
MOISTURE-DEPENDENT ENGINEERING PROPERTIES OF BEEDI BAMBARA GROUNDNUT (*VIGNA SUBTERRANEA* (L.) VERDC.) FOR POST-HARVEST PROCESSING DESIGN

**Abdullahi Saeed Hassan^{1,*}, Aminu Mohammed¹, Jamilu. M. Ahmed¹, Bala Gambo
Jahun¹, Danladi Drambi Usman¹, Abdulwahab D. Ismail¹, Lawan Garba Abubakar¹**

¹*Abubakar Tafawa Balewa University*

Email: ashassan@atbu.edu.ng, aminu@atbu.edu.ng, jamilu@atbu.edu.ng, bala@atbu.edu.ng, jahun@atbu.edu.ng, usman@atbu.edu.ng, ismail@atbu.edu.ng, lawan@atbu.edu.ng

*Corresponding author: Abdullahi Saeed Hassan

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ABSTRACT

The engineering properties of agricultural produce are fundamental to designing and optimizing post-harvest handling, sorting, processing, and storage machinery. This study investigated the physical and mechanical properties of the Beedi Bambara groundnut (*Vigna subterranea* (L.) Verdc.), a prominent regional cultivar from Bauchi State, Nigeria, as a function of moisture content ranging from 5.0% to 35.0% (wet basis). Over this moisture range, the average linear dimensions—length, width, and thickness increased from 10.3 to 14.3 mm, 9.49 to 11.65 mm, and 8.50 to 10.90 mm, respectively. The geometric mean diameter expanded from 9.64 to 12.54 mm. Volumetric characteristics, including surface area (245.8 to 390.2 mm²), seed volume (358.1 to 703.1 mm³), and 1,000-grain mass (500.2 to 810.5 g), exhibited strong positive correlations with moisture content, with the 1,000-grain mass increasing linearly ($R^2 = 0.9987$). Conversely, bulk and true densities decreased non-linearly from 1.30 to 1.08 g/cm³ and 1.32 to 1.18 g/cm³, respectively, indicating that the seed kernel's volumetric expansion outpaced its mass accumulation. Porosity and the dynamic angle of repose varied nonlinearly, peaking at 45.8% and 24.1°, respectively, near 20% moisture content before tapering at higher moisture levels. The static coefficient of friction increased significantly across all structural contact surfaces tested, showing the highest friction on plywood (0.38 to 0.66), followed by galvanized iron (0.30 to 0.52) and aluminum (0.25 to 0.48). These findings show that the engineering parameters of the Beedi cultivar are highly sensitive to moisture changes, establishing a foundational database for developing localized cracking, cleaning, and storage equipment.

Keywords: Beedi variety; *Vigna subterranea*; physical properties; mechanical properties; structural surfaces; geometric mean diameter

1 INTRODUCTION

Bambara groundnut (*Vigna subterranea* (L.) Verdc.) is an indigenous African legume and the third most important grain legume in semi-arid Africa, after cowpea and peanut (Hillocks et al., 2012). Valued for its exceptional climate resilience, high drought tolerance, and capacity to yield on nutrient-poor soils where other crops fail, it plays a vital role in food security throughout sub-Saharan Africa (Mayes et al., 2019). Nutritionally, the crop represents a "complete food," containing roughly 19–25% crude protein, 60–65% carbohydrates, and 5–7% fats, making it a critical protein source for low-income populations (Kaptso et al., 2016; Ojo & Ade-Omowaye, 2015). In Nigeria, cultivation is highly concentrated across semi-arid belts, including major producing hubs in Kano, Plateau, Sokoto, Bauchi, and Benue states. Among these, the "Beedi" cultivar represents a distinct, heavily cultivated variety in Bauchi State characterized by specific kernel configurations and uniform light-brown mottling.

Despite its vast agronomic potential and increasing industrial demand for commercial composite meals, flours, and food matrices, processing remains a critical bottleneck (Olapade & Adetuyi, 2007). Bambara groundnut pods are notoriously tough, rigid, and resistant to mechanical failure. Consequently, post-harvest shell-cracking and decortication within regional farming communities rely almost exclusively on laborious, archaic practices. These traditional methods include manual crushing with a pestle and mortar, pounding pods with heavy wooden sticks on bare ground, or breaking them individually with stones (Ojediran, 2008). Such operations not only display low throughput and excessive drudgery but also cause severe mechanical impact injuries to the internal

cotyledons. This seed damage undermines product quality, escalates microbial vulnerability, and severely lowers the germination rate of saved seed lots.

To transition from primitive post-harvest techniques to automated, mechanized systems, engineers must establish a precise understanding of the crop's moisture-dependent engineering properties (Altuntas & Demirtola, 2007). Physical attributes, such as axial spatial dimensions, geometric mean diameter, shape profiles, and surface areas, dictate optimal screen clearances in cleaner-separators and the dimensional configurations of decorticating chambers (Mohsenin, 1986). Gravimetric properties, including bulk density, true density, and internal porosity, influence structural weight estimates for bulk silos, depth boundaries for drying aeration fans, and thermal behavior profiles during rehydration processing (Mpotokwane et al., 2008). Concurrently, mechanical behaviors such as the static coefficient of friction with common structural materials (e.g., plywood, galvanized iron, and aluminum) and the angle of repose govern the slope configurations of gravity-fed hoppers, discharge chutes, and aggregate transport conveyors (Baryeh, 2001).

Because agricultural seeds absorb and desorb moisture dynamically throughout harvesting, handling, and storage cycles, their structural matrices swell, their surface textures change, and their weight varies. While baseline engineering profiles have been recorded for general Bambara groundnuts originating from specific geographic zones (Baryeh, 2001; Mpotokwane et al., 2008), data directly focusing on localized West African varieties, such as the Beedi cultivar, remain scarce.

Therefore, this study establishes the moisture-dependent physical and mechanical properties of the Beedi Bambara groundnut variety over a broad, processor-relevant moisture spectrum of 5.0% to 35.0% (wet basis). The resulting quantitative relationships will provide the structural data required to model and fabricate efficient, high-capacity post-harvest processing machinery.

2 MATERIALS AND METHODS

2.1 Sample collection and preparation

The test material comprised the Beedi variety of Bambara groundnut (*Vigna subterranea* (L.) Verdc.), procured locally from Muda Lawal Market within the Bauchi metropolis, Nigeria. The initial moisture content of the seeds was 14.0% (wet basis), determined using the ASABE standard oven-drying method for legumes (ASABE, 2012). We conducted botanical identification and authentication at the Bauchi State Agricultural Development Program (BADP). While these samples provide a robust baseline, sourcing from a single commercial market lot may not capture the full natural field variability of the cultivar across different harvest seasons and microclimates. Before the experiment, we manually cleaned the seed lots to remove foreign matter, dust, and defective (broken, split, or deformed) kernels.

To evaluate engineering properties across a post-harvest-relevant moisture spectrum (5.0% to 35.0% wet basis), samples were conditioned using standard hydration and dehydration procedures (Baryeh, 2001; Nkambule et al., 2023). To attain higher moisture levels, a calculated amount of distilled water was added to the samples based on Equation 1 (Balasubramanian, 2001; Sanchez et al., 2024):

$$Q = \frac{W_i(M_f - M_i)}{100 - M_f} \quad (1)$$

Where (Q) is the mass of water added (kg), (W_i) is the initial sample mass (kg), (M_i) is the initial moisture content (% wb), and (M_f) is the desired final moisture content (% wb). Samples were hermetically sealed in polyethylene bags and stored at 5°C for 7 days to ensure uniform moisture distribution. For moisture levels below 14%, samples were progressively desorbed using a vacuum oven until the target moisture was reached (Saeed et al., 2022).

2.2 Measurement of physical and dimensional characteristics

For each targeted moisture level, the three principal spatial dimensions—length (L), width (W), and thickness (T) were randomly measured on 100 seeds using a precision Vernier caliper (0.001 mm accuracy) (Figure 1).

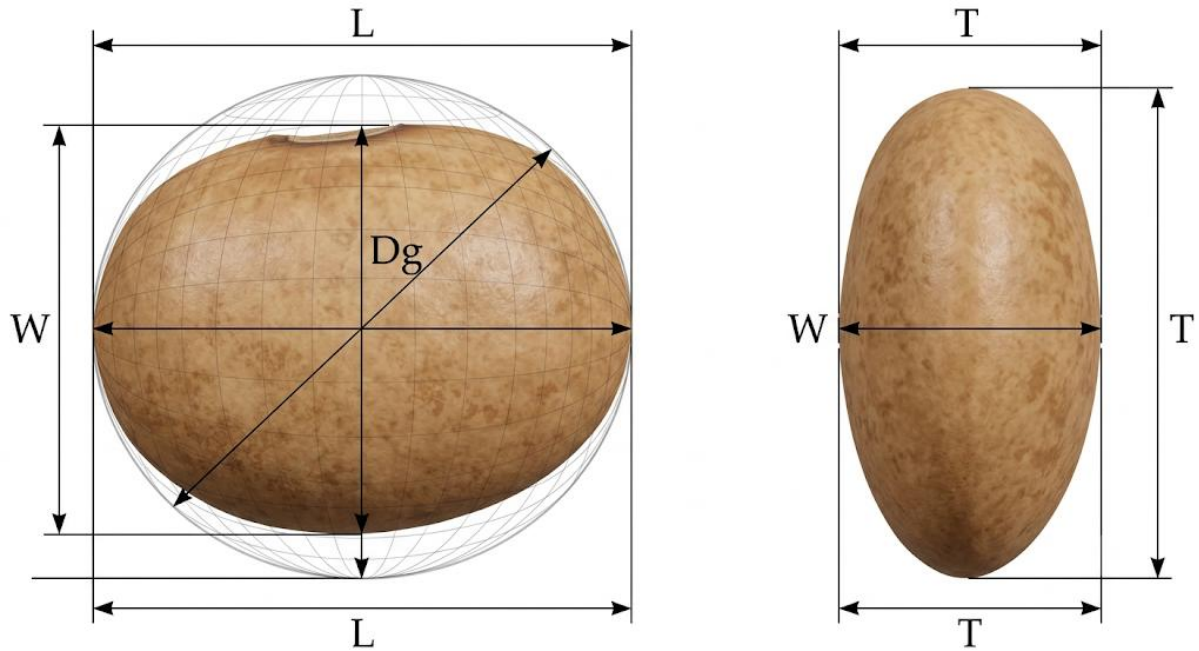


Figure 1: Conceptual presentation of the major dimensions of the Bambara seed.

The geometric mean diameter (D_g) was calculated utilizing Equation 2 (Mohsenin, 1986):

$$D_g = (LWT)^{1/3} \quad (2)$$

To evaluate the shape of the Beedi nuts, the degree of sphericity was calculated as defined by Jain and Bal (1997) and Mohsenin (1986), (Equation 3):

$$\phi_e = \frac{(LWT)^{1/3}}{L} \quad (3)$$

The surface area (S) and grain volume (V) of the seeds were mathematically derived using established theoretical frameworks for agricultural materials (Ayodele & Beatrice, 2015; Baryeh, 2001; Mpotokwane et al., 2008):

$$S = \pi D_g^2 \quad (4)$$

$$V = \frac{\pi B^2 L^2}{6(2L - B)} \quad (5)$$

(where $B = \sqrt{WT}$)

2.3 Gravimetric properties: mass, density, and porosity

The 1,000-seed mass was determined by randomly selecting 100 seeds, weighing them on a high-precision electronic analytical balance (0.001 g sensitivity), and multiplying the result by 10 to obtain the 1,000-seed equivalent mass (Kaptso et al., 2016).

True density (ρ_t) was evaluated using toluene displacement under a fume hood, with appropriate personal protective equipment, and disposed of according to environmental safety guidelines. (Mohsenin, 1986). Bulk density (ρ_b) was quantified by filling a standardized cylindrical container of known volume with seeds from a height of 150 mm and weighing the contents.

Subsequently, the inter-granular porosity (ε), which represents the percentage of void space within the bulk grain, was computed mathematically using Equation 6 (Altuntas & Demirtola, 2007):

$$\varepsilon = \left(1 - \frac{\rho_b}{\rho_t}\right) \times 100 \quad (6)$$

2.4 Evaluation of mechanical and frictional properties

The dynamic angle of repose (θ) was measured using a custom-built wooden cuboid apparatus (300×300×300 mm) with a rapid-release front panel (Galedar et al., 2010). Conditioned kernels were loaded into the chamber; when the front panel was quickly removed, the grains cascaded to form a natural slope. The angle was geometrically calculated based on the height (H) and diameter (D) of the resulting grain pile using Equation 7:

$$\theta = \tan^{-1} \left(\frac{2H}{D} \right) \quad (7)$$

The static coefficient of friction (μ) was determined against three common structural materials (plywood, galvanized iron, and aluminum sheet). A customized bottomless metallic cylinder (50 mm diameter and 50 mm height) was filled with seeds and positioned slightly above an adjustable tilting test surface. The plane was incrementally inclined using a calibrated screw mechanism until the cylinder began to slide. The static friction coefficient was calculated using Equation 8, where α is the angle of tilt at the point of kinetic initiation (Baryeh, 2001):

$$\mu = \tan \alpha \quad (8)$$

All physical, gravimetric, and mechanical tests were performed in quintuplicate (five replicates) at each moisture level to ensure statistical reliability, and the mean values were recorded.

2.5 Statistical Analysis

The data were subjected to a One-Way Analysis of Variance (ANOVA) using OriginPro 2026 software. Where significant differences were observed, mean separations were performed using Duncan's Multiple Range Test at a 95% confidence level ($p < 0.05$) to establish statistical groupings.

3 RESULTS AND DISCUSSION

3.1 Effect of moisture content on grain dimensions

The variations in the principal axial dimensions—length (L), width (W), thickness (T), and geometric mean diameter (D_g)—of the Beedi Bambara nuts concerning moisture content are presented in Figure 2A. The data reveal that all physical dimensions increased as the moisture content rose from 5.0% to 25.0% (wet basis), after which no significant dimensional changes were observed. This dimensional plateau can be attributed to the cellular architecture of the cotyledons; as the seeds absorb moisture, the internal air voids are progressively displaced by water until structural saturation is achieved at approximately 25% moisture. These findings align with hydration behaviors reported for other legumes, such as soybeans (Deshpande et al., 1993) and other Bambara groundnut varieties (Baryeh, 2001; Nkambule et al., 2023), confirming that mechanical decorticator clearance settings must account for this maximum expansion to prevent kernel damage during processing.

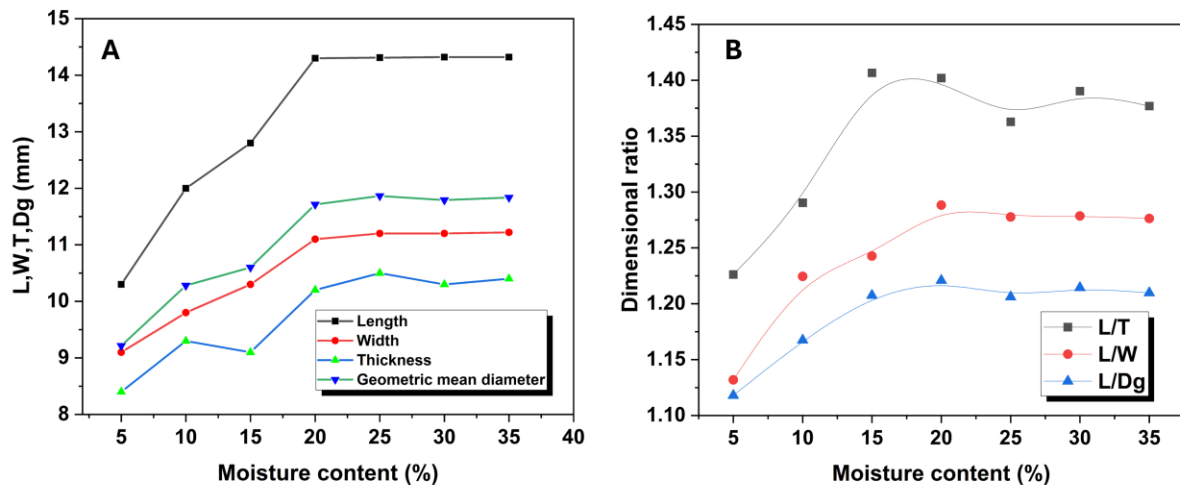


Figure 2: B illustrates the variation in the dimensional ratios (L/W , L/T , and L/D_g). As corroborated by the absolute spatial measurements in Figure 2A, the L/T ratio showed the highest values, confirming that thickness remains the smallest spatial dimension as the seed expands, followed by width and geometric diameter. These ratios increased as moisture content rose to 25% but subsequently decreased. The observed ratios for the Beedi variety were generally lower than those reported by Baryeh (2001), suggesting that the Beedi cultivar has a more uniform, compact morphological profile than other West African landraces.

Figure 2: Variation of the dimensions and dimensional ratios with moisture content.

3.2 Sphericity, surface area, and grain volume

Figure 3: A depicts the influence of moisture content on the degree of sphericity. Notably, the shape assumption heavily dictated the outcome; the equation assuming an elliptical shape yielded lower sphericity values (ranging from 0.895 at 5% to 0.840 at 35% moisture content). Because the true morphology of Bambara groundnuts is closer to an elliptical sphere, the model more accurately represents the Beedi variety. The slight decrease in sphericity with hydration indicates asymmetrical swelling, making the kernel slightly more elongated at higher moisture levels.

Figures 3B and 4A show that both surface area and grain volume increased substantially with moisture up to 25%, then plateaued. This non-linear expansion supports findings by Baryeh (2001) for Bambara groundnuts, though it contrasts with Deshpande et al. (1993), who reported a strictly linear increase in soybean surface area. This difference may be due to the more rigid and restrictive seed coat of the Bambara nut, which limits structural stretching compared with the more elastic testa of soybeans.

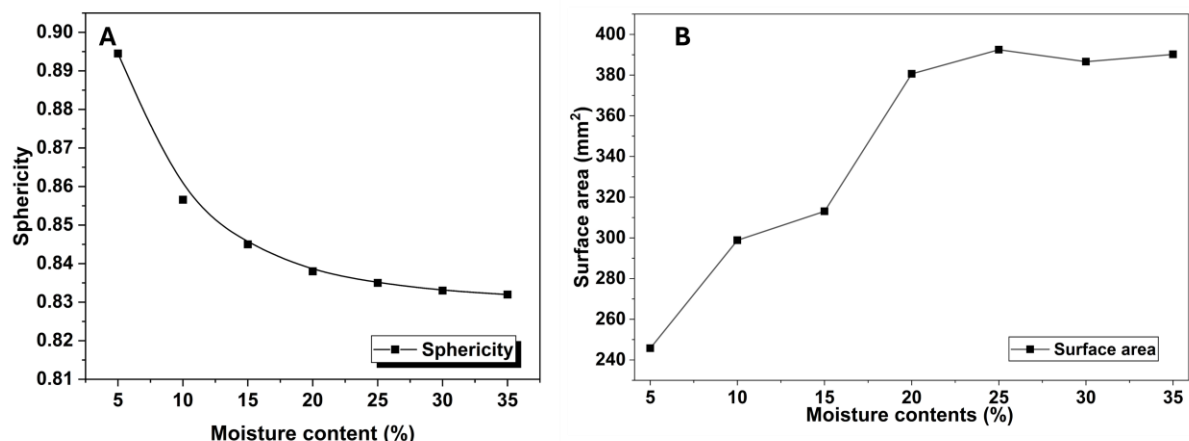


Figure 3: Variation of Sphericity (A) and surface area (B) with moisture content.

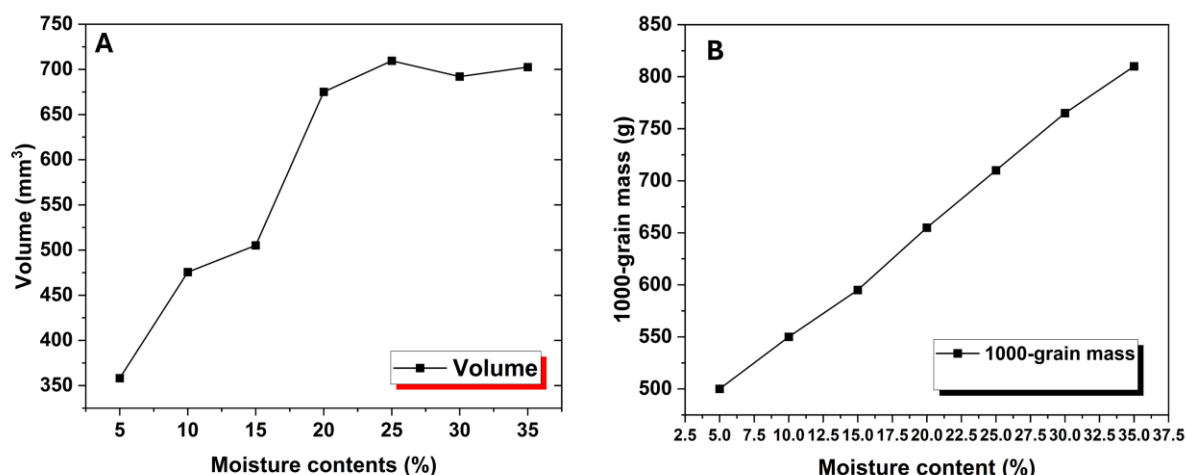


Figure 4: Variation of volume (A) and 1000-grain mass (B) with moisture content.

3.3 Gravimetric properties: mass, density, and porosity

The 1,000-grain mass exhibited a highly positive linear correlation with moisture content, as shown in Figure 4B. This variation is mathematically modeled as:

$$Y = 448 + 10.53M \quad (R^2 = 0.9987).$$

Where Y represents the 1,000-grain mass (g), and M is the moisture content (%).

This predictable mass accumulation is consistent with established literature across various seeds, including cumin, soybeans, and coffee (Aviara et al., 1999; Chandrasekar & Viswanathan, 1999). Conversely, as illustrated in Figure 5A, both bulk density and true density decreased non-linearly as moisture content increased from 5.0% to 35.0% (bulk density dropping from 1.30 to 1.08 g/cm³, and true density from 1.32 to 1.18 g/cm³). This inverse relationship occurs because the seed structure expands volumetrically faster than it gains mass from moisture absorption. While this agrees with the behaviors of soybeans and some Bambara varieties (Polat et al., 2006; Nkambule et al., 2023), it contradicts the behavior of pumpkin and karingda seeds, where densities increase with moisture (Joshi et al., 1993; Suthar & Das, 1996). We theorize that this discrepancy is fundamentally linked to the unique starch-protein matrices of individual species; seeds with higher initial porosity experience more pronounced volumetric swelling, driving the overall density downward.

The porosity of the Beedi nuts (Figure 5B) displayed a parabolic trend, initiating at 40.0%, peaking at 45.8% (around 20% moisture), and then declining to 42.5% at higher moisture levels. This non-linear response contradicts the strictly linear decreases or increases often reported in existing literature for other crops. The initial rise in porosity indicates that bulk density decreases faster than true density at lower moisture levels. However, as the seeds approach saturation (past 20%), they swell and become more pliable, packing more tightly under their own weight and reducing inter-granular void spaces.

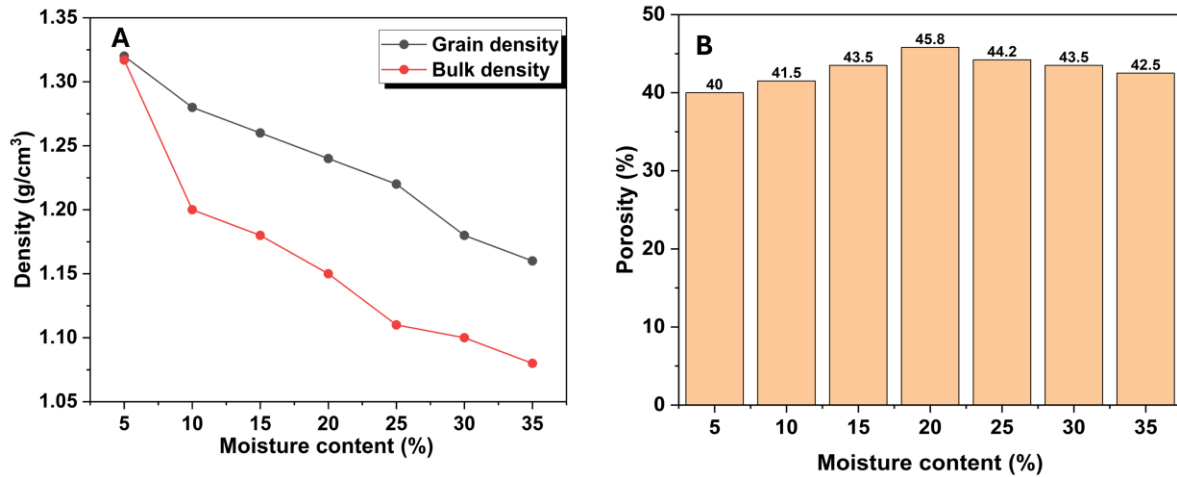


Figure 5: Variation of density (A) and porosity (B) with moisture content.

3.4 Mechanical and frictional properties

The dynamic angle of repose is a critical parameter for designing hopper slopes. As shown in Figure 6A, it increased from 20.0° at 5% moisture to a peak of 24.1° at 20% moisture, then slightly decreased to 21.5° at 35% moisture. This initial increase indicates higher inter-particle cohesion and flow resistance as the seed surfaces transition from dry to damp. The subsequent decrease at maximum moisture may be due to the lubricating effect of surface free water.

Figure 6: B depicts the variation of the static coefficient of friction against different structural surfaces. Across all moisture levels, friction was significantly highest on plywood (0.38 to 0.66), followed by galvanized iron (0.3 to 0.52), and lowest on aluminum sheet (0.25 to 0.48). The coefficient increased rapidly between 5% and 15% moisture content, then leveled off. We agree with the mechanisms proposed by Gupta and Das (1998) and Baryeh (2001): smoother, polished surfaces such as aluminum naturally offer less resistance than porous, rough materials such as plywood. Furthermore, as moisture increases, exudate creates adhesive capillary forces between the kernel and the contact surface, thereby elevating frictional resistance. Consequently, processing machinery, particularly discharge chutes, should utilize aluminum or polished galvanized steel to maintain unhindered grain flow and prevent blockages at higher moisture states.

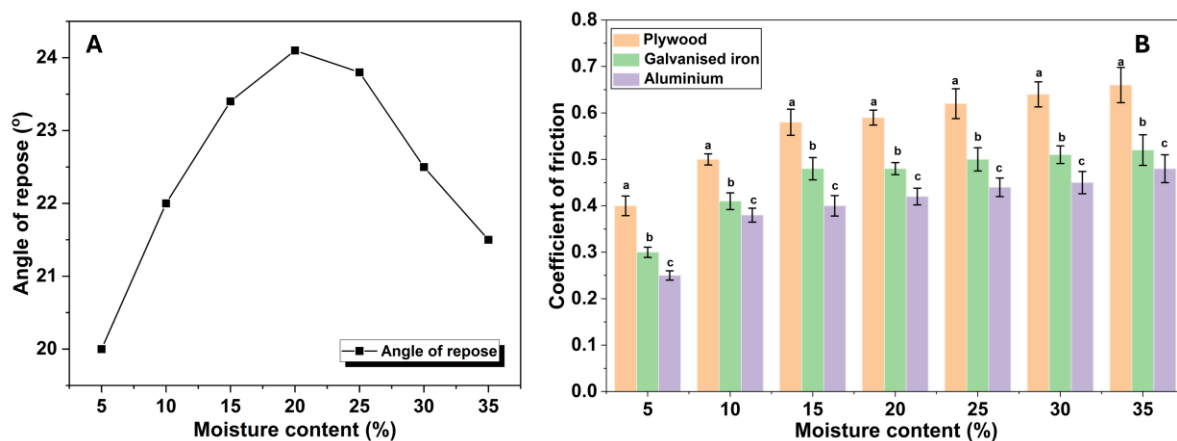


Figure 6: Variation of angle of repose (A) and coefficient of friction against different surfaces (B) with moisture content.

4 CONCLUSION

The study evaluated the engineering properties of the Beedi variety of Bambara groundnut (*Vigna subterranea* (L.) Verdc.) from Bauchi State, Nigeria, across a post-harvest moisture range of 5.0% to 35.0% (wet basis). The findings indicate that the principal linear dimensions (length, width, and thickness), geometric mean diameter, surface area, and grain volume all exhibit a non-linear expansion as moisture content rises. Regarding gravimetric properties, the 1,000-seed mass

demonstrated a strictly positive linear correlation with moisture accumulation. Conversely, both bulk density and true density decreased non-linearly, though true density consistently remained higher than bulk density across all hydration levels. Furthermore, seed flow behavior characterized by inter-granular porosity and the dynamic angle of repose increased to a peak value before declining with further moisture absorption. Mechanically, the static coefficient of friction increased significantly with moisture content across all tested structural surfaces, with plywood offering the highest frictional resistance, followed by galvanized iron and aluminum. Ultimately, these moisture-dependent quantitative parameters provide the essential baseline data required for the optimal design, structural development, and operational adjustment of handling, decorticating, sorting, and processing machinery. By enabling local equipment innovation, this dataset directly supports sustainable agro-material processing and resource utilization strategies.

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