

Soil Physicochemical Properties as Drivers of Carbon Sequestration in Tropical Bamboo: A Systematic Review of *Bambusa*, *Dendrocalamus*, and *Gigantochloa* for Ecosystem Restoration and Climate Mitigation

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ABSTRACT

Soil physicochemical properties are fundamental regulators of carbon sequestration and play a critical role in ecosystem restoration in tropical regions. Aligning with the United Nations Sustainable Development Goals (SDGs), particularly SDG 13 (Climate Change) and SDG 15 (Life on Land), tropical bamboo has gained attention as a fast-growing, high-biomass nature-based solution with strong potential to enhance soil carbon storage and contribute to climate change mitigation. However, a significant knowledge gap persists regarding how distinct soil physicochemical properties actively govern carbon sequestration within varying tropical bamboo systems. Specifically, comparative and mechanistic insights into key genera such as *Bambusa*, *Dendrocalamus*, and *Gigantochloa* lack a cohesive understanding, hindering the effective optimisation of bamboo-based restoration strategies. This review synthesises current knowledge on soil physicochemical properties, including soil organic carbon, pH, nutrient availability, texture, and bulk density, as drivers of carbon sequestration in tropical bamboo ecosystems, with a focus on these three genera. It further examines the mechanisms through which bamboo systems influence soil conditions and identifies critical research gaps. The review provides a comparative understanding of soil-bamboo interactions and highlights the role of species-specific traits and environmental factors in shaping carbon dynamics. Overall, tropical bamboo systems demonstrate strong potential to improve soil properties and enhance carbon sequestration, although outcomes vary across genera and site conditions. By linking soil processes with global sustainability goals, this review underscores the importance of tropical bamboo as a viable strategy for ecosystem restoration and climate mitigation, offering valuable insights for research, policy, and sustainable land management.

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1. INTRODUCTION

Soil constitutes one of the largest terrestrial carbon sinks and plays a critical role in regulating the global carbon cycle, thereby contributing significantly to climate change mitigation and ecosystem stability. It stores more carbon than the atmosphere and terrestrial plants combined. However, rather than acting as a passive storage vault, it functions as an active biogeochemical regulator. The capacity of this sink has been progressively threatened by anthropogenic activities and climate change. In tropical regions, which account for a substantial portion of global net primary productivity, soils are particularly vulnerable. Tropical landscapes are frequently characterised by highly weathered edaphic profiles, such as Oxisols and Ultisols, which suffer from inherent nutrient depletion, high acidity, and aluminium toxicity (Sharma et al., 2025). When these fragile ecosystems face land-use

changes, such as deforestation and the conversion of primary forests to intensive agriculture, the rapid oxidation of soil organic matter (SOM) is triggered (Totti et al., 2025). This widespread degradation unravels the physical and chemical structure of the soil, often transitioning millions of hectares of vital carbon sinks into active carbon sources.

The capacity of soil to sequester carbon and reverse this degradation is strongly governed by its physicochemical properties, including soil organic carbon, pH, nutrient availability, texture, and bulk density, which collectively influence carbon inputs, decomposition rates, and long-term stabilisation processes (Neina, 2019). Carbon stabilisation is not solely dependent on the volume of biomass input, but rather on how these specific soil properties mediate microbial and physical pathways. For instance, soil texture acts as a fundamental gatekeeper; the presence of reactive clay minerals facilitates the formation of Mineral-Associated

Organic Carbon (MAOC), effectively shielding organic compounds from microbial degradation. Concurrently, pH regulates the solubility of essential nutrients and dictates the efficiency of the soil microbiome, the primary driver of the "microbial carbon pump." Improving these properties is therefore essential for enhancing carbon storage and supporting ecosystem restoration, particularly in tropical regions where land degradation and carbon loss are prevalent. Restoring these landscapes requires resilient pioneer species capable of surviving severe edaphic constraints while simultaneously restructuring the soil matrix to support long-term carbon persistence.

In this context, tropical bamboo has emerged as a promising nature-based solution due to its rapid growth rate, high biomass production, and extensive rhizome-root systems, which facilitate organic matter accumulation, nutrient cycling, and soil structure improvement (Haida et al., 2026). Unlike traditional, slow-growing timber species that frequently fail to establish in compacted, nutrient-depleted tropical soils, bamboo functions as a highly adaptable woody grass. Its rapid aboveground canopy closure provides immediate mitigation against rainfall-driven erosion, while its dense, subterranean fine-root mats physically compress soil particles to promote aggregate occlusion (Ni and Su, 2024). This physical restructuring creates micro-environments that protect organic matter from oxygen and rapid mineralisation. Widely distributed across tropical and subtropical regions, bamboo species are increasingly utilised to restore degraded lands and improve soil quality (Kaushal et al., 2020). By bridging the gap between rapid atmospheric carbon capture and localised structural pedological rehabilitation, bamboo directly aligns with global sustainability targets, notably the United Nations Sustainable Development Goals (SDGs) 13 (Climate Action) and 15 (Life on Land).

Among them, the genera *Bambusa*, *Dendrocalamus*, and *Gigantochloa* are of particular importance due to their ecological adaptability, functional diversity, and regional significance, although they differ in growth patterns, biomass allocation, and interactions with soil environments (Samsuri et al., 2025; Liu et al., 2020). *Bambusa* species are widely recognised for producing litter with lower lignin and higher nitrogen content, functioning as rapid nutrient cyclers that quickly rejuvenate impoverished topsoils. Conversely, *Dendrocalamus* species generate massive aboveground biomass and possess robust root architectures that act as structural engineers, heavily modifying bulk density and promoting the accumulation of both labile and non-labile carbon fractions (Kaushal et al., 2020). However, despite its profound regional dominance across Southeast Asia and providing critical ecosystem services, the functional pedogenic impact of *Gigantochloa* represents a severe

taxonomic blind spot. Empirical evidence detailing how *Gigantochloa* directly influences subsurface carbon pools and soil physicochemical properties remains scarce compared to that of its well-documented related genera.

Despite growing recognition of bamboo systems in carbon sequestration and restoration efforts, there remains a lack of integrated understanding of how soil physicochemical properties function as key drivers of carbon dynamics across different bamboo genera (Yasin et al., 2026). Existing studies are often fragmented, with limited comparative analyses and insufficient synthesis of the mechanisms linking soil properties to carbon sequestration. Without resolving this critical data deficiency, particularly regarding dominant regional genera like *Gigantochloa*, large-scale restoration models risk inaccuracy, potentially leading to the deployment of sub-optimal species in vulnerable tropical landscapes. Therefore, addressing this knowledge gap is critical for optimising bamboo-based restoration interventions. Contextualising genus-specific physiological traits within the broader framework of tropical soil could provide actionable insights for optimising bamboo-based interventions in degraded environments.

2. MATERIALS AND METHODS

2.1 Objectives

This paper aims to review the current literature on soil physicochemical properties that influence carbon sequestration in tropical bamboo ecosystems, compare the effects across *Bambusa*, *Dendrocalamus*, and *Gigantochloa*, elucidate the underlying mechanisms, and identify critical research gaps to support future research on ecosystem restoration and climate change mitigation strategies. To achieve these objectives, this review addresses the following specific research questions:

1. How do soil physicochemical properties drive carbon sequestration in tropical bamboo ecosystems?
2. How do the functional traits and pedogenic impacts compare across the *Bambusa*, *Dendrocalamus*, and *Gigantochloa* genera?
3. What are the underlying physical and biogeochemical mechanisms linking bamboo root systems to long-term soil carbon stabilisation?
4. What are the critical research gaps that must be addressed to optimise bamboo-based ecosystem restoration and climate mitigation strategies?

2.2 Search Strategy, Inclusion Criteria, and Exclusion Criteria

This review adopted the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA)-