Original Research Article

Physical and Engineering properties of Fertilizers Relevant to Designing optimal of Site-Specific Maize Seed and Fertilizer Applicators and the Role of Physical and Engineering Properties

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Abstract

Maize seed dimensions varied significantly across varieties, with mean length ranging from 8.24 mm (Kaveri Hybrid 25K55) to 12.42 mm (PUSA HQPM-5). Geometric mean diameter (GMD) and sphericity, indicators of seed shape, ranged from 7.00-7.53 mm and 0.64-0.77 mm, respectively. Coefficients of variation for GMD and sphericity were consistently below 10%. The angle of repose, reflecting flow behavior, ranged from 37.01˚ (PUSA HQPM-5) to 38.53˚ (Kaveri Hybrid 25K55). The coefficient of static friction, highest for wood (0.59) and lowest for mild steel (0.53), suggests mild steel as a preferred material for seed hopper construction. Bulk density of maize varieties ranged from 727 to 811 kg/m³, with PUSA VIVEK exhibiting the lowest (754 kg/m³) and PUSA HQPM-5 the highest (808 kg/m³). True density varied from 1053 to 1192 kg/m³, with PUSA VIVEK showing the lowest and PUSA HQPM-5 the highest values. Coefficients of variation for both bulk and true densities were consistently below 3%. Fertilizer particle dimensions also varied, with mean length, breadth, and thickness ranging from 4.01-4.34 mm, 3.56-3.73 mm, and 2.69-3.43 mm, respectively. DAP exhibited the highest length (5.04 mm), NPK fertilizer complex the highest breadth (4.34 mm), and NPK fertilizer complex the highest thickness (3.75 mm). GMD ranged from 3.47-3.63 mm across all fertilizers, while sphericity ranged from 0.81 (DAP) to 0.91 (NPK complex). Bulk density of fertilizers varied from 753.77±11.40 kg/m³ (Urea) to 1236.02±12.36 kg/m³ (NPK fertilizerComplex). True density of DAP was lower (1379.76±24.9 kg/m³) compared to SSP (1950±21.97 kg/m³). The angle of repose ranged from 35.29±0.58˚ (DAP) to 33.32±0.68˚ (SSP), with field-used NPK fertilizer showing the highest bulk density (1236.02±13.62 kg/m³) and an angle of repose of 32.46±1.42˚. These findings provide valuable insights into the physical properties of maize varieties and fertilizer varieties, with implications for seed and fertilizer handling, storage, and agricultural machinery design.

Keywords*: Physical Properties;* site specific seed cum fertilizer applicator; Sphericity; NPK fertilizercomplex;

Introduction

In modern agriculture, optimizing seed and fertilizer Applicationdeployment has emerged as a critical practice for sustainable crop cultivation. Precision agriculture has revolutionized farming methodologies by providing tailored solutions that enhance resource utilization efficiency while minimizing ecological impact. At the core of this advancement lies the development of site-specific seed and fertilizer dispensing mechanisms, reliant on a profound comprehension of the physical and engineering attributes of fertilizers. Maize (*Zea mays* L.), a globally significant staple crop crucial for food security, animal husbandry, and diverse industrial applications, attained a worldwide production of approximately 1.21 billion metric tonnes (MT) in 2021, cultivated over an area of about 205.87 million hectares (ha). Notably, the United States leads in maize production, contributing around 32% of the global yield, followed by China (23%), Brazil (7%), Argentina (5%), and Ukraine (3%). These five nations collectively account for 70% of the global maize output. India, ranking 4th in maize acreage and 6th in production globally, contributes approximately 3.96% and 2.13% respectively to the global yield (FICCI Maize summit, 2023). India's burgeoning population has propelled a substantial demand for food grain production, resulting in a record-high output of 305.44 million tonnes in 2020-21 (MoA & FW, 2020-21). This surge is attributable to the adoption of high-yielding cultivars responsive to inputs and the widespread utilization of chemical fertilizers, notably nitrogenous (N) fertilizers. However, excessive nitrogen application can induce soil acidification, exacerbating soil degradation and adversely impacting crop productivity (Guo *et al.,* 2010; Schroder *et al.,* 2011). India holds the second position globally both as a producer and consumer of fertilizers, trailing only China. The consumption rate of chemical fertilizers witnessed a notable uptick of 16% from 2015-16 to 2020-21 (Ministry of Chemicals and Fertilizers, GOI, 2020-21). Import dependency is particularly pronounced for urea, with the country importing a significant portion of its annual consumption. Moreover, approximately 60% of India's diammonium phosphate (DAP) consumption is met through imports. The widespread application of agricultural chemicals has led to environmental contamination, soil deterioration, and the accumulation of harmful residues on agricultural produce. In developed nations, where high-yielding varieties and extensive chemical applications are prevalent, agricultural research focuses on mitigating contamination levels while ensuring optimal yields (Talha *et al.,* 2012; Iida *et al.,* 2001; Swisher *et al.,* 2002). Accurate delivery of granular fertilizers at prescribed rates is essential to achieve desired agricultural outcomes.

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MATERIALS AND METHODS

~~The f~~Field experiment on nutrient dynamics was conducted in the year 2022-23 and 2023-24 at the research farm of ~~the~~ Indian Council of Agricultural Research (ICAR)-Indian Agricultural Research Institute (IARI) in New Delhi. ~~The l~~Location of the farm is at 28º38´15´´ N latitude, 77º09´10´´ E longitude, and an elevation of 228.6 meters above mean sea level (Fig 1).

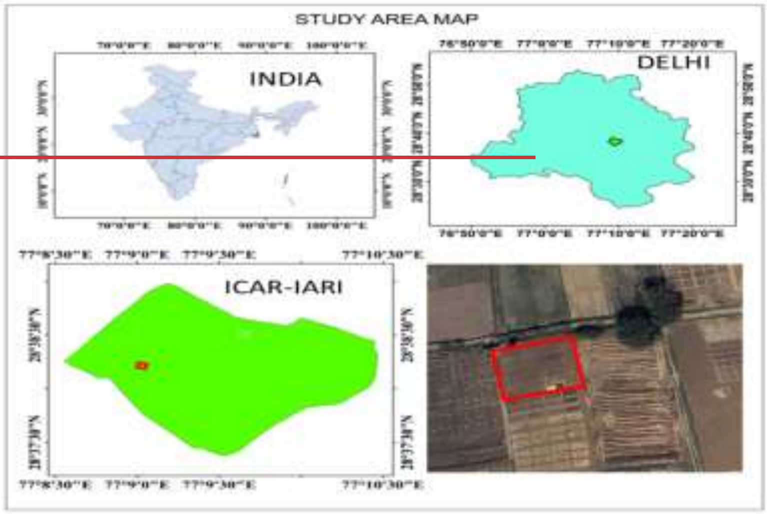

Fig 1: Study area location map

Determination of physical and engineering properties of maize seed and granular fertilizer

The physical and engineering properties of maize seeds and granular fertilizer, such as size, shape, bulk density, angle of repose, and thousand-seed ~~grain~~ weight, were analyzed to aim~~ssist~~ in the development of a seed cum fertilizer applicator. ~~The~~ M~~m~~easurement of the seeds affects the design parameters of the seed metering mechanism, such as ~~the~~ length, depth, and number of seeds required per groove surface.

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Fig 2: Varieties of maize **(a)** Kaveri Hybrid 25K55 **(b)** Pusa Vivek **(c)** PUSA HQPM-5

These properties are crucial for allowing a continuous and obstruction-free flow of maize seeds and granular fertilizer through the metering groove. The bulk density and true density were calculated for seed cum fertilizer hopper volume and thickness. Three predominant varieties of maize seeds suc as Kaveri Hybrid 25K55, Pusa Vivek and PUSA HQPM-5, were categorized into ~~respectively representing~~ short, medium and large seeds were selected for study of physical and engineering properties (Fig 2). The physical properties were determined as following:

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Size and shape

The size and shape of maize seeds were the two important factors that helped in deciding shape and size of seed metering unit. Maize seeds had a three-dimensional shape that could be measured as the length, breadth and thickness and were categorized as short, medium and large. Geometric mean size of maize seedgrain affects the groove length and depth of the rotor in seed metering plate. A sample of 100 seeds of each variety was taken and the geometric mean was determined by the following relationship in equation (1).

$$\text{Geometrical mean} = \sqrt[3]{(l \times b \times t)} \qquad (1)$$

Where, l = length of maize, mm b = breadth of maize, mm t = thickness of maize, mm Sphericity(ø) affects the uniform free flow of maize grains from the metering plate groove surface. To define the shape of seeds, sphericity (ø) was calculated by utilizing the values of physical dimensions of seed using the following relationship in equation (2).

$$\text{Sphericity} = \frac{\sqrt[3]{(l \times b \times t)}}{l} \qquad (2)$$

Bulk density

Bulk density and True density values are used to design the seed hopper. Bulk density was determined using a cube of size 10x10x10 cm. The cube was filled with maize seedgrains without any compaction, and later on the seeds filling the cube were weighed. The bulk density was determined as the ratio of the weight of the seeds and the volume of cube as following relationship in equation (3):

$$\rho = \frac{W}{V} \qquad (3)$$

Where,

ρ = Bulk density, g/cc
W = weight of the maize, g, and
V = Volume of the sample, cc

Angle of repose

The angle of repose was determined by using equipment and the following equation (4).

$$\theta = tan^{-1}\left(\frac{2H}{D}\right) \qquad (4)$$

Where,

θ = angle of repose, deg
H = height of the heap, cm, and
D = diameter of the base plate, cm

True density

True density of maize seeds and fertilizer was determined using the Hexane displacement method (Mohsenin, 1986). The volume and true density were assessed for 10 samples of the seeds, with the weight of each sample wasbeing recorded. Each sample was immersed in a jar filled with hexane liquid, and the volume of displaced hexane was measured for each sample. The true density was then calculated as the ratio of the weight of each sample to its corresponding volume. Observations were collected for 10 samples, and the average value was taken as the characteristic density value of the seeds.

Coefficient of static friction

The inclined plane method was utilized to measure the coefficient of static friction for maize seeds and granular fertilizer. The procedure involved placing the material on a horizontal surface and gradually increasing the slope. The angle (α) at which the seeds were on the verge of sliding was recorded. The coefficient of static friction was then determined as tanα. This process was repeated 20 times, and the mean value was calculated. The experiment was replicated with various samples of maize seeds and granular fertilizer.

Thousand-seed weight (1000- seed weight)

The factor for deciding the desired seed rate of maize was one thousand seed ~~grain~~ weight. Five samples each of one thousand seeds were randomly selected from the seed samples of different varieties and weighed using an electronic balance and mean weight was determined and recorded.

RESULTS AND DISCUSSION

Physical and engineering properties of maize seeds

The design of the seed metering mechanism considered the physical and engineering properties of maize seeds (Kaveri Hybrid 25K55, PUSA VIVEK, and PUSA HQPM-5). These characteristics included size, shape, bulk density, angle of repose, and coefficient of static friction. During the analysis, the following observations were made:

Size

Studies of maize varieties (including Kaveri Hybrid 25K55, PUSA VIVEK, and PUSA HQPM-5) revealed variations in physical dimensions. Mean seed length ranged from 9.32-12.42 mm, mean breadth from 7.88-8.72 mm, and mean thickness from 4.26-5.71 mm. Kaveri Hybrid 25K55 had the shortest mean seed length (8.24 mm) while PUSA HQPM-5 had the longest mean length (12.42 mm) (Fig 3). These measurements are essential for designing seed metering mechanisms. Additional details on maize seed dimensions ~~ha~~is shown ~~given~~ in Table 1.

Table 1 Variations in dimensions of maize seeds

Variety	Descriptive Statistics	Length (mm)	Width (mm)	Thickness (mm)
PUSA HQPM-5	Range	10.96-14.25	7.26-9.02	3.91-5.98
	Mean	12.42	8.16	4.53
	CV (%)	7.05	6.18	13.81
Kaveri Hybrid 25K55	Range	8.57-10.65	6.98-9.87	5.36-6.51
	Mean	9.32	8.72	5.71
	CV (%)	7.61	9.92	13.86
PUSA VIVEK	Range	8.24-12.62	7.02-9.12	3.91-5.24

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	Mean	10.27	7.88	4.26
	CV (%)	8.93	8.67	9.58

(CV= coefficient of variation)

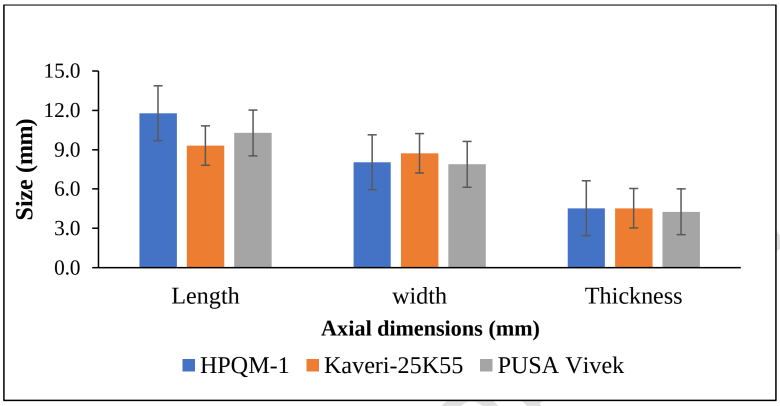

Fig 3: Size dimensions of maize seeds

Shape

The shape characteristics of maize seeds were assessed through the analysis of their geometric mean diameter (GMD) and sphericity. The GMD ranged from 7.00 to 7.53 mm, while sphericity varied between 0.64 and 0.77 mm. Across different varieties, the lowest mean GMD was observed in PUSA VIVEK at 7.00 mm, whereas the highest was found in PUSA HQPM-5 at 7.53 mm. Similarly, the lowest mean sphericity was recorded in Improved PUSA HQPM-5 at 0.64, whereas the highest was seen in Kaveri Hybrid 25K55 at 0.77 (Fig 4). Especially, the coefficients of variation for both GMD and sphericity were consistently below 10% for both types of seeds across all instances (Table 2).

Table 2 Geometric mean diameter (GMD) and Sphericity of maize seeds

Variety	Descriptive Statistics	Geometric Mean (mm)	Sphericity
PUSA HQPM-5	Range	6.90-8.60	0.58-0.72
	Mean	7.53	0.64
	CV (%)	6.50	6.97
Kaveri Hybrid 25K55	Range	6.49-7.66	0.66-0.89
	Mean	7.14	0.77
	CV (%)	5.98	9.55
PUSA VIVEK	Range	6.49-7.36	0.64-0.79
	Mean	7.00	0.68
	CV (%)	5.03	6.88

(CV= coefficient of variation)

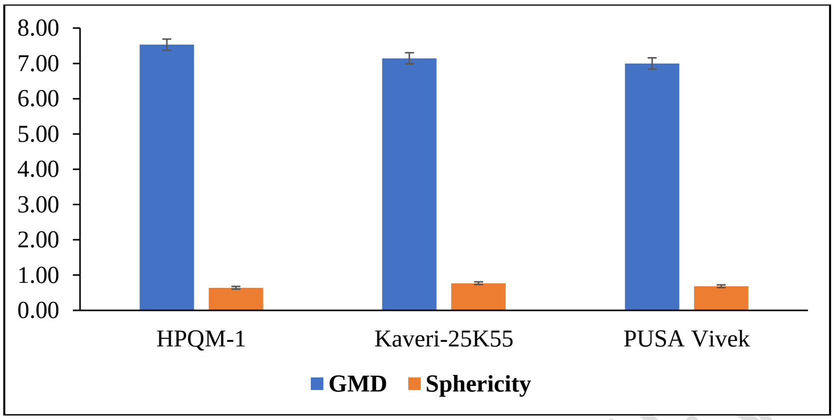

Fig 4: Geometric mean diameter (GMD) and sphericity of maize seeds

Angle of repose and coefficient of friction

The angle of repose, a crucial parameter for assessing the flow characteristics of maize varieties, ranged from 37.01˚ to 38.53˚ across the selected samples. Particularly, the PUSA HQPM-5 showed the minimum angle at 37.01˚, while the Kaveri Hybrid 25K55 demonstrated the maximum at 38.53˚ (Fig 5). This range suggests overall similarity in repose angles among the varieties. Concurrently, the coefficient of static friction varied from 0.53 to 0.59 across different materials, with the highest mean value observed for wood at 0.59 and the lowest for mild steel (MS) at 0.53 (Fig 6). In particular, mild steel showed the least friction compared to wood and galvanized iron (GI), rendering it a favorable choice for seed hopper fabrication. The coefficient of variation (CV) for the angle of repose remained consistently below 3.5% for all cases, with the highest CV recorded at 3.02% for PUSA HQPM-5 and the lowest at 0.67% for PUSA VIVEK. Similarly, for the coefficient of static friction, the CV remained below 4% (Table 3). This systematic analysis provides valuable insights for optimizing material selection and understanding the flow behavior of maize varieties.

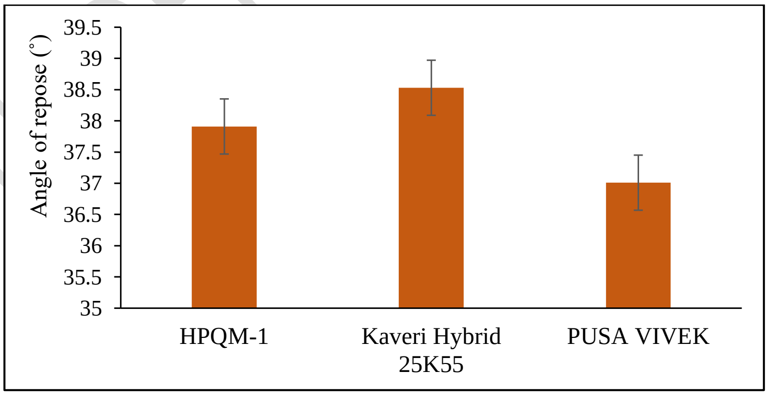

Fig 5: Effect of treatments on variations in angle of repose of maize varieties

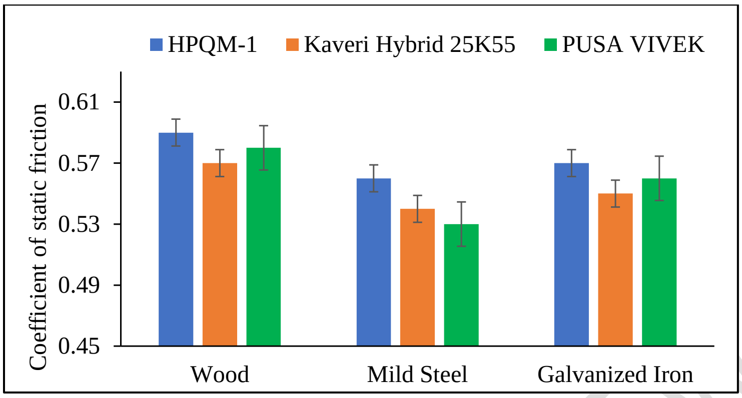

Fig 6: Coefficient of static friction of maize varieties

Table 3 Angle of repose and frictional properties of maize seeds

Variety	Descriptive Statistics	Angle of Repose (°C)	Coefficient of Friction		
			Wood	Mild Steel	Galvanized Iron
PUSA HQPM-5	Range	36.33-39.01	0.59-0.63	0.54-0.58	0.56-0.59
	Mean	37.91	0.59	0.56	0.57
	CV (%)	3.02	3.6	0.31	0.34
Kaveri Hybrid 25K55	Range	37.53-39.27	0.56-0.59	0.51-0.54	0.54-0.57
	Mean	38.53	0.57	0.53	0.55
	CV (%)	1.89	2.6	0.28	0.24
PUSA VIVEK	Range	35.85-37.36	0.55-0.61	0.52-0.55	0.54-0.56
	Mean	37.01	0.58	0.53	0.55
	CV (%)	0.67	0.84	0.31	0.41

Bulk density and true density

The bulk density values of the selected maize varieties ranged from 727 to 811 kg/m^3, with mean values of 808 kg/m^3 for PUSA HQPM-5, 765 kg/m^3 for Kaveri Hybrid 25K55, and 754 kg/m^3 for PUSA VIVEK. Particularly, PUSA VIVEK showed the lowest mean bulk density at 754 kg/m^3, while PUSA HQPM-5 revealed the highest at 667.56 kg/m^3. True density variations ranged from 1053 to 1192 kg/m^3, with PUSA VIVEK recording the lowest at 1068 kg/m^3 and PUSA HQPM-5 the highest at 1192 kg/m^3. The coefficient of variation (CV) for both bulk and true densities remained under 3%, indicating consistent measurements. Statistical analysis revealed no significant differences among the mean bulk density values, with all varieties being statistically on par. This trend was mirrored in the true density measurements as well. These density values serve as vital inputs for calculating seed hopper volumes required for the containment and metering of maize seeds, highlighting their practical utility in agricultural applications.~~.~~

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Table 4 Variations in bulk density, true density and 1000 ~~maize~~ seeds weight

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Variety	Descriptive Statistics	Bulk Density (kg/m^3)	True Density (kg/m^3)	1000 ~~Maize~~ Seed Weight (g)
PUSA HQPM-5	**Range**	802-811	1139-1223	287-296
	Mean	808	1192	293
	CV (%)	0.21	2.82	0.91
Kaveri Hybrid 25K55	**Range**	753-771	1050-1116	265-270
	Mean	765	1092	268
	CV (%)	0.44	1.76	1.39
PUSA VIVEK	**Range**	727-769	1053-1076	249-267
	Mean	754	1068	261
	CV (%)	4.2	1.19	2.57

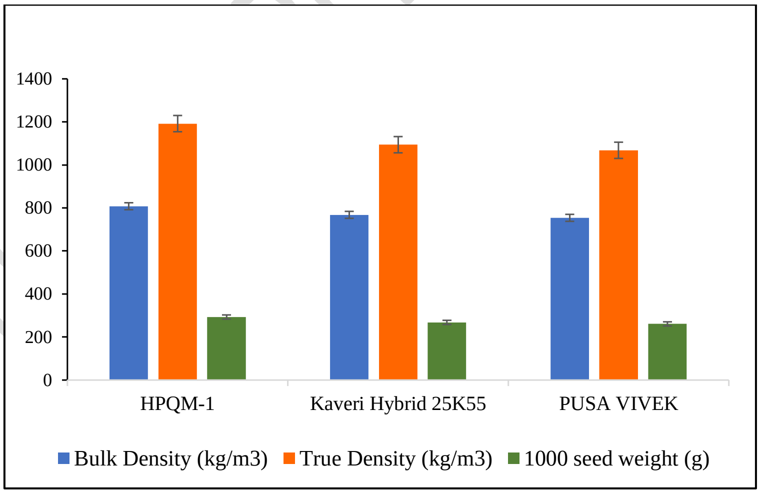

Fig 7: Variations in bulk density, true density and 1000 ~~maize~~ seeds weight

Thousand seed weight (1000 seed weight)

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Test weight (one thousand seed weight) was weighed ~~measured~~ for three maize varieties: PUSA HQPM-5 (293 g), Kaveri Hybrid 25K55 (268 g), and PUSA VIVEK

(261 g) (Table 4 and Fig 7). This parameter is essential for determining seed rate and calculating the optimal number of seeds per row. The higher thousand seed weight of PUSA HQPM-5 suggests a potential need for adjustments in seed spacing compared to the other two varieties to ensure optimal crop density.

Engineering pProperties of fertilizers

Developing a site-specific seed cum fertilizer applicator required a deep understanding of both the engineering and physical properties of fertilizer. Factors such as the type and size of seeds being planted, the soil conditions, and the required depth and spacing for optimal growth was considered for which 100 granular from each fertilizer was selected. The physical properties of the fertilizer, such as its particle size, density, and nutrient composition, are crucial for designing the applicator to ensure accurate placement and distribution. Additionally, Variability in soil types and nutrient requirements across different field areas was accounted for by engineering the applicator, requiring a robust design that can adjust to these varying conditions to achieve precise and efficient fertilizer application.

4.4.1 size

The physical properties, including length, breadth, and thickness, were measured for the design of the metering mechanism. The mean length, mean breadth, and mean thickness for Diammonium phosphate (DAP), NPK complex, and single super phosphate (SSP) fertilizer varied within the ranges of 4.01 to 4.34 mm, 3.56 to 3.73 mm, and 2.69 to 3.43 mm, respectively. The highest length value was observed for DAP at 5.04 mm, while the lowest was for NPK complex at 3.49 mm. Similarly, the highest breadth value was recorded for NPK complex at 4.34 mm, with the lowest being 3.07 mm for DAP. For thickness, the highest value was found for NPK complex at 3.75 mm, whereas the lowest was for DAP at 2.77 mm. The geometric mean diameter (GMD) ranged from 3.47 to 3.63 mm, exhibiting statistical similarity across all fertilizer typesvarieties. Sphericity varied from 0.81 to 0.91, with the highest observed for NPK fertilizer at 0.91 and the lowest for DAP at 0.81. The geometric properties of three different fertilizers are given in Table 5 and Fig 8.

Table 5 Geometric properties of different fertilizers

Variety	Length (mm)	Width (mm)	Thickness (mm)	(GMD), mm	Sphericity
DAP	4.28±0.76	3.64±0.52	2.69±0.48	3.47±0.51	0.83±0.01
NPK Complex	4.01±0.57	3.73±0.61	3.43±0.38	3.72±0.89	0.91±0.04
SSP	4.34±0.72	3.56±0.32	3.09±0.56	3.63±0.23	0.85±0.03

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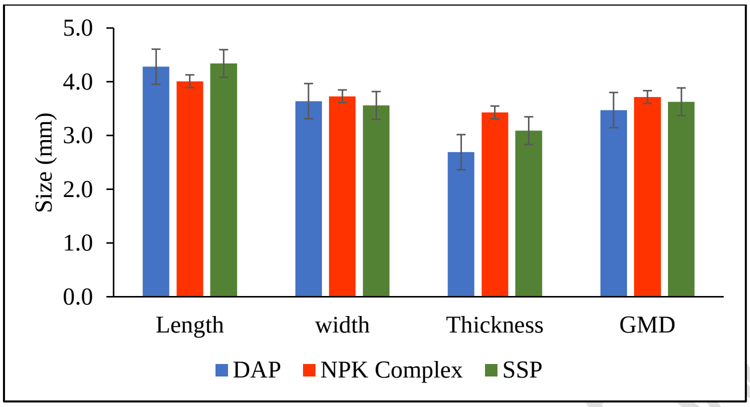

Fig 8: Linear dimensions of different fertilizer

~~4.4.2~~ Bulk density and angle of repose of fertilizer

Bulk density measurements for different fertilizer ranged from 753.77±11.40 kg/m^3 for Urea to 1236.02±12.36 kg/m^3 for NPK ~~Complex~~fertilizer. True density values varied, with DAP showing a lower range of 1379.76±24.9 kg/m^3 compared to SSP's higher range of 1950±21.97 kg/m^3. The angle of repose ranged from 35.29±0.58˚ for DAP to 33.32±0.68˚ for SSP. Especially, the NPK fertilizer used in the field demonstrated the highest bulk density at 1236.02±13.62 kg/m^3, with an angle of repose of 32.46±1.42˚(Table 6)~~.~~, additional detail was provided in Fig 9

Table 6 Variations in geometric properties of fertilizers

S~~r.~~/ No.	Property	Fertilizers			
		DAP	NPK ~~Complex~~	SSP	Urea
1.	**Bulk density, (kg /m^3)**	976.43±3.85	1236.02±13	1008.86±67	753.77±11.4
2.	**True density, (kg/ m^3)**	1379.76±264.9	1879.28±234	1950.00±217	1203.57±180
3.	**Angle of Repose (˚)**	35.29±0.58	32.46±1.42	37.69±0.43	33.32±0.68

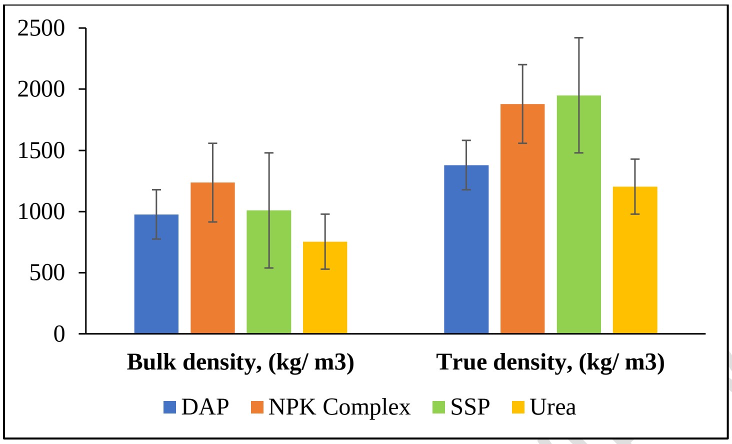

Fig 9: Variations in bulk density and true density of different fertilizer

Discussion

The development of a site-specific seed-cum-fertilizer applicator for maize necessitated a comprehensive investigation of the physical and engineering properties of selected ~~seed~~maize varieties and fertilizer. Parameters such as size, sphericity, test weight, bulk density, true density, coefficient of static friction, and angle of repose were critical in designing a precision seed cum fertilizer metering mechanism. This mechanism had to demonstrate flexibility in handling diverse seed and fertilizer types, ensuring accurate placement and optimal spacing to accommodate varietal differences. Dimensional analysis of maize seed varieties (Kaveri Hybrid 25K55, Pusa Vivek, PUSA HQPM-5) revealed minimal variations, with a maximum axial length of 12.42 mm across all samples. To ensure reliable seed metering, the plate groove diameter was set at 13.75 mm (10% larger than the maximum seed dimension). A groove depth of 8.5 mm and a seed metering plate thickness of 15 mm was chosen, surpassing the seeds' geometric mean diameter of 7.65 mm (Kepner et al., 1978). The low coefficient of variation for maize seed and fertilizer sphericity (<10%) confirmed their ellipsoid cone shape. This morphology guided the selection of an edge drop cell configuration for the metering mechanism, as this design ensures optimal handling and reliable singulation for a wide range of maize varieties.

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Conclusion

Dimensional analysis of maize varieties (Kaveri Hybrid 25K55, Pusa Vivek, and PUSA HQPM-5) revealed average seed lengths, widths, and thicknesses. Based on these measurements, a seed metering plate with groove diameters ranging from 12.5 to 15 mm was determined to be optimal for single seed placement. Analysis of mean thousand-grain weights (Kaveri Hybrid 25K55: 268 g, Pusa Vivek: 261 g, PUSA HQPM-5: 293 g) was used to determine optimal seed rates. To achieve a single seed per hill with a spacing of 67.5 cm x 20.5 cm, a theoretical seed rate of 12.25 kg/ha was calculated. The angle of repose measurements was (37.01˚- 38.53˚) for Kaveri Hybrid 25K55, Pusa Vivek, and PUSA HQPM-5 the seeds were critical for hopper design. The maximum coefficient of static friction (0.56) against mild steel informed seed flow behavior. To ensure smooth discharge, the hopper was designed with a 30.25˚ slope, accommodating the maximum observed angle of repose and coefficient of friction. The angle of repose for NPK fertilizercomplex was 32.46±1.42˚ and bulk density and true density were 1236.02±13 and 1879.28 kg/m^3 respectively.

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