Tensile Strength & Stabilization**	**Best Structural Use Case**	**Eco-Footprint & Sustainability**
	resistance to moisture.	filtration.	stretching resistance.	slope base protection.	sustainable cultivation.
Rice Straw Fiber	6–12 Months; rapidly decomposes under sustained subgrade moisture.	Moderate to High; dense matting restricts fine soil but can clog over time.	Low; low tensile capacity, tears easily under shifting heavy loads.	Very light pedestrian garden trails or temporary construction pathways.	Very Low; utilizes an agricultural waste product, highly circular.

Non-Woven PP	50+ Years; completely immune to biological rot and soil chemistry.	Extremely High; felt-like structure stops soil fines while maximizing flow.	High; structurally stable under continuous hydrostatic pressure.	Standard driveways, heavy parking lots, and municipal infrastructure.	High; synthetic polymer, permanent addition to the subsurface environment.
Plastic Geogrid	100+ Years; chemically inert and highly resistant to deformation.	N/A (Open Grid); relies on surrounding gravel to handle water flow.	Extreme; mechanically locks stone subbase to prevent horizontal shifting.	Heavy vehicular traffic, emergency fire lanes, and weak native soils.	Moderate; synthetic polymer but diverts plastic waste into circular use.

4.2 Application Insights & Engineering Trade-offs

The core engineering trade-off centers on balancing absolute structural permanence with ecological sustainability. Natural organic barriers provide an exceptional operational window (3 to 5 years for heavy woven Coconut Coir matting at 700 - 900 GSM) that bridges the phase from initial installation excavation to native soil self-compaction equilibrium. Once this state is reached, the necessity for a physical separating sheet declines, and the system relies entirely on stone aggregate grain metrics. This method circumvents long-term polymer placement and microplastic leaching entirely.

Findings and Conclusions

This study establishes that heavy woven Coconut Coir matting (700–900 GSM) serves as an optimal organic substitute for low-load permeable brick paving projects. Coir's natural chemical makeup provides structural separation for up to five years, matching the natural stabilization window of common subgrades. To secure permanent system stability across longer horizons, combining the bio-barrier with precision aggregate gradation based on Terzaghi's Filter Criteria creates a highly reliable "No-Fabric" solution. This configuration guarantees lifelong subbase filter security, eliminates subsurface plastic use, prevents mechanical blinding, and advances carbon-negative landscape construction.

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