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THE INFLUENCE OF MOISTURE LEVEL ON SPECIFIC PHYSICAL PROPERTIES OF NEEM SEEDS (*Azadirachta indica*) AS POTENTIAL CONSIDERATIONS FOR THE CREATION OF PROCESSING MACHINERY

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Abstract: *The development of equipment to mechanise the handling and processing of neem seeds requires an understanding of their physical characteristics. Thus, the physical properties of neem seeds were assessed at moisture content levels ranging from 7.78% to 20.20% on a dry basis. Standard procedures were used to evaluate the seeds' axial dimensions, weight, sphericity, aspect ratio, true and bulk densities, porosity, surface area, and coefficients of dynamic friction (μ) on surfaces made of galvanised steel, wood, and glass. Except for the true and bulk densities, all of the evaluated properties showed an increase in the results for the moisture range mentioned above. The μ on galvanized steel, wood and glass surfaces ranged from 129.00 – 145.90, 127.80 – 141.00, and 130.00 – 144.00, respectively. All the measured parameters had empirical models established for them. The high correlation coefficients of each parameter's model suggest that it can be simulated within the moisture domain under investigation.*

Keywords: *Neem seeds, Moisture contents, Physical properties, Axial dimensions, Empirical models.*

1. Introduction

The neem tree (*Azadirachta indica A. Juss*), native to the Indian subcontinent, is a member of the mahogany family known as the Meliaceae [1]. The neem tree, also known as *dongoyaro* in Nigeria, is widely distributed in tropical and semi-tropical climate regions and has good environmental adaptability [2]. Many other uses for the neem tree are possible, including as an ecological canopy in some circumstances. The leaves, barks, flowers, fruits, seeds, and roots of the neem plant were excellent sources of traditional medicine for the domestic treatment of various human illnesses and the production of industrial goods [3]. The neem seed has the highest oil concentration compared to other parts of the tree. This oil is used as lubricants, insecticides, and medications for various illnesses like diabetes, leprosy, and tuberculosis [3]. Neem leaves and seeds possess a bitter taste, which can serve as a distinctive flavour enhancer in specific dishes. In certain culinary traditions, neem leaves are incorporated into recipes such as curries, soups, and chutneys to impart this unique bitterness [4]. Additionally, neem oil can be employed on packaging materials like paper or cardboard to deter insects and pests, thereby safeguarding stored food items from contamination and deterioration [5].

Neem seeds can be finely ground into a powder, and this powder is accessible in capsule form as a dietary supplement, offering convenience and versatility in consumption. Neem powder capsules are widely utilised for their potential health

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advantages, including boosting immune function and maintaining healthy skin. Beyond culinary and dietary applications, neem seed powder also finds utility as a stabilising agent, in gel formulations, and as a thickening agent in various products [6]. Neem seed oil is combined with other natural ingredients to make multiple skin care products for the body, including body lotions, body soaps, and facial care kits [2]. Neem seeds have long been utilised for their medicinal, culinary, and functional attributes, but they also carry potential risks for human consumption. Subapriya and Nagini [7] emphasise the wide range of biologically active compounds in neem, which can yield both beneficial and harmful effects. Boeke et al. [8] further stress this notion, highlighting that while neem-based pesticides can be safely employed, they may also pose toxicity risks, particularly in non-aqueous extracts. Among the compounds found in neem seeds is azadirachtin, which can be harmful if ingested excessively. Overconsumption of neem seeds or related products can result in adverse effects such as vomiting, diarrhoea, dizziness, and even liver damage [9]. Moreover, neem seeds have demonstrated contraceptive properties and the potential to disrupt hormone levels, which could lead to complications during pregnancy or breastfeeding [10]. Hence, it's essential to recognise these risks and exercise caution, especially among vulnerable groups like pregnant women, individuals with allergies, or those undergoing medication.

The cake left over after the oil extraction is used as a component in the production of mosquito coils [1]. The neem seed oil content ranges from 40 to 50 % by mass, and their 20 % biodegradable pesticides are effective against many pests [11]. Neem seed oils are used as a preservative to extend the shelf life of cowpea grains even though they are not frequently used for cooking due to their pungent smell and bitter flavour, which are comparable to the smells of garlic and peanuts combined [12]. Despite the neem seed's economic significance in numerous human endeavours, little is known about its physical properties. To obtain the kernel, processing steps like depulping and decortication are still done by hand. These processes require manual labour, which not only takes time and effort but also results in low-quality products. Physical characteristics of the seed are thus needed for the design of machinery that can handle these processing operations. According to Oriola et al. [13], understanding the physical characteristics of agricultural materials is crucial for solving many issues relating to the design of particular machines or to the storage, handling, planting, harvesting, threshing, cleaning, sorting, sizing, grading, and drying of agricultural materials.

Additionally, studies on the physical characteristics of some crops by Oriola et al. [13], Aviara et al. [14], Sonawane et al. [15], and Abioye et al. [16] demonstrated that moisture content had an impact on the physical characteristics. These studies found that moisture content played a significant role in influencing the physical properties of crops, such as size, shape, and density. Therefore, the goal of the study is to determine the physical attributes of neem seeds that will aid in the development of effective tools and machinery for their handling operations, taking into account their moisture content.

2. Matherials and methods

2.1. Collection of samples

The ripe yellow neem fruits were gathered from the neem trees planted around Ladoke Akintola University of Technology's teaching and research farm in Ogbomoso, Oyo State, Nigeria. The fruits had to be manually depulped to obtain the neem seeds. Neem seeds (100 g each) were conditioned to five different moisture contents of 7.78, 10.70, 13.36, 16.14, 18.89, and 20.20 per cent (dry basis) after determining the initial moisture content using an OAHM 60 digital moisture analyser (ACETEQ MD7822 Model, Instruments India INC, India) as described by Oriola et al. [17]. The appropriate amount of distilled water to add to samples whose initial moisture content was below the necessary level was calculated using Equation 1. For samples whose initial moisture content was higher than the desired level, equation 2 was used to determine the appropriate drying level. The samples were sealed tightly in polyethene bags and conditioned for 24 hours in a refrigerator to achieve moisture equilibration.

$$Q = \frac{w_i(m_f - m_i)}{100 - m_f} \quad (1)$$

$$MC = \frac{(M_w - M_d)}{M_w} \quad (2)$$

Where: Q = the quantity of water to be introduced (g).

w_i = the initial weight of neem seeds prior to increasing their moisture content (g).

m_f = the ultimate moisture content of neem seeds after water incorporation (% w/b).

m_i = the initial moisture content of neem *seeds* before the introduction of water (% w/b).

MC = the eventual moisture content of the sample under drying conditions (% w/b).

M_w = the initial mass of the damp sample (g).

M_d = the ultimate mass of the sample after the drying process (g).

2.2. Determination of physical properties

2.2.1. Determination of axial dimensions

The length (L), width (W), and thickness (T) of the one hundred (100) randomly chosen neem seeds were all measured using a digital Vernier calliper (Generic LSHAZI03590, Generic, India, reading at 0.01 mm accuracy) using the techniques described by Malik and Saini [18] and Kuala et al. [19]. The experiment was replicated five times.

2.2.2. Determination of geometrical properties

The following expressions, as described by Sonawane et al. [15] and Malik and Saini [18], were used to calculate the arithmetic mean diameter (AMD), geometric mean diameter (GMD), sphericity (Ψ), volume (V) and surface area (S_a) of the seed.

$$Arithmentic\ mean\ diameter\ (AMD) = \frac{L+W+T}{3} \quad (3$$

$$Geomentic\ mean\ diameter\ (GMD) = \sqrt[3]{L \times W \times T} \quad (4)$$

$$Sphericity\ (\Psi) = \frac{(L \times W \times T)^{1/3}}{L} \quad (5)$$

$$Surface\ area\ (S_a) = \frac{\pi \times L^2 \times \sqrt{(WT)}}{2L - \sqrt{(WT)}} \quad (6)$$

$$Volume\ (V) = 0.25\left(\frac{\pi}{6}\right)L(W+T)^2 \quad (7)$$

2.2.3. Determination of aspect ratio

The aspect ratio, which expresses the proportionality between the neem seed's width and height, was calculated following the methodology outlined by Oriola et al. [13].

$$R_a = \frac{W}{L} \quad (8)$$

2.2.4. Determination of gravimetric properties

The mass-to-volume ratio, as described by Oriola et al. [20] was used to calculate the true density of the neem seeds. The seed volume was calculated using the liquid displacement method, and the mass was determined using a digital electric balance (Model: HG-5000, Range: 0 to 5000 g 0.01 g, Japan). By immersing a measuring device in a liquid, the volume of the seed was determined; the volume difference brought on by the seed's addition is equal to the volume of the seed.

$$\rho_t = \frac{M}{V_d} \qquad (9)$$

Where:

ρ_t = True density of the neem seed (g/cm^3)

M = Mass of the neem seed (g)

V_d = Volume displaced (volume of the neem seed) (cm^3)

Utilising the method outlined by Oriola et al. [13], the bulk density of neem seed was calculated as the mass of the bulk neem seed divided by the total volume of neem seed.

$$\rho_b = \frac{M}{V} \qquad (10)$$

Where:

ρ_b = Bulk density of the neem seed (g/cm^3)

V = total volume of the neem seed (cm^3)

Using the expression provided in Equation 11, the porosity (ε) of the neem seed was calculated from the experimental values obtained through bulk and true density measurements.

$$Porosity\ (\%) = 1 - \frac{\rho_b}{\rho_t} \times 100 \quad (11)$$

2.2.5. Determination of angle of repose and coefficient of static friction

On three structural surfaces, galvanized steel, wood, and glass, the dynamic angle of repose (θr) was assessed. An empty cylindrical mold with dimensions of 15 mm in diameter and 25 mm in height was used to estimate the angle of repose. The cylinder was positioned in the middle of the previously mentioned surfaces, filled with neem seeds, and slowly raised until it formed a cone of seeds. Using the following equation 12, as described by Abioye et al. [16], the angle of repose was determined from measurements of the height (H) of the free surface of the seeds and the diameter (D) of the heap formed.

$$\theta_r = \tan^{-1}\left(\frac{2\pi H}{D}\right) \qquad (12)$$

The static friction coefficients (μ) on surfaces made of wood, glass, and galvanised steel were calculated using a neem seed-filled cylinder with a 75 mm diameter and 50 mm depth. The surface was raised gradually while the cylinder was resting on it until the filled cylinder just began to slide downward [15,16]. Equation 13 was then used to calculate the μ.

$$\mu = \tan\beta \qquad (13)$$

Where: β is the angle of tilt in degrees.

2.3. Statistical analysis

The data obtained were analysed statistically with SPSS software version 22 (Statistical Package for Social Sciences, IBM Corporation, USA). The means were compared with Duncan New Multiple Range Test (DNMRT) at a 5 percent ($p< 0.05$) level of significance. All regression analysis and experimental calculations were performed using Microsoft Excel spreadsheet software, version 2016.

3. Results and discussion

3.1. The axial dimensions and geometric properties

Table 1 shows the axial dimensions and geometric properties of neem seeds at different moisture contents. The axial dimension's ranges were 6.28 to 7.40 mm, 5.87 to 6.94 mm, and 14.31 to 15.12 mm, respectively, for length, width, and thickness. The linear dimensions were seen to increase as the moisture content did. The increase in size is ascribed to swelling or expansion brought on by the seeds' intracellular spaces absorbing moisture. Sonawane et al. [15] and Abioye et al. [16] found similar results for kokum and Bambara groundnut seeds. The average diameters increased as the moisture content rose from 7.78 to 20.20% d.b., with the arithmetic and geometric mean diameters rising from 8.82 to 9.83 mm and 8.07 to

9.18 mm, respectively. For assessing the projected area of a particle moving in a turbulent or near-turbulent region of an air stream, the AMD and GMD are helpful parameters [13,16]. It was useful in creating and designing systems for separating seeds from unwanted materials like rubber and plastic. According to the regression models, moisture has a significant positive quadratic effect on the length of neem seeds and a negative impact on their width, thickness, AMD, and GMD. With an R^2 value ≥ 0.8871, it is clear that the test parameters under investigation and the corresponding parameters that affected them had a good level of agreement.

According to Kuala et al. [19] and Oriola et al. [13], the development of sizing and sorting machinery and the electrostatic separation of seeds from chaffs depend on the axial dimensions. Therefore, with these known axial dimensions, the neem seeds can be successfully graded, and the equipment for sieving and decorticating can be designed appropriately. The neem seed's sphericity, surface area, volume, and aseptic ratio increased as the moisture content rose. A comparable result was reported by Sobukola et al. [21] for maize and Adinoyi et al. [22] for sorghum, with an increase in moisture content. Sphericity is an expression of a solid shape relative to that of a sphere of the same volume, while the aspect ratio, which compares the width to the length of the seed, is a sign of its propensity to have a spherical shape [13,23]. The sphericity values demonstrate that the seeds are nearly spherical and will roll readily on surfaces, particularly in hoppers and dehulling machinery. The regression equations with R^2 ≥ 0.8408 indicate that there is a linear relationship between moisture content with surface area and moisture content with volume. Nevertheless, their quadratic models, represented by the regression equations with R^2 ≥ 0.9449, demonstrated that there was a good agreement between moisture content and their corresponding surface and volume.

3.2. Mass and porosity of the neem seeds

The combined plot in Figure 1 illustrates how the moisture content affects the mass and the percentage of porosity of the neem seeds. The seeds' mass significantly increased from 174.50 g to 269.26 g as the moisture content rose. The weight gain brought on by moisture absorption may be the cause of the increase in mass. Abioye et al. [16] noted a comparable rise in the mass of Bambara groundnut. This indicates that seeds possess the capacity to uptake moisture from their surroundings when they come into contact with water. As they take in moisture, their weight increases due to the mass of water. In essence, when moisture content rises, the seeds' weight increases due to absorbed water, and conversely, a decrease in moisture content results in decreased seed weight. Understanding this relationship is vital for trade, storage, and processing purposes, where precise measurement of seed mass is crucial. Additionally, fluctuations in moisture content can alter the seeds' structure and density, impacting their porosity. This is significant for seed quality, affecting factors like germination, storage stability, and susceptibility to damage [24]. Thus, accurate measurement of seed mass facilitates the accurate calibration of machinery and equipment utilised in these operations, guaranteeing maximum efficiency and productivity. Additionally, understanding the correlation between moisture content and porosity can assist in devising efficient storage and processing methods to uphold seed quality throughout the supply chain. Therefore, it is essential for farmers and seed producers to take this factor into account when storing or planting these seeds since it can have an impact on their viability and storage effectiveness.

Table 1:

The axial dimensions and geometric properties of neem seeds at different moisture contents

MC	Length (mm)	Width (mm)	Thickness (mm)	AMD (mm)	GMD (mm)	SP	Area (mm^2)	Volume (mm^3)	AR
7.78	14.31^{b} (0.63)	6.28^{c} (0.49)	5.87^{b} (0.63)	8.82^{d} (0.42)	8.07^{d} (0.48)	0.56^{b} (0.03)	173.57^{d} (20.32)	278.83^{d} (50.41)	0.44^{b} (0.04)
10.70	14.28^{b} (0.93)	7.01^{b} (0.60)	6.67^{a} (0.53)	9.32^{c} (0.41)	8.72^{c} (0.41)	0.61^{a} (0.04)	201.68^{c} (19.01)	350.93^{c} (50.59)	0.49^{a} (0.06)
13.36	14.34^{b} (0.93)	7.18^{ab} (0.41)	6.76^{a} (0.55)	9.43^{bc} (0.37)	8.85^{cd} (0.34)	0.62^{a} (0.03)	207.37^{cd} (15.63)	365.96^{cd} (40.86)	0.50^{a} (0.05)
16.14	14.71^{ab} (0.85)	7.37^{a} (0.47)	6.77^{a} (0.58)	9.62^{ab} (0.39)	9.01^{ab} (0.37)	0.61^{a} (0.03)	214.73^{ab} (17.39)	386.50^{ab} (45.86)	0.50^{a} (0.04)
18.89	14.71^{ab} (0.95)	7.32^{a} (0.55)	6.82^{a} (0.41)	9.62^{ab} (0.39)	9.01^{ab} (0.35)	0.61^{a} (0.03)	215.01^{ab} (16.63)	386.35^{ab} (43.99)	0.50^{a} (0.05)
20.20	15.14^{a} (1.09)	7.40^{a} (0.57)	6.94^{a} (0.44)	9.83^{a} (0.44)	9.18^{a} (0.36)	0.61^{a} (0.03)	223.16^{a} (17.80)	408.68^{a} (49.51)	0.49^{a} (0.04)
Linear Regressions	y = 0.0623x + 13.676	y = 0.0772x + 5.9734	y = 0.0663x + 5.6751	y = 0.0686x + 8.4416	y = 0.0744x + 7.7267	y = 0.0026x + 0.5673	y = 3.333x + 157.56	y = 8.7522x + 235.87	y = 0.0033x + 0.4404
Linear R^2	0.7877	0.7639	0.6774	0.8886	0.8241	0.3781	0.8408	0.8477	0.4214
Polynomial Regressions	y = 0.0068x^2 - 0.1289x + 14.896	y = -0.0114x^2 + 0.3998x + 3.9167	y = -0.0106x^2 + 0.3655x + 3.7676	y = -0.0051x^2 + 0.2121x + 7.5268	y = -0.0081x^2 + 0.3045x + 6.2592	y = -0.0009x^2 + 0.027x + 0.4116	y = -0.3365x^2 + 12.838x + 96.956	y = -0.8559x^2 + 32.929x + 81.725	y = -0.001x^2 + 0.0329x + 0.2517
Polynomial R^2	0.9005	0.9670	0.8871	0.9477	0.9443	0.881	0.9449	0.9461	0.9393

Means followed by the same letter are not significantly different ($p < 0.05$); Values in the bracket are standard deviation.
MC = Moisture content; AMD = Arithmetic mean diameter; GMD = Geometric mean diameter; SP = Sphericity; AR = Aseptic ratio

With an increase in moisture content, the neem seeds' percentage porosity decreased from 43.75% to 40.91%. The decrease was not statistically significant ($p > 0.05$), demonstrating that the increase in moisture content has little effect on the seed's porosity. The absorption of water by the seeds may fill some of the pores or voids within the seed structure, thereby causing swelling or changes in the seed structure. These alterations resulting from the absorption of moisture can lead to a slight compression of the seed, ultimately decreasing the proportion of vacant space within it. Consequently, this decrease in empty space within the seed can also influence its overall density. Sobukola et al. [21] and Sonawane et al. [15] reported a similar decrease in the percentage porosity of Bambara groundnut and Kokum seeds. However, porosity was reported to increase with an increase in moisture content for Bambara groundnut [16], safflower seed [25], and rapeseed [26].

The regression equations displaying high R^2 values, specifically $R^2 \geq 0.9441$ for the linear relationship and $R^2 \geq 0.9653$ for the quadratic relationship between moisture content and seed mass, suggest a strong agreement between moisture content and the corresponding seed masses. In contrast, the lower R^2 values, such as $R^2 \geq 0.4726$ for the linear model and $R^2 \geq 0.5429$ for the quadratic model concerning moisture content and seed porosity, indicate a more limited level of agreement. Consequently, these models with lower R^2 values possess reduced predictive capability. Understanding the influence of moisture content on both the mass and porosity of neem seeds holds significant importance in the aeration process during the pneumatic separation of seeds and chaff after the shelling process. It aids in determining the optimal moisture level required for an efficient separation process. It also helps in preventing the clogging of the pneumatic system.

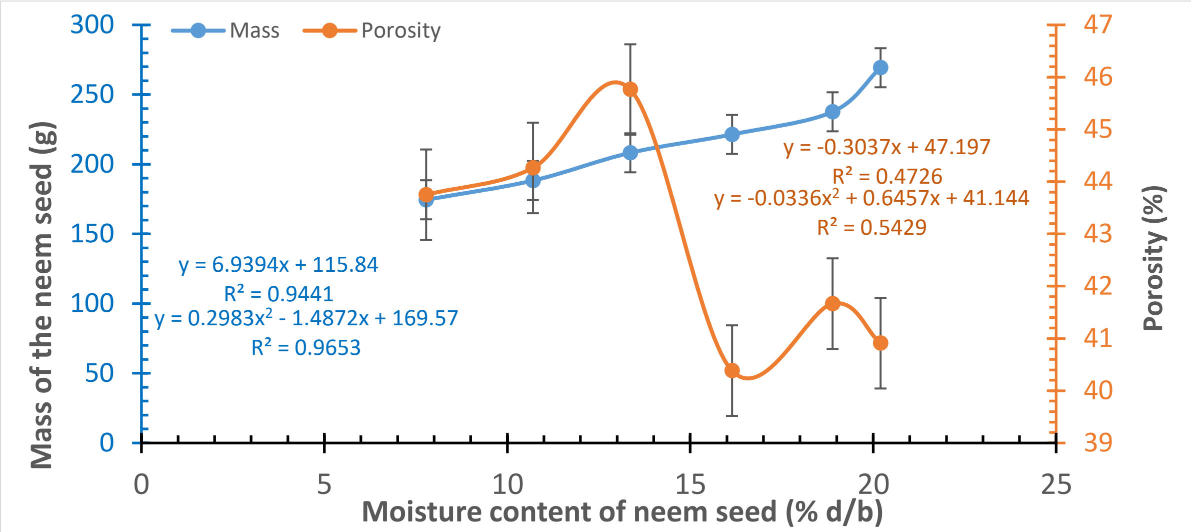

Fig. 1: Variations of moisture contents with the mass and porosity of the neem seeds.

3.3. True and bulk densities of the neem seeds

The combined graph presented in Figure 2 demonstrates the impact of moisture content on both the true and bulk densities of neem seeds. The true density of the seeds decreased from 0.64 to 0.44 g/cm^3, and the bulk density also decreased from 0.36 to 0.26 g/cm^3 as the moisture content increased. Similar trends were observed in previous studies by Aviara et al. [14] and Mohammad and Satpathy [27] for Brachystegia eurycoma and Buckwheat seeds, where both true and bulk densities decreased with increasing moisture content. The decrease in the true and bulk densities of neem seeds as moisture content increased can be attributed primarily to water introduction. This water displaces solid material, causes the seeds to swell, and may lead to slight compression and void filling within the seed structure, collectively resulting in lower overall density as moisture content rises.

Consequently, due to the swelling effect, the seeds occupy more space while maintaining their mass. This increased volume can have practical implications, affecting considerations related to storage, transportation, and processing. Lower-density seeds require more space and larger containers for storage and transportation. Furthermore, changes in density due to moisture absorption can impact aeration processes and the efficiency of seed separation techniques. Regression models were developed for true and bulk densities, showing that both parameters can be represented in linear and polynomial forms. With an R^2 value ≥ 0.9899, these models indicate a strong agreement between the true and bulk densities of neem seeds and their corresponding moisture variations. Therefore, understanding the relationship between moisture content and density is essential for industries involved in processing or storing these seeds. It enables them to control and optimise moisture levels to meet specific quality and processing requirements effectively.

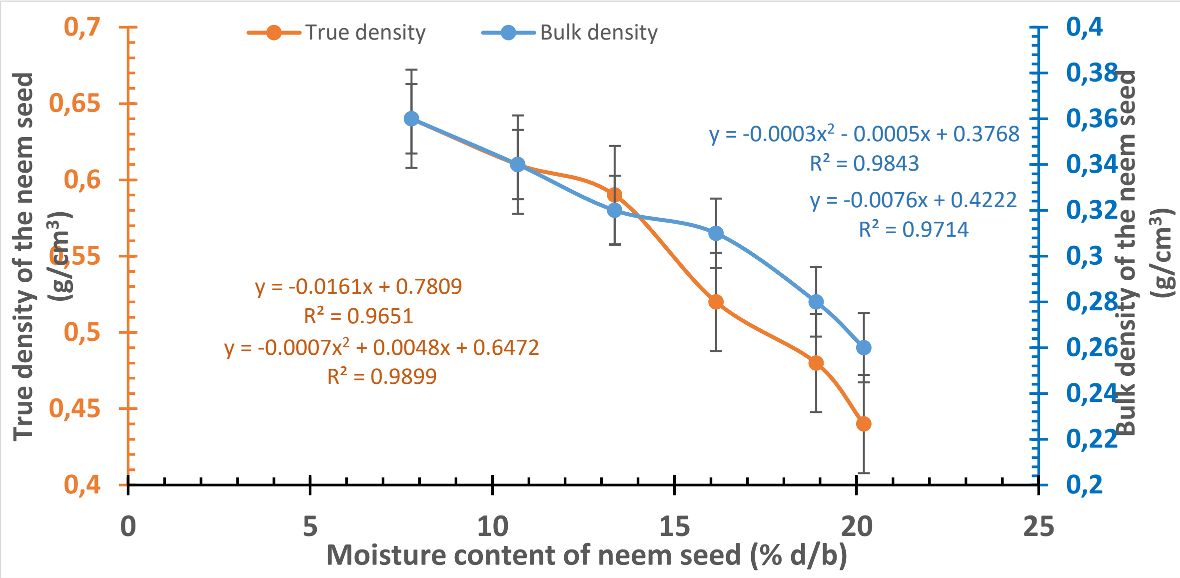

Fig. 2: Variations of moisture contents with the true and bulk densities of neem seeds.

3.4. Angle of repose and coefficient of static friction of the neem seeds

The combined graph presented in Figure 3 demonstrates the impact of moisture content on the angle of repose and coefficient of static friction of the neem seeds. The angle of repose values exhibited a noticeable increase ($p > 0.05$), rising from 22.45° to 27.75° within the moisture range of 7.78% to 20.20% d.b. It was observed that with increasing moisture content within this experimental range, the neem seeds absorbed more moisture, resulting in enhanced stability and reduced flowability. Consequently, this led to an elevation in the angle of repose for the seeds. Earlier research, by Sonawane et al. [15], Adedeji and Owolarafe [28], Prakash et al. [29], Malik and Saini [18], Adinoyi et al. [22] and Asoiro et al. [30], found that the angle of repose increased linearly with the amount of moisture in seeds like kokum seeds, neem seeds, pearl millet grain, sunflower seed, sorghum grain, *Irvingia gabonensis*, *Detarium microcapum*, *Mucuna pruriens*, and *Brachystegia eurycoma* seeds. The regression models developed to describe the relationship between the angle of repose and seed moisture content exhibited strong linear and polynomial associations, as indicated by the high R^2 values (0.9871 and 0.9921). These equations have the potential to effectively predict the angle of repose of neem seeds within the investigated range of moisture content. The angle of repose is a characteristic of granular materials and is frequently employed to validate discrete element models used to simulate the behaviour of such materials. Once these numerical models are proven to work, they can be used to look into problems like blockages, sudden changes in pressure, and low mass flow rates that happen during industrial-scale transport and storage [31].

The experimental results for the static coefficient of friction on three different structural surfaces, plotted against moisture content, are depicted in Figure 3. The figure illustrates that the static coefficient of friction for neem seeds increased as the moisture content rose, and this variation was dependent on the type of structural surface.

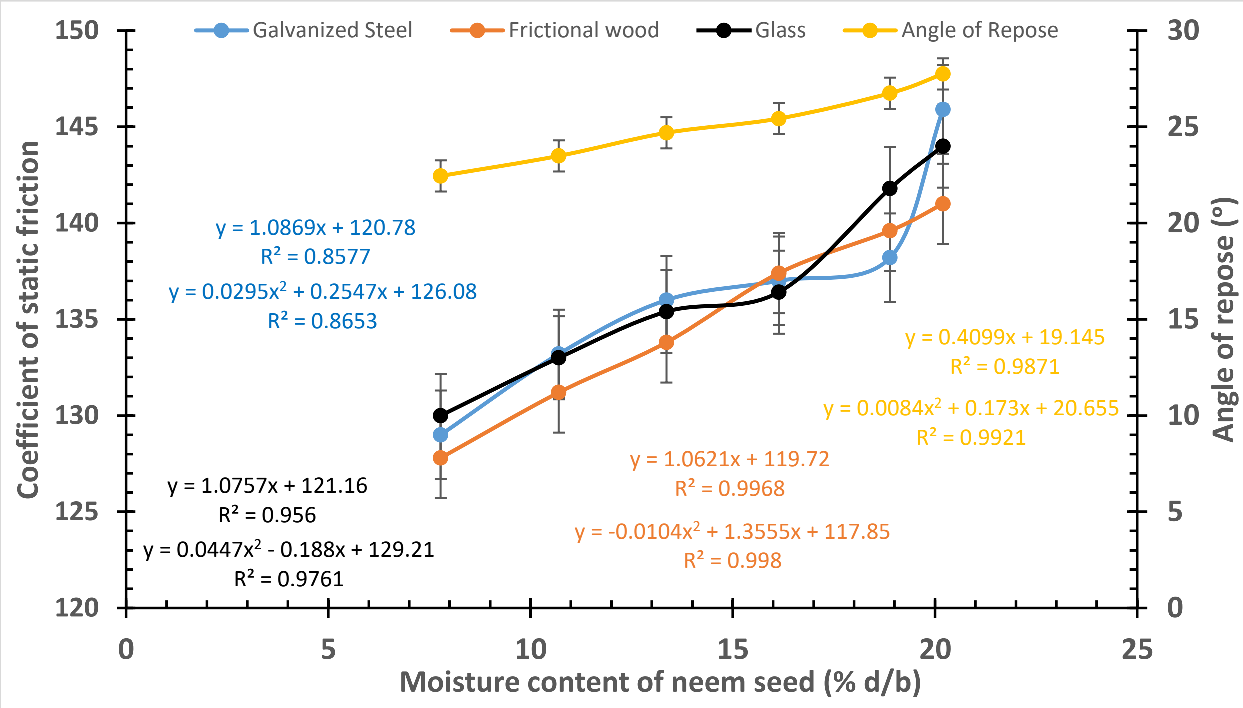

Fig. 3: Variations of moisture contents with the angle of repose and coefficient of static friction of neem seeds.

This phenomenon could be attributed to the possibility that as the moisture content increased, the projections or roughness on the surface of the seeds became more pronounced. This, in turn, led to greater shear stress at the points where the structural surface made contact with the seed's asperities, resulting in an increase in friction [14]. Galvanised steel sheets had the highest static coefficient of friction among the tested structural surfaces (ranging from 129.00 to 145.90), glass came in second (ranging from 130.00 to 144.00), and wooden surfaces with frictional properties came in last (ranging from 127.80 to 144.00). The notably high value observed on galvanised steel sheets suggests that neem seeds exhibit a steep angle of repose on these surfaces. Similar findings of an increase in the static coefficient of friction with rising seed moisture content have been reported by previous studies, such as Aviara et al. [14] for *Brachystegia eurycoma* seeds, Sonawane et al. [15] for kokum seeds, Malik and Saini [18] for sunflower seeds, Gely and Pagano [32] for sorghum grains, Shiru and Gana [33] for fluted pumpkin seeds, and Nkambule et al. [34] for groundnut seeds and pods.

The regression equations established to relate the static coefficients of friction to moisture content on galvanized steel, glass, and frictional wood surfaces demonstrate a strong linear and polynomial relationship in the equations. The high R^2 values, ranging from 0.8577 to 0.9980, suggest that these equations can be effectively employed to predict the static coefficients of friction for neem seeds within the range of moisture content examined. A study by Sonawane et al. [15] highlighted the inverse relationship between the coefficient of mobility, which signifies the freedom of movement of a substance, and the coefficient of friction (the tangent of the angle of internal friction). Specifically, a higher coefficient of friction corresponds to a lower mobility coefficient. This relationship has practical implications for the design of inclined grain transportation equipment, where a steeper angle of inclination and a larger hopper opening, and side wall slope are required when dealing with substances with higher friction coefficients. Therefore, understanding this property can greatly aid in the design of product handling equipment. Similarly, in the design of storage structures such as silos, bins, and other facilities for seeds, grains, and agricultural products, the friction coefficient plays a pivotal role. It influences the lateral and vertical loads experienced by the walls and floors of these structures. As the coefficient of friction between the stored material and the structural surface affects these loads, it becomes a critical consideration in ensuring the structural integrity and safety of storage facilities.

4. Conclusion

This study conducted an evaluation of various physical properties of neem seeds, which could prove invaluable in the design and development of handling and processing equipment. The investigation revealed significant variations in the physical dimensions and size-related characteristics of neem seeds with changing moisture content. Here are the key findings:

1. The dimensions of the neem seeds, including the arithmetic mean diameter, geometric mean diameter, sphericity, area, volume, and aspect ratio, increased as the moisture content rose within the range of 7.78% to 20.20% d.b. Specifically, these dimensions changed from 8.82 to 9.83 mm, 8.07 to 9.18 mm, 0.56 to 0.62, 173.57 to 223.16 mm^2, 278.83 to 408.68 mm^3, and 0.44 to 0.50, respectively.
2. The mass of the neem seeds also increased, shifting from 174.50 to 269.26 g, while the porosity decreased from 43.75% to 40.91%.
3. The true density of the seeds exhibited a linear decrease, decreasing from 0.64 to 0.44 g/cm^3, whereas the bulk density decreased from 0.36 to 0.26 g/cm^3.
4. The angle of repose, representing the angle at which the seeds naturally rest, increased from 22.45° to 27.75° as the moisture content increased.
5. The static coefficient of friction on three different structural surfaces, namely galvanised steel sheets (ranging from 129.00 to 145.90), glass (ranging from 130.00 to 144.00), and wooden surfaces with frictional properties (ranging from 127.80 to 144.00), increased within the moisture range of 7.78% to 20.20% d.b. evaluated.

These findings provide valuable insights for optimising milling operations, designing storage structures, and developing processing machinery tailored to neem seeds. Such knowledge is instrumental in enhancing the relevance of neem seeds among farmers and processors, ultimately benefiting the industry.

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