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Thermal And Physicochemical Characterization of Banana Stem Bagasse (Bb) For Biocomposite Applications in Construction Materials

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Natural fibers,
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Moisture behavior,
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Abstract

Banana pseudostem bagasse (Musa spp.) is an abundant agricultural residue generated after harvesting or sap extraction. Its valorization contributes to reducing agricultural waste, replacing synthetic materials, and promoting the development of bio-based sectors in construction, packaging, and related industries. This study provides a comprehensive characterization of banana bagasse to support its use as a sustainable industrial material. The analysis focused on key physical, hydric, chemical, and thermal properties. The results showed a fineness of 40 µm, a density of 220 $kg \cdot m^{-3}$, a porosity of 77%, and a specific surface area of 1.2 $m^2 \cdot g^{-1}$. Hydric properties included a moisture content of 74.5% (wet basis), a water retention capacity of 292.5%, and a water absorption of 122.5%. The chemical composition consisted of cellulose (41.6%), hemicellulose (28%), lignin (16%), pectin (5.7%), and ash content (3.7%), along with CHNO elemental composition. The calorific value was estimated at 3.7 $MJ \cdot kg^{-1}$. All analyses were conducted according to standardized protocols (ISO, ASTM, AOAC, and NBN EN). These findings highlight the low density, high porosity, and balanced lignocellulosic composition of banana bagasse, making it a promising natural reinforcement for low-cost and sustainable applications. However, limitations such as moisture sensitivity, natural variability, and limited durability must be considered for effective implementation.

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1. Introduction

The climate crisis and the depletion of natural resources have accelerated the development of sustainable and environmentally friendly construction materials (Zhang et al., 2025; Aldykiewicz et al., 2022). This transition aims to reduce greenhouse gas emissions and decrease reliance on carbon-intensive conventional materials (Selvam et al., 2025). These challenges are particularly significant in developing regions, especially in Africa, where sustainable development is closely linked to the implementation of the Sustainable Development Goals (SDGs).

Among renewable resources, lignocellulosic biomass represents a promising alternative due to its availability, renewability, and favorable properties (Hu et al., 2023). Banana pseudostem bagasse (bB), an abundant agricultural residue in tropical regions, remains largely underutilized despite its high content of cellulose, hemicellulose, and lignin (Patil et al., 2024; Kumari et al., 2025). Its mechanical strength and insulating properties make it a suitable candidate for the development of biocomposites used in bricks, panels, and mortars (Hevar Palani et al., 2025).

This study focuses on the thermal and physicochemical characterization of banana bagasse to evaluate its potential for integration into construction materials. Key parameters, including bulk density, porosity, moisture content, and thermal behavior, are critical for understanding fiber–matrix interactions and ensuring material durability (Hevar Palani et al., 2025). However, the lack of comprehensive and standardized data on these properties remains a major limitation for large-scale applications in eco-construction (Patil et al., 2024; Kumari et al., 2025).

The objective of this research is to identify the key properties governing the performance of banana bagasse-based biocomposites and to assess their suitability for construction applications. This work is part of the broader effort to promote plant-based materials as sustainable solutions, either as insulation or as reinforcement in mineral and polymer matrices (Kaufmann et al., 2025). The findings are expected to support the development of locally available, cost-effective, and environmentally sustainable construction materials (Comath et al., 2025).

2.Materials and Methods.

2.1 Raw Material Preparation

Banana pseudostems (Musa spp.) were collected from agricultural residues after harvesting. The stems were cleaned to remove impurities, then cut, washed, and air-dried prior to processing. The dried material was mechanically ground and sieved to obtain a homogeneous particle size. Final grinding was performed to achieve a fine powder with an average particle size of approximately 40 µm, suitable for physicochemical characterization and potential biocomposite applications.

2.2 Experimental Methods

The experimental characterization of banana pseudostem bagasse (bB) was carried out using a stepwise analytical approach combining classical laboratory techniques and modern analytical methods, including atomic absorption spectrometry (AAS), to evaluate its physical, hydric, thermal, and chemical properties relevant to material applications (Ezeonuegbu et al., 2021). Prior to analysis, the crushed samples were sieved to obtain a particle size of approximately 1 mm and preserved under controlled laboratory conditions. All analyses were performed in triplicate to ensure reproducibility, and results are expressed on a dry matter basis.

2.2.1 Fineness

Fineness was evaluated because it strongly influences particle distribution, interfacial adhesion, and the mechanical performance of biocomposites (Dupont et al., 2018). The procedure consisted of washing fresh bagasse (200 g), followed by draining through a 2 mm sieve and drying either under ambient conditions or in an oven until the moisture content was below 10%. The fibers were then combed to separate bundles, cut into approximately uniform lengths, and grouped into sets of 50 to 100 fibers. Measurements were performed on a flat surface, and mass was determined using a calibrated balance.

Fineness was calculated according to ISO 18826 (2016) using:

$$F = \frac{m}{L}$$

where F is the fineness, mmm is the mass of fibers, and L is the fiber length. This approach allows quantifying the degree of fiber refinement and its suitability for homogeneous dispersion in composite matrices.

2.2.2 Drying Kinetics

Drying kinetics were investigated because moisture removal is a critical step in the preparation of plant-based fillers and directly affects dimensional stability, durability, and processing behavior.
For air-drying tests, samples of different initial masses (100, 1000, and 5000 g) were spread in controlled layers of 1.0, 2.5, and 5.0 cm. The reference dry mass was obtained by oven drying at 105 ± 2 °C until constant weight. The initial moisture content was calculated as:

$$M_0 = \frac{m_0 - m_d}{m_d}$$

where m_0 is the fresh wet mass and m_d is the dry mass.

During drying, samples were periodically weighed under controlled environmental conditions (temperature, relative humidity, and airflow). Moisture evolution over time was calculated using:

$$M(t) = \frac{m(t) - m_d}{m_d}$$

where m(t) is the sample mass at time ttt.

To compare drying behavior independently of the initial conditions, the moisture ratio was calculated as:

$$MR = \frac{M(t) - M_{eq}}{M_0 - M_{eq}}$$

where M_{eq} is the equilibrium moisture content.

Airflow conditions were monitored using a hot-wire anemometer, allowing determination of the mean velocity and characterization of the drying regime through the Reynolds numberr:

$$Re = \frac{\rho v D_h}{\mu}$$

where ρ is air density, v is air velocity, D_h is the hydraulic diameter, and μ is the dynamic viscosity of air.

Additional drying tests were conducted in a forced-convection dryer (216 L capacity) at 60 °C, with an air velocity of 1.5 ± 0.1 $m \cdot s^{-1}$ and relative humidity below 15%. Under these conditions, moisture transfer was described using Fick's diffusion model:

$$MR = \frac{8}{\pi^2} \exp\left(-\frac{\pi^2 D_{eff} t}{4L^2}\right)$$

where D_{eff} is the effective moisture diffusivity, t is the drying time, and L is the half-thickness of the sample layer. This analysis made it possible to evaluate the influence of sample thickness and drying conditions on water removal.

2.2.3 Bulk Density

Bulk density was determined because it directly affects the lightweight nature, compaction behavior, and thermal insulation potential of the material (Nkongho et al., 2021). The protocol involved washing fresh bagasse, sieving (2 mm), drying under ambient or solar conditions, followed by grinding (<2 mm) and oven drying at 105 ± 5 °C for 24 h before storage in waterproof bags. Apparent density was determined by introducing a known mass of material into a graduated cylinder without tamping. Density was calculated using:

$$\rho = \frac{m}{V}$$

where ρ is the density, mmm is the mass of material, and V is the occupied volume.

2.2.4 Porosity

Porosity was determined because it controls water retention capacity, permeability, and interaction with binding matrices (Bhadha J. H., et al., 2023). Measurements were performed using helium pycnometry (Micromeritics AccuPyc II 1340) on degassed samples (80 °C for 2 h) at 25 ± 1 °C. It was calculated from the relationship between apparent density and skeletal density (Rodríguez Travieso et al., 2025).:

$$\varepsilon = 1 - \frac{\rho_a}{\rho_s}$$

where ρ_a is the apparent density and ρs is the skeletal density of the solid fraction. This parameter was used to evaluate the internal void structure of the material.

2.2.5 Specific Surface Area

The specific surface area was determined because it governs fiber–matrix interactions and mechanical performance. Samples were ground (<250 µm), oven-dried at 105 ± 2 °C for 24 h, and degassed under vacuum prior to analysis. Measurements were performed using nitrogen adsorption at 77 K according to ISO 9277 (2010), based on the BET model (Brunauer et al., 1938).

$$S = \frac{V_m N_A s}{V}$$

where S is the specific surface area, Vm is the monolayer volume, N_A is Avogadro's number, s is the molecular cross-sectional area, and V is the sample volume.

2.2.6 Moisture Content

Moisture content was determined using the oven-drying method following ISO 18134-1 (2015). Samples were conditioned at 23 °C and 50% relative humidity before drying, in accordance with standard protocols (Rao., 2024).

$$H = \frac{m_h - m_s}{m_h} \times 100$$

where m_h is the wet mass and m_s is the dry mass. This parameter is essential because moisture strongly affects swelling, stability, and microbial susceptibility.

2.2.7 Water Absorption

Water absorption (WA) was measured to assess the hydrophilic behavior of the bagasse and its compatibility with mineral or polymer matrices. WA was measured according to NBN EN 15283-2 +A1. Oven-dried samples were immersed in water at controlled temperature (20 ± 2 °C) for 24 h, then drained and weighed.

The absorption coefficient was calculated as:

$$WA = \frac{M_{sat} - M_{dry}}{M_{dry}} \times 100$$

where M_{sat} is the saturated mass and M_{dry} is the dry mass. This test provides an indication of the material's sensitivity to water and its likely dimensional behavior in service.

2.2.8 Water-Holding Capacity

Water-holding capacity was determined to quantify the maximum amount of water retained after saturation and drainage. in accordance with NF EN 13041 (2011). Dried samples were saturated under controlled conditions, then drained before weighing. The retained water was estimated from:

$$WHC = \frac{m_{after} - m_{before}}{m_{dry}}$$

where m_{after} is the mass after saturation and drainage, m_{before} is the initial dry mass, and m_{dry} is the dry sample mass. This parameter is especially important for predicting behavior in humid environments and for formulating composite mixtures.

2.2.9 Calorific Value

The calorific value was determined by bomb calorimetry to evaluate the thermal energy content of the bagasse. following the procedure described by Betene et al. (2020). Briefly, pre-dried pellets were combusted under controlled oxygen pressure after calibration of the calorimeter with benzoic acid. The gross calorific value was calculated using:

$$PCS = \frac{C \cdot \Delta T}{m_{sample}}$$

where C is the calorimeter constant, ΔT is the temperature increase, and m_{sample} is the sample mass.

The net calorific value was estimated using:

$$NCV = PCS - 2.442 \times H$$

where H is the hydrogen or moisture correction factor depending on the adopted basis. This parameter helps to assess the thermal behavior of the biomass and its organic richness.

2.2.10 Ash Content

Ash content was measured after complete calcination at 550 °C according to ISO 18122 (2015). It reflects the mineral fraction remaining after combustion and is useful for evaluating thermal behavior and inorganic residue content. Ash content was calculated as:

$$Ash(\%) = \frac{m_{ash}}{m_{initial}} \times 100$$

where m_{ash} is the residual ash mass and $m_{initial}$ is the initial dry sample mass.

2.2.11 Chemical Composition

The structural components (cellulose, hemicellulose, lignin, and pectin) were determined using classical chemical extraction and hydrolysis methods as described in previous studies (Betene, et al., 2020; Akatwijuka, 2024; Waithaka, 2025).

Cellulose content was calculated using:

$$Cellulose(\%) = \frac{M_{cellulose}}{M_{total}} \times 100$$

Hemicellulose content was determined as:

$$Hemicellulose(\%) = \frac{M_{hemicellulose}}{M_{total}} \times 100$$

Lignin content was obtained from:

$$Lignin(\%) = \frac{M_{lignin}}{M_{total}} \times 100$$

These values provide a direct indication of the structural composition of the biomass and its potential reinforcing effect in biocomposites.

2.2.12 Elemental Composition

Elemental composition (C, H, N) was determined using CHNS analysis according to ASTM D5373, which is based on the complete combustion of the sample at high temperature in an oxygen-rich atmosphere, followed by the quantitative detection of the resulting gases (CO_2, H_2O, and N_2) using a calibrated elemental analyzer.

$$O(\%) = 100 - (C + H + N)$$

2.2.13 Extractives, Organic Matter, and Mineral Matter

Extractives were determined using Soxhlet extraction with an ethanol–toluene solvent system (Akatwijuka, 2024). Briefly, the dried and finely ground sample was placed in a cellulose extraction thimble and subjected to continuous extraction for several hours under reflux conditions. The solvent mixture (ethanol–toluene) enabled the dissolution of both polar and non-polar extractable compounds. After extraction, the solvent was evaporated, and the extractives content was determined gravimetrically. The extractives content was calculated as:

$$Extractives(\%) = \frac{M_{ext}}{M_{initial}} \times 100$$

where M_{ext} is the mass of extractable substances and M_{initial} is the initial dry mass.

Organic matter content was evaluated from mass loss after calcination:

$$OM(\%) = \frac{M_1 - M_2}{M_1} \times 100$$

$$MM(\%) = \frac{M_{ash}}{M_{initial}} \times 100$$

Together, these parameters were used to assess the relative proportions of biodegradable and inorganic components in the bagasse.

3. Results and Discussion

3.1 General Properties of Banana Bagasse

The banana bagasse used in this study originates from agricultural residues. Its physicochemical characterization is summarized in 1, which presents the main physical, hydric, thermal, and chemical properties obtained.

Table 1. Physicochemical properties of banana bagasse

Category	Parameter	Value
Physical properties	Fineness,	40 ± 0.01
	Density,	220 ± 1
	Porosity,	77 ± 0.01
	Specific Surface Area	1.2 ± 0.002
Hydric properties	Moisture Content, Water	74.5 ± 0.1
	Absorption Coefficient,	122.5 ± 0.1
	Water Retention Capacity	292.5 ± 0.1
Thermal properties	Calorific Value	11 ± 0.01
Chemical properties	Ash Content,	3.7 ± 0.0012
	Cellulose,	41.6 ± 0.01
	Hemicellulose,	28 ± 0.011
	Lignin,	16 ± 0.01
	Pectin,	5.7 ± 0.012
	Carbon Content,	44 ± 0.01
	Hydrogen Content,	5.3 ± 0.012
	Nitrogen Content,	4.8 ± 0.013
	Oxygen Content,	48 ± 0.01
	Extractable Substances,	9 ± 0.0013
	Organic Matter Content,	84.8 ± 0.01
	Dry Mass Content,	43.2 ± 0.01
	Mineral Matter Content	3.7 ± 0.01

The results indicate that banana bagasse is characterized by a low apparent density (220 $kg\cdot m^{-3}$), a high porosity (77%), and a moderate specific surface area (1.2 $m^2\cdot g^{-1}$), reflecting a highly porous and lightweight lignocellulosic material. In addition, the material exhibits a high initial moisture content (74.5%), along with significant water absorption and retention capacities, confirming its pronounced hydrophilic behavior (Njoya et al., 2020).

From a chemical standpoint, banana bagasse is mainly composed of cellulose (41.6%), hemicellulose (28%), and lignin (16%), with a high organic matter content (84.8%) and low ash content (3.7%), indicating a predominantly organic structure suitable for bio-based material applications.

3.2 Physical Properties and Implications

The physical characteristics of banana bagasse strongly influence its behavior when incorporated into biocomposite materials, particularly for lightweight construction applications such as soil fiber bricks.

The low apparent density (220 $kg\cdot m^{-3}$) is a key advantage, as it contributes to the production of lightweight composites, reducing the overall structural load and improving handling during manufacturing. In addition, the relatively fine particle size (40 µm) enhances packing efficiency within the matrix, promoting better compactness and a more uniform distribution of fibers.

The high porosity (77%) plays a dual role. On one hand, it improves thermal insulation and facilitates binder penetration into the fibrous network. On the other hand, it significantly increases the material's capacity to absorb and retain water, which may lead to dimensional instability, swelling, or microcracking under fluctuating environmental conditions, as reported for lignocellulosic fibers (Njoya et al., 2020).

The specific surface area (1.2 $m^2\cdot g^{-1}$), although moderate, contributes to fiber–matrix interaction by increasing the contact interface between particles and the binder phase. This promotes mechanical interlocking and adhesion, although the effectiveness of this interaction may remain lower compared to highly reactive mineral fillers.

Taken together, the combination of low density, high porosity, and fine particle size makes banana bagasse a promising reinforcement for lightweight and potentially insulating biocomposites. However, these advantages are intrinsically linked to structural limitations that require careful control during material formulation and processing.

3.3 Hydric Behavior and Moisture Effects

The hydric behavior of banana bagasse is a critical factor governing its performance in biocomposite materials, particularly in construction applications where dimensional stability and durability are essential.
The material exhibits a high initial moisture content (74.5%), along with significant water absorption (122.5%) and retention capacity (292.5%), indicating a strongly hydrophilic nature. This behavior is mainly attributed to the lignocellulosic composition of the fibers, which contains numerous hydroxyl groups capable of forming hydrogen bonds with water molecules, as commonly reported for plant-based materials (Njoya et al., 2020).
As illustrated in Figure 1, the evolution of moisture content, water absorption, and water retention capacity confirms the strong affinity of banana bagasse for water. This pronounced hydrophilicity directly impacts the material's behavior during processing and application.

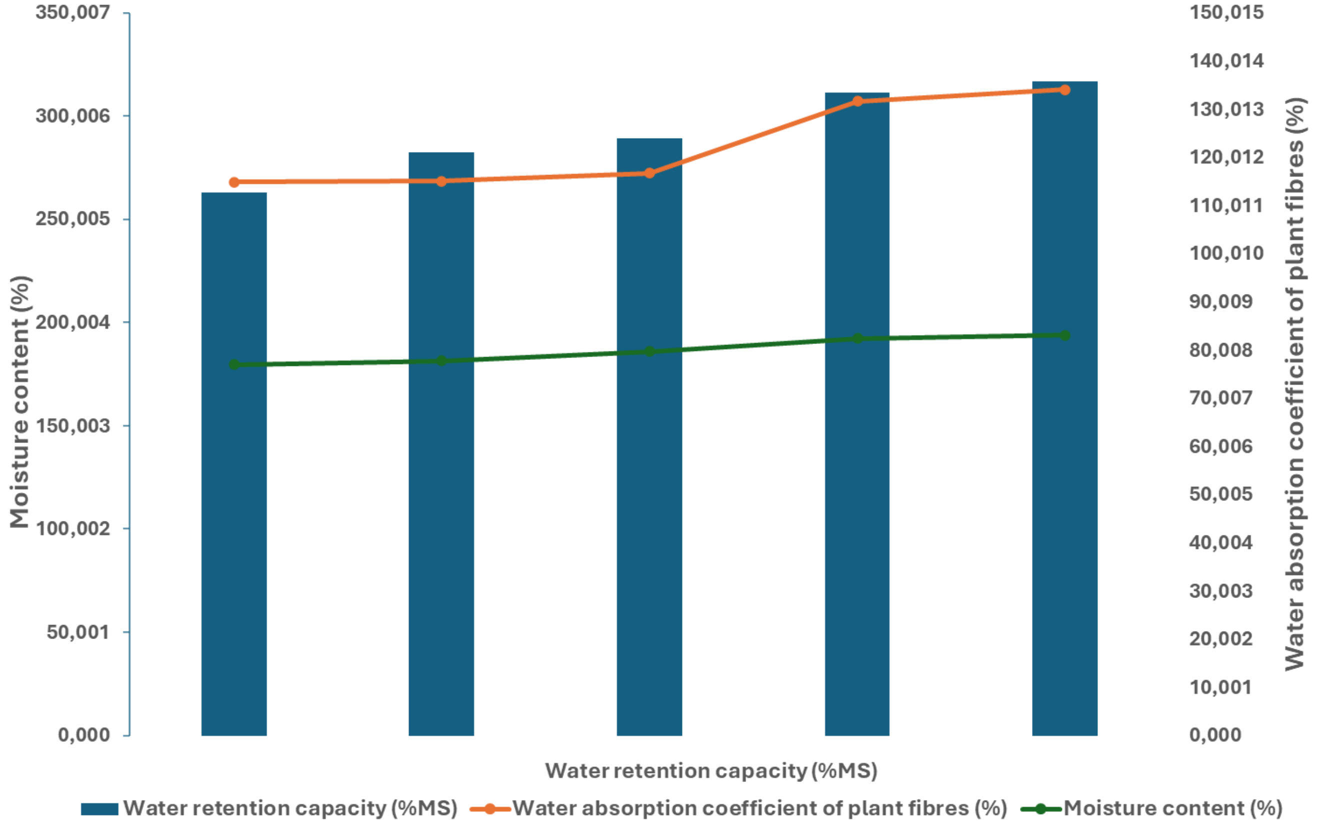

Figure 1. *Water retention capacity* in bB, *water absorption coefficient* of plant fibres in bB, and *moisture content* in bB.

Such high moisture affinity can lead to several challenges. Excessive water uptake may induce fiber swelling, reduce interfacial adhesion, and generate microcracks within the composite structure. Additionally, high moisture levels can promote biological degradation, including mold growth, and significantly reduce long-term mechanical performance.
To mitigate these effects, several strategies can be implemented. Controlled drying of the material is essential to reduce the initial moisture content and ensure reproducible processing conditions. This can be achieved by maintaining thin drying layers (typically less than 1 cm), moderate temperatures (below 40 °C), and adequate

airflow. Surface modification techniques, such as silane treatments or polymer coatings, can also be applied to reduce hydrophilicity and improve water resistance.

Furthermore, optimizing the fiber-to-matrix ratio and adjusting the mixing water content are crucial to ensure homogeneous distribution and to prevent excessive water accumulation within the composite. The incorporation of mineral additives, such as lime or pozzolanic materials (e.g., fly ash or metakaolin), contributes to improving dimensional stability and reducing moisture sensitivity.

While the high-water absorption capacity of banana bagasse represents a major limitation, appropriate pre-treatment and formulation strategies can significantly enhance its performance and enable its integration into durable and sustainable biocomposite materials (Nwabanne J. T., et al., 2025).

3.4 Thermal Properties

The thermal properties of banana bagasse provide important insights into its behavior when used in biocomposite materials, particularly under thermal stress or in applications requiring insulation.

The material exhibits a calorific value of approximately 11 MJ·kg^{-1} and a low ash content (3.7%), indicating a high proportion of organic matter. This composition is characteristic of lignocellulosic biomass and reflects the predominance of combustible constituents such as cellulose, hemicellulose, and lignin.

The relatively low ash content is advantageous for composite applications, as it limits the presence of inert mineral residues that may interfere with fiber–matrix interactions. This contributes to better compatibility with binders and improves the overall homogeneity of the material.

Although the calorific value is not directly exploited in construction applications, it remains an important parameter for understanding the thermal reactivity of the material. It may become relevant in processes involving thermal treatment or in assessing fire-related behavior.

As shown in Figure 2, the relationship between calorific value, moisture content, and ash content highlights the influence of both hydric and compositional factors on the thermal behavior of banana bagasse. In particular, moisture content plays a significant role in reducing effective thermal performance, as part of the absorbed energy is consumed during water evaporation.

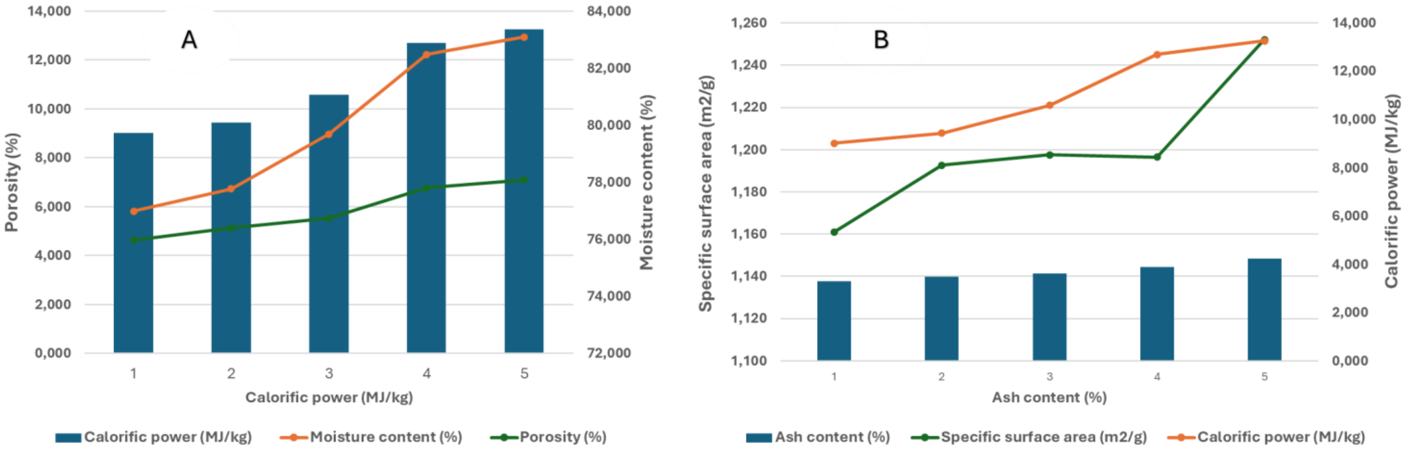

Figure 2. Evolution of the thermal properties of banana bagasse. (A) Correlation between calorific value, moisture content, and porosity; (B) Correlation between ash content, specific surface area, and calorific value

From an application perspective, the combination of low ash content and organic-rich composition suggests that banana bagasse can contribute to lightweight materials with potential insulating properties. However, its thermal stability remains dependent on its moisture content and structural composition, requiring appropriate pre-treatment and controlled processing conditions.

This suggests that, the thermal characteristics of banana bagasse support its potential use in bio-based construction materials, provided that moisture-related limitations are properly managed.

3.5 Chemical Composition and Structural Role

The chemical composition of banana bagasse plays a fundamental role in determining its mechanical behavior, durability, and interaction with matrix materials in biocomposite applications.

The material is primarily composed of cellulose (41.6%), hemicellulose (28%), and lignin (16%), along with pectin (5.7%) and a low ash content (3.7%). This composition reflects a typical lignocellulosic structure with a high organic matter content, which is favorable for bio-based material development.

Cellulose is the main structural component and contributes significantly to the mechanical strength and stiffness of the material. Its fibrous nature provides reinforcement within the composite matrix, enhancing load-bearing capacity. Lignin, on the other hand, acts as a natural binder and improves cohesion between fibers. Due to its relatively hydrophobic nature, it also contributes to partial resistance against moisture.

Hemicellulose plays an important role in fiber–matrix adhesion by facilitating bonding between the different constituents. However, its hydrophilic character may increase sensitivity to moisture, which can negatively affect dimensional stability if not properly controlled. Pectin and extractable substances, although present in smaller quantities, can influence interfacial behavior and may interfere with bonding if no pre-treatment is applied.

As illustrated in Figure 3, the distribution of the main chemical constituents (cellulose, hemicellulose, lignin, and other components) highlights the balanced composition of banana bagasse and its potential for composite reinforcement.

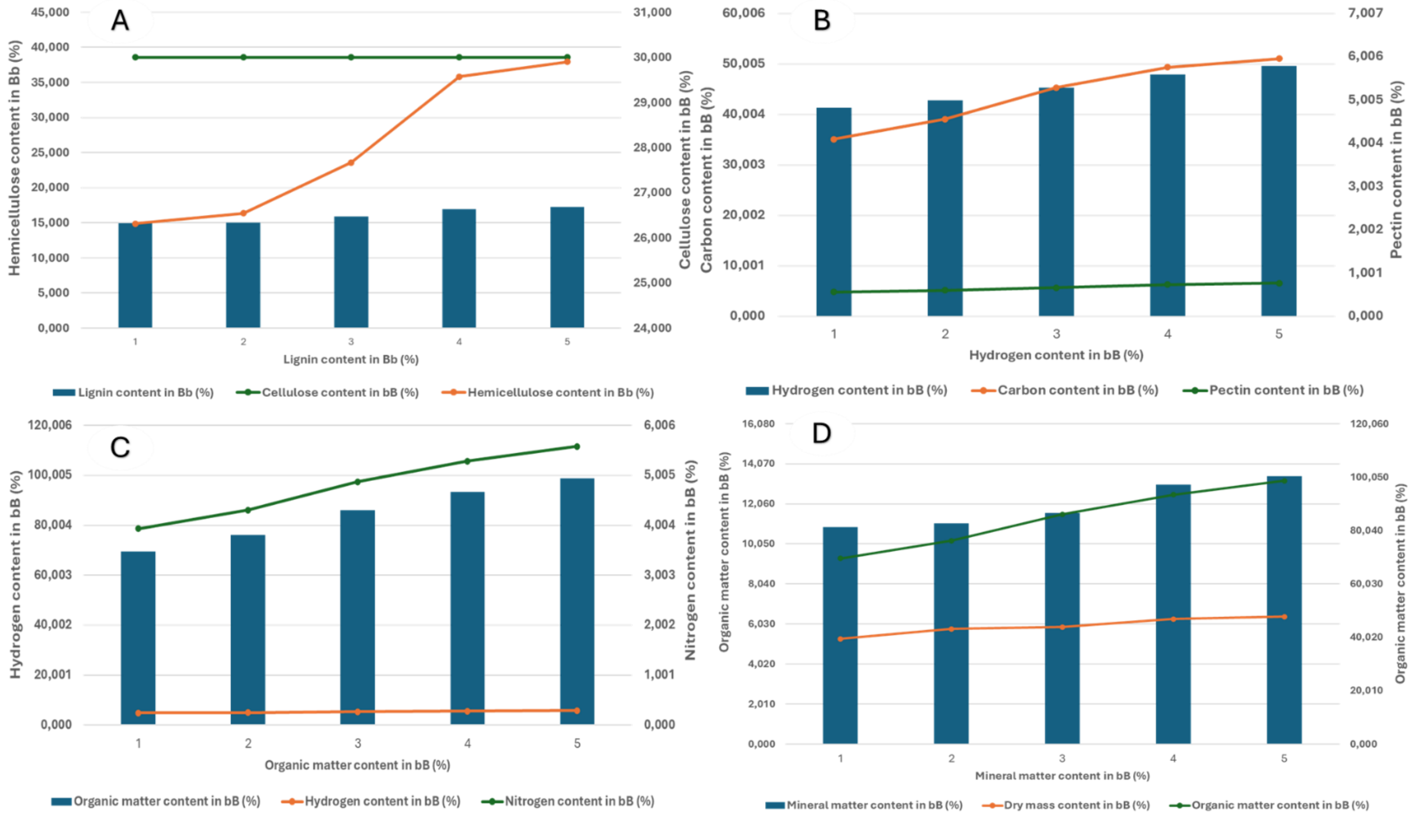

Figure 3. Evolution of the chemical composition of banana bagasse. (A) Cellulose, hemicellulose, and lignin contents; (B) Carbon, hydrogen, and pectin contents; (C) Organic matter, oxygen, and nitrogen contents; (D) Mineral matter and dry mass contents.

From a structural perspective, the high organic content (84.8%) favors compatibility with bio-based binders, while the relatively low mineral content limits the presence of inert phases that could reduce adhesion efficiency. However, the variability of chemical composition, depending on plant origin and processing conditions, may affect reproducibility and requires careful control.

To enhance performance, surface treatments such as alkaline or silane modifications can be applied to improve fiber–matrix adhesion and reduce hydrophilicity. These treatments contribute to better mechanical performance, improved durability, and enhanced resistance to environmental conditions.

It can be concluded that, the chemical composition of banana bagasse supports its use as a sustainable reinforcement material in biocomposites, provided that appropriate treatments are applied to optimize its interfacial and structural properties.

3.6 Integrated Discussion for Biocomposite Applications

The combined analysis of the physical, hydric, thermal, and chemical properties of banana bagasse highlights its strong potential as a reinforcement material in biocomposite systems, particularly for lightweight construction applications.

From a structural perspective, the low density and fibrous nature of the material contribute to the development of lightweight composites with improved workability and potential thermal insulation properties. The balanced lignocellulosic composition, dominated by cellulose, hemicellulose, and lignin, supports mechanical reinforcement and promotes compatibility with bio-based or mineral binders (Njoya et al., 2020).

However, the hydric behavior remains the primary limiting factor. The high moisture content and significant water absorption capacity can lead to dimensional instability, reduced interfacial adhesion, and long-term durability issues. These constraints are typical of lignocellulosic materials and require specific adaptation strategies to ensure reliable performance in construction environments (Nwabanne et al., 2025).

In addition, the intrinsic variability of banana bagasse, influenced by factors such as plant origin, maturity, and processing conditions, may affect the reproducibility of composite properties. This variability highlights the importance of controlled preparation protocols and standardized processing methods.

To overcome these limitations, several optimization approaches can be considered. Controlled drying remains essential to stabilize the material prior to incorporation. Surface treatments, including alkaline and silane modifications, can significantly improve fiber–matrix adhesion and reduce hydrophilicity. Furthermore, the incorporation of mineral additives or hybrid reinforcement strategies can enhance mechanical strength, durability, and resistance to environmental conditions (Kaufmann J. T. A., et al., 2025).

From an application standpoint, banana bagasse can be effectively used in the production of soil fiber bricks, lightweight panels, insulating materials, and bio-based composites. Its availability as an agricultural residue also supports a circular economy approach, promoting the valorization of local resources and reducing environmental impact.

Taken together, these results indicate that banana bagasse represents a promising and sustainable material for biocomposite applications, provided that appropriate processing strategies are implemented to address its moisture sensitivity and variability.

3.7 Limitations of the Study

The characterization of banana bagasse is subject to several experimental and environmental limitations that may influence the accuracy and reproducibility of the obtained results.

Variations in drying conditions, including layer thickness (1–5 cm), relative humidity (40–95%), and ventilation, can significantly affect measured physical properties. For instance, insufficient drying control may lead to overestimation of density (up to $+0.04\ \mathrm{g{\cdot}cm^{-3}}$), underestimation of water absorption (approximately 10%), and fluctuations in porosity (3–13%). Similarly, thermal properties such as calorific value may vary within a range of 0.2–$0.4\ \mathrm{MJ{\cdot}kg^{-1}}$ depending on residual moisture content.

In addition, atmospheric contamination, particularly due to dust deposition, and insufficient instrument calibration can introduce biases in the determination of fineness (10–20%), chemical composition (CHNO variation of 3–10%), and pectin content (5–15%). These factors highlight the importance of strict laboratory control during sample preparation and analysis.

Furthermore, the absence of mechanical testing in this study limits the direct correlation between physicochemical properties and the actual performance of biocomposites. As a result, extrapolation to mechanical behavior, such as elastic modulus (±10–15%) and strength (±10%), as well as long-term durability and water resistance (8–12%), should be considered with caution.

To reduce these uncertainties, rigorous experimental protocols are required. These include controlled drying conditions (layer thickness <1 cm, relative humidity <50%, and airflow around 0.5 $m\cdot s^{-1}$), protection against environmental contamination, and precise calibration of analytical instruments. In addition, future studies should integrate mechanical and long-term performance testing to validate the practical applicability of banana bagasse in biocomposite systems (Nwabanne J. T., et al., 2025).

3.8 Potential Applications and Perspectives

Banana bagasse–reinforced biocomposites, derived from agro-industrial residues, demonstrate significant potential for applications in the construction sector, particularly for non-load-bearing and semi-structural elements.

Due to its low density and fibrous structure, banana bagasse contributes to the development of lightweight materials that are compatible with modern construction requirements. Its porous morphology also provides beneficial thermal and acoustic insulation properties, which can enhance energy efficiency and indoor comfort in buildings. These characteristics make it suitable for applications such as lightweight partitions, insulating panels, interior finishing materials, and incorporation into cementitious or geopolymer composites, where it can help reduce shrinkage and overall structural weight.

From an environmental perspective, the valorization of banana bagasse aligns with circular economy principles by promoting the use of locally available renewable resources and reducing agricultural waste. This approach contributes to lowering the carbon footprint of construction materials and is particularly relevant for tropical and developing regions.

However, the practical implementation of banana bagasse in biocomposites requires addressing several challenges, including moisture sensitivity, variability in material properties, and limited long-term durability. These constraints must be considered in material design and processing strategies to ensure reliable performance (Seisa K., 2025).

Future research should focus on optimizing surface treatments to improve hydrophobicity and interfacial adhesion, as well as developing hybrid biocomposites combining banana bagasse with other natural or synthetic fibers to enhance mechanical strength and thermal stability (Kaufmann J. T. A., et al., 2025). In addition, long-term aging studies under environmental stress conditions are necessary to evaluate durability and service life.

Further investigations integrating life cycle assessment (LCA) approaches would also be valuable to quantify the environmental benefits and support the large-scale adoption of banana bagasse-based materials in sustainable construction.

8. Conclusion

The present study demonstrates that banana bagasse is a promising bio-based material for biocomposite applications, particularly in the production of lightweight construction elements. Its low density (220 $kg\cdot m^{-3}$) and high porosity (77%) contribute to the development of lightweight materials with enhanced thermal insulation properties, while its lignocellulosic composition—cellulose (41.6%), hemicellulose (28%), and lignin (16%)—supports mechanical reinforcement, elasticity, and crack resistance.

However, the hydric behavior of the material remains a critical constraint. The high water absorption (122.5%) and retention capacity (292.5%) require careful moisture control and optimized drying conditions to prevent dimensional instability, cracking, and biological degradation. These aspects highlight the necessity of appropriate pre-treatment and formulation strategies to ensure reliable performance.

From an application perspective, banana bagasse offers a balanced combination of structural reinforcement and insulating capacity, making it suitable for sustainable construction materials such as biocomposite bricks and panels. Its valorization as an agricultural residue also contributes to circular economy approaches and environmentally responsible material development.

These findings confirm that, with proper processing and moisture management, banana bagasse can be effectively integrated into durable and efficient biocomposite systems, supporting the transition toward low-cost and sustainable construction solutions.

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Competing Interests

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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