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Comparative analysis of mechanical properties of paddy rice for different variety-moisture content interactions

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ABSTRACT

In recent years, postharvest loss has been a serious concern. However, knowledge of the mechanical properties is vital to developing any postharvest technology for rice production better. The objective of this research is to conduct a comparative analysis of the mechanical properties of selected paddy rice at different variety-moisture content interactions. The mechanical properties of AGRA rice, CRI-Amankwatia, CRI-Enapa, and CRI-Dartey, four local varieties developed in Ghana, are compared at 11.5%, 13.0% and 16.5% on wet basis moisture content. Tukey's Honest Significant Difference (HSD) comparisons test was conducted during data analysis to compare all possible pairwise combinations of the various varieties and moisture content interaction. From the results, it was concluded that CRI-Dartey, at 16.5%, recorded the highest Sphericity and Aspect Ratio of 0.391 mm^3 and 0.298 mm^3, respectively. For grain mass, AGRA rice at 13.0% also recorded 0.0312 g as the highest score. The GM1000, Angle of Repose and Bulk density CRI-Amankwatia at 16.5 % moisture content recorded the highest score of 29.33 g, 47.3^o, and 654.0 kg/m^3, respectively. AGRA rice at 13.0% observed the highest value of 1685.8 for kg/m^3 true density, and the highest value for porosity was 70.83%, which was recorded by CRI-Enapa at 11.5 % moisture content. In all cases, the difference in mean value was less than the Least Square Difference. This indicates that there were no significant statistical differences between their mean values, indicating that technologies developed and adapted for one variety can equally be used for all the other varieties.

Keywords: Angle of Repose, Aspect Ratio, Bulk Density, Porosity, Sphericity, Mechanical Properties

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Introduction

Rice is the second most consumed food crop globally and is the staple food for more than half of the world's inhabitants (Albahri *et al.*, 2023; Ashfaq *et al.*, 2023a; Ashfaq *et al.*, 2023b). This calls for all stake holders in the rice value chain to improve the production and sustainability of rice production (Pame *et al.*, 2023; Rahman and Zhang, 2022). One of the key areas to achieve this goal is the development and adaptation of postharvest technology to improve quality and quantity and reduce postharvest losses. By increasing the effectiveness of post-harvest operations, rice quality and quantity can be guaranteed, and this would greatly reduce losses (Zhang *et al.*, 2022). The need for a reduction in postharvest losses in rice production in Sub-Saharan Africa continues to grow from year to year (Rahman and Zhang, 2022). When this need is addressed, there will be a sustainable method to increase rice supply, eradicate hunger and improve livelihoods in developing nations. However, diversity and development of new and improved varieties of agricultural materials pose special challenges for engineers and researchers regarding knowledge of the engineering properties of agricultural produce since this may call for technological change related to farm-level technical efficiency (Karunarathna and Wilson, 2017).

According to the 2019 catalogue of crop varieties released and registered in Ghana by the National Variety Release and Registration Committee (NVRRC), as at 2019 there were at least twenty-six (26) different varieties of locally released rice by the CRI in Ghana. From the catalogue, it was observed that there is limited data on the engineering properties of these varieties. It is therefore important to investigate the engineering properties because mechanical properties are necessary for the development, adaptation and adjustment of various harvesting, threshing, winnowing, handling, drying and storage systems for postharvest activities. Four varieties of paddy rice namely AGRA rice, CRI-Amankwatia, CRI-Enapa and CRI-Dartey released and registered by the Crop Research Institute of Ghana are locally produced by rice farmers in the country were selected for this study. AGRA rice and CRI-Amankwatia are old varieties released in the year 2010 and 2013, respectively, whereas CRI-Enapa and CRI-Dartey are relatively new varieties released in 2019, as indicated in Table 1. This study seeks to determine the mechanical properties of the new and old varieties and compare and contrast them at varying moisture content. The knowledge acquired will aid in the design, development and optimization of threshing and drying systems and other stages of postharvest activities for rice production in Ghana. For example, sphericity, bulk density, aspect ratio angle of repose and porosity are necessary mechanical properties for the design of hoppers and storage bins for dryers and threshers and the selection of sieve size for winnowers and cleaners. The findings will add to scientific knowledge of the engineering properties of these paddy rice varieties for use by other agricultural and biosystems engineers and researchers.

Table 1. List of paddy rice varieties and release year.

Variety	Year of Release	Potential Yield
CRI-Amankwatia	2010	8.0 t ha^{-1}
AGRA rice	2013	8.0 t ha^{-1}
CRI-Dartey	2019	9.5 t ha^{-1}
CRI-Enapa	2019	9.0 t ha^{-1}

Materials and Methods

Sample preparation

The four paddy varieties used for this study were collected from the Kwadaso Agricultural College in Kumasi by the CRI. The paddy was threshed manually by robbing them between the two palms. It was then winnowed and labelled accordingly before experimenting. The moisture content was determined on a wet basis using the Moistex Screw-Type Digital Grain Moisture Meter, as shown in Figure 2. The other tools and equipment used during the experiment include a Vernier caliper, as shown in Figure 3, for measuring the axial dimensions. Citizon electronic scale, as shown in Figure 4, for measuring the grain mass and the 100-grain weight, measuring cylinder for determining the bulk grain volume, as shown in Figure 6, and bench top laboratory oven for drying the paddy rice.

Experimental design

The design of the experiment was a 4×3 factorial arrangement in a Completely Randomized Design (CRD) in three replications. The factors were four (4) varieties (AGRA rice, CRI-Amankwatia, CRI-Enapa, and CRI-Dartey) and three (3) different moisture content (16.5 %, 13.0 %, and 11.5 % wb).

Mechanical properties

In order to determine the average axial dimensions of the various paddies, 100 grains of each variety were randomly selected at varying moisture content (Wu *et al.*, 2022; Ghadge and Prasad, 2012). The length (L), width (W), and thickness (T) representing the major, medium, and minor axes, respectively, were measured using a digital Vernier caliper with a sensitivity of 0.01 mm (Ashfaq *et al.*, 2023b; Xiao *et al.*, 2023).

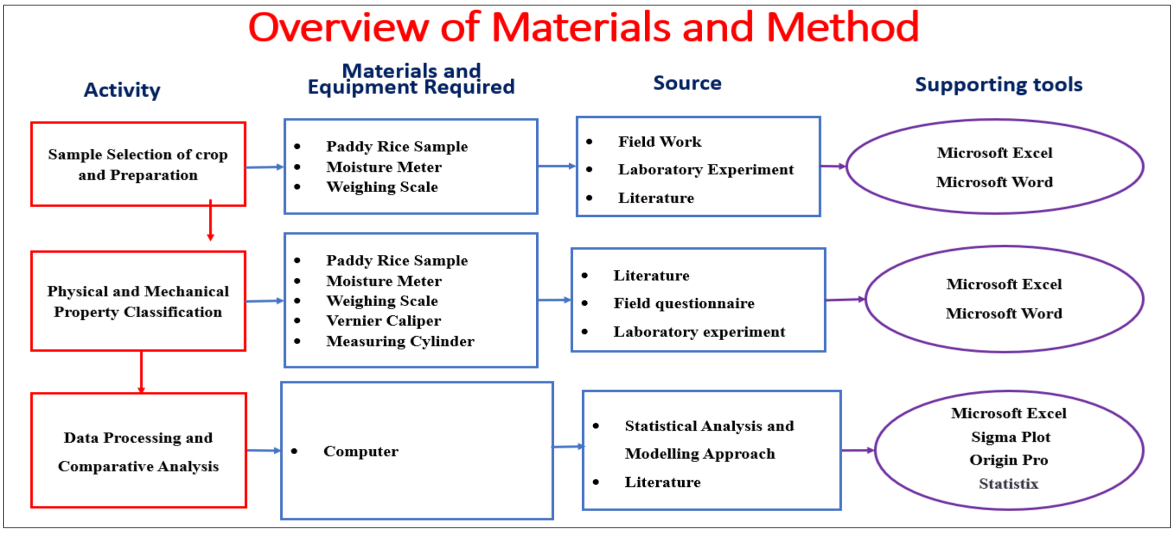

Figure 1. An Overview of Materials and Methods.

Figure 2. Moisture Meter for Measuring Paddy Rice Moisture Content.

Figure 3. Vernier Calliper for Measuring the Axial Dimensions of the Paddy Rice.

Sphericity

The sphericity of grain is the ratio of the geometric mean diameter and the major axis of the grain (L). This signifies the ability of grain to roll on a surface with a gentle slope rather than slide. The closer the sphericity of the grain is to one (1), the more spherical the grain is and the better the ability of the grain to roll. This attribute is very vital for the design of conveying equipment, plenum, and hopper, etc. (Li *et al.*, 2022; Kruszelnicka *et al.*, 2022; Haq *et al.*, 2016). It is calculated by using the following relationship given and used by Mohsenin (2020) and Carroll and Finnan (2012).

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

Aspect ratio

Aspect ratio, R_a is a grain parameter used to determine whether the paddy will roll or slide on flat surfaces. It relates the grain's medium axial dimension (W) to the major axial dimension (L) (Li *et al.*, 2022; Haq *et al.*, 2016). It is calculated by applying the following relationships given by Kruszelnicka *et al.* (2022) and Mohsenin (2020).

$$R_a = \frac{W}{L} \quad (2)$$

Gravimetric and frictional properties

Gravimetric properties of the paddy are the properties that have some form of relationship with the mass of the grain. They include the mass of individual grain M_t, 1000 grain mass GM_{1000}, bulk density ρ_b, true density ρ_t, and porosity ε (Zhang *et al.*, 2022; Venkatesan *et al.*, 2023). The thousand-grain mass and the individual grain mass were determined on the Citizon digital electronic scale with an accuracy of 0.00001 g. The water displacement method was used to determine the true density. In this method, first, 300 mL water was filled into a graduated 500 mL measuring cylinder. Then, a paddy of known mass was put into the water in this cylinder. The rise in the water level was calculated as the volume of the paddy.

Figure 4. Bench Top Laboratory Oven for Drying Paddy Rice.

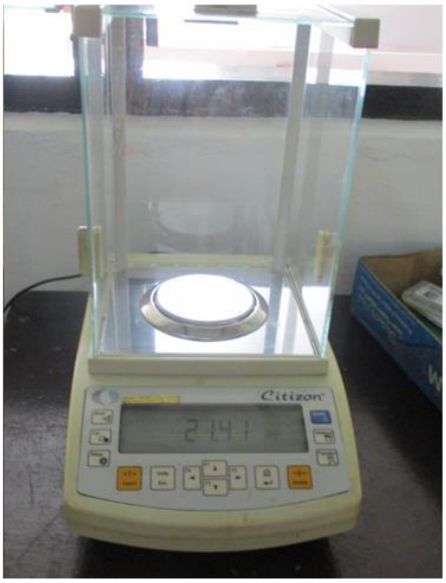

Figure 5. Electronic Weighing Scale for Measuring the Mass of Paddy Rice.

True density was calculated as the ratio of the known mass and the volume. (Aviara *et al.*, 2005; Ogunjimi *et al.*, 2002). The bulk density was also determined by filling the paddy to the brim of the 500mL volume with no separate manual compaction. The mass of the paddy in the container was also measured minus the weight of the container. The bulk density was calculated from the mass of the grains and the volume of the container. The porosity, ε of paddy was also determined at various moisture contents from bulk and true densities using the relationship given by Mohsenin (1968), Thompson and Isaacs (1967) and Tscheuschner (1987)

$$Bulk\ Density\ \rho_b = \frac{M_b}{V_b} \quad (3)$$

$$True\ Density\ \rho_t = \frac{M_t}{V_g} \quad (4)$$

$$Porosity\ \varepsilon = \frac{\rho_t - \rho_b}{\rho_t} \quad (5)$$

Figure 6. Graduated 500 ml Measuring Cylinder for Measuring Paddy Bulk Volume.

Angle of repose

The angle of repose is the threshold angle between the horizontal plane and the diagonal surface, above which the whole grain mass starts to fall under gravity (Li *et al.*, 2020). It is an important parameter for the design of hopper, storage, and transport systems for grain (Al-Hashemi and Al-Amoudi, 2018).

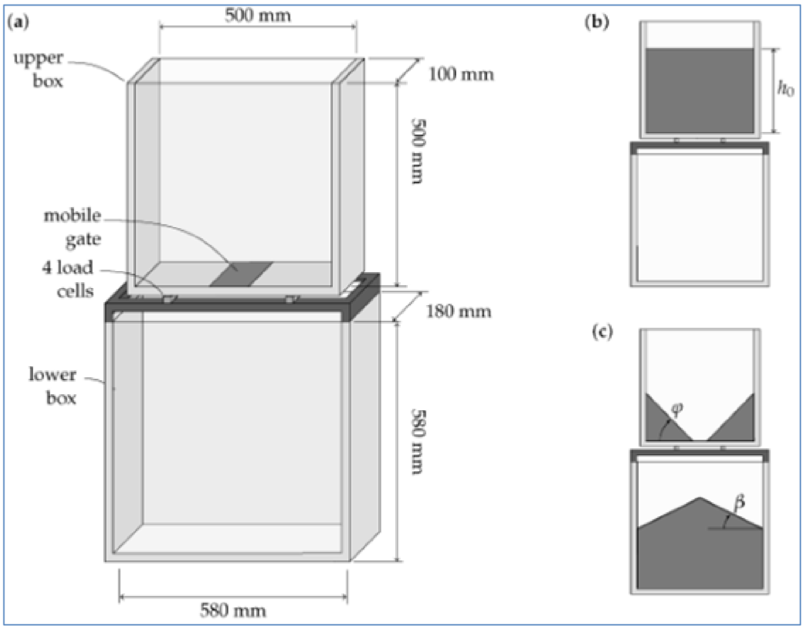

Figure 7. Apparatus for measuring Angle of Repose.

It was determined by using an angle of repose test apparatus consisting of an upper and lower graduated and transparent acrylic box, with a slide to open and close the bottom outlet for the upper chamber. The setup is supported by a steel angle bar. Paddy is put into the upper chamber and placed in the lower chamber while the bottom outlet is closed. The bottom outlet is slid open to allow the paddy to flow under gravity into the lower chamber (Moncada *et al.*, 2022; Shewry and Halford, 2002; Teferra, 2019). Once the paddy stops falling and is at rest, the angles of repose are formed and assume a natural slope in the rectangular lower chamber (Shewry and Halford, 2002; Rackl and Grötsch, 2018). The width of the lower chamber (w_l) and height (h_s) of the slope were recorded. The angle of repose β was calculated by the following formula.

$$Angle\ of\ Repose\ \beta = \tan^{-1}\left(\frac{2h_g}{W_l}\right) \quad (6)$$

Data analysis

Tukey 's Honest Significant Difference (HSD) All-Pairwise Comparisons Test was conducted to compare all possible pairwise combinations of all the various means of varieties of moisture content interaction for all 8 mechanical properties under consideration to determine which pairs are significantly different from each other in an analysis of variance (ANOVA). The test sought to examine the effect of varying moisture content of different paddy rice varieties on these parameters. The alpha value was set at 0.01, which indicates a strict threshold for determining the statistical significance level. The residual degree of freedom was set at 24 as a measure of the number of observations needed to estimate the number of parameters in the model. The critical value is then calculated and used with the standard error to compare the differences between group means. Suppose the absolute difference between two group means is less than the critical value times the standard error. In that case, those means are considered not to have any statistically significant difference from each other.

Results and Discussion

Sphericity

Table 2. explains the significant variety and moisture content interaction for sphericity and aspect ratio for all four rice varieties. For sphericity, the highest values that fall within the same homogeneous group were recorded by CRI-Dartey at 16.5%, CRI-Amankwatia at 16.5%, AGRA rice at 16.5%, and CRI-Amankwatia at 13.0% were 0.3909, 0.3891, 0.3885 and 0.3884 respectively. This is consistent with the findings of Li *et al.* (2022) and Haq *et al.* (2016) indicated a sphericity range of 0.350 to 0.527 and 0.431 to 0.545, respectively. The least sphericity value; 0.3769 was recorded by CRI-Enapa at both 13.0% and 11.5%. However, the sphericity for all the interactions ranges from 0.391 to 0.377.

Table 2. Sphericity and aspect ratio of variety-moisture content interaction for paddy rice.

Grain	*Moisture	Sphericity (ϕ)	Aspect Ratio (R_a)
AGRA rice	16.5	0.3885_{a}	0.2861_{b}
AGRA rice	13.0	0.3869_{ab}	0.2856_{b}
AGRA rice	11.5	0.3854_{ab}	0.2855_{b}
CRI-Amankwatia	16.5	0.3891_{a}	0.2871_{b}
CRI-Amankwatia	13.0	0.3884_{a}	0.2851_{b}
CRI-Amankwatia	11.5	0.3848_{abc}	0.2866_{b}
CRI-Dartey	16.5	0.3909_{a}	0.2978_{a}
CRI-Dartey	13.0	0.3862_{ab}	0.2869_{b}
CRI-Dartey	11.5	0.3872_{ab}	0.2897_{ab}
CRI-Enapa	16.5	0.3803_{bcd}	0.2706_{c}
CRI-Enapa	13.0	0.3769_{d}	0.2694_{c}
CRI-Enapa	11.5	0.3769_{d}	0.2706_{c}
LSD: Critical Value for Comparison	2.632×10^{-3}		3.221×10^{-3}

NB: Values in the same column having similar letters are not significantly different

Aspect ratio

On the aspect ratio, CRI-Dartey at moisture content 16.5%, recorded the highest value of 0.2978 while the least aspect ratio values (0.2706, 0.2694 and 0.2706) were recorded by CRI-Enapa at 16.5%, 13.0% and 11.5% respectively. From the results, it was observed that there were four (4) groups of mean values for sphericity and three (3) groups of mean values for aspect ratio; nevertheless, there were no statistically significant differences in any of the interactions.

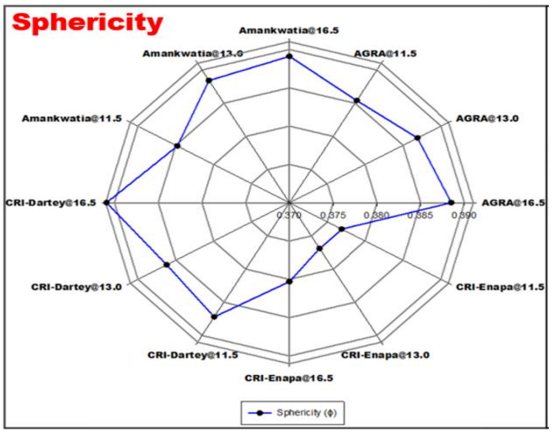

Figure 8. Variations of Sphericity of Paddy Rice for Different Variety-Moisture Content Interactions.

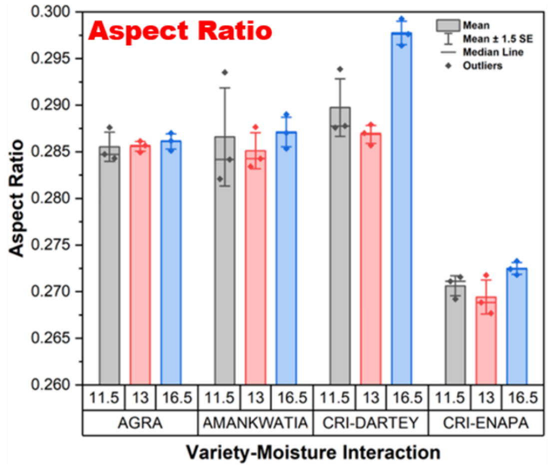

Figure 9. Variations of Aspect Ratio of Paddy Rice for Different Variety-Moisture Content Interactions

Gravimetric properties

Table 3. shows the significant variety and moisture content interaction for the gravimetric properties of selected rice varieties. For grain mass, the highest value, 0.0312 g was recorded by AGRA rice at a moisture content of 13.0% while the least values, 0.0237 g, 0.0237 g, and 0.0239 g that fall within the same homogeneous group were recorded by CRI-Enapa at moisture contents at 16.5%, 13.0% and 11.5%, respectively. In terms of thousand-grain mass (GM1000), CRI-Amankwatia recorded the highest value of 30 g at moisture content of 16.5%. In contrast, CRI-Enapa recorded the lowest values of 20.663 g and 20.650 g at moisture contents of 13.0% and 11.5%, respectively. These results are similar to the findings of Zhang *et al.* (2022); Venkatesan *et al.* (2023) and Ma *et al.* (2023), recording GM 1000 for paddy rice to be 26.4g, 17.0 to 39.0, and 30.02 g, respectively.

Table 3. Gravimetric properties of variety-moisture content interaction for paddy rice.

Grain	*Moisture	Mass (m), g	GM1000, g	Bulk Density (ρ_b), kg/m^3	True Density, (ρ_t), kg/m^3
AGRA rice	16.5	0.0276$_{bcd}$	25.231$_{bc}$	565.61$_{cd}$	1447.3$_{bc}$
AGRA rice	13.0	0.0312$_{a}$	26.380$_{b}$	522.33$_{e}$	1685.8$_{a}$
AGRA rice	11.5	0.0252$_{de}$	24.355$_{cd}$	462.45$_{f}$	1397.4$_{bc}$
CRI-Amankwatia	16.5	0.0299$_{ab}$	29.333$_{a}$	654.02$_{a}$	1482.8$_{bc}$
CRI-Amankwatia	13.0	0.0294$_{ab}$	27.946$_{a}$	606.10$_{b}$	1502.8$_{b}$
CRI-Amankwatia	11.5	0.0280$_{bc}$	25.644$_{bc}$	569.60$_{c}$	1417.1$_{bc}$
CRI-Dartey	16.5	0.0262$_{cde}$	24.455$_{cd}$	549.04$_{cde}$	1406.8$_{bc}$
CRI-Dartey	13.0	0.0262$_{cde}$	24.326$_{cd}$	534.25$_{de}$	1472.9$_{bc}$
CRI-Dartey	11.5	0.0252$_{de}$	23.790$_{de}$	452.42$_{fg}$	1381.2$_{bc}$
CRI-Enapa	16.5	0.0237$_{e}$	22.543$_{e}$	481.31$_{f}$	1352.5$_{c}$
CRI-Enapa	13.0	0.0237$_{e}$	20.663$_{f}$	446.50$_{fg}$	1434.4$_{bc}$
CRI-Enapa	11.5	0.0239$_{e}$	20.650$_{f}$	422.92$_{g}$	1450.3$_{bc}$
LSD: Critical Value for Comparison		$9.799 \text{x} 10^{-4}$	0.5232	13.131	55.605

NB: Values in the same column having similar letters are not significantly different.

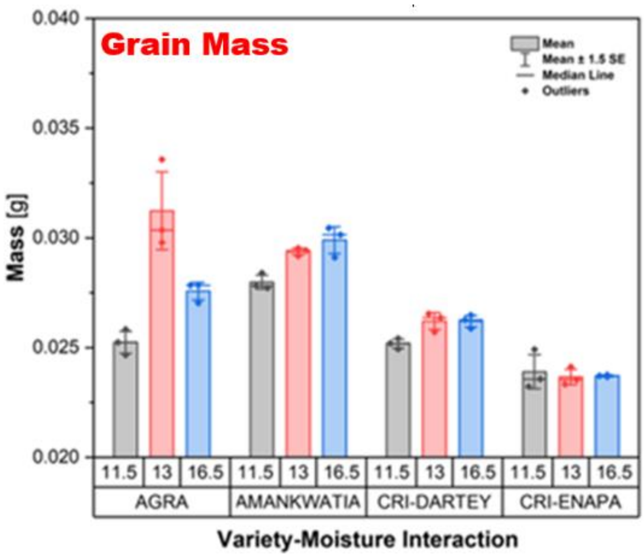

Figure 10. Variations of Grain Mass of Paddy Rice for Different Variety-Moisture Content Interactions.

CRI-Enapa at moisture content 13.0% and 11.5% fall within the same homogeneous group. In connection with bulk density, the highest value, 654.02 kg/m^3 was recorded by CRI-Amankwatia at 16.5% while the lowest bulk density value 422.92 kg/m^3 was recorded by CRI-Enapa at 11.5%, moisture content. AGRA rice at a moisture content of 13.0% recorded 1685.8 kg/m^3 while CRI-Enapa recorded 1352.5 kg/m^3 as the highest and lowest values, respectively for true density. For true density, the results are consistent with the work of Reddy and Chakraverty (2004), who recorded 1342 kg/m^3 to 1411 kg/m^3. For AGRA rice, CRI-Amankwatia, and CRI-Enapa, bulk density is proportional to moisture content. On the other hand, CRI-Dartey recorded the least bulk density occurring at a moisture content of 13.0%. This is similar to the results of Rosentrater and Bucklin (2022) which recorded bulk density of 513 kg/m^3 to 577 kg/m^3. This means that with all rice varieties, the optimum moisture content after drying should range between 13% to 11%. The test results indicated that there were five (5), six (6), seven (7), and three (3) groups of mean values for mass, GM1000, bulk density and true density, respectively, with no statistically significant differences for any of the interactions.

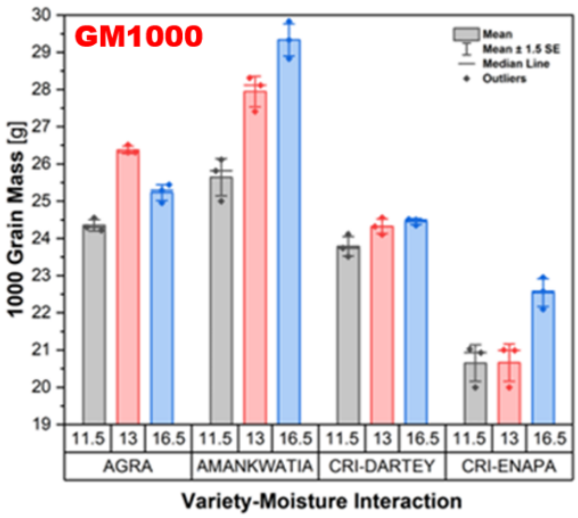

Figure 11. Variations of GM1000 of Paddy Rice for Different Variety-Moisture Content Interactions.

Porosity and Angle of Repose

Table 4. Porosity and angle of repose of variety-moisture content interaction for paddy rice.

Grain	*Moisture	Porosity, (ε), %	Angle of Repose, °
AGRA rice	16.5	60.918$_{de}$	46.173$_{b}$
AGRA rice	13.0	68.892$_{ab}$	42.573$_{c}$
AGRA rice	11.5	66.904$_{bc}$	37.553$_{e}$
CRI-Amankwatia	16.5	55.884$_{f}$	47.313$_{a}$
CRI-Amankwatia	13.0	59.669$_{e}$	46.663$_{ab}$
CRI-Amankwatia	11.5	59.799$_{e}$	35.053$_{f}$
CRI-Dartey	16.5	60.971$_{de}$	46.903$_{ab}$
CRI-Dartey	13.0	63.722$_{de}$	36.983$_{e}$
CRI-Dartey	11.5	67.262$_{bc}$	41.723$_{d}$
CRI-Enapa	16.5	64.413$_{cd}$	34.453$_{fg}$
CRI-Enapa	13.0	68.870$_{ab}$	34.623$_{fg}$
CRI-Enapa	11.5	70.830$_{a}$	34.273$_{g}$
LSD: Critical Value for Comparison		1.3230	6.101

NB: Values in the same column having similar letters are not significantly different.

Table 4 shows the significant variation and moisture content interaction for the porosity and angle of repose of selected rice varieties. In the case of porosity, CRI-Enapa at 11.5% moisture content recorded the highest value of 70.83%, whereas CRI-Amankwatia at 16.5% moisture content recorded 55.88% as low value. With CRI-Amankwatia, CRI-Dartey, and CRI-Enapa, the porosity is inversely proportional to moisture content, whilst, in the case of AGRA rice, the porosity occurred at a moisture content of 13.0%. This finding is consistent with the work of Rosentrater and Bucklin (2022), indicating a porosity of 47% to 50% for paddy rice. For the angle of repose, the highest value, 47.313° was recorded for CRI-Amankwatia at moisture content of 16.5.0% while the least values, 34.623°, 34.453°, and 34.273° fall within the same homogeneous group were recorded by CRI-Enapa at moisture contents at 13.0%, 16.5% and 11.5% respectively. The result of the Angle of Repose is similar to Dassanayake *et al.* (2009), whose work shows approximately 45° for the Pusa Basmati variety, and Rosentrater and Bucklin (2022) also having 30° to 40° for rough rice. The test results further showed that there were six (6) and seven (7) groups of mean values for porosity and angle of repose, respectively; however, there was no statistically significant difference between them for the various varieties of moisture content interaction measured.

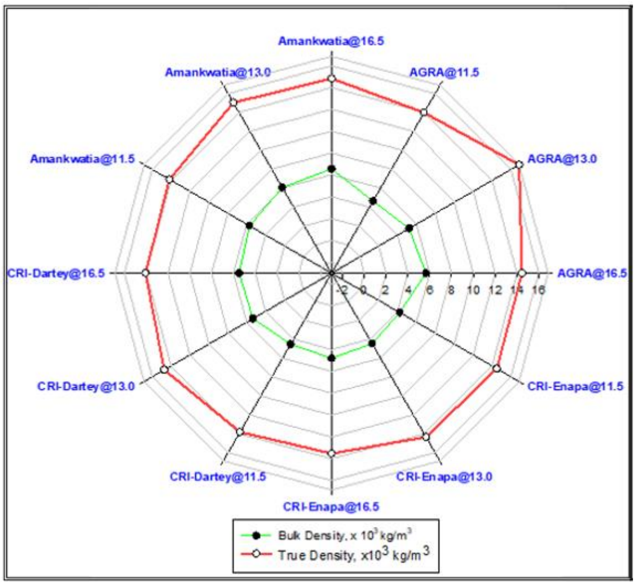

Figure 12. Variations of Bulk Density and True Density of Paddy Rice for Different Variety-Moisture Content Interactions.

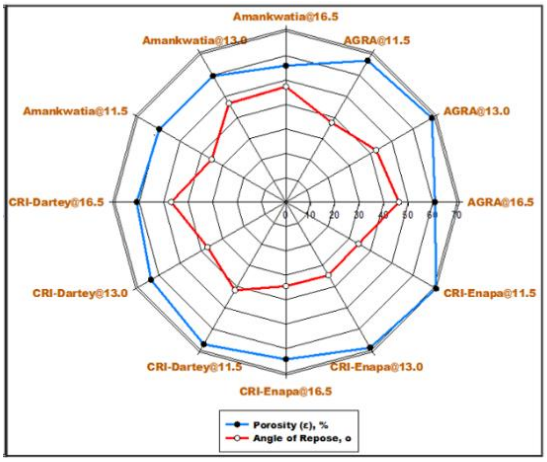

Figure 13. Variations of Porosity and Angle of Repose of Paddy Rice for Different Variety-Moisture Content Interactions.

Table 5. Units for mechanical properties of paddy rice.

Symbol	Property	Unit
L	Length	mm
W	Width	mm
T	Thickness	mm
ϕ	Sphericity	-
R_a	Aspect Ratio	-
M_t	Individual Grain Mass	g
GM 1000	Thousand Grain Mass	g
ρ_b	Bulk Density	kg/m^3
ρ_t	True Density	kg/m^3
ε	Porosity	%
β	Angle of Repose	^{o}

Conclusions

The comprehensive comparative analysis of the mechanical properties of selected paddy rice for different variety-moisture content interactions showed a significant variety and moisture content interaction for all the properties discussed. The study of these mechanical properties of paddy rice has shed light on the elaborate behaviour of rough rice at different moisture content and their implications on rice postharvest technology development and adaptation. The following conclusions were made from the comparative analysis of the paddy rice properties for different variety-moisture content interactions for moisture contents 11.5%, 13.0%, and 16.5% wb. The sphericity recorded 0.391 mm^3 to 0.377 mm^3 for CRI-Dartey at 16.5% and CRI-Enapa at 13.5%, respectively, whereas Aspect Ratio recorded 0.298 mm^3 to 0.269 mm^3 for CRI-Dartey at 16.5% and CRI-Enapa at 13.5%, respectively. For grain mass, AGRA rice at 13.0% also recorded 0.0312 g as the highest score, and CRI-Enapa at 13.0% obtained 0.0237 as the lowest score. For the GM1000, it was observed that it ranges from 29.33 g for CRI-Amankwatia at 16.5% moisture content to 22.54 g for CRI-Enapa at 16.5% interactions. Bulk density ranged from 654.0 kg/m^3 to 422.9 kg/m^3 for CRI-Amankwatia at 16.5% and CRI-Enapa at 11.5% as the highest and lowest recordings, respectively. It was also observed that the true density ranges from 1685.8 kg/m^3 for AGRA rice at 13.0% moisture content to 1352.5 kg/m^3 for CRI-Enapa at 16.5% interactions. In the case of porosity, CRI-Enapa at 11.5% received the highest score of 70.83%, and CRI-Amankwatia at 16.5 received the lowest score of 55.88%. Finally, in the case of Angle of Repose, CRI-Amankwatia at 16.5% recorded the highest score of 47.3^{o,} and CRI-Enapa at 11.5% recorded the least score of 34.27^o.

In all cases, the difference in the mean value of the mechanical properties for the different variety-moisture content interactions was less than the critical value for comparison, which is the LSD below, for which there is no statistically significant difference. This indicates that technologies developed for one variety can be equally effective for other varieties. This research provides valuable insights into the mechanical properties of rice, which can contribute to the development and adaptation of postharvest technologies for rice farmers in Sub-Saharan Africa.

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