EFFECT OF MOISTURE CONTENT ON SOME PHYSICAL AND MECHANICAL PROPERTIES OF WHEAT (*Triticum aestivum* L.) SEEDS
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በስንዴ (Triticum aestuum L.) ዘሮች የሚገኘው የእርጥበት ይዘት በአንዳንድ የአካላዊ እና መካኒካላዊ ባህረቶች ላይ ያለው ተጽእኖ

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ABSTRACT

The selection of design, improvement, and utilization of seed planting, harvesting, and postharvest implements depends on the grain physical and mechanical property information of the specific crop type and variety. However, this information is lacking for wheat varieties produced in different regions of Ethiopia. The objective of the study was to generate data on the physical and mechanical properties of grains from selected wheat varieties. Three wheat varieties (Danda'a, Jalanne, and Kakaba) were selected. A factorial combination of 3 × 5 treatment levels was adapted with three replications. The variables studied were the grain size, shape, weight, bulk density, angle of repose, and coefficient of friction. The data were subjected to analysis of variance (ANOVA), and the Dunnett multiple range test was used to separate the means. Significance was accepted at a 95% confidence interval ($p < 0.05$). As moisture increased, the grain's dimensions, shape, thousand kernel weight, coefficient of friction, and angle of repose all increased while bulk density decreased. The bulk density decreased from 0.73 to 0.54 g/cm³ as moisture increased from 8.50% to 28.50%. The study indicated large variations in the treatments used. The mean values for grain length, surface area, and volume increased from 5.786 ± 0.253 to 6.525 ± 0.361 mm, 38.514 ± 2.997 to 49.627 ± 3.201 mm², and 22.531 ± 2.644 to 32.933 ± 3.201 mm³, respectively. Similarly, thousand kernel weight, repose angle, and friction coefficient increased from 26.70 to 42.00 g, 23.20 to 34.70°, and 0.4142 to 0.8391, respectively. Variations in grain properties indicate the necessity for diverse design and calibration criteria for seed planting, harvesting, and postharvest equipment tailored to different wheat varieties at different moisture levels.

አኅፅሮተ-ጥናት

የዘር መዝራት፣ አዝመራ እና ድህረ ምርት መሳሪያዎች የንድፍ፣ የማሻሻያ እና አጠቃቀም የሚወሰነው በሚመለከታቸው የሰብል አይነት እና የእህል አካላዊ እና ሜካኒካል ባህረት መረጃ ነው። ነገር ግን ይህ መረጃ በኢትዮጵያ የተለያዩ ክልሎች ለሚመረቱ የስንዴ ዝርያዎች እጥረት ነው። የጥናቱ አላማ ከተመረጡ የስንዴ ዝርያዎች የዘርን አካላዊ እና ሜካኒካል ባህሪያት መረጃ ማመንጨት ነው። ሶስት የስንዴ ዝርያዎች (ዳንዳአ, ጃላኔ እና ቀቀባ) ተመርጠዋል. የ 35 የትርትመንት ደረጃዎች የፈክቶርያል ጥምር ከሶስት ድግግሞሽ ጋር ተወስዷል. የእህል መጠን፣ ቅርፅ፣ ክብደት፣ የጅምላ እፍጋት፣ የርፖስ አንግል እና የሰበቀ ጥምርታ ከተጠኑት ተለዋዋጮች መካከል ናቸው። ውሂቡ የልዩነት ትንተና (ANOVA) ተደርገዋል፣ እና የዱኔት ባለብዙ ክልል ሙከራ ዘዴዎቹን ለመለየት ጥቅም ላይ ውሏል። ትርጉሙ በ95% የመተማመን ልዩነት (p <0.05) ተቀባይነት አግኝቷል። እርጥበቱ እየጨመረ ሲሄድ የእህሉ ስፋት፣ ቅርፅ፣ ሺህ የዘር ክብደት፣ የሰበቀ መጠን እና የርፖስ አንግል ሁሉም ጨምረዋል፣ የጅምላ እፍጋት ግን ቀንሷል። እርጥበት ከ 8.50% እስከ 28.50% በማደጉ የጅምላ መጠኑ ከ0.73 ወደ 0.54 ግ/ሴሜ³ ቀንሷል። ጥናቱ ጥቅም ላይ በሚውሉት ትርትመንት ውስጥ ትልቅ ልዩነቶችን አመልክቷል. የእህል ርዝመት፣ የገጽታ ስፋት እና የዘር መጠን ከ 5.786 ± 0.253 ወደ 6.525 ± 0.361 ሚሜ፣ 38.514 ± 2.997 ወደ 49.627 ± 3.201 ሚሜ2, እና 22.531 ± 2.644 to 32.933 ± 3.201 በቅደም ተከተል ጨምሯል። በተመሳሳይ የሺህ የከርነል ክብደት፣ የርፖስ አንግል እና የሰበቀ ቅንጅት ከ26.70 ወደ 42.00 ግ፣ ከ23.20 ወደ 34.70° እና 0.4142 ወደ 0.8391 በቅደም ተከተል ጨምሯል። የእህል ባራቶች ልዩነት በተለያዩ የእርጥበት ደረጃ ላይ ለሚገኙ የተለያዩ የስንዴ ዝርያዎች የተዘጋጁ ዘርን ለመትከል፣ ለመሰብሰብ እና ለድህረ ምርት የሚውሉ መሳሪያዎች የተለያዩ የንድፍ እና የካሊብሬሽን መስፈርቶች እንደሚያስፈልግ ያመለክታሉ።

INTRODUCTION

Wheat (*Triticum aestivum L.*) is among the most important staple food crops and a major diet that is consumed by more than 2.5 billion people globally (*Bentley et al., 2022*). It is a staple food in all parts of the world, supplying 35% of food and providing 20% of the calories (Statista, 2022). In Ethiopia, wheat is one of the most important food grain crops. The grain is used for food utilization in different forms such as bread, porridge, soup, *injera, nifro, tella, arki,* and other industrially processed products like pasta and macaroni *(Nigussie et al., 2015*). Furthermore, farmers use wheat grain for marketing to generate income, and the straw is used as animal feed and bedding. Ethiopia's annual wheat production is about 5.80 million tons, with mean productivity of three tons per hectare (ton ha^{-1}) (CSA, 2021), which is relatively lower than the attainable yield of five tons ha^{-1} (*Zegeye et al., 2020*). Wheat accounts for about 17.00% of the total cereal grain produced in Ethiopia, making it the third most important cereal crop after teff and maize (CSA, 2021).

Certain physical attributes and engineering properties of the materials should be considered significant and crucial engineering data when designing machinery, structures, processing systems, and controls that will be used in the production, handling, and processing of food and agricultural products (*Mohsenin, 1986*). The engineering characteristics of wheat with various moisture contents must be understood to develop a machine for handling, transporting, and planting (*Tabatabaeefar, 2003*). Knowledge of the mechanical and physical characteristics of grains is necessary for the design, operation, adaptation, modification, and enhancement of any equipment. In general, the physical and mechanical characteristics of the grains from particular crop types and varieties determine and influence these processes (*Krishnakumar, 2019*). Depending on the crop type and variety, the grains of any food crop differ in terms of size, shape, mass, volume, surface area, density, porosity, angle of repose, coefficient of friction, hardness, resistance to compressive and shear forces, and force-deformation relationship (*Adinoyi et al., 2017; Surpam et al., 2019*). Variations in the location of the production environment, such as climate, soil, and cultural techniques, also impact the mechanical and physical properties of grains (*Mohite et al., 2019*). Furthermore, the grain moisture content has a major impact on how these characteristics vary, suggesting that the physical and mechanical properties are characterized as a function of the grain moisture levels (*Masane et al., 2016*).

For seed planting, threshing, cleaning, and grading, the grain's size and shape, defined by its three-dimensional (3D) parameters, are essential (*Kenghe et al., 2015; Surpam et al., 2019*). The design, selection, and proper functioning of equipment used for handling, storing, and processing grains of certain crop kinds and varieties are influenced by the mechanical characteristics of the grain, such as its coefficient of friction and angle of repose (*Fayed et al., 2020*). The significance of physical and mechanical properties, along with the characteristic variability of the grains, cannot be undermined for the widely diverse wheat cultivars adapted to different agro-ecological zones of Ethiopia and produced under varying cultural practices of the farming communities across various regions of the country.

Therefore, a comprehensive understanding and knowledge of the physical and mechanical properties of wheat grains from particular cultivars or varieties are necessary for the proper selection, design, fabrication, testing, improvement, evaluation, and operation of the machinery required for wheat harvesting, threshing, cleaning, grading, storage, conveying, milling, seed planting, and other tasks. Although it is crucial for the selection, design, improvement, and operation of seed planting, harvesting, and postharvest tools, there have been very few studies on the mechanical and physical characteristics of grains, and there is generally insufficient information on the mechanical and physical characteristics of wheat grains produced in Ethiopia.

Since the physical and mechanical characteristics of wheat grains are essential for the selection, design, development, and use of seed planting, harvesting, and postharvest tools, this study was conducted to generate data that can fill the gaps in this knowledge. The current study aimed to determine the mechanical and physical characteristics of wheat seeds at various moisture content.

MATERIALS AND METHODS

Location of the Study

The study was conducted at the Melkassa Agricultural Research Centre (MARC) in the East Shoa Zone, Oromia Regional State, Ethiopia, in 2024.

Materials and Sample Preparation

In this study, the three most important varieties of wheat - Danda'a, Jalanne, and Kakaba, were used. The Danda'a and Jalanne varieties were obtained from Kulumsa Agricultural Research Center and the Kakaba variety was sourced from a farm at Haramaya University, Ethiopia. The samples were manually cleaned to remove foreign matter, dust, dirt, and broken and immature grains. A digital oven drying machine (Universal

Oven Model of Memert Brand, Germany) was used for testing. The initial moisture content of the samples was determined by oven drying at 104 ±2ºC for 24 hours (*AOAC, 2005*). Samples at desired moisture levels were prepared by adding calculated amounts of distilled water, thoroughly mixing, and then sealing in separate polyethylene buckets. The quantity of distilled water was calculated using the following equation:

$$W_2 = W_1\left(\frac{M_1 - M_2}{100 - M_1}\right) \quad (1)$$

where: W_2 – mass of water added (g), W_1 – total seeds mass (g), M_1 –initial moisture content (%), and M_2 – final moisture content (%).

The samples were stored in a refrigerator at 4ºC for 12 days to allow the moisture to distribute uniformly throughout the samples. Before starting a test, the required quantities of the sample were allowed to warm up to room temperature (*Tabatabaeefar, 2003*). All physical and mechanical properties of wheat seed were measured at moisture levels of 8.50%, 13.50%, 18.50%, 23.50%, and 28.50% (w.b) for all seed varieties, with three replications at each moisture level.

Methods

Treatment variables

Wheat varieties and grain moisture levels were the independent variables. The physical and mechanical properties of the grains were determined at five different wet-based (w.b) grain moisture levels ranging from 8.50% to 28.50% with the levels selected at 5.00% intervals. The moisture range was chosen based on the recommended optimum moisture levels at harvesting, threshing, marketing, and safe storage (*John, 2021*). The 3 × 5 factorial combinations of treatments (3 varieties and 5 moisture levels) were arranged in a Completely Randomized Design, with the appropriate number of replications for each specific parameter.

Determination of physical properties

Grain size

The length, width, and thickness in the three dimensions (3D), designated by L, W, and T, were measured by randomly sampling 100-grain kernels at each selected grain moisture level using a digital vernier caliper with a resolution of 0.01 mm. The mass of each sampled grain was also recorded using an analytical balance, and this measurement was repeated for all the involved varieties. The representative geometric mean diameter, surface area, and degree of sphericity were calculated from basic dimensions using the following Equations 2 to 6 (*Mohsenin, 1986; Adinoyi et al., 2017; Krishnakumar, 2019*).

$$\text{Geometric mean diameter:}\quad D_g = (L \times W \times T)^{\frac{1}{3}} \quad [\text{mm}] \quad (2)$$

$$\text{Surface area:}\quad A_s = \pi D_g{}^2 \quad [\text{mm}^2] \quad (3)$$

$$\text{Volume:}\quad V = \frac{\pi \times L \times W \times T}{6} \quad [\text{mm}^3] \quad (4)$$

$$\text{Aspect ratio:}\quad R_a = \frac{W}{L} \quad (5)$$

$$\text{Sphericity:}\quad S = \frac{(L \times W \times T)^{\frac{1}{3}}}{L} \times 100 \quad [\%] \quad (6)$$

Thousand kernel weight (TKW)

The grains were counted using a digital counter and placed into a cylinder container of known weight. Thousand kernel weight (TKW) was measured by counting 1,000 seeds with a seed counter and weighing them on an electronic balance to an accuracy of 0.001 g. The cylinder with grain was weighed using a digital balance. This procedure was repeated three times at each moisture level.

Bulk density (ρ_b): Bulk density was calculated from the mass and volume of a circular container with a known volume, which was filled with the wheat samples. After filling the container, excess seeds were removed by passing a flat metal across the top surface with five zigzag motions. The grain was then carefully filled from a height of 150 mm into a 500 mL graduated cylinder of known weight. It was repeated three times. The cylinder was weighed with its content, and the difference above the cylinder weight was used to calculate the bulk density using Equation 10 (*Khanahmadzadeh et al., 2021*):

$$\text{Bulk density:}\ \rho_b = \frac{M_b}{V_b} \quad [\text{g cm}^{-3}] \quad (7)$$

where: M_b = mass of bulk grains (g); V_b - the container volume (cm^3).

Determination of mechanical properties

Angle of repose

The flow characteristics of solids is the angle of repose, which is associated with inter-particulate friction or the resistance to movement between particles. It is also related to the density, surface area, shape of the particles, and the coefficient of friction of the materials (*Sen et al., 2020*). Two cylindrical containers: one hollow and placed on top of a closed side, were used in the setup for the experiment for measurements of the repose angle. The measurements of the repose angle were taken using equation (8), as provided by *Baryeh (2002)*, *Mohsenin (1986)*, and *Saparita et al. (2019).*

$$\text{Angle of repose: } \theta = tan^{-1}\left(\frac{H}{R}\right) \tag{8}$$

where: H - depth of the slope (mm) and R - the bottom horizontal span of the slope (mm).

Coefficient of friction

The coefficient of static friction was determined using a plywood box with 350 mm in length, 190 mm in width, and 35 mm in height, featuring an open base and top faces. The box was placed on a graduated angular tilting table, on which the test surface plate was fixed. Friction was measured against aluminum, galvanized iron sheets, glass, mild steel, painted surfaces, plastic, plywood, and rubber. A hollow metal cylinder, 50 mm in diameter and 50 mm in height, open at both ends, was filled with seeds at the desired moisture content and placed on an adjustable tilting surface, ensuring that the cylinder did not come into contact with the surface. The surface was then raised gradually until the filled cylinder began to slide down (*Razavi and Milani, 2006; Khanahmadzadeh et al., 2021*). The tilt angle (α) was read from an angular scale when the box began to slide down on the test surfaces and was replicated three times at each moisture level. The coefficient of static friction was calculated using Equation (9).

$$\text{Coefficient of friction: } \mu = tan\ \alpha \tag{9}$$

Data Analysis

The data collected were organized into the required forms for every parameter and subjected to statistical analysis. Minitab 18th edition software was used for statistical analysis. Both descriptive statistics and Analysis of Variance (ANOVA) models were employed as needed, depending on the specific behavior of each parameter. The descriptive method was used to analyze the grain mean dimensions with standard deviations. Analysis of variance was applied to the bulk grain properties, using the Dunnett multiple comparison test with the least significance difference (LSD) at a 5% probability level. Mean line graphs, trend line equations, and coefficients of determination (R^2) were generated for some of the property variables.

RESULTS AND DISCUSSION

Physical Properties

Table 1 summarizes the measured and determined dimensions of 100 kernels from each wheat variety with a moisture content ranging from 8.50 to 28.50%. For the three wheat seed (*Triticum aestivum L*) varieties: Danda'a, Jalanne, and Kakaba, the physical parameters and ANOVA values are shown. The evaluated physical parameters include length, width, thickness, geometric mean diameter, surface area, volume, aspect ratio, and sphericity. The table presents the mean ± standard deviation for each parameter.

Table 1

Descriptive Statistics Wheat varieties dimension, geometric mean diameter, surface area, volume, aspect ratio, and sphericity at Moisture Content Levels from 8.50% to 28.50%.

Wheat Variety	Variable	Moisture Content Level (%)				
		8.50	13.50	18.50	23.50	28.50
Danda'a	Length, mm	5.975±0.39	6.1789±0.392	6.227±0.400	6.349±0.314	6.362±0.307
	Width, mm	2.969±0.194	3.031±0.254	3.176±0.306	3.288±0.377	3.311±0.306
	Thickness, mm	2.453±0.184	2.483±0.225	2.512±0.302	2.646±0.287	2.814±0.230
	Geometric diam., mm	3.512±0.156	3.591±0.213	3.668±0.256	3.800±0.271	3.894±0.222
	Surface area, mm^2	38.805±3.457	40.627±4.689	42.444±5.901	45.577±6.564	47.761±5.346
	Volume, mm^3	22.803±3.054	24.479±4.136	26.194±5.455	29.161±6.354	31.191±5.140
	Aspect ratio	0.492±0.044	0.499±0.044	0.512±0.057	0.518±0.055	0.521±0.046
	Sphericity, %	58.208±3.049	58.917±2.813	59.032±4.276	59.880±3.554	61.232±2.626
Jalanne	Length, mm	6.050±0.399	6.192±0.426	6.266±0.411	6.358±0.480	6.525±0.361
	Width, mm	2.958±0.242	3.030±0.303	3.156±0.230	3.238±0.246	3.321±0.211
	Thickness, mm	2.579±0.198	2.641±0.173	2.761±0.213	2.867±0.316	2.907±0.186

Wheat Variety	Variable	Moisture Content Level (%)				
		8.50	13.50	18.50	23.50	28.50
	Geometric diam., mm	3.581±0.172	3.668±0.230	3.789±0.199	3.885±0.243	3.974±0.128
	Surface area, mm^2	40.352±3.879	42.416±5.234	45.196±4.668	47.585±5.910	49.627±3.201
	Volume, mm^3	24.192±3.484	26.131±4.765	28.693±4.375	31.051±5.763	32.933±3.201
	Aspect ratio	0.490±0.049	0.491±0.050	0.505±0.046	0.510±0.056	0.511±0.048
	Sphericity, %	59.351±3.225	59.375±3.792	60.614±3.618	61.335±4.622	61.026±2.906
Kakaba	Length, mm	5.786±0.253	5.988±0.332	6.157±0.382	6.198±0.295	6.315±0.289
	Width, mm	2.954±0.187	2.972±0.214	3.056±0.252	3.105±0.250	3.218±0.266
	Thickness, mm	2.514±0.150	2.583±0.172	2.784±0.235	2.851±0.197	2.965±0.194
	Geometric diam. , mm	3.499±0.136	3.577±0.148	3.736±0.210	3.796±0.185	3.916±0.185
	Surface area, mm^2	38.514±2.997	40.254±3.317	43.968±4.982	45.343±4.371	48.264±4.502
	Volume, mm^3	22.531±2.644	24.083±2.956	27.551±4.733	28.818±4.122	31.639±4.386
	Aspect ratio	0.512±0.040	0.498±0.046	0.498±0.044	0.501±0.037	0.511±0.040
	Sphericity, %	59.856±2.870	60.537±2.081	60.769±2.725	61.297±2.687	62.064±2.685

Principal Dimension - Significant differences were observed among the measured parameters as moisture content increased. As moisture content rose, the size of the wheat kernels also grew. The dimensions (length, width, and thickness) of all varieties increased with rising moisture content. This growth was probably caused by small air voids on the kernels, which may have formed from the swelling effect of the added water. Similar findings were reported for barley grain by *Tavakoli et al., (2009),* sorghum grain by *Mwithiga and Sifuna (2006)*, and *Birehanu et al., (2024)*.

The findings confirm that the principal dimensions of wheat grains from the three varieties increased with an increase in moisture content (Table 1). The average seed length for Danda'a, Jalanne, and Kakaba increased from 5.975±0.39 to 6.362±0.307 mm, 6.050±0.399 to 6.525±0.361 mm, and 5.786±0.253 to 6.315±0.289 mm, respectively, as moisture content increased from 8.50% to 28.50%. Similarly, the average seed width for Danda'a, Jalanne, and Kakaba increased from 2.969±0.194 to 3.311±0.306 mm, 2.958±0.242 to 3.321±0.211 mm, and 2.954±0.187 to 3.218±0.266 mm, respectively, at the same moisture level. The average seed thickness for Danda'a, Jalanne, and Kakaba increased from 2.453±0.184 to 2.814±0.230 mm, 2.579±0.198 to 2.907±0.186 mm, and 2.514±0.150 to 2.965±0.194 mm, respectively, as the moisture content increased from 8.50% to 28.50%. These results align with the findings of *Majdi and Taha (2007)*, who reported that axial dimensions and mean diameter increase with the moisture content of green wheat. Changes in seed dimensions with increasing moisture are important to consider when designing equipment. As indicated in the literature, the physical properties of seeds change with the moisture content. Parameters such as moisture content, external friction, and material density are key factors influencing technological processes (*Kaliniewicz et al., 2018*). Variations in seed dimensions may also result from differences in the seeds' ability to absorb water, as well as variations in chemical composition, morphological structure, and endosperm structure. The water absorption capacity of cereal seeds is crucial not only during storage but also during conditioning before sowing.

Mean diameter. The geometric mean diameters varied among the different wheat varieties at similar moisture levels, with all test varieties showing a linear increase in diameter as moisture content increased (Table 1). The average geometric mean diameter for Danda'a, Jalanne, and Kakaba increased from 3.512±0.156 to 3.894±0.222 mm, 3.581±0.172 to 3.974±0.128 mm, and 3.499±0.136 to 3.916±0.185 mm, respectively, as moisture content increased from 8.50% to 28.50%. The geometric mean diameter is a useful parameter in the design of the metering cells. The metering cells for wheat planters should be designed based on the geometric mean diameter of 3.974±0.128 mm. The increase in the grain's geometric mean diameter may have been due to an overall increase in grain size resulting from the rise in moisture content. This diameter is primarily used in equipment designing, while the equivalent mean diameter represents the average size of bulk grain in a package (*Simonyan et al., 2007*).

Seed surface area and volume. Both surface area and volume for a seed showed significant increases with rising moisture content, with a notable variation among the varieties at similar moisture levels (Table 1). The mean seed surface area for Danda'a, Jalanne, and Kakaba increased from 38.805±3.457 to 47.761±5.346 mm^2, 40.352±3.879 to 49.627±3.201 mm^2, and 38.514±2.997 to 48.264±4.502 mm^2, respectively, the moisture content increased from 8.50% t0 28.50%. Similarly, the mean seed volume for Danda'a, Jalanne, and Kakaba increased from 22.803±3.054 to 31.191±5.140 mm^3, 24.192±3.484 to 32.933±3.201 mm^3 and 22.531±2.644 to 31.639±4.386 mm^3, respectively, at the same moisture levels. A similar linear increase in sorghum grain volume, from 29 to 38 mm^3, was reported by *Kenghe et al., (2015)* for a grain moisture increase from 10.94 to 24.22% (db.). Additionally, *Birehanu et al., (2024),* also observed a linear increase in grain volume with rising moisture levels.

Aspect ratio and Sphericity. The mean aspect ratio and sphericity of wheat seed showed a linear relationship with seed moisture content (Table 1). The seed aspect ratio showed non-significant increases for the Kakaba variety but slightly significant (P = 0.05) increases for Danda'a and Jalanne. The mean aspect ratio of Danda'a and Jalanne increased from 0.492±0.044 to 0.521±0.046, and 0.490±0.049 to 0.511±0.048, respectively, as moisture content increased from 8.50 to 28.50. Similarly, the mean seed sphericity for Danda'a, Jalanne, and Kakaba increased from 58.208±3.049 to 61.232±2.626%, 59.351±3.225 to 61.026±2.906%, and 59.856±2.870 to 62.064±2.685%, respectively, at the same moisture content levels. The shape of the Kakaba seed was the most spherical compared to the Danda'a and Jalanne. The increase in sphericity was attributed to the swelling of the grain kernels with additional water intake, where the thickness (minor diameter) increased more than the major and intermediate diameters (*Birahenu et al., 2024*).

Bulk Density. The experimental results showing the relationship between bulk density and moisture content are presented in Figure 1. A linear decrease in bulk density was observed with increasing moisture content, and this trend was statistically significant at the 5% significance level. The bulk density of Danda'a, Jalanne, and Kakaba varieties decreased from 0.71 to 0.61 g cm^{-3}, 0.73 to 0.64 g $cm^{-3,}$ and 0.70 to 0.54 g cm^{-3}, respectively, as the moisture content increased from 8.50 to 28.50%. This decline in bulk density suggests that the mass increase due to moisture absorption was less than the corresponding volumetric expansion of the bulk, as previously noted in soybean samples (*Tabatabaeefar, 2003*). An inverse relationship between bulk density and moisture content has also been reported by various other studies (*Garnayak et al., 2008; Shahbazi, 2015; Birahenu et al., 2024*). The models fitted to the data using regression analysis showed that the bulk density decreased linearly with increases in the moisture content for all cultivars. Therefore, the following equations were derived for the relationship between bulk density (ρ, g cm^{-3}) and moisture content (M, %), for each variety.

Danda'a variety: $\rho_D = 0.7597 - 0.005780M$, $R^2=0.927$

Jalanne variety: $\rho_J = 0.7461 - 0.004189\ M$, $R^2=0.769$

Kakaba variety: $\rho_K = 0.7857 - 0.00963\ M$, $R^2=0.739$

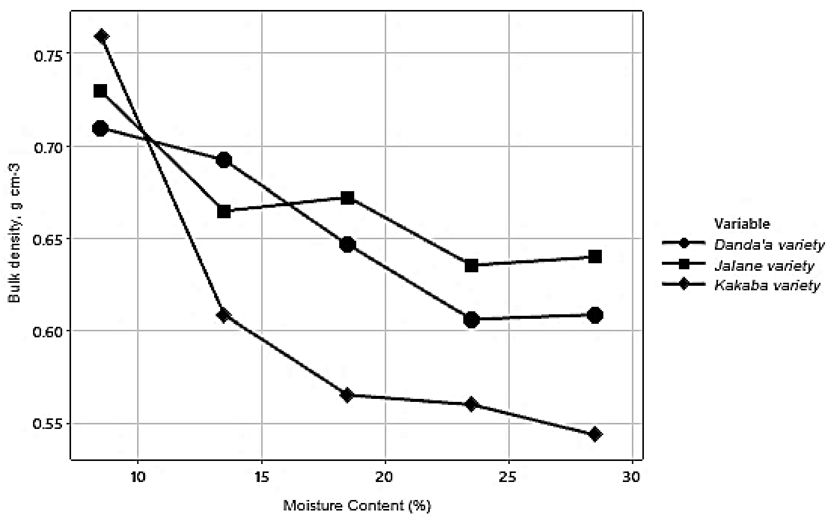

Fig. 1- Effect of moisture content on bulk density of wheat seed varieties

Thousand Kernel Weight. The results obtained for the thousand-kernel weight of wheat with an increase in moisture content are shown graphically in Figure 2. It was observed that the thousand-kernel weight increased linearly with an increase in moisture content, and this change was significant at the 5% significance level. The figure reveals that, for all the wheat seed varieties considered, the thousand-kernel seed mass increases as the moisture content increases. The thousand-kernel weight of the Danda'a, Jalanne, and Kakaba varieties increased from 28.70 to 35.00 g, 31.30 to 42.00 g, and 26.70 to 38.00 g, respectively, as the moisture content increased from 8.50 to 28.50%. The thousand-kernel weight means showed a significant variation among the test varieties, and it also increased linearly with an increase in grain moisture content. The thousand-kernel weight of Jalanne exceeded that of the Danda'a and Kakaba varieties by about 13.11% and 11.73%, respectively. The means of thousand-kernel weight at 13.50% (wb) were 36.30 g, 32.30 g, and 30.00 g for Jalanne, Kakaba, and Danda'a, respectively. The 13.50% moisture is the standard level recommended for wheat grain marketing (*John, 2021*). A mean increase in thousand-kernel weight from 20.67 g to 22.01 g was also reported for sorghum, with a corresponding moisture increase from 8.70% to 21.80% (wb) (*Sabar et al., 2020*). Regression analysis was used to find and fit the best general models to the data. The results showed that as the moisture content of the seeds increased, the thousand-grain weight of wheat increased linearly. Thus, the dependence of the thousand-kernel mass of wheat seeds (TKW, g) on the seed moisture content (M, %) was expressed by the following best-fit equations for each variety:

Danda'a variety: $TKW_D = 26.11 + 0.2720M,\ R^2=0.834$

Jalanne variety: $TKW_J = 28.18 + 0.4680M,\ R^2=0.912$

Kakaba variety: $TKW_K = 23.47 + 0.5260M,\ R^2=0.935$

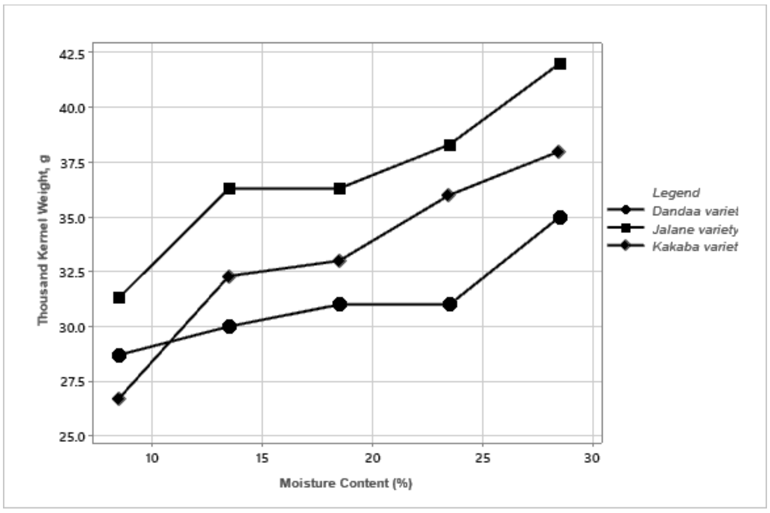

Fig. 2 - Effect of moisture content on thousand kernel weight of wheat seed varieties

Mechanical Properties

Repose Angle. The variation observed in the angle of repose of wheat seeds with increasing moisture content is shown graphically in Figure 3. It was observed that the angle of repose increased linearly with an increase in moisture content, and this change was found to be significant at the 5% level. The angle of repose exhibited a linear increase with significant differences at higher moisture content levels, regardless of the wheat variety tested. The mean repose angle increased for Danda'a from 23.20 to 34.70°, for Jalanne from 24.10 to 32.30°, and for Kakaba from 24.50 to 32.31°, as the moisture content increased from 8.50% to 28.50% (Figure 3). Overall, the angle of repose ranged from 23.20° to 34.70°, indicating flow characteristics classified as good to fair. Angles of repose between 25° to 30°, and 31° to 40°, have been reported to correspond to good and fair, flow properties, respectively (*Sen et al., 2020; Birhanu et al., 2024*). Therefore, the observed values in this study suggest that all wheat varieties demonstrated flowability ranging from good to fair under varying moisture conditions.

At higher moisture content within the experimental range, the grains tended to clump together, resulting in increased pile stability and reduced flowability, which in turn led to higher angles of repose. The observed increase in the angle of repose for the wheat seed varieties was primarily attributed to the expansion in seed size and mass at elevated moisture levels. Additionally, higher moisture content made the seed surfaces stickier, reducing their ability to roll over one another - an effect also reported by *Razavi et al. (2007)*.

Regression models fitted to the experimental data indicated a linear increase in the angle of repose with moisture content for all wheat varieties. The following equations describe the relationship between the angle of repose (θ, °) and moisture content (M, %) for each variety:

Danda'a variety: $\theta_D = 17.85 + 0.5780\ M$, $R^2=0.993$

Jalanne variety: $\theta_J = 21.39 + 0.3940\ M$, $R^2=0.971$

Kakaba variety: $\theta_K = 22.19 + 0.3680\ M$, $R^2=0.951$

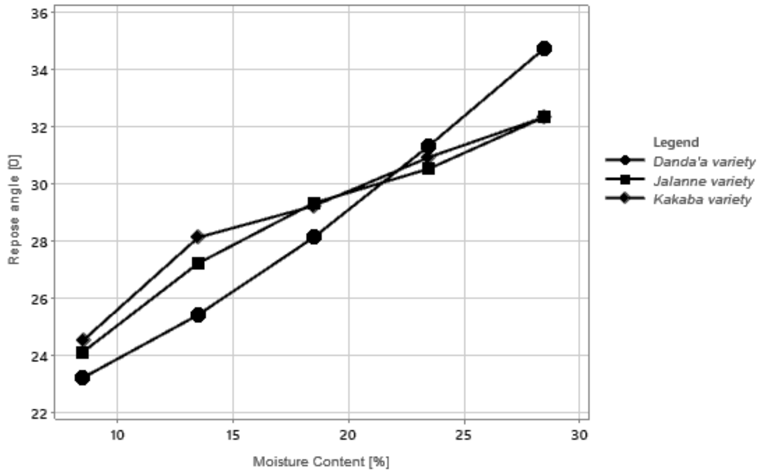

Fig. 3 - Effect of moisture content on the repose angle of wheat seed varieties

Static coefficient of friction

The static coefficient of friction for wheat seed was determined for eight different structural surfaces, as presented in Table 2. It was observed that the static coefficient of friction increased with an increase in moisture content across all surfaces. The values of the static coefficient of friction ranged from 0.4142 to 0.8391 on various surfaces for all wheat seed varieties tested at the specified moisture content levels.

Moisture content played a significant role in influencing μ, with higher moisture levels typically increasing friction due to enhanced adhesive forces between grains and surfaces. However, at the upper moisture range (near 28.50%), some smoother surfaces exhibited slight reductions in μ, possibly due to a lubricating effect from excess moisture. Varietal differences were also notable: Danda'a displayed broad friction ranges, suggesting high sensitivity to surface type, while Jalanne unexpectedly showed high friction on plywood, possibly due to grain morphology. Kakaba, unlike the other varieties, had plastics as the second-highest friction surface, indicating unique grain-surface interactions. These findings have practical implications for grain handling and storage systems, where rubber linings could be used to prevent slippage, while smoother surfaces like aluminum or painted materials might be preferred for applications requiring reduced friction. Further research could explore dynamic friction under movement or the effects of surface wear over time to optimize post-harvest processing and machinery design.

Across all moisture contents, the highest static coefficient of friction was observed on the compressed rubber surface. This could be attributed to the more unpolished surface of the compressed rubber compared to the other materials used. It was also noted that moisture had a greater effect on the static coefficient of friction than the material surface itself. This is likely due to increased adhesion between the grain and the material surface at higher moisture content. Similar results were reported by *Sahoo and Srivastava (2002)*, *Ozarslan (2002), Tabatabaeefar (2003), Bulent Coskun et al. (2005)*, and *Shepherd and Bhardwaj (1986)* for okra, cotton, lentil, wheat, sweet corn, and pigeon pea seeds, respectively. *Parde et al., (2003),* reported that the friction coefficient against the plywood, galvanized steel, and concrete surfaces for the Koto buckwheat cultivar increased significantly from 0.26 to 0.31, 0.25 to 0.29 and 0.38 to 0.43, respectively, with increases in moisture content from 14.8% to 17.9%, which were lower values than compared to the current findings.

The variation between the current findings and previously reported studies could be attributed to differences in seed variety, study location, and other related factors. The increase in grain moisture content likely caused an increase in the grain's surface roughness, which reduced its slipping characteristics and led to higher friction between the grains and the surfaces. These differences could provide important insights for the design of postharvest equipment, such as hoppers, storage structures, and auger conveyors (*Mohite et al., 2019*).

Table 2

Descriptive Statistics of Wheat varieties of static coefficient of friction

Static coefficient of friction, μs						
Surface	**Variety**	**Moisture Level (%)**				
		8.5	**13.5**	**18.5**	**23.5**	**28.5**
Aluminum	Danda'a	0.4627	0.4877	0.4986	0.5317	0.7399
	Jalanne	0.4663	0.4877	0.4986	0.5774	0.7002
	Kakaba	0.4452	0.4877	0.4986	0.5317	0.6249
Galvanized iron	Danda'a	0.4699	0.5317	0.5774	0.6619	0.7673
	Jalanne	0.4521	0.4877	0.5658	0.6249	0.6619
	Kakaba	0.4452	0.5317	0.5774	0.6619	0.7002
Glass	Danda'a	0.4949	0.5429	0.5774	0.6128	0.7002
	Jalanne	0.4593	0.4986	0.5206	0.5317	0.5774
	Kakaba	0.4699	0.5429	0.5774	0.6128	0.6494
Mild steel iron	Danda'a	0.5206	0.5774	0.6249	0.6745	0.7265
	Jalanne	0.5168	0.5317	0.5429	0.6009	0.6619
	Kakaba	0.4557	0.5774	0.6249	0.6745	0.7133
Painted	Danda'a	0.4142	0.4877	0.5658	0.6249	0.7536
	Jalanne	0.4663	0.5317	0.5429	0.5658	0.6249
	Kakaba	0.4699	0.4877	0.5658	0.6249	0.6745
Plastic	Danda'a	0.4733	0.5774	0.589	0.6249	0.7002
	Jalanne	0.4663	0.5095	0.5317	0.6009	0.6745
	Kakaba	0.4699	0.5774	0.589	0.6249	0.7002
Plywood	Danda'a	0.5023	0.5095	0.5543	0.6128	0.6873
	Jalanne	0.5774	0.6128	0.6249	0.6494	0.7133
	Kakaba	0.4521	0.5095	0.5543	0.6128	0.6494
Rubber;	Danda'a	0.6452	0.4452	0.6873	0.7002	0.8243
	Jalanne	0.6536	0.7002	0.6873	0.7536	0.8391
	Kakaba	0.6452	0.6552	0.6745	0.7002	0.7133

The relationships between the static coefficient of friction and moisture content for compressed aluminum, galvanized, glass, mild steel iron, painted, plastic, plywood, and rubber are represented by the following equations:

Aluminum
Danda'a: $CoF_a = 0.3227 + 0.01197M$, $R^2 = 0.721$
Jalanne: $CoF_a = 0.3398 + 0.01115M$, $R^2 = 0.846$
Kakaba: $CoF_a = 0.3684 + 0.008068M$, $R^2 = 0.894$

Galvanized steel
Danda'a: $CoF_g = 0.3334 + 0.01450M$, $R^2 = 0.975$
Jalanne: $CoF_g = 0.3525 + 0.01114M$, $R^2 = 0.985$
Kakaba: $CoF_g = 0.3464 + 0.01280M$, $R^2 = 0.985$

Glass
Danda'a: $CoF_{gl} = 0.4079 + 0.009610M$, $R^2 = 0.962$
Jalanne: $CoF_{gl} = 0.4179 + 0.005386M$, $R^2 = 0.961$
Kakaba: $CoF_{gl} = 0.4118 + 0.008578M$, $R^2 = 0.971$

Mild steel iron
Danda'a: $CoF_{ms} = 0.4365 + 0.01018M$, $R^2 = 0.999$
Jalanne: $CoF_{ms} = 0.4379 + 0.007188M$, $R^2 = 0.895$
Kakaba: $CoF_{ms} = 0.3826 + 0.01225M$, $R^2 = 0.939$

Painted
Danda'a: $CoF_p = 0.2673 + 0.01632M$, $R^2 = 0.98$
Jalanne: $CoF_p = 0.4163 + 0.007026M$, $R^2 = 0.93$
Kakaba: $CoF_p = 0.3624 + 0.0109\ M$, $R^2 = 0.976$

Plastic (Mica)
Danda'a: $CoF_{pl} = 0.4075 + 0.01003M$, $R^2 = 0.927$

Jalanne: $CoF_{pl} = 0.3687 + 0.01016M$, $R^2 = 0.960$
Kakaba: $CoF_{pl} = 0.4043 + 0.01016M$, $R^2 = 0.925$

Plywood (MDF)
Danda'a: $CoF_{pw} = 0.3981 + 0.009466M$, $R^2 = 0.932$
Jalanne: $CoF_{pw} = 0.5215 + 0.006168M$, $R^2 = 0.928$
Kakaba: $CoF_{pw} = 0.3714 + 0.009958M$, $R^2 = 0.995$

Rubber
Danda'a: $CoF_{ru} = 0.4336 + 0.01226M$, $R^2 = 0.497$

Jalanne: $CoF_{ru} = 0.5697 + 0.008488M$, $R^2 = 0.859$
Kakaba: $CoF_{ru} = 0.6106 + 0.003624M$, $R^2 = 0.981$

where: CoF - coefficient of friction a - aluminum, g - galvanized, gl - glass, ms - mild steel iron, p - painted, pl - plastic, pw - plywood, ru - rubber, and M - moisture content.

CONCLUSIONS

The study investigated the physical and mechanical properties of different wheat varieties at varying moisture levels, aiming to enhance process and equipment design for improved wheat grain yield and quality. Significant differences were observed among the test wheat varieties in terms of grain properties, and these properties varied with changes in moisture content.

Key findings include:

- All test varieties showed an increase in grain size as moisture content increased, with the Jalanne variety exhibiting the largest mean values for grain size and all other studied properties.
- As moisture content increased, grain dimensions, shape, thousand kernel weight, coefficient of friction, and angle of repose also increased, while bulk density decreased. Specifically, bulk density decreased from 0.73 to 0.54 g/cm³ as moisture content increased from 8.50% to 28.50%.
- Grain length, surface area, and volume increased significantly, with mean values rising from 5.786±0.253 mm to 6.525±0.361 mm, 38.514±2.997 mm² to 49.627±3.201 mm², and 22.531±2.644 mm³ to 32.933±3.201 mm³, respectively.
- Thousand kernel weight, repose angle, and friction coefficient also showed increases, highlighting the impact of moisture on these parameters.

In conclusion, the study emphasizes the need for varied design and calibration criteria for equipment used in seed planting, harvesting, and postharvest handling, based on the different physical and mechanical properties of wheat at various moisture levels. These findings suggest that to minimize seed damage and losses during operation, it is essential to tailor equipment design and operation to account for the grain's physical and mechanical properties at different moisture contents. This approach will optimize the efficiency and effectiveness of machinery used in wheat production.

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