Influence of moisture content on physico-mechanical and color characteristics of yellow, purple, and black wheat grains (*Triticum aestivum*)

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Abstract: In the present study three different color wheat varieties (yellow (YW), purple (PW), and black (BW)) were characterized by moisture dependent physical and mechanical properties. The length, width, and thickness were increased with an increase in moisture content, and the highest increase in length (13.46%) was observed for BW, width (8.10%) for YW, and thickness (11.41%) for PW. The geometric mean diameter, sphericity porosity, mass of 1000 grains, angle of repose, and coefficient of friction were increased linearly and the linear reduction was observed in bulk density and true density with an increase in moisture content. Hardness and rupture energy were decreased linearly while deformation distance increased linearly with the moisture. YW, BW, and PW can easily be identified by their color, and variation was observed with the change in moisture content. The highest variation was observed on PW. The findings of the present study can be used to design and develop/improve the handling and storage systems for different wheat varieties.

Keywords: yellow wheat; black wheat; purple wheat; physical and mechanical properties

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1 Introduction

In the context of the human diet, wheat (*Triticum aestivum*) is one of the most important cereal grains among all cereals. Unprocessed whole wheat grain is a rich source of carbohydrates, protein, fats, minerals, and essential oils (Hernandez-Espinosa et al., 2020). It also consists of phenolic acids such as sugars, sterols, arabinoxylans, etc. (Hernandez-Espinosa et al., 2020), which act as an antioxidant, anti-inflammatory, and anti-carcinogenic agent (Martini et al., 2015; Laddomada et al., 2015). Wheat grains are available in different colors i.e. red, yellow, white, black, blue, and purple wheat. Yellow, red, and amber color wheat grains are well known to wheat producers and food processors whereas black and purple wheat grains are not common (Abdel-Aal et al., 1999). Black and purple wheat varieties with high nutritive value, anthocyanins, and phenolic acids can be used as novel food ingredients to develop other high-value products (Beta et al., 2019).

The journey of developing different food products from food grain starts from farm to fork consisting of several unit operations. Major unit operations involve harvesting, transportation, storage, grading, cleaning, ventilation, drying milling, etc. require a basic understanding of the physical and mechanical properties of the grain. The characteristic dimensions are important for cleaning/grading, volume, and surface area for the modeling of ventilation, heating, cooling, and drying (Bhushan and Raigar, 2020), true density for separation equipment, bulk density and porosity for storage capacity,

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transport, and the resistance to airflow at the time of aeration and drying operation (Sologubik et al., 2013). Frictional properties (angle of repose, coefficient of friction, etc.) are important to design proper mass flow and grain storage structures, grain harvesting and handling equipment and mechanical behavior (compression, fracture characteristics, etc.) of grain is important to design harvesting, sizing, storage, transportation, and grinding machines (Bhushan and Raigar, 2020).

Studies on moisture-dependent physical and mechanical properties of wheat grains were limited and very few studies have been performed (Kang et al., 1995; Tabatabaeefar, 2003; Al-Mahasneh and Rababah, 2007; Karimi et al., 2009; Markowski et al., 2013). Saini et al. (2021) have reported moisture dependent engineering properties of purple wheat recently. There is a lack of the studies that reported on moisture dependent physico-mechanical properties of black and purple wheat varieties. Hence, the present study aimed to study the moisture-dependent physical and mechanical properties of different colored wheat varieties.

2 Material and methods

2.1 Sample preparation

Three different color wheat varieties (yellow (MP Sharbati), black (NABIMG-11), and purple (NABIMG-10)) were selected for the present study. Black (BW) and purple wheat (PW) supplied by INAWAY Direct & indirect selling pvt. Limited (longitude: 75°43′E and altitude: 213 meters from mean sea level), Haryana, India and Yellow wheat (YW) procured from a local market (longitude: 77°09′E and altitude: 213 meters from mean sea level) Narela, Delhi, India. Grains were manually cleaned to remove the broken, immature grains and foreign matters (dust, dirt). The moisture content of wheat grains was determined using the AOAC method (Ahn et al., 2014) (Table 1). To maintain the same moisture content, all the grains were dried in a hot air oven at 104℃ for 24 h. Dried grains (7.44% ± 0.53% wet basis (w.b.)) were divided into five different groups (100 g) and a weighted quantity of water was added to achieve four different moisture (Karimi et al., 2009; Saini et al., 2021) and the grains were packed in aluminum pouches and stored in a refrigerator at 4℃ (10 days). After 10 days of storage, grains were achieved the moisture content of 7.44%±0.53%, 11.01%±0.48%, 15.75%±0.11%, 20.68%±0.25%, and 26%±0.23% w.b. were used for further analysis. All the experiments have been conducted in February and March 2020.

2.2 Physical properties

2.2.1 Geometric mean diameter, sphericity, and surface area

The dimensional parameters length (L, mm), width (W, mm), and thickness (T, mm) of randomly selected 20 grains were determined using a digital micrometer (Mitutoyo, Japan) with the accuracy of 0.001 mm. The geometric mean diameter (D_g, mm), sphericity (φ), and surface area (S_a, mm^2) were calculated using Equations 1, 2, and 3 respectively (Jha and Kachru, 1998, Sologubik et al., 2013; Sharanagat et al., 2018).

$$Dg = (L \times W \times T)^{\frac{1}{3}} \quad (1)$$

$$\emptyset = \frac{(L \times W \times T)^{\frac{1}{3}}}{L} \quad (2)$$

$$S_a = \pi (Dg)^2 \quad (3)$$

2.2.2 Bulk density, true density, and porosity

Bulk density (ρ_{BD}, g mL^{-1}), true density (ρ_{TD}, g mL^{-1}), and porosity (ε, % ,) were determined as described by Nimesh and Sharanagat (2016) as Equation 4. In brief, the sample was filed in a 100 mL cylinder and after 10 times tapping the volume occupied and the corresponding mass was measured. The bulk density was determined by dividing the mass of the sample by the volume occupied by the sample. True density was measured by the toluene displacement method. The constant volume (50 mL) of toluene was taken in a 100 mL cylinder and the known mass of sample grain (approx. 5 g) was dipped in toluene. The increase in toluene volume was measured, and the true density was determined by dividing the mass by the rise in volume. Porosity was determined by using the Equation 4.

$$\varepsilon(\%) = \left(1 - \frac{\rho_{BD}}{\rho_{TD}}\right) \times 100 \quad (4)$$

2.2.3 Angle of repose and coefficient of friction

The angle of repose (Θ, Equation 5) and static coefficient of fraction (μ, Equation 6)le were determined by the method described by Sharanagat et al. (2018).

$$\theta = tan^{-1}\left(\frac{2H}{D}\right) \quad (5)$$

$$\mu = \tan\theta \quad (6)$$

Where, H- Height (mm), D- Diameter (mm)

2.2.4 Color analysis

The color analysis of food grains was performed using a hand chroma meter (CR400, Konica Minolta) described by Arora et al. (2021). Chroma meter grain color measurement assembly was attached and calibrated with the whiteboard. The color values $L*$ (0 to 100, lightness), $a*$ (-a to +a, redness-greenness), $b*$ (-b to +b, yellowness-blueness), and total color difference (ΔE) of control and conditioned samples were measured.

Table 1 Effect of moisture content on physical dimension of yellow, purple and black wheat grain.

Sample	M_C (% w.b.)	L (mm)	W (mm)	T (mm)	D_g (mm)	φ	S_a (mm^2)
Yellow wheat	11.01±0.48	6.83±0.23^{a}	3.58±0.09^{a}	3.07±0.11^{a}	4.22±0.09^{a}	0.62±0.02^{a}	55.85±2.39^{a}
	15.75±0.11	6.90±0.12^{a,b}	3.63±0.27^{a}	3.14±0.10^{a,b}	4.29±0.15^{a,b}	0.62±0.02^{a}	57.77±4.07^{a,b}
	20.68±0.25	6.98±0.41^{b}	3.75±0.14^{a}	3.16±0.11^{a,b}	4.36±0.10^{a,b}	0.63±0.03^{a}	59.63±2.65^{a,b}
	26.00±0.23	7.16±0.32^{c}	3.87±0.33^{a}	3.35±0.37^{b}	4.52±0.35^{b}	0.63±0.02^{a}	64.61±9.91^{b}
	Equation	L=6.5716+0.0216M_c (R^2 = 0.9548) RMSE=0.026 χ^2=0.0014	W=3.3421+ 0.0199M_c (R^2= 0.9776) RMSE=0.017 χ^2=5.642E-4	T=2.8609+0.0174M_c (R^2= 0.8752) RMSE=0.037 χ^2=0.0027	D_g=3.9888+0.0195M_c (R^2= 0.9612) RMSE=0.022 χ^2=9.595E-4	φ=0.6103+0.0008M_c (R^2= 0.7962) RMSE=0.002 χ^2=1.019E-5	S_a = 49.048 + 0.5674 M_c (R^2= 0.945) RMSE=0.764 χ^2=1.168
Black wheat	11.01±0.48	6.91±0.35^{c}	3.21±0.20^{c}	2.69±0.21^{c}	3.93±0.14^{c}	0.56±0.04^{c}	48.43±3.54^{c}
	15.75±0.11	7.26±0.52^{c}	3.26±0.18^{c}	2.75±0.14^{c}	4.02±0.25^{c}	0.55±0.02^{c}	50.82±6.35^{c}
	20.68±0.25	7.39±0.47^{c,d}	3.32±0.19^{c}	2.80±0.21^{c}	4.10±0.17^{c}	0.55±0.03^{c}	52.67±4.44^{c}
	26.00±0.23	7.84±0.38^{d}	3.43±0.20^{c}	2.98±0.15^{d}	4.31±0.15^{d}	0.55±0.02^{c}	58.29±4.15^{d}
	Equation	L=6.2734+0.0586M_c (R^2= 0.9661) RMSE=0.061 χ^2=0.0075	W=3.0389+ 0.0145M_c (R^2= 0.9727) RMSE=0.013 χ^2=3.674E-4	T=2.464 + 0.0186M_c (R^2= 0.9166) RMSE=0.031 χ^2=0.0020	D_g=3.6387+0.0246M_c (R^2= 0.953) RMSE=0.030 χ^2=0.0018	φ=0.5633-0.0006M_c (R^2= 0.5782) RMSE=0.003 χ^2=1.582E-5	S_a= 40.921+.6335M_c (R^2= 0.9447) RMSE=0.855 χ^2=1.463
Purple wheat	11.01±0.48	6.60±0.32^{e}	3.46±0.21^{e}	2.98±0.20^{e}	4.08±0.19^{e}	0.62±0.02^{e}	52.35±5.01^{e}
	15.75±0.11	6.79±0.22^{e}	3.59±0.08^{e}	3.09±0.18^{e,f}	4.22±0.10^{e,f}	0.62±0.01^{e}	55.99±2.59^{e,f}
	20.68±0.25	6.88±0.34^{e}	3.61±0.20^{e}	3.25±0.10^{f,g}	4.32±0.16^{f}	0.63±0.01^{e}	58.65±4.27^{f}
	26.00±0.23	6.93±0.53^{e}	3.68±0.25^{e}	3.32±0.19^{g}	4.39±0.26^{f}	0.63±0.02^{e}	60.64±7.31^{f}
	Equation	L=6.4058+0.0215M_c (R^2 = 0.9058) RMSE=0.039 χ^2=0.0030	W=3.336+ 0.0136M_c (R^2= 0.9056) RMSE=0.024 χ^2=0.0012	T=2.7272+0.0236M_c (R^2= 0.9751) RMSE=0.021 χ^2=8.840E-4	D_g=3.8753+0.0205M_c (R^2= 0.969) RMSE=0.021 χ^2=8.402E-4	φ=0.6103+0.0008M_c (R^2= 0.7962) RMSE=0.002 χ^2=1.019E-5	S_a=46.82+0.5494M_c (R^2= 0.9748) RMSE=0.493 χ^2=0.486

Note: #Values are in Mean ± SD (n=10). Mean values for each type of sample within the column followed by the superscripts a, b, c, d, e, f, and g were significantly different (p<0.05) (Where, L-Length, W-Width, T-Thickness, Dg-Geometric mean diameter, φ-Sphericity, Sa-Surface area, M_C- Moisture Content, w.b.-wet basis).

2.3 Texture analysis

For all conditioned wheat grain samples mechanical characteristics were determined using a Texture profile analyzer (Stable microsystem, TA. XT plus) as described by Jha et al. (2013) with slight modification. In brief, the samples were placed in the center of the platform in the rest position. Samples were subjected to 40% strain with a cylindrical probe having a diameter of 75 mm at a test speed of 1 mm s^{-1} and a trigger force of 5 g using a 30 kg load cell. Pre and post-test speeds remained the same for better results. Rupture force (F, N) and deformation (D_f, *mm*) values were obtained by analyzing the TPA graph (Jha et al., 2013). Rupture energy (Ea, Nmm) was calculated by using Equation 7 (Arjun et al., 2017; Mridula et al., 2008). Load cell and height calibration was performed before analysis by following the calibration process, and all the analysis was performed in triplicate.

$$E_a = 0.5 \times F \times D_f \quad (7)$$

2.4 Model fitting and statistical analysis

The linear mathematical model was fitted to express the results in a suitable format. Two different iteration algorithms (Levenberg Marquardt & Orthogonal Distance Regression (Pro)) in Origin Pro 2018 software were used to calculate R^2 and χ^2 (Chi-square) values. Origin Pro

2018 software was also used for principal component analysis (PCA) optimization. One-way analysis of variance (ANOVA) was used in IBM-SPSS software to analyze the data. Significant differences in the treatments and respective results were determined by DUNCAN's multiple range test (DMRT) (p<0.05).

3 Results and discussions

3.1 Effect of moisture content on physical properties

3.1.1 Physical dimension

The physical characteristics of three different colored wheat grains with an increase in moisture content are shown in Table 1. Physical dimensions (Length, width, and thickness) increased significantly with an increase in moisture content. The linear relationship between the physical dimension and moisture content with corresponding R^2 values has been shown in Table 1. Geometric mean diameter, sphericity, surface area, and aspect ratio of wheat grain varied significantly (p<0.05) with the change in dimension. The geometric mean diameter of all the conditioned samples was higher than the control sample (YW- 4.22 mm> PW- 4.08 mm >BW- 3.93 mm). YW exhibited the highest surface area (64.61 mm^2, 26.00% MC) and the lowest value was observed for BW (48.43 mm^2, 11.01% MC). Whereas, BW had lower sphericity (0.55-0.56) compared to YW (0.62-0.63) and PW (0.62-0.63) and increased with an increase in moisture content. The increase in moisture content results in swelling of wheat grain increased the physical dimension whereas the variation in dimension of YW, PW, and BW might be due to the variation difference. The increase in dimension led to an increase in geometric mean diameter, surface area, and sphericity. The increase in moisture content increased the surface area whereas a non-significant variation was observed in sphericity. The low value of sphericity of wheat grain compared to other grains (sorghum, red kidney bean) results in problems rolling on the surface and required major attention during the designing of processing equipment (Mwithiga and Sifuna, 2006). Findings were supported by Tabatabaeefar (2003) for wheat and Al-Mahasneh and Rababah (2007) for green wheat.

3.1.2 Density and porosity

Table 2 shows that the density and porosity of different variety varied linearly with the moisture content of wheat grain. Bulk density and true density reduced significantly (p<0.05) with an increase in moisture content. The porosity significantly (p<0.05) increased with an increase in moisture content. The lowest value (43.43%) of porosity was observed for PW at 11.01% moisture content while the highest value (52.06%) was observed for BW at 26% moisture content. The reduction in bulk and true density with an increase in moisture content might be due to the higher volumetric expansion in wheat grain with respect to the increase in mass. Whereas an increase in porosity can be explained by the reduction in the compactness with an increase in the volume of food grain (Sologubik et al., 2013). The results reported were in line with the results of green wheat (Al-Mahasneh and Rababah, 2007), wheat (Tabatabaeefar, 2003), and barley (Sologubik et al., 2013), and sorghum seeds (Mwithiga and Sifuna, 2006) with the increase in moisture content.

3.1.3 Angle of repose and coefficient of friction

The angle of repose and the coefficient of friction of all the wheat varieties increased with an increase in moisture content (Table 2). The angle of repose varied in the range of 23.58°-30.75°, 26.78°-32.46°, and 25.56°-33.77° for YW, PW, and BW, respectively with an increase in moisture content from 11.01% to 26.00%. The coefficient of friction varies with the moisture as well as a change in surface. The percentage increase in the coefficient of friction for different surfaces i.e. glass, wood, and GI sheet for YW was 21.05%, 6.12%, and 19.51%, for BW was19.44%, 16.28%, and 15.38%, and for PW was 16.22%, 15.91%, and 12.19%, respectively. Angle of repose and coefficient of friction exhibited linear relationship with moisture content having R^2 values of 0.96 (Θ), 0.99 (μ_{gs}), 0.99 (μ_{ws}) and 0.99 (μ_{GI}) for YW, 0.97 (Θ), 0.99 (μ_{gs}), 0.95 (μ_{ws}) and 0.99 (μ_{GI}) for BW and 0.81(Θ), 0.99 (μ_{gs}), 0.99 (μ_{ws}) and 0.96 (μ_{GI}) for PW. The variation in the angle of repose with an increase in moisture content might be due to the increase in surface stickiness that led to an increase in inter-grain binding/ aggregation resulting in an increase in the angle of repose. Whereas the increase in moisture content increased the grain to surface resistive force (adhesive) led to an increase in the coefficient of friction (Tabatabaeefar, 2003). The change in surface also changes the adhesive force and variation was observed in the coefficient of friction. Similar findings were also observed for wheat (Tabatabaeefar, 2003) and barley seeds (Sologubik et al., 2013).

Table 2 Effect of moisture content on density, porosity, angle of repose, and coefficient of friction of yellow, purple, and black wheat grain

Sample	Moisture content (MC) (% w.b.)	Bulk Density (ρb)	True density (ρd)	Porosity (ε)	Angle of repose (Θ)	Coefficient of friction (μ)		
						Glass surface (μ_{gs})	Wood surface (μ_{ws})	GI sheet (μ_{GI})
Yellow wheat	11.01±0.48	779.41±14.38^{b}	1391.53±1.33^{d}	43.99±1.09^{a}	23.58±0.08^{a}	0.3789±0.0042^{a}	0.4877±0.0061^{a}	0.4061±0.0058^{a}
	15.75±0.11	741.54±0.84^{b}	1346.01±2.09^{c}	44.91±0.15^{a}	27.03±0.05^{a,b}	0.4071±0.0072^{b}	0.4975±0.0015^{a,b}	0.4348±0.0088^{b}
	20.68±0.25	691.04±22.94^{a}	1333.89±0.64^{b}	48.19±1.74^{b}	29.52±1.60^{b}	0.4348±0.0088^{c}	0.5062±0.0016^{b,c}	0.4621±0.0060^{c}
	26.00±0.23	656.54±4.94^{a}	1291.45±0.47^{a}	49.16±0.40^{b}	30.75±2.48^{b}	0.4621±0.0060^{d}	0.5161±0.0031^{c}	0.4877±0.0061^{d}
	Equation	ρ_b=871.13-8.3875M_c (R^2=0.9929) RMSE=3.965 χ^2=31.446	ρ_d=1455.6-6.2573M_c (R^2=0.9594) RMSE=7.186 χ^2=103.286	ε=39.654+0.3763M_c (R^2=0.9394) RMSE=0.534 χ^2=0.569	Θ=18.942+0.4781M_c (R^2=0.9479) RMSE=0.626 χ^2=0.783	μ_{gs}=0.3188+0.0056M_c (R^2=0.9988) RMSE=0.001 χ^2=2.229E-6	μ_{ws}=0.4674+0.0019M_c (R^2=0.9991) RMSE=0.001 χ^2=1.912E-7	μ_{GI}=0.3476+0.0054M_c (R^2=0.9973) RMSE=0.002 χ^2=4.927E-6
Black wheat	11.01±0.48	758.62±3.77^{h}	1385.53±5.30^{g}	45.25±0.41^{e}	25.56±3.59^{e}	0.3600±0.0039^{e}	0.4294±0.0181^{e}	0.3865±0.0031^{e}
	15.75±0.11	693.78±5.69^{g}	1381.58±1.93^{g}	49.78±0.48^{f}	28.93±0.04^{e,f}	0.3819±0.0085^{f}	0.4369±0.0088^{e,f}	0.4030±0.0043^{f}
	20.68±0.25	649.22±5.16^{f}	1325.63±1.44^{f}	51.03±0.34^{g}	32.34±0.48^{f}	0.4081±0.0086^{g}	0.4684±0.0060^{f,g}	0.4245±0.0087^{g}
	26.00±0.23	609.95±4.49^{e}	1272.44±2.56^{e}	52.06±0.26^{h}	33.77±0.34^{f}	0.4338±0.0073^{h}	0.4997±0.0108^{h}	0.4494±0.0089^{h}
	Equation	ρ_b=857.74-9.7957M_c (R^2=0.9793) RMSE=7.950 χ^2=126.375	ρ_d=1487.6-7.9674M_c (R^2=0.9233) RMSE=12.814 χ^2=328.404	ε=41.622+0.4307M_c (R^2=0.8536) RMSE=0.996 χ^2=1.982	Θ=19.88+0.5594M_c (R^2=0.9625) RMSE=0.616 χ^2=0.759	μ_{gs}=0.3049+0.005M_c (R^2=0.9994) RMSE=0.001 χ^2=9.910E-7	μ_{ws}=0.369+0.0049M_c (R^2=0.9547) RMSE=0.006 χ^2=7.052E-5	μ_{GI}=0.3384+0.0042M_c (R^2=0.9958) RMSE=0.002 χ^2=4.675E-6
Purple wheat	11.01±0.48	776.97±3.35^{l}	1373.45±4.45^{l}	43.43±0.21^{i}	20.00±3.24^{i}	0.3693±0.0128^{i}	0.4355±0.0063^{i}	0.4136±0.0118^{i}
	15.75±0.11	723.88±12.16^{k}	1344.32±1.48^{k}	46.15±0.96^{j}	29.18±1.24^{j}	0.3869±0.0099^{i,j}	0.4547±0.0074^{j}	0.4204±0.0087^{i,j}
	20.68±0.25	667.36±0.10^{j}	1326.16±2.01^{j}	49.68±0.08^{k}	31.59±0.59^{j}	0.4071±0.0072^{j,k}	0.4888±0.0076^{k}	0.4400±0.0074^{j,k}
	26.00±0.23	635.37±4.29^{i}	1292.02±1.37^{i}	50.82±0.28^{l}	32.46±2.19^{j}	0.4328±0.0117^{k}	0.5150±0.0078^{l}	0.4610±0.0045^{k}
	Equation	ρ_b=877.38-9.6125M_c (R^2=0.981) RMSE=7.462 χ^2=111.351	ρ_d=1430.6-5.2643M_c (R^2=0.9901) RMSE=2.937 χ^2=17.253	ε=38.106+0.5128M_c (R^2=0.9585) RMSE=0.595 χ^2=0.709	Θ=13.848+0.7875M_c (R^2=0.7905) RMSE=2.263 χ^2=10.241	μ_{gs}=0.3214+0.0042M_c (R^2=0.9964) RMSE=0.002 χ^2=4.063E-6	μ_{ws}=0.3731+0.0055M_c (R^2=0.9913) RMSE=0.003 χ^2=1.627E-5	μ_{GI}=0.3739+0.0033M_c (R^2=0.967) RMSE=0.003 χ^2=2.257E-5

Note: #Values are in Mean ± SD (n=3). Mean values for each type of sample within the column followed by the superscripts a, b, c, d, e, f, g, h, i, j, k, and l were significantly different (p<0.05). (w.b.- wet basis).

3.2 Color

The increase in moisture content led to a reduction in all the color parameters for YW and BW whereas an increase in L^* value and variable tread of a^*, b^*, and ΔE was observed in PW (Table 3). The increase in moisture content increased the brightness of PW and reduction was observed for YW and BW. However, an increase followed by a decrease in a*, b*, and ΔE was observed for YW, BW, and PW. Moreover, an increase at the highest moisture content (26.00%) was observed in a^*, *b**, and *ΔE* of YW and PW. In relation to moisture content *L**, *a**, *b**, and ΔE exhibited linear equation. *L**, *a**, *b**, and *ΔE* of YW exhibited a linear relationship with R^2 values of 0.99, 0.99, 0.99, and 0.98 respectively. The linear relation followed by BW and PW produced R^2 values of 0.96, 0.99, 0.99 and 0.98 and 0.99, 0.99, 0.99 and 0.99 for *L**, *a**, *b**, and *ΔE* respectively. The Higher *L** value of PW might be due to the development of dark purple color (close to blue and green) with an increase in moisture content. Whereas reduction of *a** and *b** with an increase in moisture content led to the shifting of its natural color yellow to blue/green and black to blue/green for YW and BW, respectively participating in a reduction in brightness. The variable trend in the color parameter of different colored wheat might be due to the variation in verity.

Table 3 Effect of moisture content of color characteristic of wheat grain.

Sample	Moisture Content (M_C) (% w.b.)	*L**	*a**	*b**	*ΔE*
Yellow Wheat	11.01±0.48	37.48±0.45^c	3.72±0.07^d	14.27±0.20^c	21.26±0.45^c
	15.75±0.11	35.53±0.31^b	3.61±0.02^c	14.41±0.14^c	20.14±0.30^b
	20.68±0.25	33.12±0.08^a	3.06±0.04^a	12.48±0.01^a	17.12±0.06^a
	26.00±0.23	32.85±0.13^a	3.24±0.00^b	12.86±0.08^b	17.31±0.13^a
	Equation	$L^*=40.694-0.3241M_c$ (R^2=0.9983) RMSE=0.555 χ^2=0.557	$a^*=4.1291-0.0394M_c$ (R^2=0.9998) RMSE=0.651 χ^2=0.046	$b^*=15.765-0.1229M_c$ (R^2=0.9944) RMSE=0.498 χ^2=0.489	$\Delta E=24.38-0.2954M_c$ (R^2=0.9874) RMSE=0.687 χ^2=0.866
Black wheat	11.01±0.48	24.04±2.04^e	2.32±0.63^e	2.73±1.47^e	5.25±1.35^e
	15.75±0.11	29.21±0.21^f	2.66±0.09^e	4.59±0.09^{e,f}	8.61±0.22^f
	20.68±0.25	29.02±0.11^f	2.46±0.03^e	4.72±0.06^f	8.52±0.12^f
	26.00±0.23	27.45±0.12^f	2.09±0.02^e	3.57±0.07^{e,f}	6.62±0.11^e
	Equation	$L^*=23.878+0.1935M_c$ (R^2=0.9608) RMSE=1.768 χ^2=6.001	$a^*=2.7294-0.0188M_c$ (R^2=0.9998) RMSE=0.180 χ^2=0.065	$b^*=2.9841+0.0499M_c$ (R^2=0.9958) RMSE=0.761 χ^2=1.155	$\Delta E=5.8824+0.0745M_c$ (R^2=0.9812) RMSE=1.338 χ^2=3.558
Purple wheat	11.01±0.48	24.47±1.46^{g,h}	4.56±0.28^h	4.34±1.28^g	7.54±1.33^g
	15.75±0.11	23.81±0.09^g	4.95±0.08^i	6.38±0.07^h	9.28±0.08^{h,i}
	20.68±0.25	25.89±0.12^{h,i}	3.77±0.03^g	5.24±0.09^{g,h}	8.00±0.12^{g,h}
	26.00±0.23	26.84±0.08^i	4.52±0.06^h	6.52±0.04^h	9.70±0.08^i
	Equation	$L^*=21.84+0.1858M_c$ (R^2=0.9943) RMSE=0.575 χ^2=0.640	$a^*=4.9198-0.0257M_c$ (R^2=0.9987) RMSE=0.404 χ^2=0.326	$b^*=3.634+0.1081M_c$ (R^2=0.9962) RMSE=1.869 χ^2=0.857	$\Delta E=6.7125+0.1044M_c$ (R^2=0.9944) RMSE=0.671 χ^2=0.891

Note: #Values are in Mean ± SD (n=3). Mean values for each type of sample within the column followed by the superscripts a, b, c, d, e, f, g, h and i were significantly different (p<0.05). (L* - Lightness, a* - Redness-greenness, b* - Yellowness-blueness, ΔE - Total color difference, M_C – moisture content, w.b.- wet basis).

3.3 Mechanical characteristics

Table 4 represents the linear relation of mechanical properties of YW, BW, and YW with an increase in moisture content. The increase in moisture content from 11.01% to 26.00% (w.b) significantly (p<0.05) reduced hardness to 42.3% for YW, 46.1% for BW, and 54.37% for PW. Opposite that the deformation distance was significantly (p<0.05) increased by 4.58%, 10.81%, and 6.92% for YW, BW, and PW, respectively. Rupture energy significantly (p<0.05) decreased with an increase in moisture content and varied in the range of 77.64-46.93 N-mm, 61.30- 36.61 N-mm, and 96.15- 46.83 N-mm for YW, BW, and PW, respectively. The increase in moisture content led softening of cellulosic fibers reducing the hardness (Baümler et al., 2006) and required higher compression to crack the structure increasing the deformation distance. Gupta and Das (2000) reported that the increase in deformation distance might be due to the partial separation of cotyledons during compression before the formation of crack. A similar trend with an increase in moisture content has been reported by Tavakoli et al. (2009) for soybean grains and Baümler et al. (2006) for safflower seeds. The reduction in rupture energy with an increase in moisture content is directly related to the reduction in hardness. It is an important parameter required to design the grinding/milling equipment. The increase in rupture energy means an increase in power to grind the material. A smooth decrease in rupture energy with increasing moisture was reported by Baümler et al. (2006) for safflower seeds.

Table 4 Effect of moisture content on mechanical properties of yellow, black and purple wheat.

Sample	Moisture content (M_c) % w.b.	Hardness (F)	Deformation distance (D_f)	Rupture energy (E_a)
Yellow wheat	11.01±0.48	118.73±8.11^{c}	1.31±0.08^{a}	77.64
	15.75±0.11	99.58±16.48^{b}	1.33±0.04^{a}	66.20
	20.68±0.25	91.40±5.68^{b}	1.35±0.12^{a}	61.53
	26.00±0.23	68.51±3.32^{a}	1.37±0.06^{a}	46.93
	Equation	$F = 153.08 - 3.1874M_c$ $R^2 = 0.9752$ RMSE=2.840 $\chi^2=16.126$	$D = 1.2665 + 0.004M_c$ ($R^2 = 0.9993$) RMSE=0.072 $\chi^2=6.911E-7$	$E_a = 98.759 - 1.9436M_c$ ($R^2 = 0.9704$) RMSE=1.893 $\chi^2=7.169$
Black wheat	11.01±0.48	110.42±22.49^{e}	1.11±0.05^{d}	61.30
	15.75±0.11	93.51±21.51^{e}	1.12±0.15^{d}	52.52
	20.68±0.25	90.79±28.33^{e}	1.17±0.40^{d}	49.91
	26.00±0.23	59.52±4.61^{d}	1.23±0.16^{d}	36.61
	Equation	$F = 146.07 - 3.1326M_c$ ($R^2 = 0.9052$) RMSE=5.658 $\chi^2=64.025$	$D = 1.0057 + 0.0083M_c$ ($R^2 = 0.9381$) RMSE=0.012 $\chi^2=2.806E-4$	$E_a = 78.4 - 1.5422M_c$ ($R^2 = 0.9458$) RMSE=2.061 $\chi^2=8.494$
Purple wheat	11.01±0.48	147.74±33.63^{h}	1.30±0.12^{f}	96.15
	15.75±0.11	127.81±13.21^{g,h}	1.34±0.11^{f}	85.63
	20.68±0.25	114.68±3.85^{g}	1.37±0.09^{f}	78.55
	26.00±0.23	67.42±3.37^{f}	1.39±0.08^{f}	46.83
	Equation	$F = 208.48 - 5.1236M_c$ ($R^2 = 0.9348$) RMSE=7.551 $\chi^2=114.039$	$D = 1.2401 + 0.006M_c$ ($R^2 = 0.97$) RMSE=0.006 $\chi^2=6.894E-5$	$E_a = 134.29 - 3.1318M_c$ ($R^2 = 0.9027$) RMSE=5.738 $\chi^2=65.846$

Note: #Values are in Mean ± SD (n=5). Mean values for each type of sample within the column followed by the superscripts a, b, c, d, e, f, g and h were significantly different (*p*<0.05). (Where, M_C -Moisture content, w.b.-wet basis, hardness in 'Newton' (N), deformation distance in 'mm' and rupture energy in 'N-mm').

3.4 Principal component analysis (PCA)

PCA biplot (combination of scores and loading plot, Figure 1) showing 82.52% variations was used to visualize the effect of moisture content on engineering properties of different color wheat. The Scores of all three wheat were shown similar as well as linear variation, however, scores of BW were found isolated from scores of PW and YW. This happened due to inferior engineering properties of BW, which also resulted in no clear cluster near any hydrated BW. However, a strong cluster of loadings which was found to represent P 20.68, P 26.00 and Y 20.68, Y 26.00, indicated that 20.68% or more moisture content brought considerable changes in the engineering properties of PW and YW. Moreover, it could be also said that both the grain possesses similar changes in most properties (like width, thickness, deformation distance, etc.). Furthermore, the falling of P 26.00 and Y 26.00 near the coefficient of friction at different surfaces, indicated that higher moisture contributes more to the frictional properties. Two negatively correlated clusters near P 11.01 and B 26.00 showed that porous grains with high moisture require less rapturing force as compared to the less porous, and bulkier grains with low moisture. However, Y 11.01 and P 15.75 lies near P 11.01 which shows the nearly similar effect of moisture content on loading properties which means this much increment of moisture in the grain was not sufficient to bring changes. Moreover, it can be observed from the PCA biplot that B 11.01, B 15.75, and B 20.68 have not lied under any loading properties and it means that the increase in moisture content up to 20.68% was not sufficient to bring changes in any loading properties.

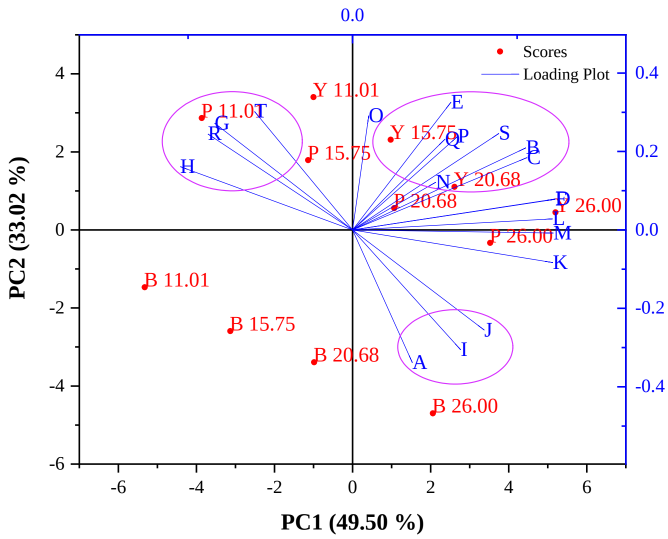

Figure 1 PCA plot of yellow, purple, and black wheat at different moisture content.

A= L; B= W; C= T; D= Dg; E= φ; F= Sa; G= ρb; H= ρt; I= ε; J= ϴ; K= μGS; L= μWS; M= μGI; N= L*; O= a*; P= b*; Q= ΔE; R= Rupture force (F); S= Deformation distance (D); T= Ea.

Y 11.01= Yellow at 11.01% M.C.; Y 15.75= Yellow at 15.75% M.C.; Y 20.68= Yellow at 20.68% M.C.; Y 26.00= Yellow at 26.00% M.C.; B 11.01= Black at 11.01% M.C.; B 15.75= Black at 15.75% M.C.; B 20.68= Black at 20.68% M.C.; B 26.00= Black at 26.00% M.C.; P 11.01= Purple at 11.01% M.C.; P 15.75= Purple at 15.75% M.C.; P 20.68= Purple at 20.68% M.C.; P 26.00= Purple at 26.00% M.C.

4 Conclusion

This study reveals that the physico-mechanical properties of wheat grains vary with changes in variety and moisture. The major dimensions (L, W and T), porosity, the mass of 1000 grains, angle of repose, and surface area increase linearly with the increasing moisture content from 11.01% (w.b) to 26.00% (w.b) whereas linear reduction was observed on bulk density and true density. The coefficient of friction is increased linearly on all the three surfaces (glass, wood, GI sheet). The mechanical properties i.e. rupture force and rupture energy decreased linearly during compression with the increase in moisture content. All the determined properties can be used to improve the existing technology and development of new multipurpose processing and handling equipment for the different varieties of wheat grain.

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