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RESEARCH ARTICLE

Engineering and germination characteristics of okra (*Abelmoschus esculentus* L.) cultivars: Implications for processing and cultivar selection

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Abstract

The geometrical, volumetric, colour, frictional, mechanical, and germination characteristics of different okra cultivars, viz. Sultani, Akköy, and Japanese were examined in this study. The linear dimensional attributes i.e., length 5.30 ± 0.20 mm, width 4.58 ± 0.25 mm, and thickness 4.21 ± 0.21 mm, were maximum for *cv*. Akköy. The mass of individual seed (0.066 g) and corresponding thousand seed mass (65.42 ± 3.12 g) was highest for *cv*. Akköy had a significant difference ($p < 0.01$) between the cultivars. The lowest surface area (64.06 mm^2) was observed for the *cv*. Japanese. Significant difference ($p < 0.01$) was found between the chroma and b^* parameters among the cultivars. The highest static friction coefficient (0.348 ± 0.016) was observed on the rubber surface for *cv*. Japanese. The highest deformation value (3.53 ± 0.22 mm) was observed at the width axis of the *cv*. Akköy at 90 mm min^{-1} speed. The evaluation of germination characteristics revealed that the difference between the cultivars in wet and dry shoot length values was significant ($p < 0.01$). The determination of various attributes of okra seeds is imperative for their primary and secondary processing, product value, consumer demand, and economic perspective. Comprehensive knowledge of seed characteristics will be beneficial in properly selecting cultivars and in the pre-treatments to be followed before sowing.

Keywords Mechanical properties · Machine design · Chroma values · Rupture force · Germination characteristics

Practical applications Assessing engineering and germination characteristics has significant applications in seed processing, agriculture, and the food industries. The information about the geometrical parameters and surface area of the okra seeds aid in designing effective grading systems. The frictional properties help in optimizing the storage and handling requirements. The mechanical properties, particularly deformation values, are relevant in minimizing the probable damage during processing. Germination characteristics help in selecting the superior cultivar for enhanced crop yield. Comprehensive knowledge and insights about these properties contribute to sustainable agricultural practices and optimized seed utilization.

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1 Introduction

Okra (*Abelmoschus esculentus* L.) is one of the prominent vegetables grown in tropical, subtropical, and warm temperate conditions in Africa, Asia, Southern Europe, and Latin America (Santos et al. 2020; Liu et al. 2021). It has a significant role in the human diet and is primarily cultivated for green pods consumed fresh, frozen, canned, or dried. The global okra production was 11.52 million tonnes (MT), with India being the leading producer (7.16 MT), followed by Nigeria (1.87 MT), as reported by FAOSTAT (2023).

The most nutrient-rich portion of the okra plant is its seeds, constituting 13.5% of dried okra (Xu et al. 2020). Okra seeds have a high concentration of health-beneficial minerals, including vital amino acids, namely lysine and tryptophan. Okra seeds contain 20–40% oil, a vital component with multiple applications for food or industrial purposes. The seed oil contains linoleic acid (32.22–43.07%) as the principal constituent, also including linolenic acid (6.79–12.34%), and oleic acid (4.31–6.98%), as described by Liu et al. (2021). Açıkgöz et al. (2016) reported the protein

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content (28.21 ± 1.55%), oil yield (22.62 ± 1.48%), and linoleic acid (49.54 ± 1.68%) in Turkish okra seeds.

In addition, the okra seed is the main factor determining the crop's quantitative and qualitative characteristics to be harvested later. From the grower's perspective, the sowing date has an imperative significance, as the seeds sown during the off-season have a substantial effect on the quality and yield attributes of the seeds. El-Waraky (2014) reported that okra seeds do not germinate under 16 °C, and the 21–30 °C range is favourable for flowering, vegetative growth, and pod development. Hedau et al. (2010) mentioned that the seeds collected from the middle internodes and lower section of the plant exhibited the highest germination and vigor, as compared with the seeds from the upper fruits, which have low yield and quality attributes.

In okra seed processing, genetic and physical characteristics of the variety affect the seed's quality, processability, durability, and performance in subsequent production. Seed production is carried out by considering not only the physiological and morphological attributes of the fruit/pod but also the seed, and the role of the variety is decisive. High-quality seeds have the expected benefits of augmented yields (Arın et al. 2021). Various internal and external factors influence the germination potential of seeds (Anonymous, 2024).

During processing, the seeds are cleaned, sorted, subjected to physical and biological quality tests using modern technologies, and then marketed in appropriate packaging. In this process, examining seeds' physical and mechanical properties is crucial. These properties directly affect the efficiency of planting, harvesting, processing, transportation, and storage, and more importantly, they become the basis for the design of appropriate machinery and equipment. Seeds' physical and mechanical properties include dimensions, size, shape, weight, density, angle of repose, coefficient of friction, colour, and textural characteristics (Hazbavi et al. 2013; Mahawar et al. 2019; Bibwe et al. 2022). Knowing the seeds' relevant size, shape, and volume facilitates the separation of unwanted materials. Such characteristics are required to develop planter mechanisms for the uniform distribution of okra seeds and targeted delivery of fertilizers during field operations. In addition, such information is also crucial for the development of shelling, crushing, and milling machines for okra seeds (Emu and Uyeri 2020).

Sahoo and Srivastava (2002) evaluated the physical properties (linear dimensions, densities, weight, volume, angle of repose, and coefficient of static friction) of okra seeds (*cv*. Pusa A4,) having 8.16–87.57% (d.b.) moisture content. Kumar et al. (2018) studied the physical properties of okra seed (*cv*. *Varsha Uphar*), corroborating its importance for developing a suitable metering mechanism for targeted delivery of seeds/fertilizers. Obomeghei et al. (2022) evaluated the physical, engineering, and thermal characteristics of okra seeds (5% moisture) cultivated in Nigeria. The gathered information has intended applications for distinctive unit operations relevant to the post-harvest unit operations of the seeds.

In okra, the hard seed coat is an essential physiological constraint responsible for the delayed germination and irregular emergence owing to the restricted water uptake (Mohammadi et al. 2011). Okra seeds of different genotypes have variable germination and vigor properties (Purquerio et al. 2010; Mohammadi et al. 2012). The okra varieties selected (*cv*. Sultani, Akköy, and Japanese) for this study have significantly higher productivity under favourable growing conditions in Turkey. The comprehensive knowledge of seed characteristics will be beneficial in properly selecting cultivars and in the pre-treatments to be followed before sowing. The literature review authenticates the insufficient published information about the physical, frictional, colourimetric, textural, and germination properties of different okra cultivars. Therefore, this study aimed to evaluate and compare the above-mentioned properties of selected okra cultivars.

2 Materials and methods

2.1 Materials

Okra cultivars (Sultani, Akköy, Japanese) seeds were procured from the farm of the Tokat Gaziosmanpasa University, Turkey (40°20'0.02.19'' N latitude, 36°28'0.30.11E longitude) and were used in the study (Fig. 1). The experiments were executed in the Biosystems Engineering Department of Tokat Gaziosmanpasa University, Turkey. The seeds were stored at 18 ± 2 °C for 6 months after harvest. Broken and damaged seeds were removed, and intact seeds were used for experimentation.

2.2 Moisture content

The seed samples were subjected to 105 ± 1 °C in a hot air oven and kept for 24 h to estimate moisture as expressed on a dry basis (Mahawar et al. 2019).

2.3 Physical properties

The spatial dimensions, including length (L_e), width (W_i), and thickness (T_h) were recorded with a digital vernier calliper (M/s Mitutoyo Japan, ± 0.01 mm). Geometric mean diameter (*GMD*) (mm), sphericity (*S*) (%), and surface area (*SA*) (mm^2) were quantified using the following equations reported in the literature (Calisir and Yildiz 2005; Mahawar et al. 2019; Altuntas and Mahawar 2022):

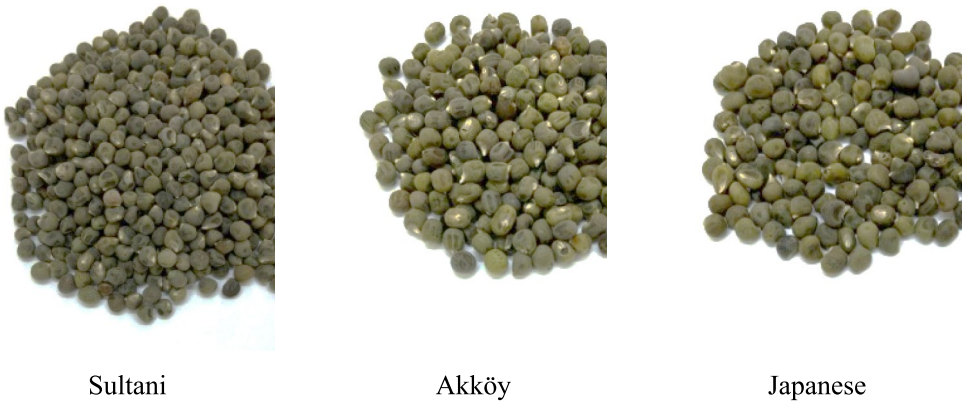


Fig. 1 Pictorial images of the okra seed cultivars

$$GMD = (L_e \times W_i \times T_h)^{1/3} \quad (1)$$

$$SA = \pi(GMD)^2 \quad (2)$$

$$S = \frac{GMD}{Le} \times 100 \quad (3)$$

Mass (M) of the individual seeds was noted using a precision scale (M/s. Kern EW620-3NM, ±0.001 g). Thousand seed mass (*TSM*) was determined by multiplying the average mass of 4 × 100 seeds of each cultivar and then extrapolating the same. Seed volume (V_s) (mm^3) measurements were determined according to Mohsenin (1980) with the following equation:

$$V_s = \frac{\pi}{6}(L_e \times W_i \times T_h) \quad (4)$$

2.4 Density

Seed density (S_d) was determined employing the liquid displacement technique, and the bulk density (B_d) was determined using the hectoliter method. The density values are reported in kg m^{-3}. Porosity (P_r) was determined as the ratio of bulk and seed density values.

2.5 Coefficient of static friction

Within the scope of mechanical properties of seeds, static friction coefficients on multiple friction surfaces [rubber (*R*), galvanized sheet (*G*), *PVC*, plywood (*P*), and laminate (*L*)] were determined. For this purpose, a friction measurement setup was used. The friction coefficient depends on the angle of inclination in the setup where the seeds were allowed to move from the surface inclined with a lever. It was estimated using the following equation:

$$\mu = tan\alpha \quad (5)$$

where μ: static coefficient of friction, α: inclination angle (°).

2.6 Colour

The colour characteristics were examined using a colorimeter (M/s. Minolta, model CR-400, Japan). Chroma value (*C*) indicates the vivid or pastel tone; pastel tones are defined as close to 0 and vivid tones are defined as close to 100. Chroma and hue angle (α) were calculated using equations 6 and 7 (Olivera et al. 2012).

$$C = (a^2 + b^2)^{1/2} \quad (6)$$

$$h^\circ = tan^{-1}(b/a) \quad (7)$$

2.7 Mechanical properties

The mechanical properties of seeds were determined using a biological material test device (Fig. 2). The rupture force along the axes of L_e, W_i, and T_h at 30, 60, and 90 mm min^{-1} speeds was taken graphically on the device. Samples were compressed along the *X*-, *Y*-, and *Z*- axes, and accordingly, the rupture force (*RF*), deformation (*D*), absorbed energy (*AE*), firmness (*F*), and power essential for cracking i.e., rupture power (*RP*) were obtained from the following equations:

$$AE = \frac{RF \times D}{2} \quad (8)$$

$$F = \frac{RF}{D} \quad (9)$$

$$RP = \left[\frac{AE \times S}{60000 \times D}\right] \quad (10)$$

where: *RF*: rupture force (N), *AE*: absorbed energy (N mm); *D*: deformation (mm), *F*: firmness (N mm^{-1}), *RP*: rupture power (W), and *S*: loading speed (mm min^{-1}).



Fig. 2 Evaluation of mechanical properties using test device

2.8 Germination attributes

The most reliable characteristic for determining seed quality is its ability to germinate. Evaluating germination attributes are considered most important for the success of any crop. The germination percentage and germination rate were calculated according to Soltani et al. (2015). The vigor and germination indexes were determined according to international standards (ISTA 1993; Mahawar et al. 2018).

2.9 Statistical analysis

Statistical Package for Social Sciences (SPSS version 17) was used to analyze the recorded data (SPSS 2017). After determining that the parameters were normally distributed, one-way ANOVA was performed for the data obtained for various properties, and a Duncan Multiple Comparison test was performed to determine the statistical significance between the cultivars.

3 Results and discussion

3.1 Moisture content

Seed durability is prominently dependent on its moisture content as the presence of higher moisture levels invites the attack by bacteria and fungi. If moisture is not within the desirable level, it will be prone to deterioration in bulk or bagged conditions. The moisture content of *cv*. Sultani, Akköy, and Japanese used in the study were determined as $10.41 \pm 0.32\%$, $9.93 \pm 0.45\%$ and $9.90 \pm 0.64\%$ (d.b.), respectively. The moisture values are considered safe for short time storage.

3.2 Physical properties

Parameters such as seed size, shape, weight, and surface properties, in particular, play a critical role in both reducing the risk of mechanical damage and obtaining high-quality seed material.

Generally, the seeds vary in weight and size because seeds on a plant mature differently depending on their location on the fruit. Weight is essential in determining seed quality. When seeds are large and uniform, germination and development occur rapidly. This allows the planted seeds to penetrate the soil layer easily. Thousand-seed weight is also a heritable varietal trait.

Within the scope of biotechnical characteristics of the seed samples of the cultivars, geometric properties (*GMD,* T_h, W_i, L_e, *SA,* and *S*), *M,* and volumetric properties (*STM,* V_s, B_d, S_d, and P_r) were determined (Table 1). While the groups' *GMD,* T_h and *SA* values were significant ($p < 0.05$), no statistically significant difference was observed between the cultivars in L_e, W_i, and *S* values. T_h values ranged between 3.97 mm and 4.21 mm and Sultani and Akköy cultivars were in the same group. The lowest SA value was determined in the Japanese cultivar (64.06 mm^2) against the Sultani and Akköy cultivars. While there was a statistically significant difference at the $p < 0.01$ level between the cultivars in terms of *TSM* and B_d, there was a significant difference at the $p < 0.05$ level between the cultivars in terms of *M* and V_s. There was no statistically significant difference between the cultivars in S_d and P_r values. Seed mass ranged between 0.055–0.066 g. Sultani and Japanese cultivars were in the same group.

Davies (2020) reported the mean L_e, W_i, T_h, *GMD,* and *SA* values of okra seeds as 0.57 cm, 0.55 cm, 0.50 cm, 0.51 cm, and 0.91 cm^2, respectively. They reported average thousand seed mass, bulk density, seed density, and porosity values as 93.54 g, 463.84 kg m^{-3}, 739.41 kg m^{-3}, and 37.27%, respectively. Açıkgöz et al. (2016) determined the L_e, W_i, T_h, *GMD*, *SA* and *S* values of okra seeds at 11.65% moisture content as 5.29 mm, 4.32 mm, 4.53 mm, 4.70 mm, 69.21 mm^2, and 0.89, respectively. Hazbavi (2013) determined the L_e, W_i, T_h, *GMD*, *SA,* and *S* values of okra seeds at 10% moisture content as 5.29 mm, 4.63 mm, 4.36 mm, 4.74 mm, 90.9% and 70.69 mm^2, respectively. The thousand seed mass, bulk density, seed density, and porosity values were 60.23 g, 610.1 kg m^{-3}, 1067.14 kg m^{-3}, and 40.01%, respectively. Kumar et al. (2018) reported okra seeds' L_e, W_i, and T_h values at 6.58% moisture content as 5.73, 4.83, and 4.49 mm, respectively. Bulk and seed densities were reported as 0.54 gcm^{-3} and 1.07 gcm^{-3}, respectively. The findings of this study corroborate

Table 1 Geometric characteristics of okra seeds cultivars

	Sultani	Akköy	Japanese	F value
L_e (mm)	5.27 ± 0.25	5.30 ± 0.20	5.26 ± 0.20	0.09^{ns}
W_i (mm)	4.53 ± 0.15	4.58 ± 0.25	4.43 ± 0.15	1.53^{ns}
T_h (mm)	4.15 ± 0.17^{a}	4.21 ± 0.21^{a}	3.97 ± 0.19^{b}	4.39*
GMD (mm)	4.62 ± 0.11^{b}	4.66 ± 0.13^{a}	4.51 ± 0.12^{ab}	4.08*
S (%)	87.72 ± 3.09	88.10 ± 3.51	85.86 ± 2.59	1.51^{ns}
SA (mm^2)	67.08 ± 3.17^{b}	68.46 ± 3.76^{a}	64.06 ± 3.56^{ab}	4.11*
M (g)	0.058 ± 0.007^{b}	0.066 ± 0.007^{a}	0.055 ± 0.007^{b}	6.25*
TSM (g)	53.72 ± 1.35^{b}	65.42 ± 3.12^{a}	49.10 ± 1.35^{c}	47.64**
V_s (mm^3)	51.99 ± 3.65^{ab}	53.67 ± 4.46^{a}	48.52 ± 4.10^{b}	4.14*
B_d (kg m^{-3})	673.12 ± 4.17^{a}	649.92 ± 9.72^{b}	671.38 ± 5.03^{a}	18.25**
S_d (kg m^{-3})	1242.41 ± 69.52	1411.81 ± 272.10	1255.88 ± 285.08	0.83^{ns}
P_r (%)	45.68 ± 3.25	52.63 ± 8.80	44.27 ± 12.62	1.21^{ns}

L_e: Length, *W_i*: Width, *T_h*: Thickness, *GMD:* Geometric mean diameter, *S:* Sphericity, *SA:* Surface area, *M:* Seed mass, *TSM:* Thousand seed mass, *V_s*: Seed Volume, *B_d*: Bulk density, *S_d*: Seed density, *P_r*: Porosity, ±: standard deviation

$^{**}p < 0.01$, $^{*}p < 0.05$, ^{ns}:non-significant value. The difference between identical letters on the same line is non-significant

those of other previous studies. As mentioned in the literature, the dimensional characteristics and shape of the seeds are used to classify and separate the primary agricultural material from unwanted seeds and other materials.

3.3 Colour

Colour is a crucial quality characteristic of a seed. Each cultivar has its own unique colour as the presence of pigment may be in different portions of the grain. Improper storage and adverse weather conditions cause colour deterioration. Furthermore, various diseases, particularly fungi and bacteria, can cause colour alterations.

Statistical results for multiple comparisons between groups in terms of colour characteristics are also given in Table 2. It was determined that the difference between the groups in terms of Chroma and b^* values was significant ($p < 0.01$). No statistically significant difference was observed between the cultivars in L^* and a^* values.

Bortey and Dzomeku (2016) emphasized that seed colour at harvest may indicate seed maturity and quality in terms of germination of okra. Matsufuji et al. (2001) observed that darker-coloured *Corchorus olitorius* seeds were more mature and recorded higher seed germination. The presence of colour in starch indicates low quality of seeds, affecting consumer acceptability (Galvez and Resureccion 1993).

3.4 Frictional characteristics

The results predicted that for all the cultivars, the static coefficient of friction values was maximum on rubber (*R*), followed by plywood (*P*), PVC, laminate (*L*), and galvanized sheet (*G*). The highest static friction coefficient (0.348 ± 0.016) was observed on the rubber surface, and the lowest value (0.162 ± 0.015) was on the galvanized sheet, both for the Japanese seeds. The statistical analysis results confirmed a non-significant difference between the cultivars regarding friction surfaces. The graphical representation of the static friction coefficients on selected surfaces is shown in Fig. 3. Davies (2020) reported the static coefficient of friction values of okra seeds on the galvanized sheet, plywood, and rubber surfaces as 0.411, 0.423, and 0.421, respectively. Hazbavi (2013) reported them as 0.395 (*G*), 0.534 (*P*), and 0.562 (*R*). It was seen that the findings of the study are at low values compared to the available literature.

Table 2 Colour characteristics of okra seeds cultivars

Cultivars	*L**	*a**	*b**	*Chroma*	*Hue angle*
Sultani	29.66 ± 0.91	1.43 ± 0.26	2.92 ± 0.43b	3.27 ± 0.30b	63.50 ± 7.26b
Akköy	30.46 ± 2.06	1.14 ± 0.43	4.34 ± 0.51a	4.51 ± 0.45a	74.90 ± 5.98a
Japanese	29.43 ± 1.03	1.11 ± 0.09	3.35 ± 0.50b	3.54 ± 0.48b	71.49 ± 2.73a
F value	0.71 ^{ns}	1.77 ^{ns}	11.56**	12.29**	5.36*

$^{**}p < 0.01$, $^{*}p < 0.05$, ^{ns}: non-significant value. The difference between identical letters on the same line is non-significant

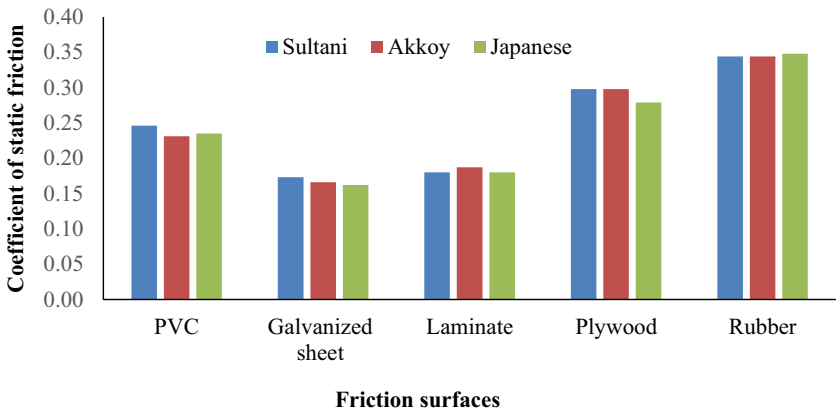


Fig. 3 Coefficient of static friction on different friction surfaces

3.5 Mechanical characteristics

Mechanical properties such as seed hardness has a direct correlation with the risk of mechanical damage during germination process and consequently, its success. While high hardness increases breakage resistance during processing, seeds with very low hardness can be damaged during transport. The mechanical and textural parameters concerning the loading axes and loading speeds, *viz.* 30 mm min^{-1} (Table 3), 60 mm min^{-1} (Table 4), and 90 mm min^{-1} (Table 5), are presented. It was observed that the rupture force along the length axis was higher than the width and thickness axis for all the cultivars. The highest RF was observed for *cv.* Sultani at 30 mm min^{-1} loading speed and length axis. The highest deformation value (3.53 ± 0.22 mm) was observed for *cv.* Akköy at 90 mm min^{-1} speed and length axis. The statistical analysis revealed that the mechanical properties had significant differences concerning loading speed and axis for all the cultivars.

Emu and Uyeri (2020) evaluated some mechanical properties (fracture force, fracture energy, and deformation) of okra seeds (*cv.* Kirikou) procured at five maturity stages. The fracture properties exhibited a strong positive correlation with the maturity of seeds. The fracture force (19.04 to 84.15 N) and fracture energy (0.02 to 0.09 N m) increased linearly; however, the relative deformation at the fracture point followed a declining trend with the maturity. Hazbavi (2013) evaluated the rupture force of okra seeds with variable moisture content (7.1 to 20% d.b) and observed a corresponding reducing trend (13.75 to 9.44 N) with an increase in the seed moisture.

3.6 Germination parameters

Varieties with varying germination and emergence rates require adaptations to planting system components such as planting depth, planting time, and seedbed preparation. The most reliable characteristic for determining seed quality is the seed's ability to germinate. The vigor index is a value that shows seeds' viability and performance level during

Table 3 Mechanical parameters of different cultivars according to loading axes (30 mm min^{-1})

C	Axes	RF (N)	D (mm)	AE (N mm)	F (N mm^{-1})	RP (W)
Sultani	L	162.62 ± 30.22^{a}	2.35 ± 0.30^{a}	193.82 ± 21.47^{a}	69.13 ± 12.36^{a}	0.027 ± 0.005^{c}
	W	98.26 ± 15.21^{b}	1.93 ± 0.18^{a}	152.61 ± 22.69^{b}	66.42 ± 12.74^{b}	0.046 ± 0.006^{b}
	T	84.46 ± 7.01^{c}	1.77 ± 0.48^{b}	147.57 ± 25.14^{c}	58.52 ± 13.27^{c}	0.065 ± 0.013^{a}
	F value	23.32**	22.87**	31.83**	14.88**	25.32**
Akköy	L	110.38 ± 15.83^{a}	1.79 ± 0.32^{b}	95.36 ± 22.78	50.96 ± 13.74^{b}	0.016 ± 0.003^{c}
	W	81.24 ± 18.51^{c}	1.96 ± 0.33^{a}	107.40 ± 23.36	52.69 ± 12.25^{a}	0.035 ± 0.005^{b}
	T	87.76 ± 19.72^{b}	1.75 ± 0.22^{c}	113.66 ± 24.38	50.77 ± 13.96^{b}	0.074 ± 0.031^{a}
	F value	5.48**	40.13**	34.39**	17.73**	44.12**
Japanese	L	147.44 ± 49.23^{a}	2.09 ± 0.13^{a}	75.22 ± 24.25	50.45 ± 13.37^{b}	0.014 ± 0.001^{c}
	W	98.40 ± 18.48^{b}	1.63 ± 0.23^{c}	70.57 ± 23.14	58.74 ± 14.99^{a}	0.030 ± 0.002^{b}
	T	99.68 ± 21.86^{b}	1.82 ± 0.17^{b}	102.92 ± 23.69	50.44 ± 12.74^{b}	0.050 ± 0.005^{a}
	F value	32.98**	22.47**	38.57**	18.22**	37.14**

C: Cultivar, *RF:* Rupture force, *D:* Deformation, *AE:* Absorbed energy, *F:* Firmness, *RP:* Rupture power, ±: standard deviation

$^{**}p < 0.01$. *The difference between the same letters in the same column is non-significant*

Table 4 Mechanical parameters of different cultivars according to loading axes (60 mm min^{-1})

C	Axes	RF (N)	D (mm)	AE (N mm)	F (N mm^{-1})	RP (W)
Sultani	L	139.02 ± 17.71^{a}	2.48 ± 0.33^{b}	121.46 ± 22.14^{a}	56.85 ± 11.25^{b}	0.019 ± 0.007^{c}
	W	103.80 ± 14.69^{b}	3.21 ± 0.25^{a}	110.19 ± 21.36^{b}	59.28 ± 13.45^{b}	0.037 ± 0.008^{b}
	T	89.86 ± 4.56^{c}	2.00 ± 0.28^{c}	121.38 ± 23.21^{a}	72.58 ± 14.74^{a}	0.063 ± 0.021^{a}
	F value	17.76**	31.20**	22.17**	17.29**	27.12**
Akköy	L	113.70 ± 15.83^{a}	2.24 ± 0.56^{a}	99.93 ± 12.36^{c}	62.67 ± 12.74^{a}	0.018 ± 0.003^{c}
	W	115.04 ± 18.51^{a}	2.06 ± 0.49^{b}	111.87 ± 23.36^{b}	58.33 ± 12.36^{b}	0.038 ± 0.005^{b}
	T	95.90 ± 19.72^{b}	1.58 ± 0.29^{c}	134.90 ± 28.69^{a}	45.17 ± 12.85^{c}	0.054 ± 0.008^{a}
	F value	12.78**	30.43**	21.36**	18.43**	44.12**
Japanese	L	116.64 ± 35.94^{a}	2.02 ± 0.53^{a}	77.97 ± 14.28^{c}	43.57 ± 11.27^{c}	0.014 ± 0.003^{b}
	W	95.90 ± 10.31^{c}	1.90 ± 0.22^{b}	120.51 ± 14.36^{b}	85.70 ± 12.63^{a}	0.047 ± 0.027^{a}
	T	105.14 ± 10.88^{b}	1.67 ± 0.21^{c}	149.25 ± 12.25^{a}	72.07 ± 12.78^{b}	0.048 ± 0.026^{a}
	F value	23.98**	21.74**	36.78**	18.73**	35.78**

C: Cultivar, *RF:* Rupture force, *D:* Deformation, *AE:* Absorbed energy, *F:* Firmness, *RP:* Rupture power ±: standard deviation

$^{**}p < 0.01$. *The difference between the same letters in the same column is non-significant*

Table 5 Mechanical parameters of different cultivars according to loading axes (90 mm min^{-1})

C	Axes	RF (N)	D (mm)	AE (N mm)	F (N mm^{-1})	RP (W)
Sultani	L	129.28 ± 25.26^{a}	2.24 ± 0.36^{b}	76.66 ± 12.78^{c}	50.91 ± 17.58^{b}	0.015 ± 0.003^{c}
	W	98.06 ± 12.52^{b}	2.27 ± 0.21^{a}	87.08 ± 14.25^{b}	53.15 ± 12.36^{b}	0.032 ± 0.005^{b}
	T	100.00 ± 9.10^{b}	2.08 ± 0.24^{c}	100.76 ± 13.36^{a}	69.65 ± 11.28^{a}	0.058 ± 0.009^{a}
	F value	12.87**	31.20**	29.36**	17.12**	24.19**
Akköy	L	107.54 ± 16.26^{b}	2.63 ± 0.24^{b}	84.85 ± 25.36^{c}	52.39 ± 13.85^{b}	0.016 ± 0.004^{c}
	W	109.26 ± 4.67^{b}	3.53 ± 0.22^{a}	106.49 ± 21.14^{b}	65.73 ± 13.78^{a}	0.039 ± 0.016^{b}
	T	116.40 ± 17.47^{a}	2.08 ± 0.53^{c}	128.30 ± 24.12^{a}	62.30 ± 13.96^{a}	0.053 ± 0.016^{a}
	F value	11.48**	40.13**	25.31**	18.59**	43.07**
Japanese	L	90.48 ± 20.66^{c}	2.53 ± 0.12^{a}	154.10 ± 21.58^{a}	70.69 ± 12.58^{a}	0.025 ± 0.008^{c}
	W	106.04 ± 16.96^{a}	1.72 ± 0.25^{b}	117.92 ± 24.36^{b}	59.29 ± 12.54^{b}	0.039 ± 0.012^{b}
	T	102.72 ± 14.93^{b}	2.20 ± 0.13^{b}	99.96 ± 22.78^{c}	42.93 ± 13.69^{c}	0.045 ± 0.010^{a}
	F value	11.78**	12.78**	28.74**	17.93**	34.28**

C: Cultivar, *RF:* Rupture force, *D:* Deformation, *AE:* Absorbed energy, *F:* Firmness, *RP:* Rupture power ±: standard deviation,

$^{**}p < 0.01$. *The difference between the same letters in the same column is non-significant*

germination and seedling development. The germination rate is associated with both viability and biotic and abiotic factors. Therefore, it is imperative to measure the germination rate in the germination studies (Soltani et al. 2015). Statistical results for multiple comparisons between groups are given in Table 6. Fresh root mass (0.082 g) for *cv*. Sultani, dry root mass for *cv*. Akköy (0.015 g) and fresh root length (53.83 mm) for *cv*. Japanese were recorded highest. The fresh seedling mass (0.22 g), dry seedling mass (0.09 g), and fresh seedling length (38.88 mm) were maximum for the Akköy cultivar. It was determined that the difference between the cultivars in terms of wet and dry shoot length values was significant ($p < 0.01$). It was determined that there was no statistical difference between the cultivars in terms of germination index, germination rate, germination percentage, and vigor index (Fig. 4). Higher seedling dry mass indicates swift germination and high seed strength, and vice versa. Japanese variety, which has low germination vigor, shallow planting, and soil conditions that retain moisture, should be preferred. Conversely, the Akköy and Sultani varieties, which have high emergence rates, are compatible with mechanical row planting systems and can successfully emerge with standard seed quantities and constant depths.

Additionally, differences in seed size and shape affect the accuracy of seeding standards in pneumatic or mechanical precision planters. Therefore, seed calibration by variety is essential for uniform emergence and uniform plant development. Germination differences can also impact irrigation timing, post-emergence supplementation, and early fertilization strategies.

Table 6 Germination parameters of different cultivars

	Fresh root mass (g)	Dry root mass (g)	Fresh root length (mm)	Fresh seedling mass (g)	Dry seedling mass (g)	Fresh seedling length (mm)	Number of roots (piece)
Sultani	0.082 ± 0.013	0.014 ± 0.001	47.89 ± 17.42	0.16 ± 0.02^{b}	0.06 ± 0.003^{b}	37.35 ± 4.31	11 ± 4.58
Akköy	0.077 ± 0.007	0.015 ± 0.004	39.22 ± 5.19	0.22 ± 0.01^{a}	0.09 ± 0.008^{a}	38.88 ± 4.62	9 ± 1.16
Japanese	0.060 ± 0.007	0.011 ± 0.001	53.83 ± 19.01	0.15 ± 0.02^{c}	0.06 ± 0.005^{b}	34.38 ± 6.24	9 ± 3.51
F value	4.43^{ns}	1.52^{ns}	0.70^{ns}	13.68**	24.88**	0.60^{ns}	0.47^{ns}

$^{**}p < 0.01$, ^{pd}: *non-significant value. The difference between identical letters on the same line is non-significant*

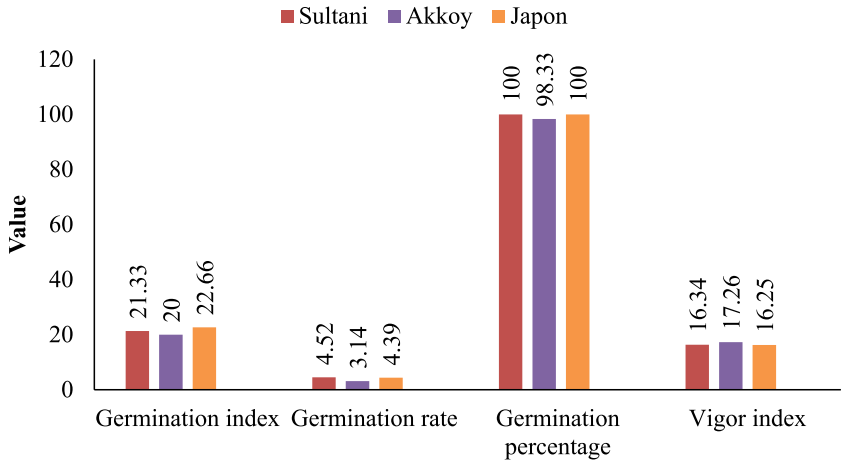


Fig. 4 Germination parameters of okra cultivars

3.7 Correlation analysis

The correlation matrix between the physical properties, colour, friction properties, and volumetric properties of all the cultivars were examined. The statistically significance and distinct relationships among the parameters is reported in detail as supplementary material (Table S1-S12).

4 Conclusion

The study provided information about the variety-specific differences in the physical, colour, mechanical, and germination properties of okra cultivars (Sultani, Akköy, Japanese). Such properties have significant practical implications, particularly for machining and precision planting technologies. Large and smooth-surfaced seeds (Sultani and Akköy) are comparatively easy to process in cleaning and sorting machines. In contrast, the smaller, irregularly structured Japanese cultivar seeds may require specific settings in such machines. The results showed significant difference ($p < 0.05$) between the cultivars in terms of T_h, *GMD* and *SA*. The lowest *SA* value (64.06 mm^2) was for the Japanese cultivar. While there was a statistically significant difference ($p < 0.01$) between the cultivars in terms of *TSM* and Bds, there was a significant difference ($p < 0.05$) in terms of *M* and V_s. There was no statistically significant difference in S_d and P_r values. Seed mass varied between 0.055 and 0.066 g. The highest rupture force (162.62 ± 30.22 N) was observed for *cv*. Sultani at 30 mm min^{-1} loading speed and the length axis. Maximum deformation value (3.53 ± 0.22 mm) along the width axes was observed in the Akköy cultivar at 90 mm min^{-1} speed. The maximum seedling dry mass and vigor index were observed for the Akköy cultivar. Post-harvest properties are to be considered for machine development, and simultaneously to understand its different processing aspects concerning the cost-economics and consumer adaptability.

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Declarations

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