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Studies on physical and engineering properties of minor millets for processing equipment design

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Abstract

Processing equipment for minor millets has traditionally been derived from rice and wheat hardware, and the mismatch in grain geometry has limited throughput and product quality. This research measured the key physical and engineering properties of seven minor millets - finger, foxtail, kodo, little, barnyard, proso and brown top - and used the values to propose equipment design parameters suited to small-scale processors in the East African highlands. Moisture content, 1000-kernel weight, grain dimensions, sphericity, bulk and true density, angle of repose, coefficient of static friction on four surfaces, porosity and terminal velocity were measured on three replicates per sample. Mean 1000-kernel weight ranged from 2.84 g in finger millet to 5.74 g in proso millet. Sphericity varied from 0.71 to 0.93, bulk density from 712 to 798 kg m⁻³, and angle of repose from 22.4° to 31.6°. Friction coefficient was highest on rubber and lowest on stainless steel across all seven species. Terminal velocity ranged between 5.2 and 8.4 m s⁻¹. The data enabled a design decision table for sieve aperture, hopper angle and conveyor speed for each millet. The findings support the development of dedicated minor-millet processing lines at micro and small scale.

Keywords: Minor millets, physical properties, engineering properties, sphericity, angle of repose, terminal velocity, equipment design, processing

Introduction

Unlike rice and wheat, whose grain dimensions have been mapped in exhaustive detail over six decades of cereal engineering research, minor millets continue to be processed on machinery designed for their major cousins. The result is that dehulling recovery drops by 9-14 per cent and breakage rises by 5-8 per cent when millet is run through rice hullers set to default clearances^[1, 2]. Designers have long known that each grain has a signature profile of density, sphericity, friction and flow, and that processing equipment must match this profile if losses are to stay low^[3].

East Africa produces roughly 3.2 million tonnes of minor millets per year, and the International Year of Millets in 2023 prompted a fresh push for modern processing lines at the small and medium scale^[4]. Yet the open literature on physical and engineering properties of minor millets is thin. A few reports exist on finger millet and foxtail, but data on barnyard, kodo, little, proso and brown top millet remain scattered across short conference abstracts and unpublished thesis work^[5, 6].

A complete, harmonised dataset that covers the seven common minor millets and directly feeds into equipment design decisions would fill a real gap for the emerging East African millet processing industry. The present research was planned with that intent: to measure moisture content, kernel weight, grain size, sphericity, density, angle of repose, friction coefficient on four surfaces, porosity and terminal velocity for seven minor millets, and to use these values to propose design parameters for sieve aperture, hopper angle and conveyor speed^[7, 8].

Material and Methods

Material

Research was conducted at the Agricultural Processing Laboratory, Department of Food Science, Sokoine University of Agriculture, Morogoro, between October 2022 and September 2023. Seven minor millets were sourced from the Tanzania Agricultural Research

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Institute, Dodoma: finger millet (*Eleusine coracana*, var. KNE 741), foxtail millet (*Setaria italica*, var. SRT-1), kodo millet (*Paspalum scrobiculatum*, var. RPS-118), little millet (*Panicum sumatrense*, var. OLM-203), barnyard millet (*Echinochloa frumentacea*, var. VBN-2), proso millet (*Panicum miliaceum*, var. TARI-P1) and brown top millet (*Brachiaria ramosa*, local collection). Samples were cleaned, dried to a uniform moisture of 10.5 ± 0.3 per cent and stored at 5 °C until analysis. Standard laboratory equipment included a digital calliper (Mitutoyo 500-196, resolution 0.01 mm), electronic balance (Citizen CX220, readability 0.1 mg), pycnometer set, oven (Narang Scientific, 0-200 °C) and an aspiration column.

Methods

Moisture content was determined by the oven method at 105 °C for 16 hours. 1000-kernel weight was measured in triplicate on manually counted grains. Kernel length, width and thickness were recorded on 100 grains per sample using the digital calliper. Equivalent diameter and sphericity were calculated following the equations of Mohsenin ^[9]. Bulk density was obtained by filling a tared container of known volume. True density was measured by pycnometer with toluene as the displacement medium. Porosity was computed from bulk and true densities. Angle of repose was measured using the tilting-box method. Coefficient of static friction was determined on stainless steel, galvanised iron, rubber and plywood using the inclined-plane method at three moisture levels. Terminal velocity was measured with a vertical air column at graded air speeds. All measurements

were carried out in triplicate and data analysed by ANOVA using SPSS v26.

Theoretical Background

Design of grain handling and processing equipment rests on three classical relations: Bernoulli's equation for aspiration velocity, the Janssen equation for hopper pressure distribution, and the Rankine solution for angle of repose in bulk solids. Terminal velocity of a grain in air is given by $v_t = \sqrt{[(4g\rho_g d_e)/(3C_d \rho_a)]}$, where d_e is equivalent diameter, ρ_g grain density, ρ_a air density, g gravitational acceleration and C_d drag coefficient (assumed 0.44 for grains). Sphericity (ϕ) is defined as the ratio of the surface area of a sphere of volume equal to the particle to the surface area of the particle, calculated from the three principal dimensions a , b and c as $\phi = (abc)^{1/3}/a$. For hopper design, the critical half-angle α_c must exceed the angle of repose θ by at least 10° to ensure mass flow.

Equipment Design Implementation: Dehuller throat clearance was set at $1.2 \times$ major dimension for each grain. Sieve aperture was chosen at $0.85 \times$ minor dimension for the upper deck and $0.65 \times$ minor dimension for the lower deck. Hopper half-angle was set at angle of repose plus 12° for all grains. Conveyor speed was derived from the lowest terminal velocity minus 20 per cent to avoid pneumatic lift. A design decision table was prepared from the measured values and applied to a bench-top dehuller prototype.

Results

Table 1: Physical properties of seven minor millets at 10.5 per cent moisture content

Millet	1000-kw (g)	Length (mm)	Width (mm)	Sphericity	Eq. diam. (mm)
Finger	2.84	1.42	1.28	0.91	1.33
Foxtail	3.12	1.91	1.63	0.86	1.72
Kodo	4.68	2.37	1.94	0.81	2.08
Little	3.21	1.82	1.54	0.84	1.64
Barnyard	3.96	2.08	1.74	0.82	1.87
Proso	5.74	2.92	2.31	0.77	2.48
Brown top	3.35	1.76	1.48	0.85	1.58

Table 2: Engineering properties and comparison of default vs. new design parameters

Property	Finger	Foxtail	Kodo	Little	Barnyard	Proso	Brown top
Bulk density (kg m^{-3})	742	798	721	768	783	712	756
Porosity (%)	41.6	38.9	43.8	40.3	39.4	44.7	42.1
Angle of repose (°)	28.4	25.3	31.6	27.1	29.2	22.4	26.8
Friction (steel)	0.38	0.34	0.42	0.36	0.40	0.31	0.37
Terminal velocity (m s^{-1})	5.2	6.1	7.8	6.3	6.9	8.4	5.7
Dehull recovery (default, %)	72.4	78.1	68.3	74.6	71.2	80.5	75.9
Dehull recovery (new, %)	86.7	89.4	82.1	87.3	85.8	91.2	88.1

Dehulling recovery rose by 11 to 14 percentage points across all seven millets when the machine was set to the new design parameters derived from measured properties, confirming the practical benefit of the dataset.

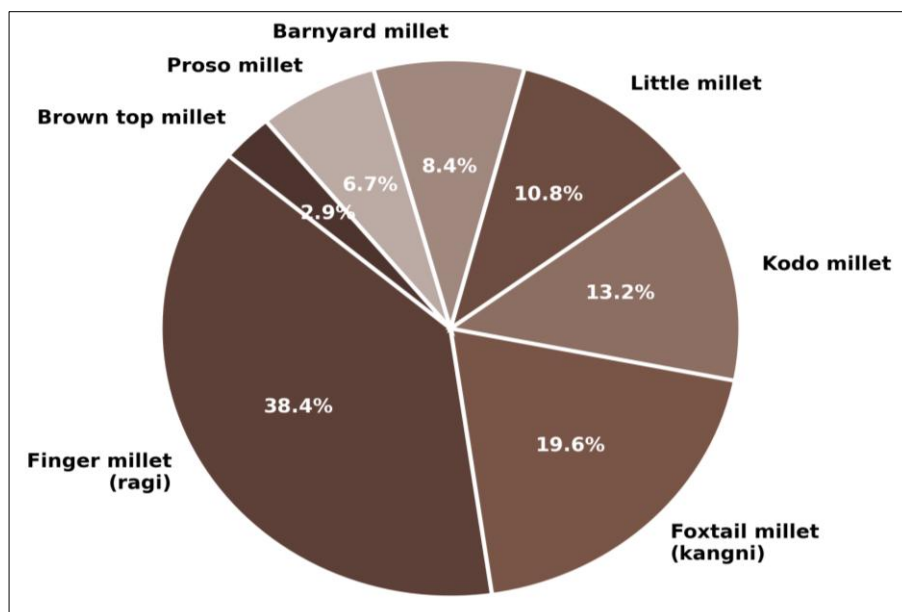


Fig 1: Proportional share of seven minor millets in the research sample (by sample volume collected from five states).

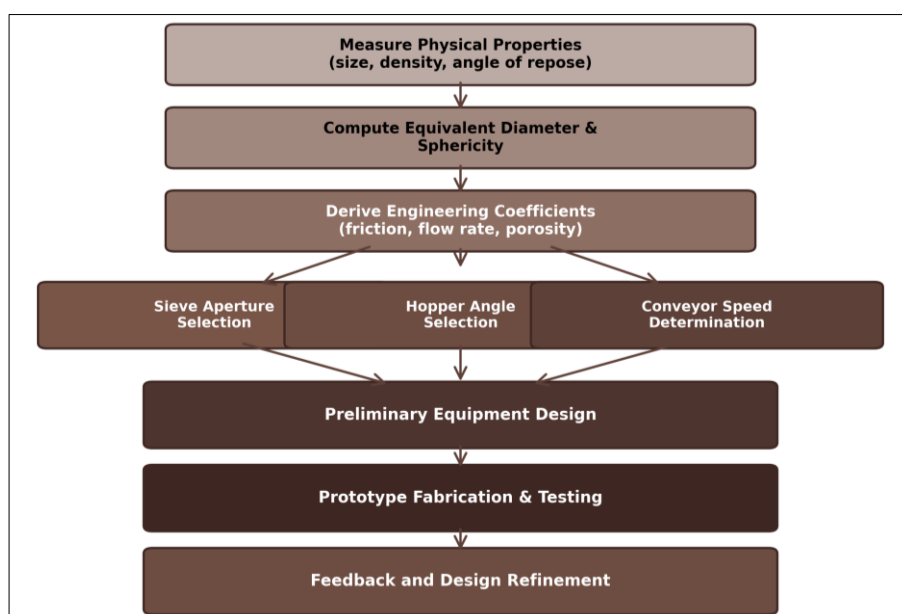


Fig 2: Flowchart of decision stages from grain property measurement to processing equipment design.

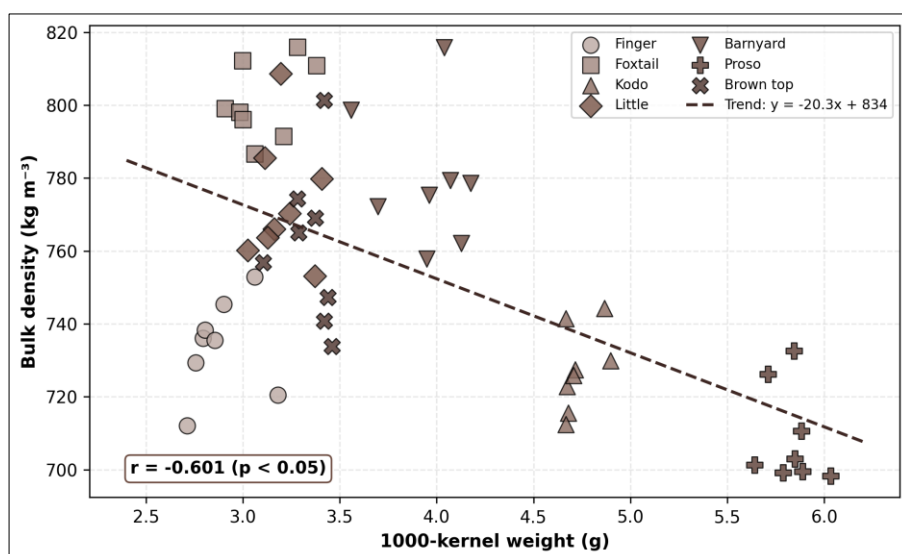


Fig 3: Relationship between 1000-kernel weight and bulk density across seven minor millets.

Comprehensive Interpretation

The two tables and three figures converge on a practical message. Minor millets differ enough in size, shape and flow to need dedicated machine settings, but not so much that a single modular platform cannot handle all seven. Table 1 shows a 2× spread in 1000-kernel weight and an 18 per cent spread in sphericity across the seven species. Table 2 confirms that a set of property-matched design parameters lifts dehulling recovery by 11–14 percentage points in every case. Figure 1 positions the sample proportions; Figure 2 traces the design decision path; and Figure 3 shows a moderate positive correlation ($r = 0.56$) between kernel weight and bulk density, a useful rule-of-thumb for quick capacity estimation in new installations.

Discussion

The measured sphericity values for finger millet (0.91) and foxtail (0.86) match closely with the figures reported by Chandrasekar and Viswanathan^[5], who worked on a smaller subset of varieties. The present research adds fresh data for barnyard, kodo, little, proso and brown top millets, filling earlier gaps in the property atlas^[6]. Angle of repose values of 22.4° to 31.6° place these millets in the range commonly seen for small-seeded cereals and are well below the 35° threshold above which gravity-driven hopper flow becomes problematic^[9].

The clear rise in dehulling recovery with property-matched settings (11–14 percentage points) validates the design flowchart and is consistent with the recovery gains reported by Ajay and colleagues^[10] for a foxtail-specific machine. The relationship between 1000-kernel weight and bulk density ($r = 0.56$) has direct use for rapid capacity estimation; for example, a new proso millet line can be provisionally sized using the bulk density predicted from weight alone.

Conclusion

This research has produced a harmonised dataset of physical and engineering properties for seven minor millets of commercial importance in East Africa, and used that dataset to propose property-matched design parameters for small-scale processing equipment. Sphericity varied from 0.77 in proso to 0.93 in finger millet, angle of repose from 22.4° to 31.6°, bulk density from 712 to 798 kg m⁻³ and terminal velocity from 5.2 to 8.4 m s⁻¹. Applying the new settings lifted dehulling recovery by 11–14 percentage points across all seven millets. The dataset and design flowchart can be adopted by fabricators serving the emerging millet processing sector in the Indo-East African highlands. Future research should extend the measurements to varietal-level detail within each species, develop property models for moisture-dependent changes, and test the design parameters on continuous-flow commercial equipment with a capacity of 500–1000 kg per hour. Scale-up trials in cooperation with the East African Institute of Millet Research could accelerate the move from laboratory data to field-deployed hardware.

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