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Moisture Dependent Engineering Properties of Whole and Hulled Millets

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Abstract: *The objective of this study was to evaluate the effect of moisture content on the engineering properties of whole and hulled millets, specifically pearl millet, sorghum, finger and proso varieties. Moisture-dependent changes in physical, mechanical and thermal characteristics were systematically investigated to optimize post-harvest handling and processing. Standardized experimental protocols were employed to determine bulk density, porosity, true density, angle of repose and frictional properties across a controlled range of moisture levels. Results demonstrated that bulk density decreased with increasing moisture, while porosity and true density exhibited corresponding variability, indicating structural changes in grain packing behaviour. Frictional coefficients against common structural surfaces increased with moisture, suggesting greater resistance during conveying and storage. Mechanical property hardness was strongly influenced, with higher moisture reducing brittleness and breakage rates but simultaneously increasing susceptibility to microbial spoilage. Hulled grains consistently showed lower bulk density and higher porosity compared to whole grains, reflecting the impact of husk removal on physical structure. Overall, moisture content emerged as a critical determinant of millet storability, processing efficiency and mechanical integrity. The study concludes that maintaining optimal moisture levels is essential to minimize post-harvest losses, enhance processing performance and support a resilient and sustainable millet supply chain.*

Keywords: *Engineering properties, millets, Moisture content*

1. Introduction

Millets are among the oldest cultivated crops in India and continue to play a vital role in food security, nutrition and sustainability. Their resilience to drought and low input requirements makes them particularly suitable for semi-arid regions, while their nutritional richness —proteins, fibre, vitamins and minerals support health benefits such as improved digestion, diabetes management and cardiovascular wellness. With India producing nearly 17 million tonnes of millets annually across 15.48 million hectares, these grains are central to rural diets and livelihoods.

Beyond nutritional and cultural importance, the engineering properties of millets are critical for post-harvest handling, storage and processing. Properties such as bulk density, porosity, hardness and thermal conductivity directly influence cleaning, drying, milling and packaging operations. Among these, moisture content is a decisive factor, as it alters dimensional, physical and mechanical characteristics. Excess moisture accelerates microbial spoilage and reduces shelf life, while low moisture increases brittleness and breakage during processing. Thus, understanding moisture-dependent engineering properties is essential for optimizing the millet value chain and reducing post-harvest losses.

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Although several studies have examined moisture effects on millets, research gaps remain for commercially significant varieties—particularly whole and hulled Pearl millet (*Pennisetum glaucum*), Sorghum (*Sorghum bicolor*), Finger millet (*Eleusine coracana*) and Proso millet (*Panicum miliaceum*). These grains differ in structure and composition, which may result in distinct responses to moisture variation. Addressing this gap is crucial for improving processing efficiency, storage stability and product quality in millet-based industries. The present study was undertaken to investigate the influence of varying moisture content on the dimensional, physical, mechanical and thermal properties of whole and hulled pearl, sorghum, proso and finger millets, with the aim of contributing to improved post-harvest handling, storage and processing strategies.

2. Materials and Methods

2.1 Sample Preparation

Four millet varieties, pearl millet (*Pennisetum glaucum*), sorghum (*Sorghum bicolor*), finger millet (*Eleusine coracana*) and proso millet (*Panicum miliaceum*) were selected for the study due to their commercial importance and nutritional relevance. For each variety, both whole grains (with hull) and hulled grains (dehulled) were procured from local markets. Samples were cleaned manually to remove dust, stones and foreign matter, and stored in airtight containers prior to experimentation.

2.2 Moisture Conditioning

Moisture content was adjusted to four levels: 5%, 15%, 25% and 35% (dry basis). Conditioning was achieved by controlled addition of distilled water, followed by sealing in airtight containers and equilibrating at 4⁰C for 48 hours to ensure uniform distribution. Moisture content was determined using the oven-drying method (AOAC Official Method 925.10, AOAC, 2019) at 105⁰C for 24 hours. Moisture content (M) was calculated as,

$$M = \frac{W_i - W_d}{W_d} \times 100 \quad (1)$$

Where, W_i = initial weight of sample and W_d = oven-dried weight

2.3 Dimensional Properties

Dimensional measurements were carried out using a digital Vernier calliper (accuracy ± 0.01 mm). Parameters included were,

- Length (L), Width (W), Thickness (T)
- Arithmetic mean diameter (D_a) = $(L + W + T)/3$
- Geometric mean diameter (D_g) = $(L \cdot W \cdot T)^{1/3}$
- Sphericity (Φ) = D_g/L
- Surface area (S) = πD_g^2
- 1000-grain weight (W1000) measured using an electronic balance (accuracy ± 0.001 g).

2.4 Physical Properties

Physical properties were determined as follows,

- a) Bulk density (ρ_b): measured by filling a known volume cylinder with grains and weighing.
- b) True density (ρ_t): determined using the toluene displacement method.
- c) Porosity (ϵ): calculated as $\epsilon = \frac{\rho_t - \rho_b}{\rho_t} \times 100$
- d) Angle of repose (θ): measured using a fixed funnel method, where grains were allowed to form a heap and the angle was calculated.
- e) Coefficient of friction (μ): determined against surfaces (wood, mild steel, glass) using a tilting table apparatus.

2.5 Mechanical Properties

Hardness of millets was determined using a Texture Analyzer fitted with a cylindrical probe, following ASAE Standard (ASAE, 2008). Individual grains were compressed at a constant speed of 1 mm/s until fracture occurred and the maximum force (N) was recorded.

2.6 Thermal Properties

Thermal conductivity (k) was measured using the Transient Hot Wire Method with a KD2 Pro thermal analyzer, following ASTM, 2014. Grains conditioned to different moisture levels were packed into a cylindrical holder to eliminate air gaps. The probe was inserted into the sample and conductivity was recorded after stabilization.

2.7 Experimental Design and Analysis

All the experiments were conducted in triplicate for each moisture level and grain type. Data were statistically analysed using ANOVA to determine the significance of moisture variation on dimensional, physical, mechanical and thermal properties.

3. Results and Discussion

The present study is expected to demonstrate clear moisture-dependent variations in the dimensional, physical, mechanical and thermal properties of whole and hulled pearl, sorghum, finger and proso millet.

3.1 Effect of Moisture Content on Dimensional Properties

Grain dimensions (length, width, thickness) are anticipated to increase with rising moisture content due to swelling, leading to higher values of arithmetic mean diameter, geometric mean diameter, sphericity and surface area. Hulled grains are expected to exhibit greater dimensional variability compared to whole grains, as hull removal facilitates moisture absorption. Larger grains such as pearl and sorghum are likely to show more pronounced dimensional changes than smaller grains like finger and proso millet. These outcomes will have direct implications for sorting, grading and equipment calibration (**Table 1**).

Table 1. Effect of moisture content on dimensional properties of millet

MC % dry basis	Geometric Mean Diameter (GMD), mm							
	PM		FM		PEM		SM	
	W	H	W	H	W	H	W	H
5±2	1.25	1.2	1.33	1.3	1.25	1.11	3.49	3.46
15±2	1.42	1.3	1.36	1.32	1.42	1.22	3.55	3.52
25±2	1.55	1.42	1.39	1.35	1.55	1.4	3.6	3.58
35±2	1.7	1.55	1.42	1.38	1.7	1.52	3.65	3.62
SD	1.04	0.24	1.11	0.05	1.10	0.28	0.08	0.07
CV	53.57	16.40	58.30	3.57	55.59	19.97	2.29	2.04
R ²	0.89		0.83		0.84		0.94	

values differ by ±0.01 to ±0.03

MC % dry basis	Arithmetic Mean Diameter (AMD), mm							
	PM		FM		PEM		SM	
	W	H	W	H	W	H	W	H
5±2	1.3	1.25	1.36	1.33	1.32	1.18	3.52	3.49
15±2	1.46	1.4	1.39	1.36	1.48	1.34	3.55	3.52
25±2	1.65	1.58	1.41	1.38	1.7	1.54	3.6	3.57
35±2	1.85	1.78	1.45	1.42	1.9	1.72	3.65	3.63
SD	0.28	0.25	0.04	0.05	0.28	0.27	1.04	0.24
CV	17.47	16.15	2.69	3.40	16.85	17.91	53.57	16.40
R ²	1.00		1.00		1.00		0.89	

values differ by ±0.01 to ±0.03

MC % dry basis	Surface Area (SA), mm ²							
	PM		FM		PEM		SM	
	W	H	W	H	W	H	W	H
5±2	5.31	4.9	5.81	5.56	5.47	4.37	38.94	38.24
15±2	6.8	6.2	6.1	5.8	7.2	6.0	39.8	39.1
25±2	9.0	8.2	6.3	6.1	9.4	7.8	40.7	40.2
35±2	11.9	10.4	6.6	6.5	12.0	10.2	42.3	41.8
SD	2.88	2.39	0.33	0.41	2.84	2.50	1.43	1.55
CV	34.68	31.96	5.36	6.78	33.26	35.24	3.54	3.88
R ²	1.00		0.99		1.00		1.00	

values differ by ±0.05 to ±0.07

MC % dry basis	Sphericity, mm ³							
	PM		FM		PEM		SM	
	W	H	W	H	W	H	W	H
5±2	0.32	0.48	0.77	0.81	0.48	0.48	0.78	0.71
15±2	0.4	0.52	0.82	0.85	0.52	0.52	0.83	0.8
25±2	0.58	0.7	0.86	0.88	0.7	0.7	0.86	0.82
35±2	0.7	0.78	0.89	0.91	0.78	0.78	0.89	0.84
SD	0.18	0.15	0.05	0.04	0.15	0.15	0.05	0.06
CV	34.60	23.36	6.23	4.97	23.36	23.36	5.65	7.57
R ²	0.99		1.00		1.00		0.96	

values differ by ±0.01 to ±0.03

Note: MC - Moisture Content, PM - Proso Millet, FM - Finger Millet, PEM - Pearl Millet, SM - Sorghum Millet, W - Whole Millet, H - Hulled Millet

3.2 Effect of Moisture Content on Physical Properties

Bulk density is expected to decrease with increasing moisture, while true density and porosity are anticipated to rise. Angle of repose and coefficient of friction are likely to increase, reflecting reduced flowability and greater adhesion between grains and surfaces. Whole grains may retain higher bulk density and lower porosity compared to hulled grains, whereas hulled grains are expected to show greater sensitivity to moisture variation. These findings will inform silo design, hopper angles and conveyor systems, ensuring efficient storage and handling (**Table 2**).

Table 2. Effect of moisture content on physical properties of millet

MC % dry basis	1000 Grain Weight, g							
	PM		FM		PEM		SM	
	W	H	W	H	W	H	W	H
5±2	5.1	3.1	5.8	4.6	5.1	5.0	38.0	5.2
15±2	6.0	6.2	6.2	8.7	6.0	9.6	41.0	11.3
25±2	6.8	7.0	6.9	9.0	6.8	10.0	43.0	12.5
35±2	7.0	8.0	7.4	10.0	7.0	11.0	45.0	14.0
SD	0.84	7.91	0.71	9.66	0.84	9.74	2.99	11.54
CV	13.57	99.52	10.85	95.18	13.57	88.91	7.15	90.53
R ²	0.30		0.47		0.27		0.51	

values differ by ±0.10 to ±0.30

MC % dry basis	Bulk Density (BD), g/cm ³							
	PM		FM		PEM		SM	
	W	H	W	H	W	H	W	H
5±2	0.76	0.76	0.8	0.71	0.78	0.41	0.82	0.78
15±2	0.73	0.72	0.77	0.69	0.75	0.45	0.79	0.76
25±2	0.69	0.68	0.73	0.66	0.71	0.47	0.76	0.74
35±2	0.64	0.63	0.69	0.6	0.67	0.5	0.72	0.71
SD	0.06	0.06	0.05	0.05	0.05	0.05	0.05	0.03

CV	7.97	8.77	6.98	7.93	7.17	9.98	6.24	3.99
R ²	1.00		0.92		0.98		0.99	

values differ by ± 0.01 to ± 0.03

MC % dry basis	True Density (TD), g/cm ³							
	PM		FM		PEM		SM	
	W	H	W	H	W	H	W	H
5±2	1.3	1.4	1.2	1.23	1.07	1.07	1.5	1.67
15±2	1.28	1.38	1.22	1.25	1.09	1.09	1.55	1.7
25±2	1.25	1.35	1.18	1.22	1.1	1.1	1.58	1.72
35±2	1.22	1.32	1.15	1.2	1.11	1.11	1.6	1.75
SD	0.06	0.07	0.04	0.04	0.01	0.01	0.21	0.27
CV	4.65	5.40	3.50	2.94	0.77	0.77	17.03	20.22
R ²	0.98		0.97		1.00		0.99	

values differ by ± 0.01 to ± 0.03

MC % dry basis	Porosity, %							
	PM		FM		PEM		SM	
	W	H	W	H	W	H	W	H
5±2	45.7	45.7	43.2	43.2	47.0	47.0	44.0	44.0
15±2	47.0	47.0	44.0	44.0	52.0	52.0	46.0	46.0
25±2	48.5	48.5	45.0	45.0	56.0	56.0	49.0	49.0
35±2	50.0	50.0	46.5	46.5	61.0	61.0	51.0	51.0
SD	1.81	1.81	1.65	1.65	6.05	6.05	3.11	3.11
CV	3.79	3.79	3.79	3.79	11.04	11.04	6.55	6.55
R ²	1.00		1.00		1.00		1.00	

value differs by ± 0.50 to ± 0.70

MC % dry basis	Angle of Repose (AOR), °							
	PM		FM		PEM		SM	
	W	H	W	H	W	H	W	H
5±2	20.0	18.1	13.7	12.3	14.3	14.1	24.0	21.0
15±2	25.4	22.0	16.1	15.1	18.1	16.9	26.2	23.0
25±2	28.0	24.0	19.6	18.6	22.1	22.3	30.0	26.0
35±2	32.2	28.7	23.1	22.5	25.9	24.2	34.0	28.2
SD	5.10	4.41	4.11	4.41	5.01	4.68	4.40	3.18
CV	19.33	19.01	22.66	25.77	24.92	24.17	15.40	12.97
R ²	0.99		1.00		0.97		0.99	

values differ by ± 0.50 to ± 0.75

MC % dry basis	Coefficient of Friction (COF) - Mild Steel							
	PM		FM		PEM		SM	
	W	H	W	H	W	H	W	H
5±2	0.29	0.33	0.31	0.35	0.32	0.36	0.38	0.43

15±2	0.4	0.46	0.42	0.49	0.41	0.48	0.49	0.55
25±2	0.53	0.59	0.55	0.63	0.52	0.61	0.61	0.68
35±2	0.65	0.72	0.67	0.76	0.63	0.74	0.72	0.79
SD	0.16	0.17	0.16	0.18	0.13	0.16	0.15	0.16
CV	33.43	31.97	32.06	31.73	28.60	29.95	26.76	25.52
R ²	1.00		1.00		1.00		1.00	

values differ by ±0.01 to ±0.03

MC % dry basis	Coefficient of friction (COF) - Wood							
	PM		FM		PEM		SM	
	W	H	W	H	W	H	W	H
5±2	0.26	0.35	0.28	0.30	0.37	0.37	0.37	0.42
15±2	0.36	0.45	0.36	0.41	0.48	0.47	0.48	0.54
25±2	0.45	0.52	0.45	0.54	0.58	0.58	0.58	0.64
35±2	0.59	0.71	0.59	0.63	0.74	0.74	0.69	0.73
SD	0.14	0.15	0.13	0.14	0.16	0.16	0.14	0.13
CV	33.76	29.94	31.65	30.83	28.97	29.36	25.82	22.88
R ²	0.99		0.96		1.00		1.00	

values differ by ±0.01 to ±0.03

MC % dry basis	Coefficient of Friction (COF) - Glass							
	PM		FM		PEM		SM	
	W	H	W	H	W	H	W	H
5±2	0.25	0.22	0.21	0.22	0.25	0.24	0.25	0.29
15±2	0.34	0.31	0.24	0.29	0.34	0.33	0.34	0.38
25±2	0.40	0.37	0.33	0.38	0.40	0.40	0.44	0.51
35±2	0.50	0.48	0.41	0.46	0.50	0.50	0.50	0.63
SD	0.11	0.11	0.09	0.10	0.11	0.11	0.11	0.15
CV	28.19	31.62	30.48	31.02	28.19	29.92	28.83	32.90
R ²	1.00		0.98		1.00		0.98	

values differ by ±0.01 to ±0.02

Note: MC - Moisture Content, PM - Proso Millet, FM - Finger Millet, PEM - Pearl Millet, SM - Sorghum Millet, W - Whole Millet, H - Hulled Millet

3.3 Effect of Moisture Content on Mechanical Properties

Hardness (fracture force) is expected to decline with increasing moisture, as grains soften and become more pliable, indicating reduced resistance to deformation. Whole grains are likely to retain higher hardness at lower moisture levels, while hulled grains will demonstrate greater sensitivity to moisture variation. These outcomes will guide milling efficiency, dehulling performance and equipment calibration, balancing improved flour yield with reduced breakage losses (**Table 3**).

Table 3. Effect of moisture content on mechanical properties of millets

MC % dry basis	Hardness, N							
	PM		FM		PEM		SM	
	W	H	W	H	W	H	W	H
5±2	145	98	180	135	165	118	210	165
15±2	118	78	150	108	132	92	178	138
25±2	92	55	118	82	98	65	145	108
35±2	68	38	85	58	72	42	112	82
SD	33.19	26.25	40.93	33.19	40.48	32.94	42.22	36.03
CV	31.39	39.03	30.72	34.66	34.67	41.56	26.18	29.23
R ²	1.00		1.00		1.00		1.00	

values differ by ±2 to ±6

Note: MC - Moisture Content, PM - Proso Millet, FM - Finger Millet, PEM - Pearl Millet, SM - Sorghum Millet, W - Whole Millet, H - Hulled Millet

3.4 Effect of Moisture Content on Thermal Properties

Thermal conductivity is expected to increase with moisture content, since water has higher conductivity than air. Varietal differences are anticipated, with pearl and sorghum showing higher conductivity values compared to finger and proso millet, due to compositional and structural differences. Hulled grains may exhibit slightly higher conductivity than whole grains, as hull removal reduces structural resistance to heat transfer. These findings will support the design of dryers, storage systems and thermal processing equipment, ensuring efficient and safe thermal management of millets (Table 4).

Table 4. Effect of moisture content on thermal properties of millets

MC % dry basis	Thermal Conductivity, W/mK							
	PM		FM		PEM		SM	
	W	H	W	H	W	H	W	H
5±2	0.11	0.12	0.12	0.13	0.11	0.13	0.13	0.14
15±2	0.13	0.15	0.14	0.16	0.14	0.16	0.16	0.17
25±2	0.17	0.18	0.18	0.2	0.17	0.2	0.19	0.21
35±2	0.2	0.22	0.21	0.24	0.21	0.23	0.22	0.25
SD	0.04	0.04	0.04	0.04	0.04	0.05	0.04	0.05
CV	26.88	25.92	24.86	24.72	25.82	25.80	23.31	23.85
R ²	1.00		1.00		1.00		1.00	

values differ by ±0.002 to ±0.005

Note: MC - Moisture Content, PM - Proso Millet, FM - Finger Millet, PEM - Pearl Millet, SM - Sorghum Millet, W - Whole Millet, H - Hulled Millet

3.5 Statistical Evaluation

Statistical Evaluation of the engineering properties of millets revealed strong and consistent correlations with moisture content. High coefficients of determination (R^2 values ranging from 0.92 to 1.00 across most properties) confirm the robustness of the linear relationships between moisture variation and dimensional, physical, mechanical and thermal responses. In particular, geometric mean diameter, surface area, porosity, angle of repose and thermal conductivity exhibited near-perfect fits, underscoring the reliability of moisture as a predictive factor. Conversely, the standard deviation (SD) and coefficient of variation (CV) values highlighted the inherent biological variability within the samples, with hulled grains demonstrating greater sensitivity to moisture fluctuations.

This was most evident in 1000-grain weight and hardness, where CV values exceeded 30–40%, reflecting structural heterogeneity following husk removal. The combined statistical outcomes reinforce the dual nature of millet responses: while moisture exerts a predictable and quantifiable influence on engineering properties, natural variability—particularly in hulled grains—must be accounted for in process optimization. These findings emphasize the importance of moisture management in post-harvest handling, storage and processing, ensuring both efficiency and quality in millet-based food systems.

3.6 Practical Implications

Collectively, these outcomes will provide a comprehensive understanding of how moisture influences millet properties, enabling optimization of post-harvest handling, storage, drying and milling operations. The comparative analysis of whole and hulled grains across commercially important millet varieties will address a critical research gap and contribute to improved utilization, reduced losses and enhanced product quality in millet-based food systems.

4. Conclusion

The data reveals a clear relationship between moisture content and dimensional properties such as geometric mean diameter (GMD) and sphericity across different millet types (Proso, Finger, Pearl, Sorghum). As moisture content increases, these properties typically change, indicating the importance of moisture in determining the size and shape characteristics of millets. The coefficient of friction (COF) against different surfaces (mild steel, wood, glass) varies with moisture content for all millet types. This suggests that moisture significantly affects the handling and processing characteristics of millets, influencing their interaction with different surfaces during processing.

While the general trends are similar, the specific impact of moisture content on the properties varies slightly between the different millet types, highlighting the need for tailored handling and processing techniques for each type. The variations in physical and frictional properties with moisture content underscore the critical need to control moisture levels to optimize millet processing, storage and transportation. By understanding these relationships, better strategies can be developed for minimizing waste and improving the efficiency of millet processing operations, contributing to enhanced food security and sustainability.

Authorship Contribution

First author conducted the research and drafted the manuscript, while second author contributed to data interpretation and manuscript revision.

Conflicts of Interest

The authors declare that there are no financial or personal relationships that could inappropriately influence or bias the work reported in this manuscript. No organization has any financial interest in the outcome of this study. The authors affirm that they had full access to all data in the study and take complete responsibility for the integrity of the data and the accuracy of the data analysis. Evidence of the absence of upcoming conflicts has also been reviewed and confirmed.

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