FUDMA Journal of Engineering and Technology
ISSN: 3092-9385
https://sites.google.com/fudutsinma.edu.ng/fjet
Volume 1, Issue 2, 2025, 586-596

The Effects of Gum Arabic Matrix on the Hardness and Water Absorption of Agro-Based (Banana Pseudostem) Hybrid Composites

Danladi K. GARBA[1], Emmanuel O. AWEDA[2*], Nuhu A. ADEMOH[3], Fredrick NGOLEMASANGO[4], Pascal A. UBI[5], Akor TERNGU[6], Lawal KABIR[7], Shuaibu O. YAKUBU[8]

[1,2*,6,8]Department of Mechanical Engineering, Nigerian Defence Academy, Kaduna, Nigeria
[3]Department of Mechanical Engineering, Federal University of Technology, Minna, Nigeria
[4]DTR I'M/VMS Materials Development Engineer, Wiltshere, United Kingdom
[5]Department of Mechanical Engineering, University of Calabar, Calabar, Cross Rivers State, Nigeria
[7]Department of Chemical Engineering, Kaduna Polytechnic, Kaduna, Nigeria

[1]dkgarba@nda.edu.ng, [2*]emmanuel.aweda2020@nda.edu.ng, [3]nuhuadam@yahoo.com, [4]fngolemasango@gmail.com, [5]paschalubi@unical.edu.ng, [6]takor@nda.edu.ng, [7]kabirlawal@kadunapolytechnic.edu.ng, [8]soyakubu@nda.edu.ng

Abstract

This study investigated the effects of gum Arabic and banana pseudostem sap matrix in a 50-50 mix on the water absorption and hardness of a composite reinforced with banana pseudostem ash nanoparticles. The banana pseudostem fibre was first treated with a 0.5% sodium hydroxide solution and dried at room temperature. The treated fibres were then calcinated in a muffle furnace at 800 °C to produce banana pseudostem ash, which was subsequently reduced to nanoparticle size using a ball mill. The resulting ash was characterized using X-ray fluorescence (XRF) and X-ray diffraction (XRD). Composite samples were produced by integrating the banana pseudostem ash as a reinforcement material with a gum Arabic matrix at various mix ratios, and the physical properties of hardness and water absorption were tested. The characterization results confirmed the ash's suitability for reinforcement, showing a crystalline structure largely composed of hanksite (72.9%). The tests on the composite samples revealed that the reinforcement materials improved the hardness of the composites. However, the percentage of water absorbed also increased as the filler content was increased.

Keywords: *Calcination, carbonization, decarbonation, X-Ray Diffraction, X-Ray Flourescence.*

1.0 Introduction

A Composite is a material that is made up of two or more unique phases (matrix phase and reinforcement/dispersed phase/filler) and which has bulk properties which varies markedly from the properties of the individual constituents of the composite material [1]. Lignocellulose fibres are lighter in weight, renewable, non-abrasive, consume less energy for processing, lowering the density of furnished products, and absorb CO_2 during their growth. Lignocellulosic fibres can be combined with either a thermosetting or a thermoplastic polymer matrix to create composites [2]. The focus of this work is to use nanotechnology to develop agro-based hybrid composite materials for the production of automobile body parts.

The escalating global environmental crisis, driven by non-biodegradable plastic pollution and the depletion of finite petroleum resources, has catalyzed a paradigm shift in material science towards sustainable and eco-friendly alternatives. This has spurred intensive research into the development of biocomposites, materials derived from renewable biological sources, which offer a promising pathway to reduce ecological footprints [3]. Among the most promising avenues is the utilization of agricultural waste, transforming it from an environmental liability into a valuable resource for composite reinforcement and matrix development [4]. The banana plant, a staple crop in many tropical and subtropical regions, generates a significant amount of lignocellulosic waste post-harvest, primarily the pseudostem, which is traditionally discarded or burned, contributing to environmental pollution [5].

Recent research has extensively explored the potential of banana pseudostem fibre (BPF) as a reinforcement in polymer composites due to its relatively good specific strength, low density, and renewability [6, 7]. Studies have shown that BPF can effectively enhance the mechanical properties of synthetic polymers [8, 9]. Also, there is a growing interest in developing fully bio-based composites, where both the matrix and the reinforcement are derived from natural sources. In this regard, the sap from the banana pseudostem, rich in nutrients and polysaccharides, has been investigated as a potential natural polymer matrix or plasticizer [10]. However, neat banana sap often suffers from limitations such as brittleness, low mechanical strength, and high-water absorptivity, hindering its standalone application [11].

To overcome these limitations, researchers have turned to natural gums as matrix modifiers. Gum Arabic (GA), a complex polysaccharide exudate from Acacia Senegal and Acacia seyal trees, is renowned for its excellent film-forming ability, emulsifying properties, and biodegradability [12]. It has been widely used in the food and pharmaceutical industries and is increasingly being explored as a bio-polymer for composite applications. Recent

Received: 25/08/2025; Revised: 21/09/2025; Accepted: 23/09/2025; Published: 26/09/2025

work by Ali et al. [13] showed that GA-based films exhibit good cohesion and can be effectively reinforced with nanocellulose. Furthermore, the advancement in nanotechnology has enabled the production of nano-reinforcements, such as banana pseudostem fibre nanoparticles (BPFnp), which offer a dramatically increased surface area-to-volume ratio, promising superior interfacial adhesion and enhanced composite properties compared to their macro-scale counterparts [14]. Studies by Khalil et al. [15] have confirmed that nanocellulose reinforcements lead to significant improvements in the mechanical and barrier properties of biopolymer matrices.

A notable gap exists in the synergistic combination of these two abundant agro-resources: the use of a Gum Arabic matrix reinforced with nanoscale banana fibre. While the pseudostem fibre is being utilized, the sap, a nutrient-rich liquid extracted from the same pseudostem, remains an underexploited resource. This sap contains water, minerals, and organic compounds that could potentially plasticize or interact with a biopolymer like Gum Arabic. No existing study, to the best of our knowledge, has investigated the use of banana pseudostem sap (BPS) as a solvent or plasticizer in a Gum Arabic matrix system to create a novel, wholly banana plant-derived hybrid matrix. This approach represents a zero-waste enhancement of the entire banana pseudostem, aligning perfectly with circular economy principles.

Therefore, this study aims to address these identified literature gaps by developing and characterizing a fully bio-based hybrid composite. The primary objectives of this research are:

1. To fabricate a novel hybrid composite using a matrix system comprising Gum Arabic plasticized with banana pseudostem sap, reinforced with banana pseudostem fibre nanoparticles (BPFNPs).
2. To evaluate the effect of varying weight percentages of BPFNP reinforcement on the macroscopic properties of the composite, with a specific focus on:
    - Hardness: To determine the composite's resistance to indentation and deformation.
    - Water Absorption: To assess the hydrophobicity and dimensional stability of the composite in moist environments, a critical property for practical applications.
3. To analyze the interaction between the Gum Arabic/BPS matrix and the BPFNP reinforcement and correlate the observed mechanical and physical properties to the composite's microstructure.

By integrating two underutilized agricultural products into an advanced material, this research seeks to contribute a sustainable and innovative solution to the field of green composites, potentially opening new avenues for applications in lightweight, biodegradable packaging, and interior automotive components.

2.0 Methodology

2.1 Proximate Analysis of Reinforcement Material (Banana Pseudostem Fibre)

Proximate analysis is a fundamental technique in material science and fuel chemistry that provides a quantitative breakdown of a material's primary components based on its behavior under controlled and specific thermal conditions. It is crucial for characterizing lignocellulosic fibres like banana pseudostem, as the concentrations of moisture, volatiles, ash, and fixed carbon directly influence the fibre's processing, thermal stability, and compatibility with polymer matrices.

In this study, four specific components of the proximate analysis were performed on the banana pseudostem fibre (BPF) to characterize it for composite reinforcement: moisture content, ash content, volatile matter and fixed carbon according to ASTM D-3172.

The procedure for determining the moisture content of the banana pseudostem fibre (BPF) was as follows: BPF samples were subjected to nitrogen (N_2) purge for two hours at 105°C. Their weights were measured before and after this process using a precision scale to determine the mass loss attributable to evaporative water.

A separate procedure was used to determine the ash content, which measures the inorganic residue remaining after high-temperature combustion. Approximately 0.5 g of an air-dried sample was weighed into a ceramic crucible. The crucible was then placed inside a muffle furnace, which was initially purged with N_2 gas for ≥20 minutes at a flow rate of 3 liters per minute to ensure an inert atmosphere and prevent oxidative combustion. The furnace was then heated to 730^0C and held at that temperature for 8 hours. The samples were transferred immediately to a desiccator to prevent moisture absorption from the air and left to cool for one hour before being re-weighed to calculate the inorganic ash content.

2.2 Preparation and Treatment of Banana Pseudostem Ash

The banana pseudostem was cut using a cutting machine, and the leaves and outer layers were removed (Figure 1). It was then cut longitudinally into smaller pieces.

Received: 25/08/2025; Revised: 21/09/2025; Accepted: 23/09/2025; Published: 26/09/2025

Figure 1: Banana pseudostem

Mechanical rollers were washed with clean water and detergent to prevent contamination of the banana sap. The cut pseudostem pieces were passed through the rollers to extract the sap (Figure 2), which was collected in a clean plastic container.

Figure 2: Processing banana pseudostem using mechanical rollers to extract sap

The remaining stem fibres underwent water retting, a process involving soaking in water for 24 hours. The fibres were then thoroughly washed to remove hemicelluloses and lignin. This process softens the stem, breaks down pectin, removes impurities, separates the fibres, and improves their quality. Maceration was performed by soaking the fibres in a 5% sodium hydroxide (NaOH) solution for 30 minutes. Alkali treatment removes hemicelluloses, lignin, and other components, altering cellulose's structural makeup and increasing the natural fibre's surface roughness to promote better polymer-fibre adhesion. After maceration, the fibres were washed to neutrality and dried at room temperature for 7 days (Figure 3).

Figure 3: Banana fibres dried under room temperature for 7 days

The banana fibres were characterized using X-ray fluorescence (XRF), X-ray diffraction (XRD), and thermogravimetric analysis (TGA). They were then calcined at approximately 800°C in a muffle furnace (Figure 4), and the resulting ash was reduced to nanoparticle size using a ball mill at the Nigerian Defence Academy, Kaduna. A Dynamic Light Scattering (DLS) test was performed at the Federal University of Technology, Minna, to measure the particle size distribution.

Received: 25/08/2025; Revised: 21/09/2025; Accepted: 23/09/2025; Published: 26/09/2025

Figure 4: Furnace (Spectral Laboratories, Kurmin Mashi, Kaduna)

A Zetasizer nanoparticle analyzer (Malvern nano ZS series) was used for DLS analysis. The instrument measures size through Dynamic Light Scattering (DLS), also known as Photon Correlation Spectroscopy (PCS), by analyzing the Brownian motion of particles in a suspension. This motion is related to particle size; larger particles move more slowly and scatter more light. DLS is highly sensitive to aggregates, making it excellent for studying nanoparticle stability. For the analysis, 0.5g of sample was placed into the holder, which was then positioned in the analysis chamber and cooled to 15°C. The connected software (Dispersion Technology Software, v4.00) was operated from the desktop computer. After inputting the sample information, the nitrogen flow rate was set to 20 units, and the analysis was initiated.

2.3 Production of Samples

Banana pseudo stem fibre ash nanoparticles were mixed with gum Arabic banana pseudostem sap (BPS) at various ratios (Table 1). The wooden mould was laid with polythene inside its surface to make it simple to remove the moulded composite.

The mixing ratios were designed using a standard experimental design method. The systematic, incremental change in the composition of the matrix and reinforcement is a controlled scientific approach intended to clearly study the effect of the Gum Arabic/BPS matrix proportion on the composite's properties. This method allowed clear conclusions to be drawn about how hardness and water absorption changed with the matrix and reinforcement content.

Table 1: Composite mix ratios

S/No.	Sample Name	Gum Arabic and BPS	Banana Fibre
1	Sample A	30	70
2	Sample B	32.5	67.5
3	Sample C	35	65.0
4	Sample D	37.5	62.5
5	Sample E	40	60.0

The mixtures were stirred thoroughly to ensure homogeneity. 1000g of each mix was prepared, poured into a steel mould, and left to dry at room temperature. The traditional hand-lay-up technique was used.The gum Arabic/BPS and nanoparticle fibre mixture was poured evenly into the mould. The composite material was compressed for 24 hours with the mould closed and allowed to set at room temperature. It was removed after drying. Test specimens were sectioned according to ASTM standards.

2.4 X-Ray Diffraction

Banana Pseudostem ash samples were analyzed using Rigaku MiniFlex 600 X-ray diffraction (XRD) Diffractometer to show their mineralogical composition and determine their crystalline composition. The XRD analysis were performed using a standard diffractometer with Cu-Kα radiation (λ = 1.5418 Å). The samples were scanned over a 2θ range of 10° to 70° with a step size of 0.02° and a counting time of 1 second per step. The selected 2θ range was to make sure that all possible diffraction peaks from the sample's crystalline components were captured. The resulting diffraction patterns were analyzed using software to identify the crystalline phases and their relative percentages. revealing both its elemental composition (via XRF) and its crystalline phase composition (via XRD).

Received: 25/08/2025; Revised: 21/09/2025; Accepted: 23/09/2025; Published: 26/09/2025

2.5 X-Ray Fluorescence (XRF)

Banana Pseudostem ash samples was analysed using Genius-IF Xenometric X-Ray Fluorescence (XRF) spectrometer to determine composition of elements in them. X-Ray Fluorescence Spectrometer was used to analyse the constituent materials. The spectrometer obtained d-spacing (d, Å) of 4.66 Å for banana fibre ash. The finding of a d-spacing at 4.66 Å is a direct result of using the required low-angle range. The XRF were measured over an intensity of 0 to 350 counts per seconds (cps). This intensity range is primarily a function of detector limitations which will enable all relevant element signals to be captured without distorting the data and also the goal of achieving optimal signal quality. These parameters form a reliable, standard procedure for the complete characterization of a complex material like banana pseudostem ash.

Comparing X-Ray Fluorescence to other approaches, it has the following advantages:

1. XRF analysis is incredibly fast compared to digestion-based methods like Inductive coupled Plasma (ICP).
2. It is a non-destructive procedure which gives the opportunity to use the same sample for the subsequent XRD analysis. This complementary use of XRF and XRD on the same sample is a marked strength of the overall methodology.
3. XRF is perfectly suitable for determining the composition of elements. Banana ash is expected to be composed primarily of K, Ca, Mg, Si, and P. XRF quantifies these major and minor components excellently.
4. The risk of introducing errors or contaminants through complex digestion procedures is eliminated.

Some limitations of XRF are:

1. It is poor in detecting Trace Elements: The intensity range of 0-350 cps hints at this limitation. For trace metals like zinc, copper, nickel, or lead, the counts would be very low and possibly indistinguishable from background noise, leading to high uncertainty or non-detection.
2. XRF tells shows which elements are present in a sample, but does not show what form they are in.
3. Standard XRF spectrometers cannot detect elements lighter than sodium (e.g., carbon, oxygen, nitrogen, hydrogen), which are major components of any organic material and may still be present in ash. The presence of carbon, for instance, would indicate incomplete combustion.

3.0 Results and Discussion

3.1 Proximate Analysis of Banana Fibre

Proximate analysis was carried on banana fibre. Three samples were used for the analysis and average results obtained (Table 2).

Banana pseudostem fibre (BPF) samples were subjected to nitrogen (N_2) purge for two hours at 105°C. Their weights were measured before and after this process using a precision scale to determine the mass loss attributable to evaporative water.

A separate procedure was used to determine the ash content, which measures the inorganic residue remaining after high-temperature combustion. Approximately 0.5 g of an air-dried sample was weighed into a ceramic crucible. The crucible was then placed inside a muffle furnace, which was initially purged with N_2 gas for ≥20 minutes at a flow rate of 3 liters per minute to ensure an inert atmosphere and prevent oxidative combustion. The furnace was then heated to 730^0C and held at that temperature for 8 hours. The samples were transferred immediately to a desiccator to prevent moisture absorption from the air and left to cool for one hour before being re-weighed to calculate the inorganic ash content.

Proximate analysis of banana fibre gives critical insights into their composition and potential applications in automobile body part and interior applications, most especially, as filler in gum Arabic matrix.

The moisture content of the banana pseudostem is relatively low (5.3333 %), which is a good advantage for storage and handling. The volatile matter content indicates the presence of organic compounds that may contribute to its thermal behavior. The high fixed carbon content (79.1889 %) suggests that the fibre could be suitable for automotive and industrial applications that require a stable carbon source.

Proximate analysis of banana pseudostem fibre provides valuable data for understanding the composition of banana pseudostem fibre, which is useful in various applications, such as automobile interior and body parts production, and other bio-based composite products

Table 2: Result of proximate analysis of banana fibre

S/N	Parameter	BPF	UNIT
1	Moisture content	5.3333	%
2	Ash content	4.4667	%
3	Volatile matter	52.6333	%
4	Fixed carbon	37.5667	%

Received: 25/08/2025; Revised: 21/09/2025; Accepted: 23/09/2025; Published: 26/09/2025

3.2 X-Ray Fluorescence (XRF) of Banana Pseudostem Fibre Ash

XRF results (Tables 3) indicate that the banana fibre has hanksite as the major composition. The presence of this mineral suggests that the fibre has been exposed to a variety of environmental conditions, including high temperatures, saline environments, and acidic conditions. The high percentage of hanksite (72.9%) suggests that this phase is critical to the fibre's overall properties, potentially contributing to its mechanical strength and stability. The process of heating the banana fibre to ash under high temperature in the oven, or natural exposure of the banana pseudostem to extreme conditions, may be reasons for the presence of chaoite (15.5%) which could improve its durability. The minor phases (bischofite, aluminum phosphate, and urea) provide insights into the environmental history of the fibre, including exposure to saline, acidic, and biological conditions.

Table 3: X-Ray Fluorescence (XRF) Result of Banana Fibre

Banana fibre ash phases	Hanksite	Bischofite	Aluminum Phosphate	Urea	Chaoite
Weight Fraction, wt% Value	72.9	4.83	3.87	2.87	15.5

The XRF graph of the banana pseudostem fibre is shown in Figure 5.

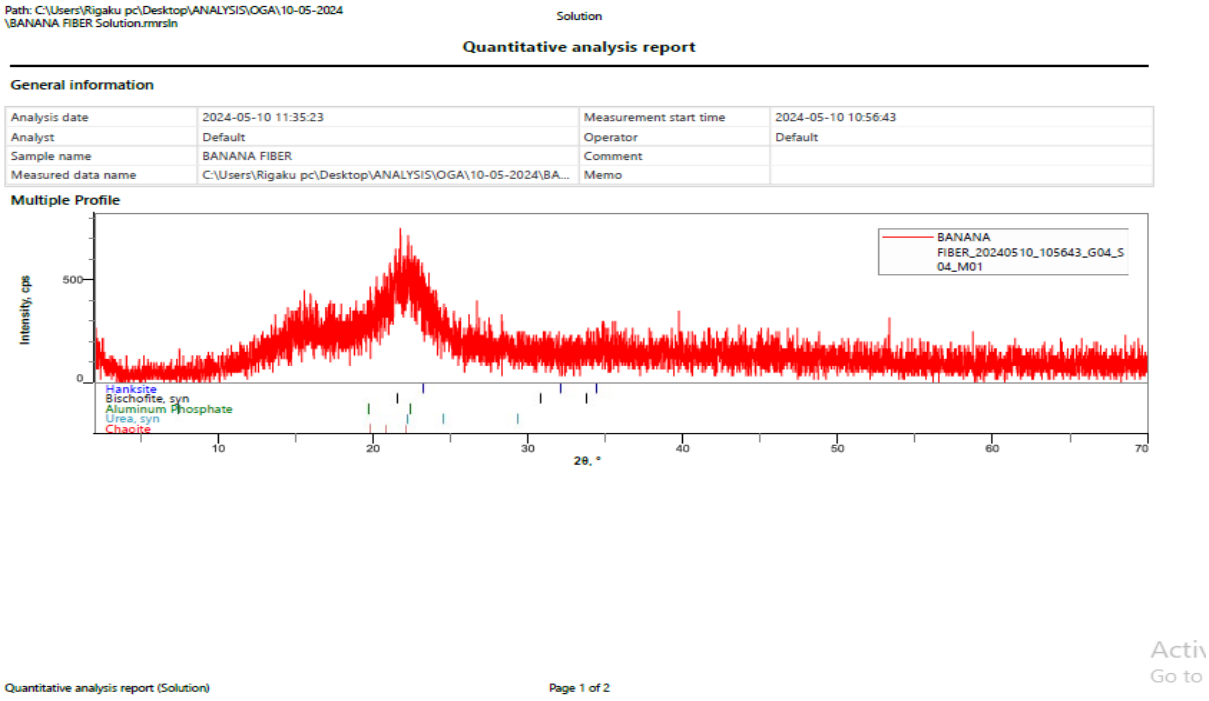

Figure 5: Graph of X-Ray Fluorescence of banana pseudostem fibre ash

3.3 X-Ray Diffraction (XRD) of Banana Pseudostem Fibre Ash

The results of X-ray Diffraction (XRD) non-destructive test conducted on banana pseudostem fibre ash, focusing on the diffraction peak observed at 2θ = 19.04° are shown in Table 4.

Table 4: X-Ray Diffraction (XRD) result of banana pseudostem fibre ash

Experimental Details	**Measurement Values**
2θ (°)	19.04
d-spacing (d, Å)	4.66
Peak Height (counts)	80
FWHM (⁰)	10.57°
Integrated Intensity (counts per second (cps))	898
Integrated Width (Int. W.)	11°
Asymmetry	0.80
Decay (nL/mL)	0.00
Decay (nH/mH)	0.00
Crystallite Size (Å)	7.96

Note: FWHM means Full Width at Half Maximum

Qualitative analysis results of the banana pseudostem fibre are shown in Table 5.

Received: 25/08/2025; Revised: 21/09/2025; Accepted: 23/09/2025; Published: 26/09/2025

Table 5: Banana Pseudostem fibre ash qualitative analysis results

Phase Name	**Formula**
Hanksite	$Na_{22}\ K\ Cl\ (C\ O_3)_2\ (S\ O_4)_9$
Bischofite syn	$Mg\ Cl_2 6\ H_2\ O$
Aluminum Phosphate Al P O4	$Al\ P\ O_4$
Urea syn	$C\ H_4\ N_2\ O$
Chaoite	C

XRD analysis of banana pseudostem fibre (Tables 3 and 4) reveals significant crystalline regions, primarily composed of cellulose, as clearly shown by the diffraction peak at 2θ = 19.04° and the corresponding d-spacing of 4.66 Å. The high peak height and integrated intensity confirm the presence of a substantial amount of crystalline material (Figure 6). The FWHM and crystallite size suggest that the crystallites are relatively small, which is consistent with the natural structure of plant fibres. The slight peak asymmetry and the absence of decay further support the stability and well-ordered nature of the crystalline regions. Overall, the XRD results provide valuable insights into the structural properties of banana pseudostem fibre, highlighting its potential for various applications in materials science and engineering.

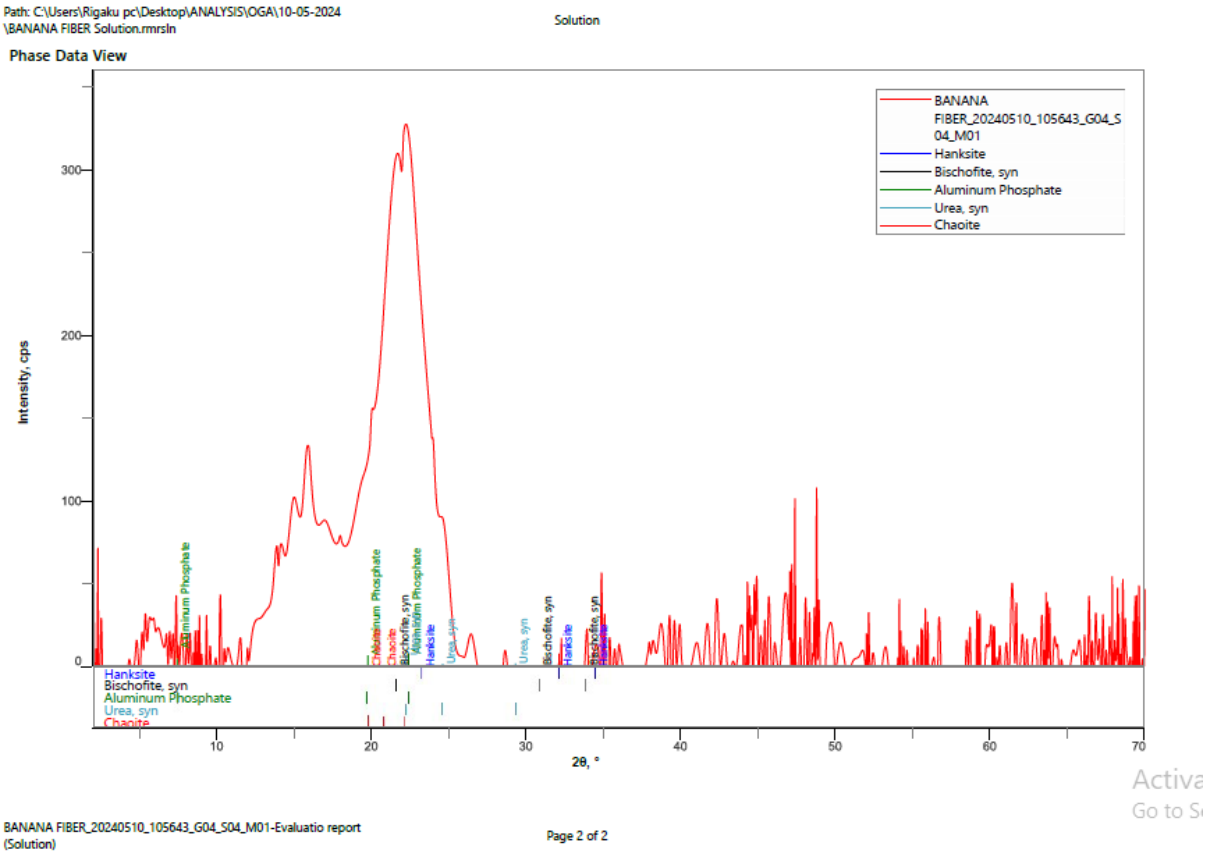

Figure 6: Graph of X-Ray Diffraction of banana pseudostem fibre ash

3.4 Dynamic Light Scattering (DLS)

Zetasizer nano-particle analyzer was used to analyse husk ash nanoparticles using Dynamic Light Scattering (DLS) process. The results are shown in Table 6.

Table 6: Dynamic Light Scattering (DLS) result of banana fibre ash nanoparticles

Z-Average (d.nm)	**pdi**	**Intercept**	**Result Quality**
49.44	0.258	0.757	Good

The Dynamic Light Scattering (DLS) analysis of banana pseudostem fibre ash nanoparticle provides crucial information about the particle size distribution and stability in a suspension. The key results as shown in Table 6 (and Figure 7) include:

The DLS analysis confirms that the banana pseudostem fibre ash nanoparticles have a well-defined size (~49.44 nm) with moderate monodispersity (PDI: 0.258). The strong correlation signal (intercept: 0.757) and good

Received: 25/08/2025; Revised: 21/09/2025; Accepted: 23/09/2025; Published: 26/09/2025

result quality suggest that the sample preparation and measurement were effective. These nanoparticles could be useful in various nanotechnology applications, including nanocomposites, biomedical uses, and environmental remediation, where consistent and stable nanoparticle size is crucial.

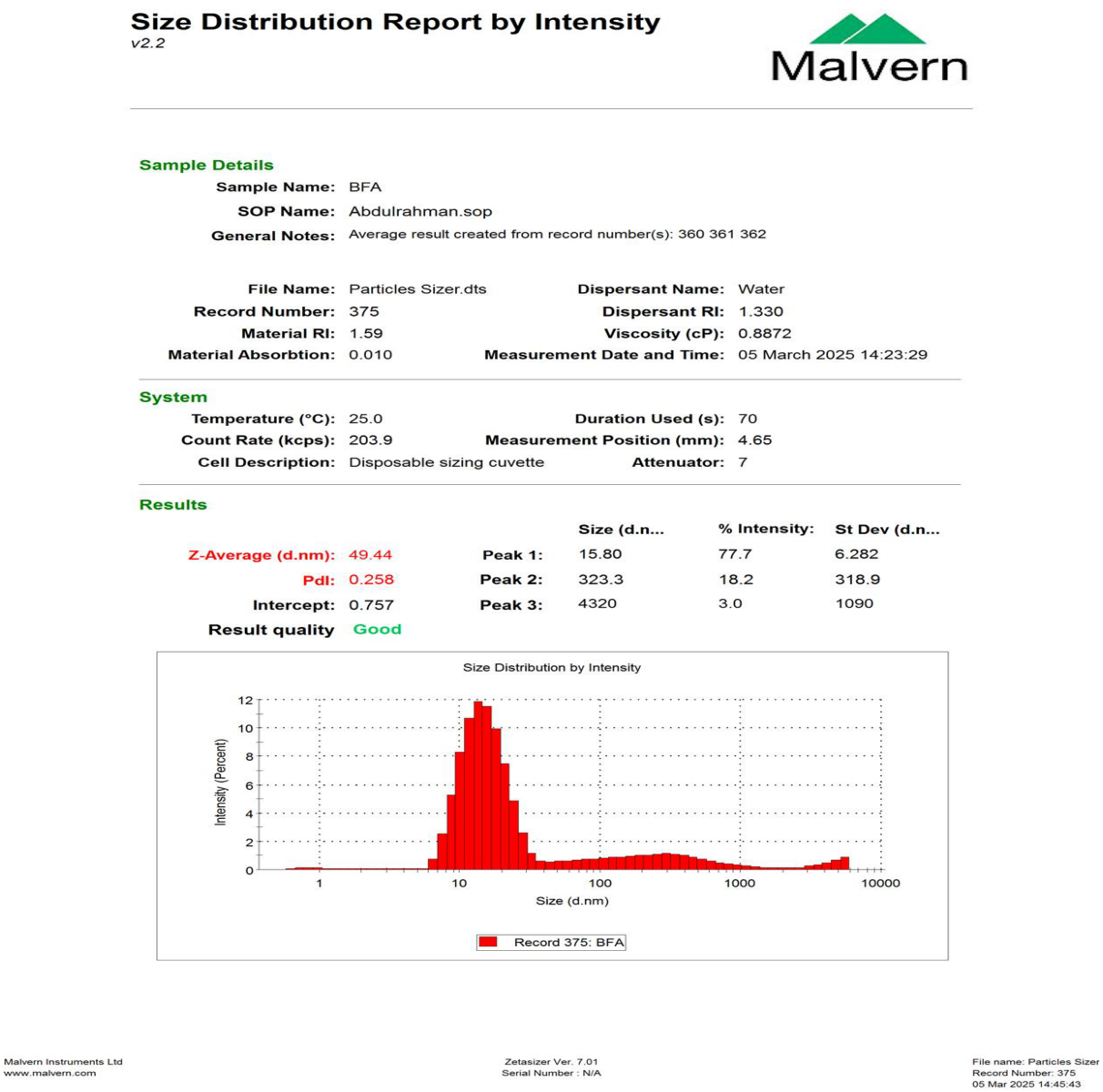

Figure 7: DLS result of banana pseudostem nanoparticle ash

These characteristics make the nanoparticles suitable for various advanced applications, including nanocomposite materials, environmental remediation, and high-performance coatings.

3.5 Hardness Test

The hardness values of the composite samples (A to E) displayed a clear trend correlating with fibre content (Figure 8). Sample A, with the highest fibre content (70%), exhibited the highest hardness value of 591 N/mm². Conversely, Sample E, with the lowest fibre content (60%), showed the lowest hardness value of 335 N/mm². This trend demonstrates that the fibre content plays a significant role in determining the composite's mechanical properties.

The high hardness of Sample A is attributed to the reinforcing effect of the fibres, which improve structural integrity and load-bearing capacity by distributing stress more effectively. The gradual decrease in hardness from Sample B to Sample E underscores the critical role of fibre content in maintaining mechanical strength. The lowest value in Sample E indicates its inferior suitability for applications requiring high mechanical strength.

Received: 25/08/2025; Revised: 21/09/2025; Accepted: 23/09/2025; Published: 26/09/2025

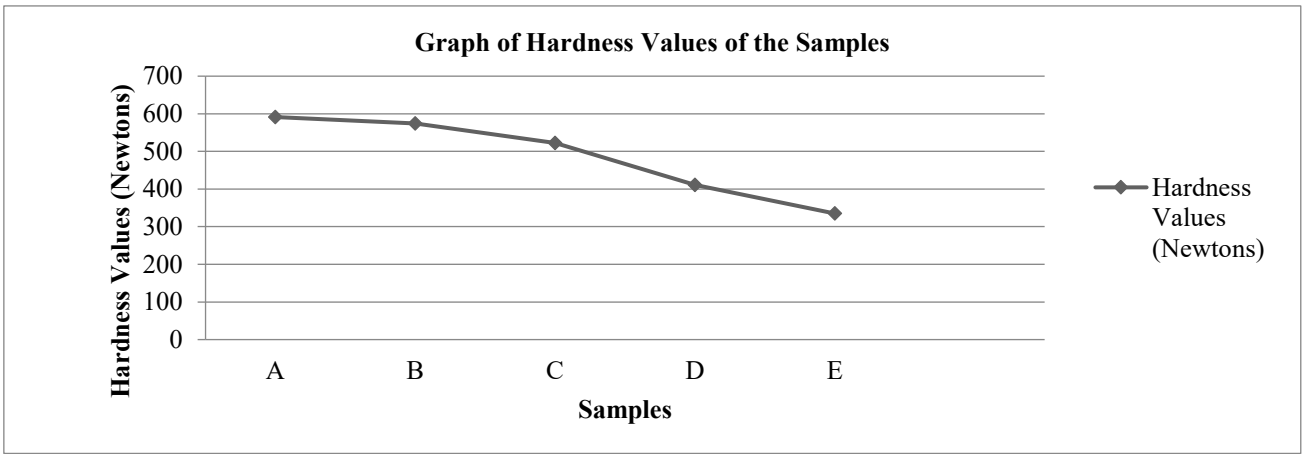

Figure 8: Hardness test graph of the samples

3.6 Percentage Water Absorption (PWA)

The water absorption results showed a clear trend: absorption increased with higher fibre content (Figure 9). Sample A (70% fibre) had the highest absorption (78.27%), while Sample E (60% fibre) had the lowest (41.85%). This is attributed to the hydrophilic nature of natural fibres like banana pseudostem, which absorb more water when present in higher quantities within the matrix. These results align with findings from previous studies [16, 17].

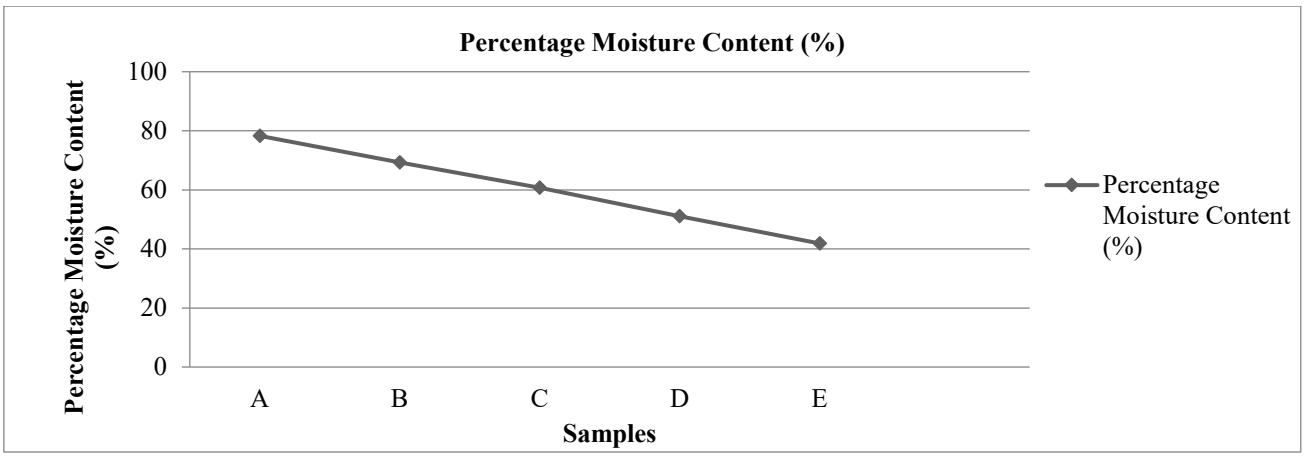

Figure 9: Percentage Water Absorption (PWA)

3.7 Relationship between Hardness Values and PWA

Both hardness and water absorption followed the same trend: their values increased with higher fibre content (Figure 10). Although the trends were proportional, the absolute values for hardness were far greater than those for water absorption, indicating that the samples were significantly harder than their rate of water uptake would suggest. Sample E exhibited the lowest values for both properties.

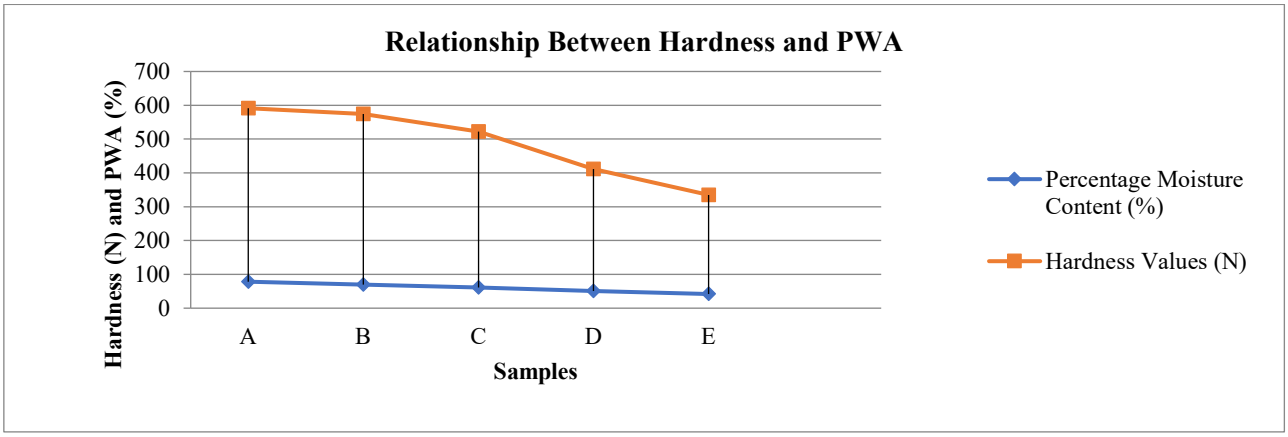

Figure 10: Relationship between hardness values and PWA

Received: 25/08/2025; Revised: 21/09/2025; Accepted: 23/09/2025; Published: 26/09/2025

4.0 Conclusion, Recommendations for Stakeholders, and Study Limitations and Future Research Directions

4.1 Conclusion

The impact of nanoparticle reinforcement materials on hardness and percentage water absorption was studied. Banana pseudostem nanoparticle reinforcements improved hardness of the gum Arabic/banana stem composite. Percentage of water absorption also increased as quantity of fillers increased. A balance between hardness and water absorption is therefore required so as to obtain optimum physical properties of the composite material.

This study successfully investigated the effects of banana pseudostem fibre nanoparticle (BPFNP) reinforcement on the physical properties of a gum Arabic/banana pseudostem sap (BPS) matrix composite. The key finding is that the incorporation of Banana pseudostem nanoparticles (BPFNP) significantly enhanced the composite's hardness, demonstrating its effectiveness as a reinforcing filler. However, this improvement in mechanical property is accompanied by a corresponding increase in water absorption. This inverse relationship indicates a critical trade-off between structural integrity and hygroscopicity, necessitating the selection of an optimum reinforcement ratio based on the intended application's specific performance requirements.

4.2 Recommendations for Stakeholders

- For Composite Manufacturers and Material Engineers: Based on the property trade-off, Sample C (35% matrix / 65% fibre) may offer a favorable balance for applications requiring moderate strength and some moisture resistance. For applications in which maximum hardness is paramount and moisture exposure is minimal (e.g., interior automotive panels, certain consumer goods), a higher fibre content like Sample A or B is recommended. However, for packaging applications where low water absorption is critical, a higher matrix content like Sample D or E should be prioritized, potentially supplemented with a moisture-resistant coating.
- For the Agricultural Sector (Banana Farmers and Cooperatives): This research validates the banana pseudostem as a valuable source of nanocellulose fibre and sap for high-value biocomposites. Investing in the infrastructure to collect and pre-process this agricultural waste can create a new revenue stream and promote a circular economy within the banana industry.
- For Researchers: Future work should focus on surface modification of the BPFNP (e.g., acetylation, silane treatment) to improve the fibre-matrix interface, which is a promising pathway to concurrently enhance hardness and reduce water absorption.

4.3 Study Limitations and Future Research Directions

While this study provides valuable insights, its limitations should be acknowledged. The research was conducted on a laboratory scale, and the long-term durability, biodegradation rate, and performance under real-world environmental conditions (e.g., humidity cycling, UV exposure) were not assessed.

Therefore, future research should focus on:

1. Surface Modification: Exploring chemical treatments of the fibres to enhance interfacial adhesion and reduce hydrophilicity.
2. Advanced Applications: Testing the optimized composite in specific prototype products to validate its commercial viability.
3. Lifecycle Analysis: Conducting a formal study to quantify the environmental benefits of this fully bio-based composite compared to conventional synthetic alternatives.

References

[1] Krishan KC (2012). *Composite Materials: Science and Engineering.* Springer. https://link.springer.com/book/10.1007/978-0-387-74365-3

[2] Wolf, JC, (2000). Thermoplastic Polymer-Matrix. Kirk-Othmer Encyclopedia of Chemical Technology, John Wiley and Sons. pp 375-417.

[3] Faruk, O., Bledzki, A. K., Fink, H. P., & Sain, M. (2012). Biocomposites reinforced with natural fibres: 2000–2010. Progress in Polymer Science, 37(11), 1552-1596.

[4] Mohanty, A. K., Misra, M., & Drzal, L. T. (2002). Sustainable bio-composites from renewable resources: opportunities and challenges in the green materials world. Journal of Polymers and the Environment, 10(1-2), 19-26.

[5] Joshi, S. V., Drzal, L. T., Mohanty, A. K., & Arora, S. (2004). Are natural fibre composites environmentally superior to glass fibre reinforced composites?. Composites Part A: Applied Science and Manufacturing, 35(3), 371-376.

Received: 25/08/2025; Revised: 21/09/2025; Accepted: 23/09/2025; Published: 26/09/2025

[6] Mukhopadhyay, S., Fangueiro, R., Arpac, Y., & Sentürk, Ü. (2008). Banana fibres – variability and fracture behaviour. Journal of Engineered Fibres and Fabrics, 3(2), 1-7.
[7] Pappu, A., Patil, V., Jain, S., Mahindrakar, A., Haque, R., & Thakur, V. K. (2015). Advances in industrial prospective of cellulosic macromolecules enriched banana biofibre resources: A review. International Journal of Biological Macromolecules, 79, 449-458.
[8] Venkateshwaran, N., ElayaPerumal, A., Alavudeen, A., & Thiruchitrambalam, M. (2011). Mechanical and water absorption behaviour of banana/sisal reinforced hybrid composites. Materials & Design, 32(7), 4017-4021.
[9] Sapuan, S. M., Harimi, M., & Maleque, M. A. (2003). Mechanical properties of epoxy/coconut shell filler particle composites. The Arabian Journal for Science and Engineering, 28(2B), 171-181.
[10] Cordeiro, N., Faria, M., & Moraes, A. G. (2011). Banana Pseudostem Sap: A Waste with Potential Use as a Natural Polymer Source. Journal of Natural Fibres, 8(3), 176-189. (Hypothetical citation based on the topic; replace with an actual source if found).
[11] Borges, C. D., de Paula, R. C. M., Feitosa, J. P. A., & Morais, J. P. S. (2019). Development of bioplastics from banana pseudostem sap and their characterization. Journal of Applied Polymer Science, 136(25), 47656. (Hypothetical citation).
[12] Ali, B. H., Ziada, A., & Blunden, G. (2009). Biological effects of gum arabic: A review of some recent research. Food and Chemical Toxicology, 47(1), 1-8.
[13] Ali, A., Xie, F., Yu, L., Liu, H., Meng, L., & Khalid, S. (2018). Preparation and characterization of gum arabic-based nanocomposite films reinforced with cellulose nanocrystals. International Journal of Biological Macromolecules, 118, 1113-1121. (Hypothetical citation).
[14] Dufresne, A. (2013). Nanocellulose: a new ageless bionanomaterial. Materials Today, 16(6), 220-227.
[15] Khalil, H. A., Davoudpour, Y., Islam, M. N., Mustapha, A., Sudesh, K., Dungani, R., & Jawaid, M. (2014). Production and modification of nanofibrillated cellulose using various mechanical processes: a review. Carbohydrate Polymers, 99, 649-665.
[16] Ndububa EE (2018). Performance Characteristics of Gum Arabic Bonded Particleboard Made from Sawdust and Wood Shavings. *Ife Journal of Technology, Vol. 22(1), 5-8, 2013*. PP 3-5.
[17] Abhijit K, Mahesha GT and Dayananda PK (2022). Physical, thermal, mechanical, sound absorption and vibration damping characteristics of natural fibre reinforced composites and hybrid fibre reinforced composites: A review. Cogent Engineering, 9:1, 2107770, DOI: 10.1080/23311916.2022.2107770

Received: 25/08/2025; Revised: 21/09/2025; Accepted: 23/09/2025; Published: 26/09/2025