Physical Property Characterization of Ethiopian Maize Varieties for Adaptive Multi-Crop Planter Design

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Abstract

Smallholder maize production in sub-Saharan Africa, crucial for regional food security, grapples with persistent yield gaps driven by labor-intensive planting practices and a critical lack of mechanization specifically designed to accommodate the traits of native plant varieties. This study characterizes three maize varieties (CML-539, Melkassa 3, and Melkassa 6Q) to develop design parameters for adaptive multi-crop planters. Geometric properties including length, width, and thickness were measured using digital calipers, with 100 seeds per variety. Analysis was performed for elongation, geometric and arithmetic mean diameters, surface area, projected area, transverse cross-sectional area, sphericity, flakiness ratio, aspect ratio, shape index, and roundness. Gravimetric properties including bulk and true densities, porosity, thousand seed mass, and angle of repose were systematically analyzed to optimize seed-handling mechanisms in planter design. Physical property analysis revealed distinct varietal requirements: CML-539's irregular morphology (9.42 mm length, 49.30% porosity) necessitates vibration-assisted metering and aerated delivery systems; Melkassa 6Q's uniform properties (71.11± 6.66% sphericity, 811.62 kg m^{-3} bulk density) permit gravity-fed mechanisms; and Melkassa 3's intermediate characteristics of > 2.3 elongation ratio and 19.31% density variation require adjustable furrow openers of 25-30° rake angles. Geometric variability necessitates the implementation of adaptive solutions, such as curved seed tubes and adjustable furrow openers, to effectively prevent tilt and bridging. The resulting modular planter system, incorporating moisture-responsive metering, adaptive cell sizing, and aerated delivery, aligns with Ethiopia's agroecological standards of 75 cm row spacing and depth range of 4 to 7 centimeters. This framework offers a scalable, sustainable model for precision smallholder mechanization, transferable to global maize systems.

Keywords: Angle of repose, Maize varieties, Multi crop planter, Physical property, Sphericity

Introduction

Maize (*Zea mays* L.), a staple crop critical to global food security, is the most widely cultivated cereal worldwide, achieving a yield of 27,800 kg per hectare surpassing rice, wheat, and millets (FAO, 2023). Its versatility extends to human nutrition, animal feed, and industrial processing, while its grain traits and maturation periods are genetically adapted to thrive across diverse agroecological conditions. In Ethiopia, maize dominates cereal production, accounting for 88.69% of the total output (Central Statistical Agency, 2021). However, productivity remains constrained by labor-intensive manual planting practices. Traditional methods, plagued by inconsistent seed spacing, uneven depth placement, and significant physical exertion for farmers, compromise germination rates and yield optimization (Sinha *et al.*, 2021; Soyoye, Ademosun, & Agbetoye, 2018).

The design of seed planters' hinges on critical physical of seed properties. Maize kernels, characterized by their angular shapes and varying densities, require carefully designed metering systems to reduce mechanical damage during the singulation process (Pascual, Rafael, Remocal, &

Regalado, 2021; Shah *et al.*, 2022). Key parameters include sphericity (governing seed plate cell dimensions), angle of repose (dictating hopper wall slopes for uninterrupted flow), and terminal velocity (influencing seed tube aerodynamics) (Sinha *et al.*, 2021). Density further modulates grain friction coefficients and brittleness, necessitating adaptive components to maintain seed integrity across postharvest handling and planting phases (Dinberu & Megersa, 2023). Neglecting these properties risks planter inefficiencies, including clogging, seed fracture, and placement inaccuracy factors that erode farmer trust and adoption (Omar *et al.*, 2023).

In Ethiopia, agricultural mechanization strategies disproportionately prioritize wheat production, systematically neglecting the mechanization needs of smallholder farmers reliant on maize cultivation. Current multi-crop planters, predominantly retrofitted from temperate-region prototypes, demonstrate limited functional compatibility with indigenous maize varieties and local agroclimatic conditions. These mismatches manifest in critical agronomic inefficiencies, including excessive depth variability and seed spacing (±25% inaccuracy), undermining crop establishment and yield predictability (Liang *et al.*, 2021; Seyoum, Paul, & Sinafikeh, 2013; Theodrose, Kindie, Mezegebu, Nigussie, & Mengistu, 2024). These inefficiencies arise from a systemic failure to integrate agronomic and operational parameters into planter design optimization (Ayele, 2022; Kebede, 2019).

Resolving these inefficiencies requires engineering property optimized planter components tailored to Ethiopia's agroecology. Critical priorities are fluted roller meters that are 10% larger than kernel sizes to lower shear stress (< 2 MPa) (Liang *et al.*,, 2021; Singh, Sahoo, & Bisht, 2017), double-disk furrow openers with optimized rake angles for consistent depth in different soils, and seed tubes calibrated for velocity to achieve at least 85% spatial accuracy. This research thoroughly analyzed essential engineering characteristics to enhance a tractor-drawn multi-crop planter in accordance with Ethiopia's agricultural standards. Key parameters, such as planting depth, intra- and inter-row spacing, and planting density per hectare, are presented in Table 1.

Table 1- Optimal planting depth and inter- and intra-row spacing for maize seeds

Crop	Inter & intra row spacing (cm)	Depth (cm)	Plant per hectare	Location in Ethiopia	Reference
Maize	65 × 15	4-5	102,564	Metu, kombolcha	(Tolossa & Gizawu, 2024)
	65 × 25	5-6	61,538	North Mecha	(Getaneh, Belete, & Tana, 2016)
	75 × 25	5-6	53,334	EIAR, MARC	(Alemayehu *et al.*, 2017) (Bisrat, Laike, & Hae, 2015)
	75 × 20	4-6	66,667	Jimma and Illu-Ababora	(Muhidin, 2019)

Materials and Methods

Study location

The experiments were conducted at the Melkassa Agricultural Research Center of the Ethiopian Institute of Agricultural Research (EIAR). Located in the East Shewa Zone of the Oromia Region, at an altitude of 1,550 m above sea level, approximately 107 km from Addis Ababa, Ethiopia (Central Statistical Agency, 2021).

Determining maize seed physical properties

A representative sample of 100 seeds per variety was subjected to dimensional analysis using a digital caliper (resolution: ±0.01 mm) to measure axial dimensions (length *l*, width *w*, thickness *t*), as shown in Fig. **1**. These measurements were used to calculate derived parameters such as the geometric mean diameter, sphericity, and aspect ratio, which are essential for understanding seed behavior and optimizing planter components.

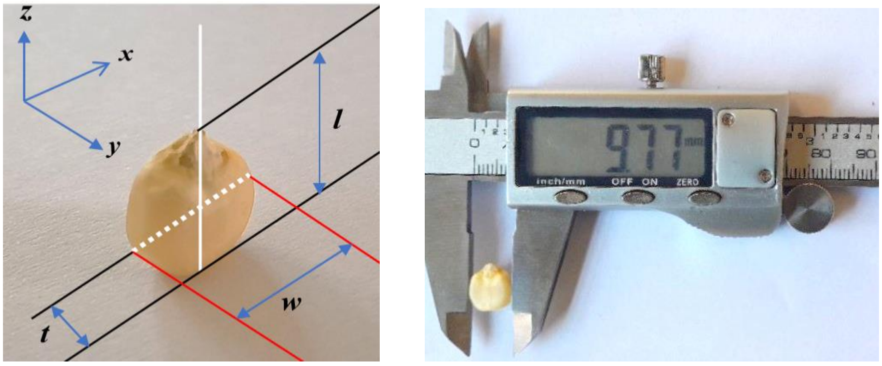

Fig. 1. Maize seed dimensions (length, width, and thickness), and digital caliper

Mathematical modeling of seed properties

The engineering properties of Maize seeds were calculated using established mathematical models. These properties are critical for understanding seed behavior and optimizing the design of a tractor-drawn multi-crop planter.

Mean diameters

Mean diameters are fundamental geometric parameters used to quantify seed size and uniformity, which are critical for designing and optimizing seed metering mechanisms, hoppers, and other planter components. The arithmetic mean diameter (D_a), calculated as the average of the three principal linear dimensions length (l), width (w), and thickness (t) is expressed in Equation (1) (Kawuyo, Aviara, Mari, & Ahmed, 2022; Zewdie, Olaniyan, Wako, Alemu, & Lema, 2024):

$$D_a = \frac{(l+w+t)}{3} \quad (1)$$

This parameter provides a simplified measure of seed size and ensures compatibility with diverse seed dimensions. Geometric mean diameter (D_g) is calculated as the cube root of the product of the three principal linear dimensions: length (l), width (w), and thickness (t) diameters, as stated in Equation (2) (Panwar, Swarnkar, Kumar, & Shukla, 2023; Soyoye *et al.*, 2018):

$$D_g = (l \cdot w \cdot t)^{\frac{1}{3}} \quad (2)$$

It is particularly useful for characterizing irregularly shaped seeds and optimizing seed flow, spacing, and interaction with planter components. Square mean diameter (D_s) which approximates the effective size of irregularly shaped seeds, is calculated using Equation (3) (Zewdie *et al.*, 2024):

$$D_s = \left((l \cdot w)+(l \cdot t)+(w \cdot t)\right)^{\frac{1}{3}} \quad (3)$$

where, l is the longest intercept, w is the longest intercept normal to l, t is the longest intercept normal to l and w. These parameters collectively ensure efficient seed handling and mechanical design for multi-crop planters.

Geometric properties

Geometric properties of seeds, such as projected area, surface area, and cross-sectional areas, are critical for analyzing seed orientation, flow dynamics, and mechanical interactions within planter components. The projected Area (A_p), which represents the two-dimensional area of a seed as seen from a specific angle, is calculated using Equation (4) (Liang *et al.*, 2021; Zewdie *et al.*, 2024):

$$A_p = \frac{\pi}{4}(l \cdot w) \quad (4)$$

This parameter is essential for understanding seed visibility in 2D planes and optimizing optical sorting systems. The surface area (A_s) representing the total outer surface area of the seed, is approximated using the geometric mean diameter and is expressed in Equation (5) (Liang *et al.*, 2021; Zewdie *et al.*, 2024):

$$A_s = \pi D_g^2 \quad (5)$$

It is crucial for predicting seed friction and drag in airflow systems. The transverse surface area (A_t), which represents the cross-sectional area perpendicular to the seed's major axis, is calculated using Equation (6) (Liang *et al.*, 2021; Zewdie *et al.*, 2024):

$$A_t = \frac{\pi}{4}(w \cdot t) \quad (6)$$

This parameter quantifies the seed's resistance in seed tubes and other mechanical components. Finally, the cross-Sectional area (A_{cs}), which represents the surface exposed when the seed is sliced along a specific plane, is given in Equation (7) (Liang *et al.*, 2021; Zewdie *et al.*, 2024):

$$A_{cs} = \frac{\pi}{4}(l \cdot t) \quad (7)$$

Shape indices

Shape indices are critical parameters for quantifying seed morphology, which directly influence seed flow, orientation, and mechanical interactions in planter components. The sphericity (Φ), which indicates how closely a seed resembles a sphere, is calculated using Equation (8) (Panwar *et al.*, 2023):

$$\Phi = \frac{(l \cdot w \cdot t)^{\frac{1}{3}}}{l} \quad (8)$$

A perfect sphere has a sphericity of 100 %, and this parameter is essential for optimizing seed flow in hoppers and tubes. The flakiness ratio (F_r), which measures seed flatness, is expressed in Equation (9) (Liang *et al.*, 2021; Panwar *et al.*, 2023; Zewdie *et al.*, 2024):

$$F_r = \left(\frac{t}{w}\right) 100\ \% \quad (9)$$

It helps prevent clogging in seed metering mechanisms. The aspect ratio (A_r), which quantifies the relative width-to-thickness proportion, is calculated using Equation (10) (Panwar *et al.*, 2023):

$$A_r = \left(\frac{w}{t}\right) 100\ \% \quad (10)$$

This parameter is crucial for assessing seed stability during orientation. The shape index (S_I), which provides an indication of the relative proportions of the seed's dimensions, is given in Equation (11) (Liang *et al.*, 2021; Zewdie *et al.*, 2024):

$$S_I = \frac{l}{\sqrt{w \cdot t}} \quad (11)$$

It is useful for analyzing shape irregularities and optimizing seed sorting systems. Finally, the roundness (R) which quantifies how closely the two-dimensional profile of a seed approximates a perfect circle and is calculated using Equation (12) (Ghabshyam, Raghunandan, Pankaj, & Kripanarayan, 2023; Zewdie *et al.*, 2024):

$$R = \frac{4\ A_p}{\pi\ l^2} \quad (12)$$

where, A_p is the projected area of the seed and l is the seed length.

Determination of angle of repose

The angle of repose for maize seeds was determined using a funnel setup, where seeds flowed freely onto a closed container to form a conical heap, following methodologies validated in seed flow studies (Huang, 2022; Kawuyo *et al.*, 2022). The apex height (h) and the base radius (r) of the formed cone were measured to calculate the angle of repose (θ), as mentioned in Equation (13) below (Zewdie *et al.*, 2024). Using the trigonometric relationship, the angle of repose is computed as:

$$\theta = \tan^{-1}\left(\frac{h}{r}\right) \quad (13)$$

Determination of the gravimetric parameters

The gravimetric properties of three maize varieties, including porosity, density ratio, and true and bulk density, were analyzed using toluene displacement and weight-volume methods as presented in Equations (14)-(18) below (Soyoye *et al.*, 2018; Zewdie *et al.*, 2024). Each variety's thousand-seed mass was determined using a digital balance with a precision of 0.001 g, complemented by supplementary tools like graduated cylinders, beakers, and stirring rods, as illustrated in Fig. **2** (Panwar *et al.*, 2023).

True density ρ_t (kg m^{-3}):

$$\rho_t = \frac{\text{Weight of the maize sample (g)}}{\text{Volume of toluene displaced (cm}^3\text{)}} \quad (14)$$

Bulk density ρ_b (kg m^{-3}):

$$\rho_b = \frac{\text{Weight of the maize sample (g)}}{\text{Volume of toluene displaced (cm}^3\text{)}} \quad (15)$$

Porosity ε (%):

$$\varepsilon = \left(1 - \frac{\rho_b}{\rho_t}\right) 100\ \% \quad (16)$$

Density ratio R_ρ (%):

$$R_\rho = \left(\frac{\rho_b}{\rho_t}\right) 100\ \% \qquad (17)$$

Thousand seed mass T_{sm} (g):

$$T_{sm} = \left(\frac{\sum_i^n \text{weight of Maize samples (g)}}{n}\right) 1000,\ i = 1, 2, 3\ldots, n \qquad (18)$$

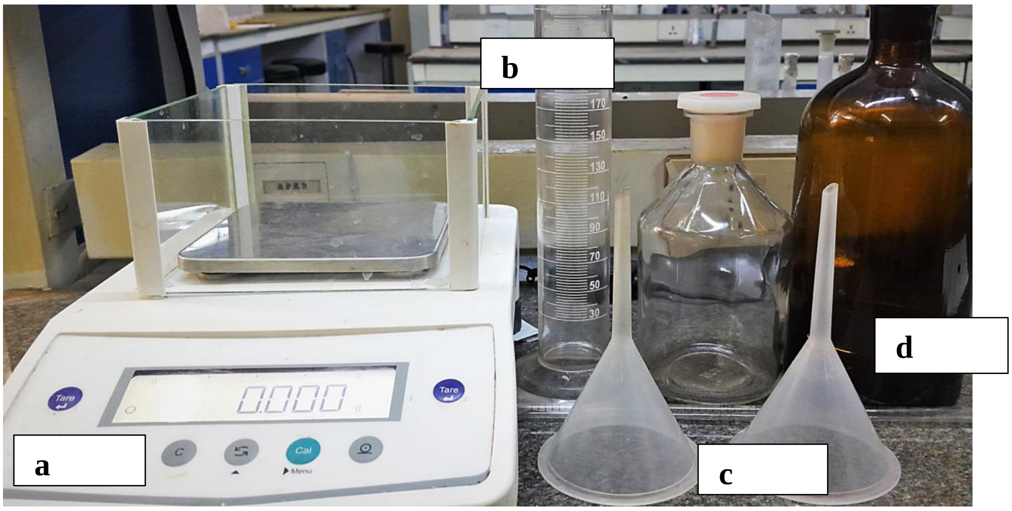

Fig. 2. Instruments for measuring gravimetric properties: (a) Digital balance, (b) 250 ml cylinder, (c) funnels, and (d) toluene; Photo taken during lab experiment by author

Statistical analysis

Statistical analysis was conducted using Minitab Statistical Software to compute key metrics, including means, standard deviations, and variance. These statistical parameters were used to validate the robustness of the data and inform the design and optimization of the multi-crop planter. The results ensured compatibility with the physical properties of maize seeds, enhancing the planter's efficiency and performance (Liang *et al*., 2021; Zewdie *et al*., 2024).

Results and Discussion

The physical properties of three maize varieties (CML-539, Melkassa 3, and Melkassa 6Q) were analyzed to optimize multi-crop planter design, as illustrated in the Table 3 and Table 4 below. Kernel dimensions varied significantly across varieties. Melkassa 3 and CML-539 exhibited the longest seed lengths of 10.99 ± 0.94 mm and 9.42 ± 8.06 mm, respectively, as shown in Table 2. This data highlights the need for adjustable seed plates with cell sizes that are 15-20% larger than the maximum seed dimensions to avoid any clogs, corroborating the findings of Liang *et al.* (2021) and Sinha (2021). The thickness, essential for effective singulation, remained consistent within the range of 4.824-4.984 mm. However, Melkassa 3 exhibited a higher variance of 0.892, which corresponds with Liang *et al.* (2021) findings that attribute this variability to the wear of seed plates.

Elongation ratios revealed critical design differences: Melkassa 3 and Melkassa 6Q exhibited higher thickness elongation (2.337± 0.514 and 2.334± 0.457, respectively) than CML-539 (1.997± 0.383), increasing tilt risks during free fall. This aligns with Panwar (2023b), which associates ratios greater than 2.0 with trajectory errors, highlighting the need for curved seed tubes. Mean diameters further guided hopper design: CML-539's geometric mean diameter (8.019± 2.736 mm, CV 34.12%) highlighted irregular shapes, contrasting with Melkassa 6Q's stability (8.198± 0.382 mm, CV 4.66%), and enabled more uniform flow dynamics, supporting conventional hopper design. Such variability aligns with Dinberu (2023), who noted similar challenges in Ethiopian maize, advocating steeper hopper angles (> 35°) for low-sphericity grains.

A Comparative analysis underscored Ethiopia's unique needs. Melkassa 3's width (8.913 mm) exceeded the 8.5 mm threshold for fluted rollers (Sharma & Dewangan, 2023), while CML-539's arithmetic mean diameter of 7.509 mm (Table 2), fell below the 8.0 mm benchmark, explaining reported spacing deviations (Omar *et al.*, 2023). Melkassa 6Q's sphericity mirrored commercial hybrids, suggesting compatibility with standardized planters. CML-539's irregular seeds (CV of 34.12%) require vibration-assisted metering to prevent mechanical damage, while Melkassa 3's high elongation ratio exceeding 2.3 demands air-assisted tubes to ensure stable seed orientation crucial for smallholder planting.

Table 2- ANOVA of physical properties and elongation indices in maize varieties

Parameter	Variety	Mean	SD	Variance	CV	Minimum	Maximum	Mean ± SD
l **(mm)**	CML-539	9.657	0.880	0.775	9.110	7.710	11.720	9.657±0.88
	M-3	10.994	0.941	0.886	8.560	7.410	13.160	10.994±0.941
	M-6Q	10.902	0.807	0.651	7.400	8.330	12.740	10.902±0.807
w (mm)	CML-539	8.616	0.656	0.4296	7.610	6.860	10.50	8.616±0.4296
	M-3	8.913	0.901	0.812	10.110	5.930	10.860	8.913±0.901
	M-6Q	8.869	0.861	0.742	9.710	7.130	10.790	8.869±0.861
t (mm)	CML-539	4.984	0.909	0.827	18.240	3.770	8.360	4.984±0.909
	M-3	4.893	0.945	0.892	19.310	3.220	9.150	4.893±0.945
	M-6Q	4.824	0.861	0.741	17.850	3.340	8.260	4.824±0.861
E_w	CML-539	1.118	0.166	0.028	14.870	0.104	1.416	1.118±0.166
	M-3	1.246	0.166	0.028	13.360	0.949	1.891	1.246±0.166
	M-6Q	1.241	0.154	0.024	12.430	0.833	1.582	1.241±0.154
E_t	CML-539	1.997	0.383	0.146	19.160	1.096	2.873	1.997±0.383
	M-3	2.337	0.514	0.264	21.990	0.953	3.460	2.337±0.514
	M-6Q	2.334	0.457	0.209	19.600	1.008	3.503	2.334±0.457
E_l	CML-539	1.908	1.283	1.647	67.240	0.940	14.203	1.908±1.283
	M-3	1.881	0.371	0.138	19.740	0.937	2.754	1.881±0.371
	M-6Q	1.896	0.371	0.138	19.570	0.924	2.723	1.896±0.371
D_a (mm)	CML-539	7.509	1.077	1.161	14.350	6.617	17.261	7.509±1.077
	M-3	7.776	0.514	0.264	6.610	6.366	8.956	7.776±0.514
	M-6Q	7.710	0.436	0.190	5.660	6.743	8.862	7.71±0.436
D_g (mm)	CML-539	8.019	2.736	7.485	34.120	7.030	34.803	8.019±2.736
	M-3	8.266	0.461	0.213	5.580	6.403	9.333	8.266±0.461
	M-6Q	8.198	0.382	0.146	4.660	7.307	9.180	8.198±0.382

l= length, w= width, t= thickness, E_w= Elongation at width, E_t =Elongation at thickness, E_l= Elongation at length, M-3= Melkassa 3, M-6Q= Melkassa 6Q, CML-539= Maize line 539, SD= Standard deviation, and CV= coefficient of variation

Table 3 highlights key geometric properties of maize varieties critical for planter optimization. The square mean diameter demonstrated only slight variation, ranging from 5.631 to 5.791 mm, with CML-539 showing higher variability (CV 10.74%) compared to Melkassa 3 (3.95%) and Melkassa 6Q (3.31%). This observation, shown in Table 3, is consistent with Dinberu (2023), who attributed this stability to the reliable performance of seed plates. Surface area and projected area revealed stark contrasts: CML-539 exhibited extreme variability, with a surface area coefficient of variation (CV) of 43.78% and a projected area CV of 82.22%. This variability underscores the irregular shape of the kernels, which poses a challenge for achieving uniform seed distribution in non-spherical grains. In contrast, Melkassa 6Q's lower surface and projected area variability (CV 11.27-11.96%) suggests suitability of this variety for the standardized metering systems (Kara, 2011; Masa, Tana, & Abdulatif, 2017).

Sphericity further differentiated varieties: CML-539 (78.31±13.09%) surpassed Melkassa 3 and Melkassa 6Q, indicating marginally better flowability (Table 3). However, its high sphericity variability (CV 16.72%) contrasts with Melkassa 6Q's uniformity (CV 9.37%), reinforcing the need for adaptive hopper designs, particularly because low-sphericity grains below 75% necessitate steeper angles to prevent clogging (Girma, Tola, & Olaniyan, 2024; Rabbani, Hossain, Asha, & Khan, 2016). Shape index and roundness underscored design risks: CML-539's higher shape index (1.485 ± 0.224) and roundness variability of 62.98% correlate with Panwar (2023b) findings of increased seed bridging in asymmetric grains, necessitating vibration-assisted hoppers.

CML-539's flakiness ratio of 57.73± 13.63 and cross-sectional area variability of 160.75% far exceed values reported by Sharma (2023) for commercial hybrids of flakiness < 50% and CV < 20%, demanding robust metering mechanisms. Conversely, Melkassa 3 and Melkassa 6Q's moderate aspect ratios align with Omar (2023) guidelines for gravity fed seed tubes but require air assistance to counter tilting caused by elongation. These results validate that Ethiopia's maize diversity, particularly CML-539's irregularity, demands planter components tailored to local varietals, such as adjustable cell sizes and aerated seed tubes, to achieve the precision required for smallholder farming systems.

Table 3- ANOVA of geometric properties of areas and shape indices for selected maize varieties

Parameter	Variety	Mean	SD	V	CV	Min	Max	Mean ± SD
D_s (mm)	CML-539	5.631	0.605	0.366	10.740	5.237	11.282	5.631±0.605
	M-3	5.791	0.229	0.052	3.950	4.963	6.277	5.791±0.229
	M-6Q	5.759	0.190	0.036	3.310	5.309	6.259	5.759±0.19
A_s (mm^2)	CML-539	180.760	79.130	6262.06	43.780	137.570	936.010	180.76±79.13
	M-3	190.765	25.157	632.873	13.190	127.299	251.992	190.765±25.157
	M-6Q	187.356	21.107	445.492	11.270	142.822	246.720	187.356±21.107
A_p (mm^2)	CML-539	71.170	58.510	3423.43	82.220	44.010	645.230	71.17±58.51
	M-3	77.025	10.442	109.026	13.560	34.511	102.524	77.025±10.442
	M-6Q	75.924	9.082	82.485	11.960	49.918	95.514	75.924±9.082
A_{ts}	CML-539	37.570	40.820	1665.92	108.63	22.530	437.130	37.57±40.82
	M-3	34.261	7.553	57.055	22.050	19.018	61.587	34.261±7.553
	M-6Q	33.490	6.047	36.566	18.060	22.235	50.847	33.49±6.047
A_{cs} (mm^2)	CML-539	169.00	271.60	73786.9	160.75	116.40	2854.00	169±271.6
	M-3	161.506	17.721	314.032	10.970	96.610	205.251	161.506±17.721
	M-6Q	158.703	14.757	217.778	9.300	125.791	198.562	158.703±14.757
Φ (%)	CML-539	78.310	13.090	171.470	16.720	63.570	186.810	78.31±13.09
	M-3	71.252	7.843	61.513	11.010	58.001	101.031	71.252±7.843
	M-6Q	71.107	6.659	44.348	9.370	59.272	96.844	71.107±6.659
F_r (%)	CML-539	57.730	13.630	185.680	23.600	7.040	106.360	57.73±13.63
	M-3	55.517	12.684	160.887	22.850	36.312	106.768	55.517±12.684
	M-6Q	55.113	12.840	164.876	23.300	36.726	108.257	55.113±12.84
A_r (%)	CML-539	190.800	128.300	16468.4	67.240	94.000	1420.300	190.8±128.3
	M-3	188.138	37.133	1378.87	19.740	93.661	275.389	188.138±37.133
	M-6Q	189.579	37.100	1376.41	19.570	92.373	272.286	189.579±37.1
S_i	CML-539	1.485	0.224	0.050	15.050	0.392	1.973	1.485±0.224
	M-3	1.698	0.261	0.068	15.380	0.985	2.264	1.698±0.261
	M-6Q	1.693	0.223	0.050	13.160	1.049	2.191	1.693±0.223
R	CML-539	1.139	0.717	0.515	62.980	0.815	8.168	1.139±0.717
	M-3	1.050	0.110	0.012	10.470	0.689	1.396	1.05±0.11
	M-6Q	1.054	0.120	0.014	11.370	0.803	1.321	1.054±0.12

M-3= Melkassa 3, M-6Q= Melkassa 6Q, CML-539= Maize line 539, SD= Standard deviation, CV= Coefficient of variation, V=Variance, D_s= Square Mean Diameter, A_s= Surface Area, A_p= Projected Area, A_{ts}= Transverse Surface Area, A_{cs}= Cross-Sectional Area, Φ= Sphericity, F_r= Flakiness Ratio, A_r= Aspect Ratio, S_i= Shape Index, and R= Roundness

The gravimetric properties essential for optimizing the design and functionality of maize planter hoppers and storage systems are presented in Table 4. True density showed a near-perfect negative correlation with thousand seed mass (-0.991) and a strong negative correlation with porosity (-0.904), while bulk density positively correlated with flowability metrics. Melkassa 6Q's optimal combination of high bulk density (811.62 kg m^{-3}), low porosity (36.99%), and favorable density ratio (0.630) suggests superior flow characteristics compared to CML-539's high-porosity grains (49.30%), which require greater aeration power (Liang *et al.*, 2021; Panwar *et al.*, 2023; Soyoye *et al.*, 2018).

Thousand-seed mass varied significantly among varieties, with Melkassa 6Q (297.06 g) and Melkassa 3 (290.84 g) exceeding CML-539 (224.11 g) by 32.5% (Table 4). This highlights the impact of varietal mass loading on seed metering mechanisms, as higher thousand seed mass of greater than 280 g increases torque and drive power requirements, consistent with Dinberu (2023) and Panwar (2023b). Melkassa 6Q's steeper angle of repose (31°) aligns with its high bulk density and correlates with increased inter-kernel friction, necessitating steeper hopper angles, while Melkassa 3's smoother grains (26° repose) may require flow restrictors. These findings, consistent with Liang *et al.* (2021) and Panwar (2023b), demonstrate how correlated physical properties directly inform equipment specifications for different maize varieties.

Table 4- Statistical description of gravimetric properties of maize varieties

Variable	T_{sm} (kg)	ρ_t (kg m^{-3})	ρ_b (kg m^{-3})	ε (%)	R_ρ	ϑ (^{0})
CML-539	224.110	1482.461*	751.548	49.304*	0.507	28
M-3	290.840*	1275.386	725.715	43.098	0.569	26*
M-6Q	297.060*	1288.146	811.621*	36.993	0.630	31*
Mean	270.670	1348.660	762.962	43.132	0.569	28.333
SD	40.442	116.047	44.076	6.156	0.062	2.517
Variance	1635.550	13466.900	1942.660	37.891	0.004	6.333
CV	14.940	8.600	5.780	14.270	10.820	8.88
Minimum	224.110	1275.390	725.715	36.993	0.507	26
Maximum	297.060	1482.460	811.621	49.304	0.630	31
M± SD	270.67±40.44	1348.6±116.047	762.96±44.076	43.13±6.156	0.57±0.062	28.34±2.517

* Significant at $p < 0.05$, M-3 = Melkassa 3, M-6Q = Melkassa 6Q, CML-539 = Maize line 539, ρ_b= Bulk density, ρ_t = True density, ε = Porosity, T_{sm} = Thousand seed mass, CV = coefficient of variance, M = mean, SD = standard deviation, ϑ = Angle of repose, and R_ρ= Density Ratio.

Table 5 provides a comprehensive overview of the physical characteristics of different maize varieties, focusing on geometric parameters, shape indices, and gravimetric properties. This information is vital for the optimal performance of adaptive multi-crop planters, as it directly impacts mechanical reliability, reduces seed damage and variation, and ensures precise depth control for improved spacing accuracy. This integrated system enhances seed placement precision while simultaneously improving input use efficiency and operational reliability across diverse seed morphologies and field conditions, demonstrating robust improvements in both agronomic outcomes and field productivity.

Table 5- Maize physical properties and their implications on multi-crop planter design optimization

Parameter/seed variety	Design requirement	Engineering implication
Large kernel size and thickness (M-3); Table 2	Seed metering plate: requires a length ≥ 12 mm and depth ≥ 8.5 mm (Liang *et al.*, 2021)	Reduces clogging and increases singulation accuracy (Jyotirmay *et al.*, 2024) and ensures uniform dispersal and minimal seed waste

		(Kimmelshue, Goggi, & Kenneth, 2022).
High elongation ratio (M-3 and M-6Q); Table 2	Seed tube: helical baffles (30° pitch), diameter ≥ 16 mm (Rabbani *et al.*, 2016)	Ensures vertical drop, optimal planting depth, and reduces germination failure (Omar *et al.*, 2023; Soyoye *et al.*, 2018)
Low sphericity and high shape index (CML-539); Table 2 and Table 3	Hopper: adjustable orifice (15–20 mm) (Kimmelshue *et al.*, 2022)	Reduces clogging (85%) (Panwar *et al.*, 2023) and flow disruptions (CV < 8%) for consistent seed flow and minimal damage (Liang *et al.*, 2021)
High geometric mean diameter (CML-539); Table 3	Hopper wall: slope angle ≥ 45°, optional agitator (Balanian, Karparvarfard, Mousavi Khaneghah, Raoufat, & Nejadian, 2021)	Prevents bridging, improving seed placement and spacing uniformity (Meseret, 2024; Woldesenbet, 2014)
High flakiness and irregular geometry (CML-539); Table 3	Delivery system: seed delivery ranges 15-20 RPM (Pandey & Sawant, 2023)	Prevents bridging, reduces seed damage, and ensures smooth, efficient seed flow (Liang *et al.*, 2021)
Bulk density variability (CML-539, M-3, and M-6Q); Table 4	Hopper: sloped walls ≥ 45°, internal agitator (3-5 RPM) (Soyoye *et al.*, 2018)	Ensures continuous mass flow (CV < 10%) and minimizes refills (≤ 2/ha) (Balanian *et al.*, 2021; Girma *et al.*, 2024)
Medium length kernels (CML-539); Table 2 and Table 3	Singulation mechanism (Liang *et al.*, 2021; Bhiman, Patel, Yaduvanshi, & Gupta, 2019; Van Loon, Krupnik, López-Gómez, Timsina, & Govaerts, 2020)	Maintains singulation accuracy (>90%) for consistent seed spacing and reduced seed waste (Patel, Bhimani, Yduvanshi, & Gupta, 2024)

M-3= Melkassa 3, M-6Q= Melkassa 6Q, CML-539= Maize line 539, RPM= revolution per minute, CV= coefficient of variation

Conclusion

This study analyzes three maize varieties (CML-539, Melkassa 3, and Melkassa 6Q) to establish quantitative relationships between seed physical properties and planter design parameters for adaptive multi-crop systems. The distinct physical properties of each variety dictate specific design requirements: CML-539's irregular dimensions (9.42 mm length, 49.30% porosity) and steep repose angle (31°) necessitate aerated seed tubes, vibration-assisted hoppers, and enlarged seed plates (15-20% oversizing), while Melkassa 6Q's uniform sphericity (71.11 ± 6.66%), high bulk density (811.62 kg m^{-3}), and lower repose angle (26°) enable simpler gravity-fed systems. Melkassa 3's intermediate characteristics, specifically an elongation ratio > 2.3 and density variation of 19.31%, require adjustable furrow openers with 25-30° rake angles to maintain consistent sowing depth. These findings demonstrate that varietal specific modifications, particularly for seed metering, hopper design, and depth control, are essential for optimizing planting efficiency and seed integrity. The results demonstrate a seed-property-driven framework for modular planters that addresses diverse maize varieties while meeting standard agronomic requirements of 75 cm row spacing, and 4-7 cm planting depth, offering a scalable precision agriculture solution. Future field tests and real-time sensing could enhance this seed-specific planter design for precision agriculture.

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References

1. Alemayehu, A., Tamado, T., Nigussie, D., Yigzaw, D., Kinde, T., & Wortmann, C. S. (2017). Maize common bean intercropping to optimize maize-based crop production. *The Journal of Agricultural Science*, *155*(7), 1124-1136. https://doi.org/10.1017/S0021859617000193
2. Ayele, S. (2022). The resurgence of agricultural mechanisation in Ethiopia: rhetoric or real commitment? *Journal of Peasant Studies*, *49*(1), 137-157. https://doi.org/10.1080/03066150.2020.1847091
3. Balanian, H., Karparvarfard, S. H., Mousavi Khanghah, A., Raoufat, M. H., & Azimi-Nejadian, H. (2021). Prediction of Seed Flow Rate of a Multi-Slot Rotor Feeding Device of a Corn Planter. *Journal of Agricultural Machinery*, *11*(1), 17-27. https://doi.org/10.22067/jam.v11i1.79992
4. Bhiman, J., Patel, S., Yaduvanshi, B., & Gupta, P. (2019). Optimization of the operational parameters of a picking-type pneumatic planter using response surface methodology. *Journal of AgriSearch*, *6*(1), 38-43. https://doi.org/10.21921/jas.v6i1.14919
5. Bisrat, G., Laike, K, A., & Hae, K. K. (2015). Evaluation of Conservation Tillage Techniques for Maize Production in Ethiopia. *Ethiopian Journal of Agricultural Sciences*, *25*(2), 47-58.
6. Central Statistical Agency. (2021). Farm Management Practices Agricaltural Sample Survey 2020/21. In *Central Statistical Agency: Vol. III* (Issue 12). https://www.statsethiopia.gov.et
7. Dinberu, A., & Megersa, M. (2023). Effect of Inter and Intra Row Spacing on Growth , Yield and Yield Components of Sorghum (*Sorghum bicolor* (L.) Moench) at Assosa District , Western Ethiopia. *American Journal of Plant Biology*, *8*(1), 20-24. https://doi.org/10.11648/j.ajpb.20230801.14
8. FAO. (2023). *Standard operating procedure for soil bulk density; Cylinder method*. Food and Agriculture Organization of the United Nations. https://doi.org/10.4060/cc7568en
9. Getaneh, L., Belete, K., & Tana, T. (2016). Growth and Productivity of Maize (*Zea mays* L.) as Influenced by Inter- and Intra-Row Spacing in Kombolcha, Eastern Ethiopia. *Journal of Biology, Agriculture and Healthcare*, *6*(13), 90-101.
10. Ghabshyam, P., Raghunandan, S., Pankaj, G., & Kripanarayan, S. (2023). A review of methodologies and influencing factors in planter performance evaluation for higher maize yield. *The Pharma Innovation Journal*, *12*(12), 1465-1471. www.thepharmajournal.com
11. Girma, O., Tola, S., & Olaniyan, A. (2024). Design and development of a tractor-drawn multi-row garlic planter. *Agricultural Engineering International: CIGR Journal*, *26*(2), 34-56.
12. Huang. (2022). Measurement of physical properties of sorghum seeds and calibration of discrete element modeling parameters. *Agriculture (Switzerland)*, *12*(5), 2-19. https://doi.org/10.3390/agriculture12050681
13. Jyotirmay, M., Prem, S. T., Krishna, P. S., Balaji, M. N., Jagjeet, Singh, A., & Ramesh, K. S. (2024). Flexible orifice seed metering plate to address variability in seed shape, size and orientation enhances field performance of a pneumatic planter. *Discover Applied Sciences*,

6(11). https://doi.org/10.1007/s42452-024-06275-5

14. Kara, B. (2011). Effect of seed size and shape on grain yield and some ear characteristics of maize. *Research on Crops*, *12*(3), 680-685.
15. Kawuyo, U. A., Aviara, N. A., Mari, H. H., & Ahmed, B. M. (2022). Physical properties of four varieties of sorghum grain at different moisture contents. *Arid Zone Journal of Engineering, Technology & Environment*, *18*(1), 159-168. www.azojete.com.ng
16. Kebede, M. B. (2019). Effect of Inter and Intra Row Spacing on Growth , Yield Components and Yield of Hybrid Maize (*Zea mays* L.) Varieties at Haramaya , Eastern Ethiopia. *American Journal of Plant Sciences*, *10*(7), 1548-1564. https://doi.org/10.4236/ajps.2019.109110
17. Kimmelshue, C. L., Goggi, S., & Moore, K. J. (2022). Seed Size, Planting Depth, and a Perennial Groundcover System Effect on Corn Emergence and Grain Yield. *Agronomy*, *12*(2). https://doi.org/10.3390/agronomy12020437
18. Liang, G., Chi, B., Li, N., Chen, W., Qin, W., Wu, X., & Huang, X. (2021). Evaluating agronomic factors for maize production in a semi-arid Loess Plateau. *Agronomy Journal*, *113*(6), 5157-5169. https://doi.org/10.1002/agj2.20818
19. Masa, M., Tana, T., & Abdulatif, A. (2017). Effect of Plant Spacing on Yield and Yield Related Traits of Common Bean Varieties at Areka ,Southern Ethiopia. *Journal of Plant Biology & Soil Healt*, *4*(2).
20. Meseret, A. (2024). Design, Fabrication and Performance Evaluation of Two Row Animal Drawn Maize Planter with Fertilizer Applicator. *Ethiopian Institute of Agricultural Research*, *5*(2), 153-166. https://doi.org/10.46592/turkager.1487496
21. Muhidin, B. (2019). Effect of Inter-and Intra-Row Spacing on Yield and Yield Components of Maize QPM Hybrid, BHQPY545 in Southwestern Ethiopia Muhidin. *International Journal of Research Studies in Agricultural Sciences*, *6*(10), 19-26. https://doi.org/10.20431/2454-6224.0703003
22. Omar, S., Abd Ghani, R., Khalid, N., Jolánkai, M., Tarnawa, Á., Percze, A., Mikó, P. P., & Kende, Z. (2023). Effects of Seed Quality and Hybrid Type on Maize Germination and Yield in Hungary. *Agriculture*, *13*(9), 2-14. https://doi.org/10.3390/agriculture13091836
23. Pandey, H. S., & Sawant, C. P. (2023). Design and Development of a Seed Metering Mechanism for Ginger Planter. *Journal of Scientific and Industrial Research*, *82*(10), 1071-1080. https://doi.org/10.56042/jsir.v82i10.225
24. Panwar, G., Swarnkar, R., Kumar, N., & Shukla, K. (2023). Evaluation of physical properties of maize and pigeonpea seeds for seed metering mechanism. *Journal of Experimental Agriculture International*, *45*(12), 89-97. https://doi.org/10.9734/jeai/2023/v45i122269
25. Pascual, K. S., Rafael, M. L., Remocal, A. T., & Regalado, M. J. C. (2021). Development and evaluation of four-wheel tractor-attached multi-crop planter for mechanized seeding of maize in the Philippines. *CIGR Journal*, *23*(3), 143.
26. Patel, S. K., Bhimani, J. B., Yduvanshi, B. K., & Gupta, P. (2024). Radish (*Raphanus raphanistrum* subsp. sativus) Seed Planter Parameters Optimization using Response Surface Methodology. *Journal of Scientific and Industrial Research*, *83*(5), 483-489. https://doi.org/10.56042/jsir.v83i5.2823
27. Rabbani, M. A., Hossain, M. M., Asha, J. F., & Khan, N. A. (2016). Design and development of a low cost planter for maize establishment. *Journal of Science Technology and Environment Informatics*, *4*(1), 270-279. https://doi.org/10.18801/jstei.040116.30
28. Seyoum, A., Paul, D., & Sinafikeh, A. (2013). Crop production in Ethiopia: Regional patterns and trends. *Food and Agriculture in Ethiopia: Progress and Policy Challenges*, *9780812208*, 53-83. https://doi.org/10.9783/9780812208610.53
29. Shah, K., Alam, M. S., Nasir, F. E., Qadir, M. O., Haq, I. U., & Tahir Khan, M. (2022). Design and performance evaluation of a novel variable rate multi-crop seed metering unit for precision

agriculture. *IEEE Access*, *10*(September), 133152-133163. https://doi.org/10.1109/ACCESS.2022.3231136

30. Sharma, P. T., & Dewangan, K. N. (2023). Design and development of a vertical plate precision seed metering device with positive seed knockout mechanism. *Agricultural Engineering International: CIGR Journal*, *25*(1), 27-42.
31. Singh, S., Sahoo, D. C., & Bisht, J. K. (2017). Development and performance evaluation of manual/bullock operated multicrop planter for hilly region. *Agricultural Engineering International: CIGR Journal*, *19*(1), 81-86.
32. Sinha, A. K., Sinha, A. K., Sharma, S., Khar, S., Gupta, V., Parkash, S., Mishra, S. K., & Gupta, S. (2021). Maize sowing with multi crop planter under rain fed conditions in Rajouri District of J & K proved beneficial. *Journal of Krishi Vigyan*, *9*(2), 120-123. https://doi.org/10.5958/2349-4433.2021.00023.4
33. Soyoye, B. O., Ademosun, O. C., & Agbetoye, L. A. S. (2018). Determination of some physical and mechanical properties of soybean and maize in relation to planter design. *Agricultural Engineering International: CIGR Journal*, *20*(1), 81-89.
34. Theodrose, S., Kindie, T., Mezegebu, G., Nigussie, D., & Mengistu, K. (2024). Calibration and Evaluation of CERES-Maize and CROPGRO-Dry Bean Crop Simulation Models of the DSSAT in the Great Rift Valley Region of Ethiopia. *International Journal of Applied Agricultural Sciences*, *10*(4), 149-156. https://doi.org/10.11648/j.ijaas.20241004.11
35. Tolossa, A., & Gizawu, T. (2024). Effect of Intra and Inter Row Spacing on Yield, Yield Components and Growth Parameter of Hybrid Maize at Mettu, South Western Ethiopia. *Journal of Environment and Earth Science*, *10*(1), 16-19. https://doi.org/10.7176/JEES/10-1-03
36. Van Loon, J., Krupnik, T. J., López-Gómez, J. A., Timsina, J., & Govaerts, B. (2020). A standard methodology for evaluation of mechanical maize seed meters for smallholder farmers comparing devices from Latin America, Sub-Saharan Africa, and Asia. *Agronomy*, *10*(8). https://doi.org/10.3390/agronomy10081091
37. Woldesenbet, M. (2014). Effect of Spacing on the Growth Parameters of Common Bean at Keker , Southwestern Ethiopia. *International Journal of Research in Agricultural Sciences*, *1*(5), 15-18.
38. Zewdie, B., Olaniyan, A. M., Wako, A., Alemu, D., & Lema, T. (2024). Engineering properties of common bean in perspective of physical and frictional parameters for threshing machine design. *INMATEH Agricultural Engineering*, *73*(2), 771-783. https://doi.org/10.35633/inmateh-73-65

ویژگی‌های فیزیکی ارقام ذرت اتیوپی برای طراحی دستگاه کاشت سازگار با چند محصول

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چکیده

تولید ذرت توسط خرده‌مالکان در کشورهای جنوب صحرای آفریقا، که برای تامین امنیت غذایی منطقه‌ای بسیار مهم است، با معضلات مداوم عملکرد دست و پنجه نرم می‌کند که ناشی از شیوه‌های کاشت پرزحمت و ضعف در مکانیزاسیون است، به‌طوری‌که مطابق با ویژگی‌های ارقام گیاهی بومی طراحی نشده است. این مطالعه سه رقم ذرت (CML-539، Melkassa 3 و Melkassa 6Q) را برای توسعه پارامترهای طراحی برای کاشت‌کننده‌های سازگار با چند محصول توصیف می‌کند. برای ۱۰۰ دانه از هر رقم، خواص هندسی شامل طول، عرض و ضخامت با استفاده از کولیس‌های دیجیتال اندازه‌گیری شد. تجزیه و تحلیل برای کشیدگی، قطرهای میانگین هندسی و حسابی، مساحت سطح، مساحت تصویر شده، سطح مقطع عرضی، کرویت، ضریب فرورفتگی، نسبت ابعاد، شاخص شکل و گردی انجام شد. خواص وزنی شامل چگالی حجمی و واقعی، تخلخل، جرم هزار دانه و زاویه استقرار به‌طور سیستماتیک برای بهینه‌سازی مکانیسم‌های جابه‌جایی بذر در طراحی دستگاه کاشت تجزیه و تحلیل شدند. تجزیه و تحلیل خواص فیزیکی، الزامات متمایزی را برای هر رقم نشان داد: مورفولوژی نامنظم CML-539 (طول ۹/۴۲ میلی‌متر، تخلخل ۴۹/۳۰٪) نیاز به سیستم‌های اندازه‌گیری ارتعاشی و هوادهی را نشان می‌دهد؛ خواص یکنواخت Melkassa 6Q (کرویت ۶/۶۶٪ ± ۷۱/۱۱، چگالی حجمی ۸۱۱/۶۲ کیلوگرم بر متر مکعب) امکان استفاده از مکانیسم‌های تغذیه گرانشی را فراهم می‌کند؛ و ویژگی‌های متوسط Melkassa 3 با نسبت کشیدگی بیش از ۲/۳ و تغییر چگالی ۱۹/۳۱٪ نیاز به شیاربازکن‌های قابل‌تنظیم با زاویه شیب ۲۵ تا ۳۰ درجه را مشخص می‌کند. تغییرپذیری هندسی، پیاده‌سازی راه‌حل‌های تطبیقی، مانند لوله‌های بذر انحنادار و شیاربازکن‌های قابل‌تنظیم را برای جلوگیری موثر از کج شدن و پشته‌سازی ضروری می‌سازد. سیستم کاشت مدولار حاصل، شامل اندازه‌گیری حساس به رطوبت، اندازه‌گیری تطبیقی سلول‌ها و هوادهی، با استانداردهای کشاورزی–اکولوژیکی اتیوپی مبنی بر فاصله ردیف ۷۵ سانتی‌متر و عمق کاشت ۴ تا ۷ سانتی‌متر مطابقت دارد. این چارچوب، یک مدل مقیاس‌پذیر و پایدار برای مکانیزاسیون دقیق خرده‌مالکان را ارائه می‌دهد و قابل‌انتقال به سیستم‌های جهانی تولید ذرت است.

واژه‌های کلیدی: خواص فیزیکی، زاویه استقرار، کاشت چند محصولی، کرویت، واریته ذرت

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