

Scanning Electron Microscopy-Based Characterization of Moisture-Dependent Physical and Geometric Properties of Teff (*Eragrostis tef*) Grains

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Scanning Electron Microscopy-Based Characterization of Moisture-Dependent Physical and Geometric Properties of Teff (*Eragrostis tef*) Grains

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Abstract

Accurate determination of cereal grain size is essential for the design and optimization of harvesting, cleaning, grading, drying, handling, and milling equipment. However, measuring teff grain dimensions is particularly challenging because of its extremely small size and the limitations of conventional measurement methods. This study evaluated the use of scanning electron microscopy to characterize the physical properties of three teff varieties at different moisture contents. SEM provided high-resolution images that enabled precise measurement of grain length, width, projected area, and sphericity. The results showed that grain dimensions and projected area increased with increasing moisture content in all varieties, whereas sphericity remained nearly constant. At the highest moisture content, Dagim exhibited the largest grain dimensions, with a length of 1.40 mm, width of 0.80 mm, and projected area of 0.87 mm², followed by Bishoftu with 1.17 mm, 0.71 mm, and 0.63 mm², and Felagot with 1.08 mm, 0.62 mm, and 0.60 mm², respectively. The study demonstrates that SEM is a rapid, reliable, and accurate technique for determining the physical characteristics of teff grains, providing improved precision over conventional measurement methods. The generated data provide valuable engineering information for the design and optimization of teff processing and handling equipment.

Keywords: Characterization; Moisture content; Particle mean diameter; Teff grain; Scanning Electron Microscopy

1. Introduction

Teff (*Eragrostis tef* (Zucc.) Trotter) is an ancient, self-pollinated staple cereal crop originating in the Horn of Africa, where it has been cultivated for millennia, predominantly in Ethiopia and Eritrea (Vavilov 1951, Gebremariam et al. 2012). Globally recognized as the smallest grain in the world, an individual teff kernel measures approximately 0.9-1.7 mm in length and 0.5-1.0

mm in width, exhibiting an average thousand-kernel weight ranging between 0.25 g and 0.42 g (Bultosa 2007, Zewdu & Solomon 2007). Etymologically, the name "teff" originates from the Amharic word *teffa*, which translates to "lost" a direct reference to how easily these minute seeds are mislaid if accidentally dropped during harvest, post-harvest handling, or processing operations (Assefa et al. 2015, Baye 2014). Despite its minuscule physical footprint, teff boasts exceptional nutritional density, offering high concentrations of complex carbohydrates, essential minerals such as iron and calcium, dietary fiber, and high-quality gluten-free proteins (Gebremariam et al. 2012, Abebe et al. 2007). These health benefits have driven a surge in international demand for teff-based flour and gluten-free dietary products (Lee 2018, Shumoy & Raes 2017).

However, the tiny size of teff creates severe engineering and processing challenges throughout its production chain (Mohsenin 1986, Stroshine 1998). Precise determination of physical parameters including length, width, thickness, geometric mean diameter, projected surface area, and sphericity is fundamental for designing, optimizing, and operating agricultural machinery (Sahay & Singh 2001, Irtawange 2000). These physical dimensions directly dictate the structural parameters required for seed drills, threshing drums, grain cleaners, pneumatic sorters, dryers, storage silos, and roller mills (Sahay & Singh 2001, Sirisomboon et al. 2007). Without accurate baseline dimensions, post-harvest processing systems suffer from high grain losses, low cleaning efficiency, and excessive power consumption (Irtawange 2000, Bojnanská & Francáková 2002). Traditional dimensional measurement approaches, such as manual caliper gauging or standard optical light microscopy, present major operational limitations when applied to micro-grains like teff (Igthin & Patel 2015, Igthinathane et al. 2009). Vernier calipers and micrometers introduce human bias, sample deformation, and significant measurement errors because the applied pressure can crush or misorient tiny seeds (Igthin & Patel 2015, Klavins et al. 2016). Optical microscopy often lacks the required depth of field and spatial resolution, making it difficult to clearly delineate seed boundaries and accurately quantify subtle dimensional variations (Igthinathane et al. 2009, Kaláb et al. 1995). Furthermore, measuring hundreds of individual micro-grain samples manually is labor-intensive, time-consuming, and prone to poor statistical reproducibility (Klavins et al. 2016, Sologubik et al. 2013).

An additional complexity in characterizing cereal grains is the dynamic influence of moisture content (Balasubramanian 2001, Coskuner & Karababa 2007). During harvesting, conditioning,

storage, and milling, cereal grains undergo continuous moisture exchange with their surrounding atmosphere (Coskuner & Karababa 2007, Tavakoli et al. 2009). Water absorption causes physical swelling across the grain structure, altering directional dimensions, volumetric expansion rates, surface friction coefficients, and aerodynamic behavior (Sacilik et al. 2003, Gharibzahedi et al. 2014). Understanding how teff grain dimensions scale with changing moisture levels is critical for adapting machine clearances, selecting screen sieve apertures, and optimizing pneumatic airflow velocities during cleaning and separation (Balasubramanian 2001, Wandkar & Ukey 2014).

To overcome the measurement limitations of traditional tools, Scanning Electron Microscopy (SEM) has emerged as an advanced analytical solution (Goldstein et al. 2012, Bultosa et al. 2002). Operating at high magnifications and precise accelerating voltages, SEM provides sub-micron image resolution and superior depth of field, enabling automated, accurate, and non-destructive two-dimensional characterization of micro-sized biological materials and food matrices (Goldstein et al. 2012, Qian & Kuhn 1999). While SEM imaging has been widely utilized to analyze starch granule structures and cellular morphology in major cereals (Wolter et al. 2013, Jane et al. 1992), its application in systematically capturing moisture-dependent physical dimension shifts among distinct teff cultivars remains limited (Delcour & Hosene 2010, Tester et al. 2004)

Different teff cultivars exhibit distinct agronomic profiles, grain colors (white, red, and brown), and physical size traits (Tefera et al. 2003, Agza et al. 2018). Evaluating how moisture content impacts principal dimensions, projected surface area, and shape factors (such as sphericity) across diverse teff varieties is vital to building comprehensive engineering databases (Agza et al. 2018, Kibar & Öztürk 2008). Such empirical data enable equipment designers and agricultural engineers to optimize cleaning sieves, pneumatic separators, and milling equipment specifically tailored to teff (Altuntaş & Yıldız 2007, Stroshine & Hamann 1994).

Therefore, this review synthesizes the physical and dimensional characteristics of teff varieties across controlled moisture levels using advanced imaging methodologies like Scanning Electron Microscopy (ASAE Standards 1994, Abewa et al. 2019). High-resolution 2D SEM micrographs enable the accurate quantification of grain length, width, thickness, projected area, and sphericity while eliminating the measurement uncertainties associated with conventional manual tools (ASAE Standards 1994, Kachru et al. 1994). The overarching goal is to present reliable,

moisture-dependent baseline engineering data to support the design, modeling, and performance optimization of teff handling, conditioning, grading, and milling systems (Abewa et al. 2019, Markowski et al. 2013).

2. Materials and Methods

2.1 Material

Three varieties of teff grain were selected for this study based on distinct characteristics such as varieties, color, and year of release. Felagot (DZ-Cr-442RIL77C), Dagim (DZ-Cr-438RIL91A), and Bishoftu (DZ-Cr-497 RIL133) were selected based on variety, color, and year of release as shown in Figure 1. Samples were sourced from DZARC under EIAR's national teff improvement program. To ensure consistency, samples were sorted and stored at room temperature before testing.

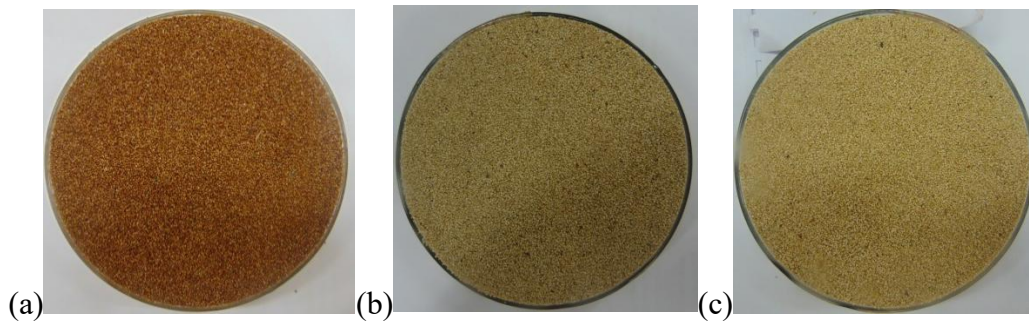


Fig.1 Teff grain varieties (a) Felagot, (b) Dagim and (c) Bishoftu

2.2 Moisture Contents (MC)

Electronic balance scales ranged from 0 to 3 kg with an accuracy of 0.1 g, and scales ranged from 0 to 250g with an accuracy of 0.01mg were used for weighing grain samples. This instrument provides accurate grain mass measurements, which are crucial for determining grain mass, moisture content, and densities.

Moisture content determination plays a critical role in accurately characterizing physical and physical expansion behaviors in cereal grains (Zewdu & Solomon 2007, ASAE Standards 1994). The initial moisture level of grain samples is directly measured using the standardized forced-air laboratory oven drying method in accordance with ASAE Standard S352.3 (ASAE Standards 1994, Abewa et al. 2019). In this procedure, grain samples are maintained at a controlled drying temperature typically between 100°C and 105°C for a designated period until constant mass is

achieved (Tefera et al. 2003, ASAE Standards 1994). Sample weights are precisely recorded before and after drying, and the resulting mass loss represents the evaporated moisture (Zewdu & Solomon 2007, Abewa et al. 2019). Moisture content (MC) on a wet basis is calculated as the ratio of mass loss to the original sample weight and expressed as a percentage using Equation (1) (Zewdu & Solomon 2007, ASAE Standards 1994):

$$MC = \frac{(w-d)}{w} \times 100 \quad (1)$$

Where MC = moisture content (%), w = wet mass (g) and d = dry mass (g).

2.3. Particle mean diameter

SEM was employed to examine the physical and structural characteristics of teff grain. Operating at magnifications ranging from 10× to 500,000× and accelerating voltages between 1 kV and 30 kV, SEM provided high-resolution images that enabled precise analysis of grain size distribution and shape. The teff varieties analyzed for this characterization were Felagot (DZ-Cr-442RIL77C), Dagim (DZ-Cr-438RIL91A) and Bishoftu (DZ-Cr-497RIL133) selected according to their distinct characteristics such as varieties, color, and year of release. SEM analysis was conducted at the Microbiology Laboratory, Department of Applied Biology, School of Applied Science, Adama Science and Technology University.

Dimensions of each grain, length L (mm), Width W (mm), and thickness T (mm) were determined by SEM. Geometric mean diameter D_g (mm) and Arithmetic mean diameter D_a (mm) are calculated using the following equation (Mohsenin 1986, Klavins et al. 2016).

$$D_g = \sqrt[3]{W \times T \times L} \quad (2)$$

$$D_a = \frac{W + T + L}{3} \quad (3)$$

The sphericity (ϕ) of the grain, which is a measure of how closely the shape of the particle approaches that of a perfect sphere, is calculated using the following formula:

$$\phi = \left(\frac{WT}{L^2} \right)^{\frac{1}{3}} \quad (4)$$

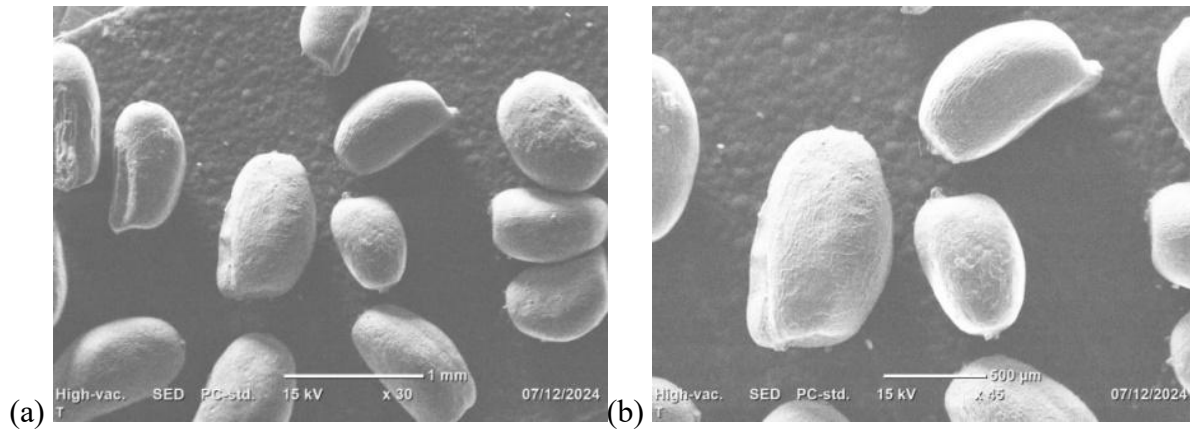
The principal two-dimensional dimensions of individual teff kernels length (L , mm) and width (W , mm) were directly measured from high-resolution 2D Scanning Electron Microscopy (SEM) micrographs (Klavins et al. 2016, Goldstein et al. 2012). Because conventional 2D SEM micrographs capture a planar projection that precludes direct vertical thickness measurement, grain thickness (T , mm) was estimated based on historical empirical relationships and published ratio datasets for teff grains reported in existing literature (Zewdu & Solomon 2007, Abewa et al. 2019). Utilizing the measured directional dimensions (L , W) alongside the estimated thickness (T), the arithmetic mean diameter (D_a , mm) and geometric mean diameter (D_g , mm) were calculated using Equations (5) and (6), respectively (Mohsenin 1986, Klavins et al. 2016):

$$T = \frac{D_g^3}{W \times L} \quad (5)$$

$$T = 3D_a - W - L \quad (6)$$

3. Results and Discussions

High-resolution Scanning Electron Microscopy was utilized to examine size three teff varieties (*Felagot*, *Bishoftu*, and *Dagim*). Because teff grains are extremely small, conventional optical measurement methods are prone to precision errors. The representative SEM acquired at various magnifications ($\times 30$, $\times 45$ and $\times 60$) and accelerating voltages (15 kV) allowed accurate 2D dimensional measurements of grain length and width, as illustrated in Figure 2.



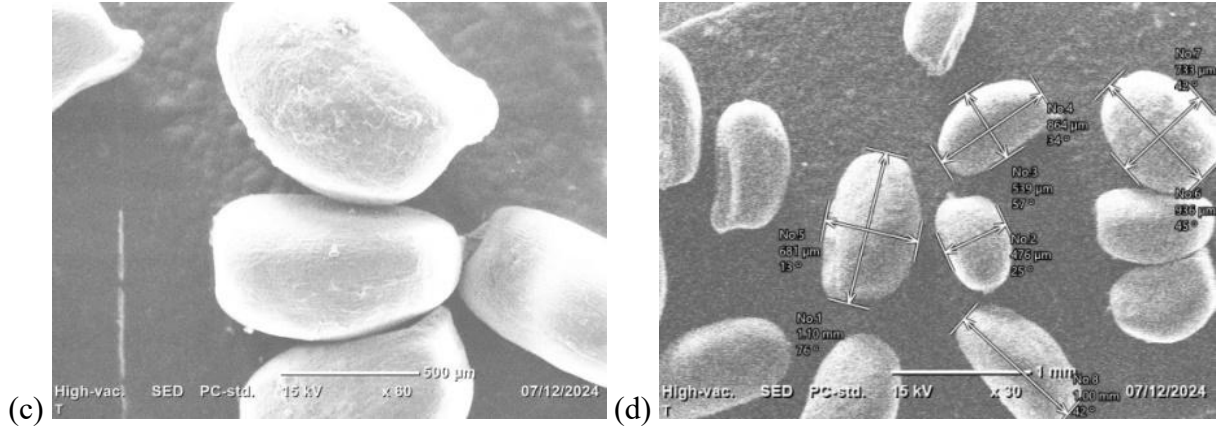


Fig.2 SEM image (a) $\times 30$, 1mm, (b) $\times 45$, 500 μm , (c) $\times 60$, 500 μm and (d) $\times 30$, 1mm

The principal physical dimensions (length, width, and thickness), projected area, and sphericity of the three teff varieties (*Felagot*, *Bishoftu*, and *Dagim*) measured at three distinct moisture content levels are summarized in Table 1. The data demonstrate the varietal differences and moisture-dependent trends across all measured properties.

Table 1. Physical properties of selected teff varieties at different moisture content levels (mean $\pm$ SD)

Teff Variety	Moisture Level	MC (%)	Width (mm)	Thickness (mm)	Length (mm)	Projected Area (mm ²)	Sphericity (ϕ)
Felagot	MC1	1.30 $\pm$ 0.03	0.52 $\pm$ 0.07	0.52 $\pm$ 0.08	0.90 $\pm$ 0.08	0.42 $\pm$ 0.06	0.69 $\pm$ 0.05
	MC2	9.14 $\pm$ 0.12	0.58 $\pm$ 0.08	0.58 $\pm$ 0.09	1.00 $\pm$ 0.09	0.52 $\pm$ 0.07	0.69 $\pm$ 0.05
	MC3	15.00 $\pm$ 0.18	0.62 $\pm$ 0.08	0.62 $\pm$ 0.10	1.08 $\pm$ 0.10	0.60 $\pm$ 0.09	0.69 $\pm$ 0.05
Bishoftu	MC1	1.50 $\pm$ 0.05	0.59 $\pm$ 0.14	0.57 $\pm$ 0.08	0.98 $\pm$ 0.15	0.44 $\pm$ 0.12	0.71 $\pm$ 0.06
	MC2	9.50 $\pm$ 0.10	0.66 $\pm$ 0.16	0.64 $\pm$ 0.09	1.09 $\pm$ 0.17	0.55 $\pm$ 0.15	0.71 $\pm$ 0.06
	MC3	15.28 $\pm$ 0.15	0.71 $\pm$ 0.17	0.68 $\pm$ 0.10	1.17 $\pm$ 0.18	0.63 $\pm$ 0.17	0.71 $\pm$ 0.06
Dagim	MC1	1.80 $\pm$ 0.04	0.67 $\pm$ 0.08	0.61 $\pm$ 0.07	1.17 $\pm$ 0.17	0.61 $\pm$ 0.09	0.72 $\pm$ 0.05
	MC2	10.14 $\pm$ 0.09	0.75 $\pm$ 0.09	0.68 $\pm$ 0.08	1.30 $\pm$ 0.19	0.76 $\pm$ 0.11	0.72 $\pm$ 0.05
	MC3	16.35 $\pm$ 0.21	0.80 $\pm$ 0.10	0.73 $\pm$ 0.08	1.40 $\pm$ 0.20	0.87 $\pm$ 0.13	0.72 $\pm$ 0.05

Across all evaluated moisture levels, a clear dimensional hierarchy was observed among the varieties, with *Dagim* consistently exhibiting the largest overall dimensions, followed by *Bishoftu* and *Felagot*. To further illustrate the specific effects of moisture uptake on each dimensional parameter, the variations in grain length, width, and thickness across the three moisture levels are graphically depicted in Figure 3 – Figure 6.

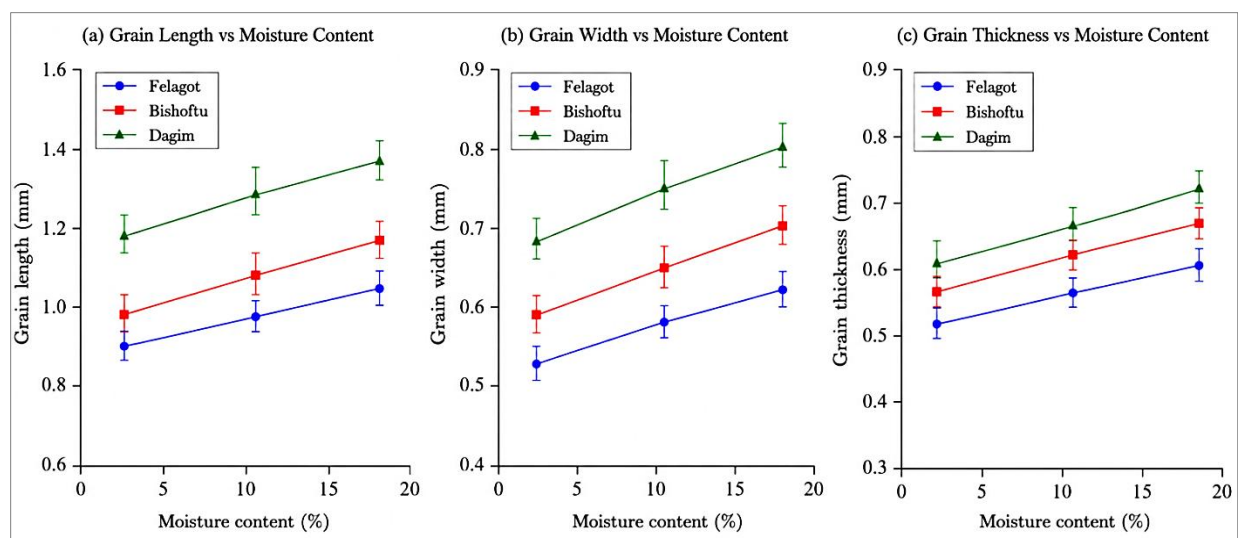


Fig.3 Effect of moisture content on grain dimensions of teff varieties

Figure 3 illustrates the effect of moisture content on the grain dimensions (length, width, and thickness) of three teff varieties (Felagot, Bishoftu, and Dagim). Grain dimensions increased progressively with increasing moisture content for all varieties, indicating that moisture absorption caused grain expansion.

In Figure 3(a), grain length increased steadily with moisture content, with Dagim exhibiting the greatest length (1.17–1.40 mm), followed by Bishoftu (0.98–1.17 mm) and Felagot (0.90–1.08 mm). Figure 3(b) shows a similar trend for grain width, increasing from 0.52–0.62 mm for Felagot, 0.59–0.71 mm for Bishoftu, and 0.67–0.80 mm for Dagim. Likewise, Figure 3(c) indicates that grain thickness increased from 0.52–0.62 mm in Felagot, 0.57–0.68 mm in Bishoftu, and 0.61–0.73 mm in Dagim.

Overall, Dagim consistently exhibited the largest grain dimensions, followed by Bishoftu and Felagot. The nearly linear increase in all dimensions demonstrates a positive relationship between moisture content and grain size.

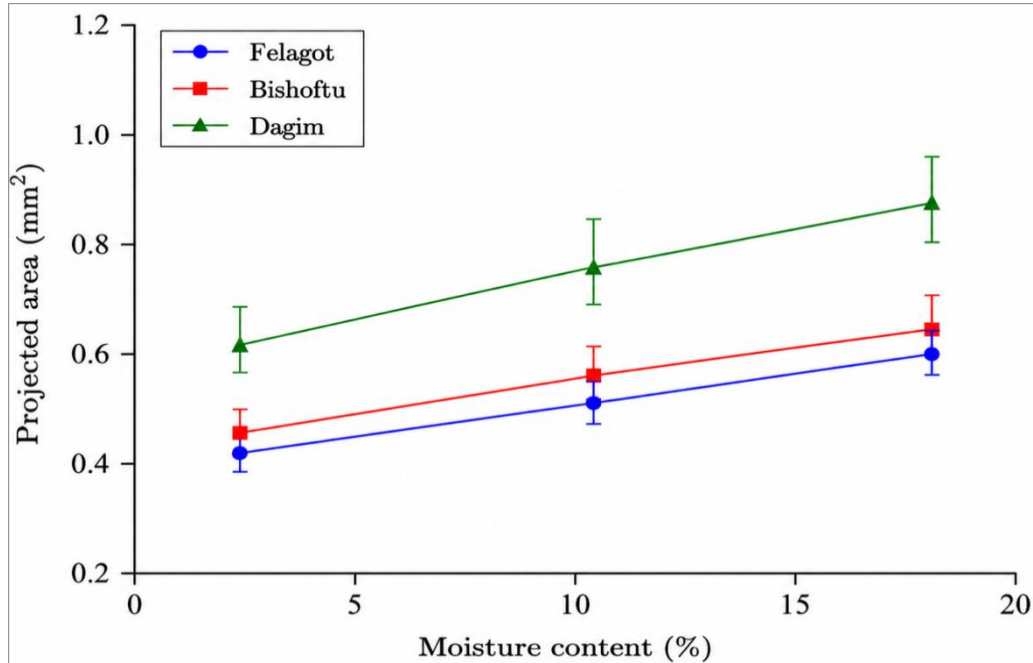


Fig.4 Effect of moisture content on projected area of teff varieties

Figure 4 illustrates the effect of moisture content on the projected area of three teff varieties (Felagot, Bishoftu, and Dagim). Projected area increased progressively with increasing moisture content for all varieties, indicating that moisture absorption caused grain swelling and increased grain size.

Felagot exhibited the smallest projected area, increasing from 0.42 to 0.60 mm², followed by Bishoftu (0.44-0.63 mm²), while Dagim consistently recorded the largest projected area (0.61-0.87 mm²). The nearly linear increase suggests a strong positive relationship between moisture content and projected area, resulting from the expansion of grain dimensions during water absorption. The small standard deviation error bars indicate limited variation among samples, confirming the consistent trend across varieties.

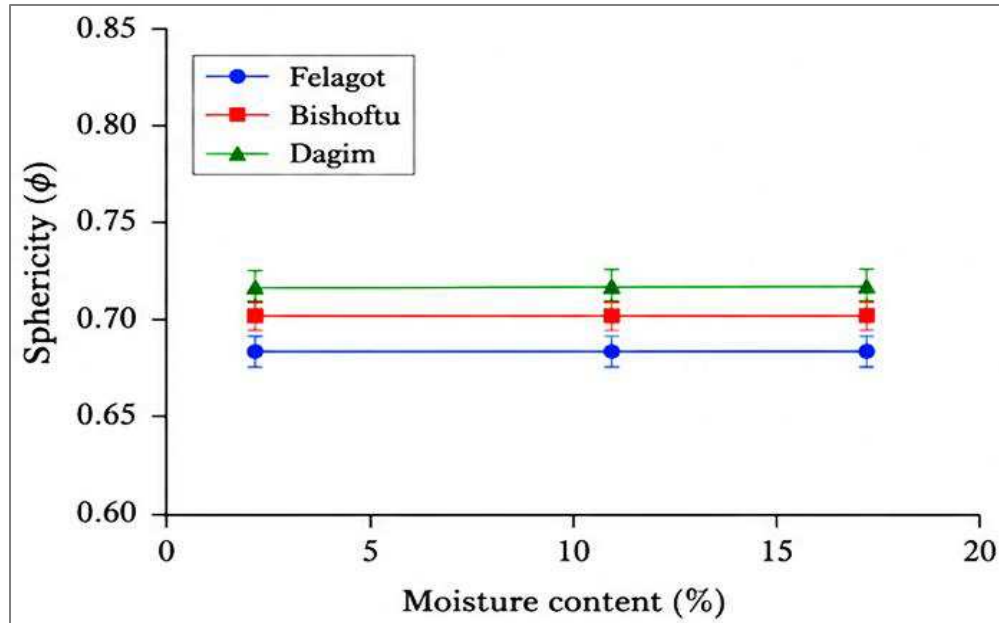


Fig. 5 Effect of moisture content on sphericity of teff varieties

Figure 5 shows the effect of moisture content on the sphericity of three teff varieties (Felagot, Bishoftu, and Dagim). Unlike grain dimensions and projected area, sphericity remained nearly constant across the studied moisture range, indicating that moisture increased grain size without significantly altering grain shape.

Felagot maintained a sphericity of about 0.69, while Bishoftu and Dagim showed slightly higher values of approximately 0.71 and 0.72, respectively. Dagim consistently had the highest sphericity, followed by Bishoftu and Felagot, reflecting inherent varietal differences rather than the effect of moisture content. The small standard deviation error bars further confirm the stability of grain shape. These results suggest that moisture has little influence on grain geometry, although the increase in grain size should be considered in the design of handling, grading, and milling equipment.

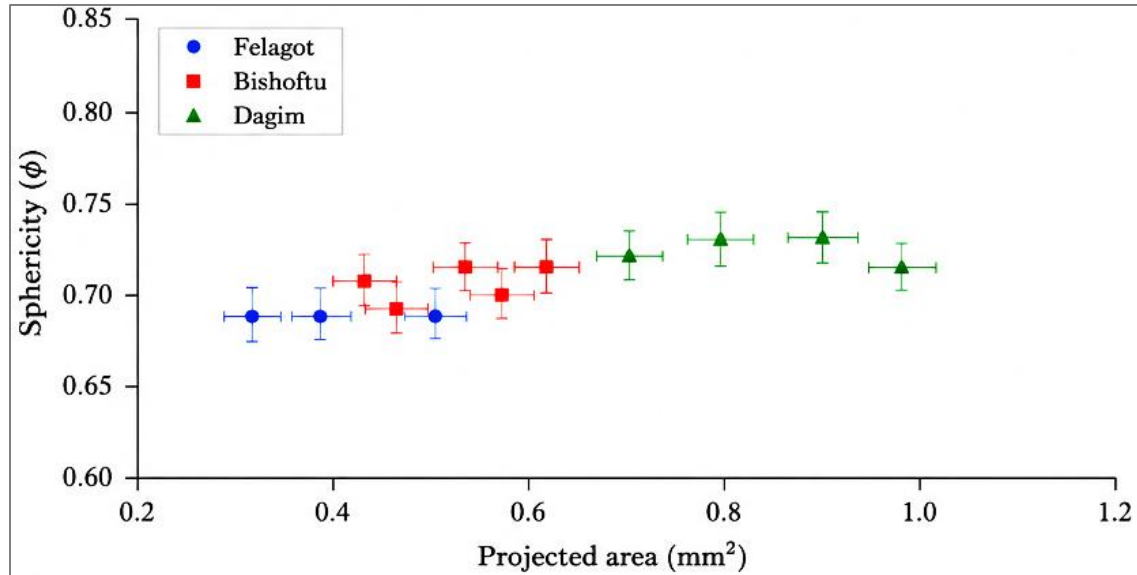


Fig. 6 Relationship between grain size and shape characteristics

Figure 6 illustrates the relationship between projected area and sphericity of three teff varieties (Felagot, Bishoftu, and Dagim). Projected area increased with moisture content, whereas sphericity remained nearly constant, indicating that grain size increased while grain shape was largely maintained.

The scatter plot shows three distinct clusters corresponding to the varieties. Dagim exhibited the largest projected area (0.61–0.87 mm²) and highest sphericity (≈ 0.72), followed by Bishoftu (0.44–0.63 mm²; ≈ 0.71), while Felagot had the smallest projected area (0.42–0.60 mm²) and lowest sphericity (≈ 0.69). Overall, the results indicate a weak positive relationship between projected area and sphericity, suggesting that moisture primarily causes grain expansion rather than changes in grain shape. These findings are important for the design of grading, sorting, conveying, and milling equipment, where moisture-induced changes in grain size should be considered while grain shape remains relatively stable.

4. Conclusion

- This study demonstrated that SEM is an effective technique for characterizing the physical properties of teff grains at different moisture contents. The high-resolution SEM images enabled accurate measurement of grain dimensions and projected area, making SEM particularly suitable for the analysis of the extremely small teff grains.

- The results showed that grain length, width, thickness, and projected area increased with increasing moisture content for all three teff varieties, whereas sphericity remained nearly constant. Dagim consistently exhibited the largest grain dimensions and projected area, followed by Bishoftu and Felagot, indicating clear varietal differences in grain morphology.
- Unlike many previous studies that relied on manual measurements or optical microscopy, this study used SEM to directly characterize teff grain size with greater image clarity and measurement precision. Because teff grains are extremely small, conventional measurement methods are often time-consuming and more susceptible to measurement errors, whereas SEM provides more reliable and reproducible measurements. The findings confirm that SEM is a practical and efficient method for determining the physical characteristics of teff grains under different moisture conditions. The technique provides detailed information on grain morphology while reducing the uncertainty associated with conventional measurement methods.
- Overall, the physical property data generated in this study provide valuable information for the design and optimization of teff handling and processing equipment, including cleaning, grading, drying, conveying, and milling systems. The results also provide a useful reference for future studies on the engineering properties of teff grains under varying moisture conditions.

Declarations

Author Contributions

Lemi Demissie Boset: Conceptualization, investigation, data analysis, writing original draft preparation, and writing review and editing.

Data Availability

The datasets generated during and/or analyzed during the current study are available from the corresponding author on reasonable request.

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Consent to publication

Not applicable.

Ethics Approval

Not Applicable.

Consent to participate

Not applicable.

Clinical trial number

Not applicable.

Competing interests

No competing interests.

References

- Abebe, Y., Bogale, A., Hambidge, K. M., Stoecker, B. J., Bailey, K., & Gibson, R. S. (2007). Phytate, zinc, iron and calcium content of selected raw, dry-processed and fermented cereal and legume-based Ethiopian foods. *Journal of Food Composition and Analysis*, 20(3-4), 161–168.
- Abewa, A., Solomon, W. K., & Bultosa, G. (2019). Moisture-dependent physical and aerodynamic properties of teff grain varieties. *Journal of Food Process Engineering*, 42(5), e13120.
- Agza, B., Alemu, B., & Bultosa, G. (2018). Nutritional and physical quality evaluation of improved teff varieties. *African Journal of Food Science*, 12(9), 231–240.
- Altuntaş, E., & Yıldız, M. (2007). Effect of moisture content on some physical and mechanical properties of faba bean seeds. *Journal of Food Engineering*, 78(1), 174–183.
- ASAE Standards. (1994). S352.3: Moisture measurement—unground grain and seeds. *ASAE Standards*, 563–564.
- Assefa, K., Cannarozzi, G., Girma, D., Kamies, R., Chanyalew, S., Plaza-Wüthrich, S., ... & Tadele, Z. (2015). Genetic improvement in tef (*Eragrostis tef*): Progresses and prospects. *New Biotechnology*, 32(1), 163–173.

- Balasubramanian, S. (2001). Physical properties of raw and parboiled mustard seeds. *Journal of Food Engineering*, 47(3), 227–231.
- Baye, K. (2014). Teff (*Eragrostis tef*): Its nutrient composition and nutritional health benefits. *International Food Policy Research Institute (IFPRI) Working Paper*, 67, 1–28.
- Bojnanská, E., & Francáková, H. (2002). The evaluation of teff grain physical quality parameters. *Acta Fytotechnica et Zootechnica*, 5(2), 41–44.
- Bultosa, G. (2007). Physicochemical characteristics of grain and flour in 13 teff (*Eragrostis tef*) varieties. *Journal of Applied Sciences Research*, 3(11), 1442–1451.
- Bultosa, G., Hall, A. N., & Taylor, J. R. (2002). Physico-chemical characterization of grain tef (*Eragrostis tef*) starches. *Starch-Stärke*, 54(10), 461–468.
- Coskuner, Y., & Karababa, E. (2007). Physical properties of coriander seeds (*Coriandrum sativum* L.). *Journal of Food Engineering*, 80(2), 408–416.
- Delcour, J. A., & Hosney, R. C. (2010). *Principles of Cereal Science and Technology*. AACC International, St. Paul.
- Gebremariam, M. M., Zarnkow, M., & Becker, T. (2012). Teff (*Eragrostis tef*) as a raw material for malting, brewing and manufacturing of gluten-free foods and beverages: A review. *Journal of Food Science and Technology*, 51(11), 2881–2895.
- Gharibzahedi, S. M. T., Etemadi, H., Mirzaghahi, M., & Zamanipoor, M. H. (2014). Controllable physical and engineering characteristics of small grain cereals during moisture conditioning. *Measurement*, 50, 119–127.
- Goldstein, J., Newbury, D. E., Echlin, P., Joy, D. C., Romig, A. D., Lyman, C. E., ... & Lifshin, E. (2012). *Scanning Electron Microscopy and X-Ray Microanalysis*. Springer Science & Business Media.
- Igathinathane, C., Pordesimo, L. O., & Batchelor, W. D. (2009). Major axis orientation and dimension measurement of grain kernels using image processing. *Computers and Electronics in Agriculture*, 65(1), 25–33.
- Igthin, J., & Patel, M. (2015). Limitations of manual dimension measurement techniques in small-seeded legumes and cereals. *Journal of Food Process Engineering*, 38(2), 145–154.

- Irtawange, A. I. (2000). The effect of moisture content on some physical properties of African yam bean (*Sphenostylis stenocarpa*). *Journal of Agricultural Engineering and Technology*, 8, 41–52.
- Jane, J. L., Shen, L., Chen, J., Lim, S., Kasemsuwan, T., & Nip, W. K. (1992). Physical and chemical properties of various starches. *Cereal Chemistry*, 69(5), 528–535.
- Kachru, R. P., Gupta, R. K., & Alam, A. (1994). *Physico-Chemical Properties of Agricultural Seeds*. Indian Council of Agricultural Research, New Delhi.
- Kaláb, M., Allan-Wojtas, P., & Miller, S. S. (1995). Microscopy and other imaging techniques in food structure analysis: A review. *Trends in Food Science & Technology*, 6(6), 177–186.
- Kibar, H., & Öztürk, T. (2008). Physical and mechanical properties of rice agricultural seeds. *Journal of Agricultural Sciences*, 14(2), 177–183.
- Klavins, L., Rutkis, R., & Bikovens, O. (2016). Advanced image-based morphological characterization of small cereal and pseudocereal grains. *Computers and Electronics in Agriculture*, 128, 12–21.
- Lee, H. J. (2018). Gluten-free ancient grains: Nutritional values and processing challenges. *Trends in Food Science & Technology*, 78, 112–124.
- Markowski, M., Żuk-Gołaszewska, K., & Kwiatkowski, D. (2013). Influence of water content on physical properties of amaranth seeds. *International Agrophysics*, 27(2), 171–177.
- Mohsenin, N. N. (1986). *Physical Properties of Plant and Animal Materials*. Gordon and Breach Science Publishers, New York.
- Qian, J. Y., & Kuhn, M. (1999). Characterization of native and acid-modified amaranth starch granules. *Starch-Stärke*, 51(3), 88–92.
- Sacilik, K., Öztürk, R., & Keskin, R. (2003). Some physical properties of hemp seed. *Biosystems Engineering*, 86(2), 191–198.
- Sahay, K. M., & Singh, K. K. (2001). *Unit Operations of Agricultural Processing*. Vikas Publishing House Pvt Ltd, New Delhi.
- Shumoy, H., & Raes, K. (2017). Tef (*Eragrostis tef*): Nutritional export, post-harvest losses and processing. *Comprehensive Reviews in Food Science and Food Safety*, 16(6), 1113–1127.
- Sologubik, C. A., Campañone, L. A., Gely, M. C., & Pagano, A. M. (2013). Effect of moisture content on physical properties of barley grains. *Industrial Crops and Products*, 43, 762–767.

- Stroshine, R. (1998). *Physical Properties of Agricultural Materials and Food Products*. Purdue University Press, West Lafayette.
- Stroshine, R. L., & Hamann, D. D. (1994). *Physical Properties of Agricultural Materials*. Purdue University Press, West Lafayette.
- Tavakoli, H., Rajabipour, A., & Mohtasebi, S. S. (2009). Moisture-dependent physical properties of wheat grain. *International Agrophysics*, 23(1), 85–91.
- Tefera, H., Assefa, K., Hundera, F., Kefyalew, T., & Tefame, T. (2003). Heritage and agronomic potential of tef (*Eragrostis tef*) varieties released in Ethiopia. *Ethiopian Journal of Agricultural Sciences*, 18(1), 11–24.
- Tester, R. F., Karkalas, J., & Qi, X. (2004). Starch—composition, fine structure and architecture. *Journal of Cereal Science*, 39(2), 151–152.
- Vavilov, N. I. (1951). The origin, variation, immunity and breeding of cultivated plants. *Chronica Botanica*, 13(1), 1–364.
- Wandkar, S. V., & Ukey, P. D. (2014). Engineering properties of agricultural grains and seeds: A comprehensive review. *International Journal of Engineering Research and Applications*, 4(7), 108–117.
- Wolter, A., Hager, A. S., Zannini, E., & Arendt, E. K. (2013). Influence of sourdough on in vitro starch digestibility and predicted glycemic index of gluten-free breads. *Food & Function*, 4(8), 1210–1221.
- Zewdu, A. D., & Solomon, W. K. (2007). Moisture-dependent physical properties of tef seed. *Biosystems Engineering*, 96(1), 57–63.