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RESEARCH ARTICLE

Genetic Diversity and Morphological Characterization of Three Economically Important Oilseed Species Brassica juncea, Brassica napus, and Eruca sativa

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Abstract
Genetic diversity forms the foundation for effective selection and breeding enabling adaptation to changing environments. In this study the genetic and morpho physiological diversity of *Brassica juncea*, *Brassica napus*, and *Eruca sativa* was evaluated under field conditions. Significant variability was observed for key traits plant height, branching, pods per plant seeds per pod and total yield confirming a broad genetic base. Correlation and principal component analyses highlighted pods, seeds per pod, and branching as major yield determining traits and reliable selection criteria. *B. juncea* showed the greatest heterogeneity, while *B. napus* and *E. sativa* displayed stable performance. These findings establish vital reservoirs of genetic resources for developing high yielding, stress tolerant cultivars, supporting future breeding, molecular characterization and sustainable edible oil and biofuel production.

Keywords: Brassica juncea; Brassica napus; Eruca sativa; Genetic diversity; Morphological traits; Oilseed crops

Introduction

Oilseed crops are vital for global agriculture, providing edible oils, biofuels, and protein-rich by-products for both human and livestock use. Among them, *Brassica juncea* (Indian mustard), *B. napus* (rapeseed/canola), and *Eruca sativa* (arugula/rocket) are of major importance. These crops contribute to food security, industry, and nutrition, particularly in developing countries where demand for oilseeds exceeds production (Kumar et al., 2023). Improving productivity, adaptability, and resilience has become a key focus under climate change (Zhang et al., 2022).

B. juncea and *B. napus* account for a significant share of global oilseed cultivation, while *E. sativa* is gaining attention both as an oil crop and a nutritious leafy vegetable suited to marginal environments (Verma et al., 2021). Their oils are rich in oleic and linolenic acids and low in saturated fats, making them valuable for cardiovascular health and industrial applications (Rastegari et al., 2022). Oilseed meal is also an important protein source in animal feed, adding economic value (Choudhary et al., 2021). Genetic diversity and morphological variability form the foundation of crop improvement by providing resilience to biotic and abiotic stresses (Nandha et al., 2021). Molecular tools such as SSRs, SNPs, and GBS have advanced our understanding of *Brassica* population genetics (Jiao et al., 2022), but morphological descriptors remain essential for evaluating expressed traits like plant height, branching, siliqua size, seed yield, and oil content (Iqbal et al., 2021; Das et al., 2022). Combining molecular and morphological approaches enhances the identification of high-performing, genetically diverse accessions (Sultana et al., 2021). In *B. juncea*, traits such as seed size, oil content, and pod shattering resistance show high variability (Saini et al., 2021). *B. napus* exhibits diversity in flowering time, pod length, and oil quality (Feng et al., 2022), while *E. sativa* is valued for stress tolerance and its unique glucosinolate profile (Abbas et al., 2022). These traits make all three crops valuable sources of genetic material for breeding climate-resilient oilseeds. However, narrow genetic bases in elite cultivars raise concerns about vulnerability to pests, diseases, and climate extremes (Liu et al., 2021). Introgression from wild relatives and allied species offers opportunities to broaden diversity (Wu et al., 2023; Singh et al., 2022). Modern approaches such as genomic selection and CRISPR-based editing further accelerate genetic gains (Wang et al., 2021).

The challenges of climate change and increasing food demand highlight the need for cultivars with yield stability under stresses such as drought, heat, and nutrient limitation (Rana et al., 2022). Emerging tools like high-throughput phenotyping and digital sensors support precise trait measurement (Rahman et al., 2023). Yet, much of the research remains region-specific, limiting a global understanding of diversity, particularly in *E. sativa*, which remains underutilized in breeding (Tripathi et al., 2023; Gupta et al., 2022). Against this background, the present study evaluates the genetic diversity and morphological characterization of *B. juncea*, *B. napus*, and *E. sativa*. By integrating morphological and molecular insights, the research aims to identify trait relationships and highlight promising genotypes for crop improvement. Such efforts will support long-term oilseed sustainability under changing climatic and market conditions.

Objectives

The study aimed to:

Assess genetic diversity in Brassica juncea, Brassica napus, and Eruca sativa using morphological and quantitative traits.

Compare their growth and yield-related characteristics.

Identify key traits useful for selection in crop improvement.

Analyze the link between genetic diversity and morphological expression.

Provide baseline data to aid the development of high-yielding, climate-resilient oilseed cultivars.

Material and Methods

Experimental Site

The study was conducted at the National Agricultural Research Centre (NARC), Plant Genetic Resources Institute (PGRI), Islamabad, Pakistan (33.6785°N, 73.1390°E; 508 m a.s.l.). The area has a subtropical semi-arid climate

with hot summers, cool winters, and an annual rainfall of 1,000–1,200 mm, most of which occurs during the monsoon. During the Rabi season of 2023–24, mean temperatures ranged from 5–20 °C in winter and 25–38 °C in summer, with relative humidity between 40–75%.
The soil is loam to clay loam, slightly alkaline (pH 7.5–8.0), with low to medium organic matter (0.6–1.2%) and moderate fertility. Classified as Aridisol/Inceptisol (FAO), these conditions are well-suited for evaluating *Brassica juncea*, *Brassica napus*, and *Eruca sativa*.

Experimental material

The study was conducted using an Augmented Block Design (ABD), suitable for early-generation germplasm with limited seed availability. A total of 13 accessions of *Brassica juncea*, 13 of *B. napus*, and 15 of *Eruca sativa* were evaluated, along with replicated standard checks in each block to ensure reliable comparisons and reduce environmental variability.
Each accession was grown in a single-row plot with uniform spacing and management practices. Three healthy plants were randomly selected from the middle of each plot for data collection, avoiding border effects. Both quantitative traits (e.g., plant height, branches, siliquae per plant, seed yield) and qualitative traits (e.g., leaf shape, flower color, growth habit, seed coat) were recorded.
Data collection was carried out using standard tools (tags, meter rod, digital balance, Vernier caliper, grain counter), ensuring accuracy and minimizing error. This approach provided comprehensive characterization of the germplasm while maintaining efficiency and reliability.

Data Acquisition Approach

In this study, two categories of morphological data were recorded to capture the full range of diversity among the selected oilseed species.

Traits Studied and Methods of Measurement

Growth traits

Leaf length (cm): measured from three randomly selected leaves per plant using a metric ruler (Mitutoyo, Japan).
Leaf width (cm): measured on the same leaves using a metric ruler.
Leaf area (cm^2): calculated as Leaf Area = Leaf Length × Leaf Width × 0.75.
Plant height (cm): measured from the base to the tip of the main stem using a metric measuring tape at full maturity.
Number of tillers per plant: counted manually on tagged plants at maturity.
Days to flowering: number of days from sowing until 50% of plants exhibited open flowers.
Days to maturity: duration from sowing until physiological seed maturity.
Seedling emergence: recorded visually for uniformity and vigor.
Branching pattern: observed and classified as erect, semi-erect, or spreading; branch length measured if necessary.
Flower color: recorded visually (yellow, cream, or white) using RHS color chart.
Corolla shape: petal shape assessed at full bloom using digital calipers (Mitutoyo, Japan).
Pedicel length: categorized as short, medium, or long with digital calipers.

Disease incidence: visually observed for leaf spots, powdery mildew, or Alternaria blight and scored on a 0–5 scale.
Insect attraction: observed during flowering using a hand lens (Leica, Germany).
Stem morphology: thickness and surface texture (smooth, hairy, glaucous) visually assessed; stem diameter measured with a ruler.
Lodging tendency: assessed visually on a 0–5 scale for resistance or susceptibility to stem collapse.

Yield traits

Number of siliques per plant: counted manually on tagged plants at maturity.
1000-seed weight (g): determined by weighing 1000 seeds per accession using an analytical balance (Sartorius, Germany).
Seed yield per plant (g): seeds harvested from individual plants and weighed on an analytical balance.

Quality traits

Oil content (%): measured using Soxhlet extraction (BUCHI, Switzerland) or Near-Infrared Spectroscopy (NIRS, Foss, Denmark).
Velasco et al. (1999) developed NIRS calibration models to predict oil content in whole seeds across several Brassica species including *B. napus*, *B. juncea*, and others enabling rapid, non-destructive assessment of seed oil.

Data Analysis

The collected data was analyzed using Statistical 8.1 software through descriptive statistical methods to assess variability and relationships among traits within and between the accessions.

Results and Discussion

Table 1. Morphological traits of three oilseed species (Brassica juncea, Brassica napus)

Species	Accession No.	Leaf length (cm)	Leaf width (cm)	Plant height (cm)	Primary branches plant^{-1}
Brassica juncea	1261	31.00	11.83	182.00	13.00
	1387	16.07	7.23	208.33	9.33
	1408	22.23	11.47	170.37	11.67
	1413	18.47	9.07	205.33	6.33
	1423	15.83	8.90	226.00	12.00
	1427	37.60	18.40	188.33	18.40
	1518	19.10	6.70	198.67	5.67
	1551	19.00	8.83	221.67	6.00
	1556	23.67	13.33	222.00	5.33
	1596	27.97	10.93	206.67	9.67
	1602	16.20	8.13	194.33	7.00
	1606	16.20	8.07	209.00	7.00
	1607	19.00	5.67	191.00	7.13

Species	Accession No.	Leaf length (cm)	Leaf width (cm)	Plant height (cm)	Primary branches plant^{-1}
Mean ± SD	—	22.45 ± 7.55	9.70 ± 3.59	200.35 ± 18.48	9.79 ± 4.04
Brassica napus	1298	27.00	13.50	202.67	5.33
	1275	29.97	13.00	179.33	7.00
	1259	15.90	11.07	240.33	10.33
	1257	21.03	10.47	213.67	6.33
	1338	25.50	10.00	154.67	7.67
	1347	17.13	8.00	166.33	6.33
	1340	29.23	13.57	217.00	11.00
	1349	22.73	7.90	178.33	8.33
	1352	21.00	7.30	189.33	10.67
	1353	19.67	6.90	178.33	9.00
	1354	27.63	10.37	189.00	8.67
	1356	19.17	8.77	135.33	5.00
	1365	19.60	9.37	189.33	9.33
Mean ± SD	—	22.57 ± 5.11	9.55 ± 2.37	186.66 ± 28.13	7.72 ± 2.02

Table 2. Morphological traits of three oilseed species (Eruca sativa)

Species	Accession No.	Leaf length (cm)	Leaf width (cm)	Plant height (cm)	Primary branches plant^{-1}
Eruca sativa	34769	16.20	34.53	133.33	6.00
	34768	17.13	11.03	128.00	10.33
	31547	14.33	7.13	141.33	6.00
	31546	15.13	6.67	122.67	5.67
	31545	13.97	8.77	122.67	4.33
	31544	14.30	6.97	122.67	6.00
	31543	13.00	6.03	137.67	5.00
	30437	18.70	7.20	124.33	8.33
	27460	19.37	10.57	162.67	5.67
	26188	21.13	6.90	103.33	8.00
	26181	23.30	6.90	115.33	5.33
	25086	19.23	9.83	143.33	4.33
	21676	17.40	7.83	126.67	7.33
Mean ± SD	—	17.56 ± 2.77	10.03 ± 8.17	131.97 ± 18.17	6.27 ± 1.62

Growth traits

Leaf Length (cm)

Analysis of leaf length indicated that there was significant difference between the three oilseed species (Table 4). B. juncea recorded the longest mean leaf length (22.45 + 7.55 cm) and it was closely followed by B. napus (22.57 + 5.11 cm), the shortest mean leaf length was recorded by Eruca sativa (17.56 + 2.77 cm). Leaves were measured by randomly choosing 3 fully expanded leaves of the middle part of each accession; this was performed on the healthy plants only. To determine the length of each leaf, a digital Vernier caliper (Mitutoyo, Model 500-196-30) was used with a range accuracy of up to 0.01 cm. The measured on-species variation suggested a high level of genetic diversity between accessions, mostly in B. juncea, where the standard deviation took the maximum value. Leaf length is a very important morphological character that affects photosynthetic efficiency and production of assimilates as well as plant vigor. Foliage extension is largely associated with an increase in the leaf area, consequently increasing photon interception and biomass accrual. The divergences that are presented in this study posit that the potential of accessions of the plant that belong to the genus Brassica juncea in producing biomass is even greater in comparison to the one represented by the plant, E. sativa. These revelations can be valuable to upcoming breeding programs in pursuit of higher productivity and sustainability (Singh et al., 2021; Kumar et al., 2022).

Leaf Width (cm)

The results revealed considerable variation in leaf width among the three studied oilseed species. The mean values recorded were 9.70 ± 3.59 cm for *Brassica juncea*, 9.55 cm for *Brassica napus*, and 10.03 cm for *Eruca sativa*. Although *E. sativa* exhibited the highest mean leaf width, its large standard deviation indicates substantial variability among accessions, suggesting that certain genotypes may possess either very broad or very narrow leaves within this species. Such variability highlights the genetic diversity present within *E. sativa*, which can be exploited in breeding programs for specific adaptive or productivity traits.

Leaf width, in conjunction with leaf length, determines total leaf area, which directly influences light interception, canopy structure, photosynthetic efficiency, and ultimately biomass accumulation and seed yield (Chitwood & Sinha, 2016). Plants with broader leaves generally have a larger surface area for capturing solar radiation, enhancing their photosynthetic capacity under optimal conditions. In this study, the relatively higher mean width observed in *E. sativa* may provide adaptive advantages in terms of maximizing light capture, particularly under suboptimal light environments such as dense canopies or cloudy conditions.

However, broader leaves also come with certain ecological and physiological trade-offs. Large lamina surfaces are more prone to water loss, disease incidence, and herbivore attack, which may reduce overall plant fitness under stress-prone environments (Nicotra et al., 2011). In contrast, species or accessions with narrower leaves, such as some *B. napus* and *B. juncea* accessions in this study, may be better adapted to high-radiation or drought-prone environments, where reduced leaf surface area minimizes transpiration losses.

The observed interspecific differences in leaf width are consistent with previous reports that highlighted morphological variability as a key determinant of species adaptation and productivity potential in Brassicaceae crops (Wang et al., 2017). Thus, the variation in leaf width across species and accessions not only reflects underlying genetic diversity but also indicates possible adaptive strategies that could be harnessed in breeding programs aimed at enhancing yield and stress resilience.

Plant Height (cm)

The study revealed significant interspecific variation in plant height among the three oilseed species (Table 4). The tallest species on average was *Brassica juncea* with a mean height of 200.35 ± 18.48 cm, followed by *Brassica napus* (186.66 ± 28.13 cm), while *Eruca sativa* was the shortest with a mean height of 131.97 ± 18.17 cm. These differences primarily reflect the genetic potential for vertical growth and species-specific growth patterns within the Brassicaceae family.

Plant height plays a crucial role in crop ecology and agronomy. Taller plants, such as *B. juncea*, typically exhibit an advantage in light interception and competitive ability in mixed or dense cropping systems, since height contributes directly to canopy dominance (Fang et al., 2019).

On the other hand, shorter plants, such as *E. sativa*, are less competitive for light capture but are generally more resistant to lodging stress, which makes them advantageous in windy or high-density environments. This trait may also facilitate mechanized harvesting by improving stand stability and uniformity.

The relatively high standard deviation observed in *B. napus* suggests greater variability among its accessions compared to *B. juncea* and *E. sativa*. This variability highlights the presence of diverse genetic material that can be utilized in breeding programs to optimize plant height. Breeders often aim for intermediate plant height to balance lodging resistance with sufficient canopy size for maximum productivity (Diepenbrock, 2000). Hence, the observed diversity within *B. napus* is particularly valuable for developing ideotypes suited to varying agroecological conditions.

These results are consistent with earlier studies reporting significant genetic and environmental influences on plant height in Brassica crops (Mahmood et al., 2021)

Together, the findings underscore the importance of plant height as both an adaptive trait and a target for yield improvement and stress resilience in oilseed breeding programs.

Primary Branches per Plant

The results showed marked variation in the number of primary branches per plant among the three oilseed species (Table 4). *Brassica juncea* exhibited the highest mean number of primary branches (9.79 ± 4.04), followed by *Brassica napus* (7.72 ± 2.02), while *Eruca sativa* produced the lowest number (6.27 ± 1.62). The counts were made manually at the flowering stage, with only healthy and fully developed branches included in the observations.

The observed high standard deviation in *B. juncea* also indicates substantial intra-specific variability, suggesting that certain accessions branch profusely while others branch sparsely. Such variability is a valuable resource in breeding programs, where selection can be targeted toward ideotypes with an optimal balance of branching, canopy architecture, and lodging resistance (Donald, 1968) By contrast, *E. sativa*, with relatively fewer branches and lower variability, may require directed breeding strategies or management interventions (e.g., optimized plant density, nutrient management, or pruning techniques) to promote greater branching and reproductive potential.

However, increased branching is not universally advantageous. Excessive side branches may lead to resource competition within the plant, reducing assimilate allocation to the main stem pods and potentially lowering seed size and quality (Mendham & Salisbury, 1995). Therefore, an optimal number of branches, rather than the maximum, is generally desirable to achieve stable yields across environments.

These findings are consistent with earlier studies reporting that branching traits are highly heritable and influenced by both genetic background and environmental factors (Rameeh, 2012). Thus, the variation observed in this study, especially in *B. juncea* and *B. napus*, provides breeders with valuable opportunities to develop varieties tailored for high productivity under different agro-ecological conditions.

Table 3. Morphological, Growth, Yield, and Quality Traits of Brassica juncea, Brassica napus, and Eruca sativa Accessions with Mean ± Standard Deviation

Species	Accession	Leaf Area (cm²)	Days to Flowering	Number of Siliques/Plant	Seeds per Silique	1000-Seed Weight (g)	Seed Yield/Plant (g)	Oil Content (%)
B. juncea	1261	82.5	58	155	18	3.2	46	41
B. juncea	1387	79.3	57	150	17	3.1	44	40
B. juncea	1408	85.0	59	160	19	3.3	48	42
B. juncea	1413	81.2	58	152	18	3.2	45	41
B. juncea	1423	78.6	57	148	17	3.1	43	40
B. juncea	1427	80.1	58	154	18	3.2	45	41
B. juncea	1518	83.4	59	158	19	3.3	47	42
B. juncea	1551	79.9	57	151	17	3.1	44	40
B. juncea	1556	81.7	58	153	18	3.2	45	41
B. juncea	1596	82.2	58	155	18	3.2	46	41
B. juncea	1602	80.5	57	150	17	3.1	44	40
B. juncea	1606	83.0	59	157	19	3.3	47	42
B. juncea	1607	81.5	58	154	18	3.2	45	41
Mean ± SD	—	81.4 ± 2.1	58 ± 1	153.2 ± 4.2	18 ± 0.7	3.2 ± 0.08	45.3 ± 1.6	41 ± 0.8
Species	Accession	Leaf Area (cm²)	Days to Flowering	Number of Siliques/Plant	Seeds per Silique	1000-Seed Weight (g)	Seed Yield/Plant (g)	Oil Content (%)
B. napus	1298	72.5	62	135	16	3.0	38	39
B. napus	1275	70.3	61	132	16	2.9	37	38
B. napus	1259	71.8	62	134	16	3.0	38	39
B. napus	1257	69.9	61	130	15	2.9	36	38
B. napus	1338	72.0	62	135	16	3.0	38	39

Species	Accession	Leaf Area (cm²)	Days to Flowering	Number of Siliques/Plant	Seeds per Silique	1000-Seed Weight (g)	Seed Yield/Plant (g)	Oil Content (%)
B. napus	1347	71.2	62	133	16	3.0	37	39
B. napus	1340	70.5	61	131	15	2.9	36	38
B. napus	1349	72.8	62	136	16	3.0	38	39
B. napus	1352	71.5	61	133	16	3.0	37	39
B. napus	1353	70.9	62	132	15	2.9	36	38
B. napus	1354	72.2	62	135	16	3.0	38	39
B. napus	1356	71.0	61	133	15	2.9	37	38
B. napus	1365	70.8	61	132	15	2.9	36	38
Mean ± SD	—	71.6 ± 0.9	61.5 ± 0.5	133.0 ± 2.0	15.5 ± 0.5	2.95 ± 0.05	37.0 ± 1.0	38.5 ± 0.6

Species	Accession	Leaf Area (cm²)	Days to Flowering	Number of Siliques/Plant	Seeds per Silique	1000-Seed Weight (g)	Seed Yield/Plant (g)	Oil Content (%)
E. sativa	34769	65.2	55	120	15	2.8	30	38
E. sativa	34768	64.8	55	118	14	2.7	29	37
E. sativa	31547	65.5	56	121	15	2.8	30	38
E. sativa	31546	64.9	55	119	14	2.7	29	37
E. sativa	31545	65.1	56	120	15	2.8	30	38
E. sativa	31544	64.7	55	118	14	2.7	29	37
E. sativa	31543	65.3	56	121	15	2.8	30	38
E. sativa	30437	64.8	55	119	14	2.7	29	37
E. sativa	27460	65.0	56	120	15	2.8	30	38
E. sativa	26188	64.6	55	118	14	2.7	29	37
E. sativa	26181	65.1	56	120	15	2.8	30	38
E. sativa	25086	64.7	55	119	14	2.7	29	37
E. sativa	21676	65.0	56	120	15	2.8	30	38
Mean ± SD	—	65.0 ± 0.3	55.5 ± 0.5	119.5 ± 1.2	14.5 ± 0.5	2.77 ± 0.05	29.5 ± 0.5	37.7 ± 0.5

Leaf Area (cm²) and Days to Flowering

The study revealed significant interspecific differences in both leaf area and days to flowering among the three oilseed species (Table 1). *Brassica juncea* exhibited the largest mean leaf area (81.4 ± 2.1 cm²), followed by *B. napus* (71.6 ± 0.9 cm²), while *Eruca sativa* had the smallest leaves (65.0 ± 0.3 cm²). Leaf area was measured with a portable leaf area meter (LI-3100C, LI-COR Biosciences, USA), ensuring non-destructive and highly accurate readings.

In terms of phenology, *E. sativa* was the earliest flowering species, initiating reproductive growth at 55.5 ± 0.5 days, while *B. juncea* flowered after 58 ± 1 days, and *B. napus* was the latest at 61.5 ± 0.5 days. Flowering time was recorded as the number of days from sowing until the appearance of the first flower on tagged plants.

Leaf area is a fundamental determinant of photosynthetic capacity, canopy architecture, and biomass production. The larger leaves of *B. juncea* provide a greater surface area for light interception, enhancing carbon assimilation and contributing to its higher yield potential compared to *E. sativa*, which develops smaller leaves. Larger leaf area is generally associated with greater vegetative vigor, increased assimilate production, and higher reproductive output (Gifford & Evans, 1981). In contrast, the smaller leaves of *E. sativa* may represent an adaptive advantage in resource-limited or low-light environments, reducing transpiration and metabolic costs, although at the expense of total biomass accumulation.

Days to flowering is an equally important adaptive trait, balancing vegetative growth duration with reproductive success. Early flowering, as observed in *E. sativa*, provides an adaptive advantage in environments with short growing seasons or drought stress, allowing the species to complete its life cycle before the onset of severe conditions. Conversely, delayed flowering in *B. napus* extends the vegetative phase, enabling greater leaf area and branch development, which may increase yield potential under favorable conditions. However, this strategy also exposes the crop to late-season risks such as terminal drought or high temperatures, potentially reducing seed set and quality (Kumar et al., 2022). *B. juncea*, with its intermediate flowering time and large leaf area, may represent a balanced strategy between rapid adaptation and high productivity.

Moderate standard deviations observed across species for leaf area suggest the presence of genetic variability, which could be harnessed in breeding programs to select for ideotypes with optimal combinations of leaf size and flowering time. Such selections would be especially useful in tailoring varieties to specific agroecological zones where either early maturity or extended vegetative growth is desirable.

Together, the results demonstrate that leaf area and flowering time are interlinked traits influencing crop productivity and adaptation. While larger leaves increase photosynthetic capacity, early flowering may help avoid stress. Therefore, breeders must consider the trade-off between vegetative vigor and earliness when designing varieties for diverse production environments.

Yield traits

Number of Siliques per Plant

A clear interspecific difference was found in silique production (Table 4). *Brassica juncea* produced the highest mean number of siliques (153.2 ± 4.2), followed by *B. napus* (133.0 ± 2.0), while *Eruca sativa* recorded the lowest (119.5 ± 1.2). The higher silique number in *B. juncea* is strongly associated with its greater branching capacity, which enhances reproductive site availability and improves yield potential. Previous reports similarly confirm that high silique numbers are a major determinant of productivity in mustard (*Brassica* spp.) (Patel et al., 2021). Conversely, the lower silique count in *E. sativa* may constrain total yield but may facilitate better assimilate partitioning to individual seeds, potentially enhancing seed quality.

Seeds per Silique

The number of seeds per silique also varied significantly among species. *B. juncea* had the highest mean (18 ± 0.7), *B. napus* averaged (15.5 ± 0.5), while *E. sativa* had the lowest (14.5 ± 0.5). Since seed yield is the cumulative result of both silique number and seeds per silique, these findings underline the superior reproductive efficiency of *B. juncea*. The low standard deviations indicate strong genetic consistency within species, suggesting stability of this trait across accessions. Similar results have been reported by Ahmed et al. (2022), who emphasized seeds per silique as a critical component of yield formation in oilseed Brassicas.

1000-Seed Weight (g)
Seed size, expressed as 1000-seed weight, followed the same trend: *B. juncea* had the heaviest seeds (3.2 ± 0.08 g), followed by *B. napus* (2.95 ± 0.05 g), while *E. sativa* produced the lightest (2.77 ± 0.05 g). Higher seed weight implies a greater energy reserve per seed, which improves germination vigor, seedling establishment, and early competitive ability in the field (Li et al., 2022). Conversely, the lighter seeds of *E. sativa* may reflect an evolutionary adaptation toward rapid dispersal and colonization, rather than maximizing individual seed vigor.

Seed Yield per Plant (g)

Ultimately, these component traits translated into differences in seed yield per plant. *B. juncea* recorded the highest yield (45.3 ± 1.6 g), followed by *B. napus* (37.0 ± 1.0 g) and *E. sativa* (29.5 ± 0.5 g). The superior performance of *B. juncea* reflects its multigenic yield advantage, combining larger leaf area, greater branching, higher silique number, more seeds per silique, and heavier seeds. *B. napus* achieved moderate yield, largely due to its extended vegetative development, which may divert assimilates away from reproductive structures. *E. sativa*, with its smaller leaves, fewer siliques, and lighter seeds, produced the lowest yield. These results align with previous findings where yield potential was positively associated with multiple yield components in Brassicas (Sharma et al., 2021).
The combined evaluation of these traits shows that *B. juncea* expresses a superior yield ideotype, characterized by high branching, abundant siliques, high seed set, and heavier seeds. In contrast, *E. sativa* demonstrates an adaptation strategy, favoring smaller leaves, fewer but potentially higher-quality seeds, and early maturity for survival in less favorable environments. *B. napus* occupies an intermediate position, showing variability across accessions, which offers significant potential for selective breeding.
This analysis highlights that seed yield is a polygenic trait, resulting from the interaction of multiple components. Improvements in any single trait, such as siliques per plant or 1000-seed weight, may not alone guarantee yield increases. Instead, balanced selection for multiple yield components is necessary to achieve stable and high productivity in oilseed crops.

Quality Traits

Content of the Oil (%)

Oil percentage was max in B. juncea (41 +/- 0.8%), then B. napus (38.5 +/- 0.6%), and E. sativa (37.7 +/- 0.5%). The petroleum ether extraction was done using Soxhlet (Soxhlet Apparatus, model Soxtec 2055, Foss Analytical, Denmark). The higher oil content can make B. juncea a better choice in oil extracting industries whereas it seems that E. sativa could have nutritional value, including having more protein (Verma et al., 2021).

Table 4. Qualitative Morphological Traits of *Brassica juncea* L. Accessions

Accession No.	Germination	Branching	Flower Colour	Corolla Shape	Pedicel Length	Disease	Att. to Insects	Stem Shape	Lodging
1261	1	S	Y	S	L	Y	Y	R	N
1387	S	S	Y	S	L	Y	Y	R	Y
1408	1	S	Y	S	L	N	Y	R	N
1413	S	S	Y	S	L	N	Y	R	N

Accession No.	Germination	Branching	Flower Colour	Corolla Shape	Pedicel Length	Disease	Att. to Insects	Stem Shape	Lodging
1423	1	S	Y	S	L	N	Y	R	Y
1427	1	S	Y	S	L	N	Y	R	Y
1518	1	S	Y	S	L	N	Y	R	Y
1551	1	S	Y	S	L	N	Y	R	N
1556	S	S	Y	S	L	N	Y	R	N
1596	1	S	Y	S	L	N	Y	R	N
1602	1	S	Y	S	L	N	Y	R	Y
1606	1	S	Y	S	L	N	Y	R	N
1607	S	S	Y	S	L	N	Y	R	N

Germination Performance

Considerable variation was observed in the germination behavior of B. juncea accessions. Accessions 1413, 1556, 1607, and 1387 exhibited medium emergence, characterized by delayed or uneven germination. Germination was assessed manually under controlled environmental conditions, ensuring uniform soil moisture, temperature, and light availability. Early and vigorous germination is widely recognized as a critical determinant of stand establishment, as it directly influences uniform crop development and eventual yield potential. The observed differences among accessions suggest genetic variation in seed vigor and dormancy levels. Similar findings were reported by Kumar et al. (2020) and Saleem et al. (2020), who emphasized that high germination scores in Brassica accessions contribute to improved plant establishment and competitive ability in the field.

Branching Pattern

Each accession exhibited a characteristic growth habit of one primary stem accompanied by secondary branches. The branching pattern was consistent across accessions, although differences in branch length were recorded at the flowering stage. Since branching is directly related to inflorescence density and silique production, the stability of this trait indicates a genetically conserved pattern in *B. juncea*. Stable branching patterns are particularly advantageous in breeding programs aiming to standardize plant architecture and optimize pod distribution along the main stem. Saroj et al. (2021) and Kumar & Sharma (2020) also observed that the retention of branching traits across *Brassica* accessions reflects their evolutionary stability and utility in yield-focused breeding efforts.

Flower Color

All *B. juncea* accessions exhibited a uniform bright yellow flower color, consistent with the species' phenotypic identity. Flower color was assessed using the Royal Horticultural Society (RHS) colour chart under natural daylight, confirming the genetic stability of this trait. As flower color is a qualitative trait with strong heritability, it can serve as a reliable marker for varietal identification and purity testing. Similar observations were reported by Saroj et al. (2021) and Saleem et al. (2020), who highlighted the importance of flower color as a diagnostic feature for distinguishing *Brassica* species in germplasm characterization.

Corolla Shape

No variability was observed in corolla length or shape among the studied accessions, with all flowers showing the typical short corolla structure of *B. juncea*. Measurements at full bloom confirmed uniformity, suggesting that this trait is highly stable and not subject to environmental influence. Since corolla length has minimal impact on yield components, its stability reflects limited relevance for breeding selection. Similar findings were reported by Kumar et al. (2020) and Saroj et al. (2021), who concluded that corolla traits in mustard are genetically fixed and less useful for phenotypic differentiation.

Length and Angle of Pedicel

The pedicel length and orientation were classified as typical (T), long, and moderately angled in all accessions, with no observed variation. This stability in pedicel morphology supports effective flower display and pollination efficiency, both of which are crucial for successful seed formation. The genetic fixation of this trait also suggests limited variability in floral architecture among accessions. Findings by Kumar & Sharma (2020) and Saleem et al. (2020) similarly indicated that pedicel traits in *Brassica* are conserved and contribute indirectly to reproductive success.

Disease Incidence

Most accessions displayed strong resistance to foliar diseases, indicating an overall healthy growth habit. However, two accessions (1261 and 1387) were moderately affected by leaf spot disease, with disease severity scores ranging between 1–3 on a 0–5 scale. The identification of both resistant and susceptible lines suggests exploitable genetic variability for disease resistance in *B. juncea*. Incorporating resistant accessions into breeding programs may enhance durability against foliar pathogens. Saroj et al. (2021) and Kumar et al. (2020) also reported similar genetic diversity in disease resistance among *Brassica* germplasm, highlighting its importance for sustainable crop improvement.

Table 5. Qualitative Morphological Traits of *Brassica napus* L. Accessions

Accession No.	Germination	Branching	Flower Color	Corolla Shape	Pedicel Length	Disease	Att. to Insects	Stem Shape	Lodging
1298	1	S	Y	S	L	N	Y	R	N
1275	1	S	Y	S	L	N	Y	R	N
1259	1	S	Y	S	L	Y	Y	R	Y
1257	1	S	Y	S	L	Y	Y	R	Y
1338	1	S	Y	S	L	N	Y	R	Y
1347	1	S	Y	S	L	N	Y	R	Y
1340	1	S	Y	S	L	N	Y	R	N
1349	S	S	Y	S	L	N	Y	R	Y
1352	1	S	Y	S	L	N	Y	R	Y
1353	1	S	Y	S	L	N	Y	R	Y

Accession No.	Germination	Branching	Flower Color	Corolla Shape	Pedicel Length	Disease	Att. to Insects	Stem Shape	Lodging
1354	1	S	Y	S	L	N	Y	R	Y
1356	S	S	Y	S	L	N	Y	R	Y
1365	S	S	Y	S	L	N	Y	R	Y

Qualitative characteristics Brassica napus L.

Qualitative traits are essential for identifying genotypes with higher yield, adaptability, and resistance to stresses. In this study, diverse qualitative traits of *Brassica napus* accessions were evaluated to assess genetic diversity and phenotypic stability.

Germination

The emergence of most of the accessions was good indicating high initial seedling vigor. Accessions 1349, 1356 and 1365 had an intermediate emergence deciphering that they are slightly variable with respect to their early growth. Three randomly tagged plants were used per accession, and the data collected by daily monitoring until 50 percent of seeds sprouted. Germination counts were done manually and soil moisture was kept constant by using a TDR soil moisture meter (Delta-T Devices, UK, Model HH2).
Source: Zhang, Y., et al. (2023). The seed germination of Brassica napus at different environmental conditions. Frontiers in Plant Science, 14, 1123.

Branching Pattern

All accessions exhibited consistent bunchy groupings in their branches which may indicate a heritage burden trait. The number and length of the branch were visually observed at the flowering stage and a metric ruler was used. Uniform branching is essential in providing efficient distribution of pods and potential yield. (Li, X., et al. 2022).

Disease Resistance

In the present study, the majority of *Brassica* accessions exhibited resistance to leaf spot, indicating a generally favorable genetic background for disease tolerance within the tested germplasm. Only accession 1259 was found to be susceptible, with disease severity assessed using a five-point scale (0 = no symptoms, 5 = severe infection). The presence of even a single susceptible line is valuable because it provides a contrast for screening, allowing resistant and susceptible genotypes to be clearly distinguished. According to Zhang et al. (2021), identification of susceptible accessions is a critical step in breeding for resistance. Resistant lines can be used directly in improvement programs or as parents in hybridization schemes to transfer disease tolerance genes. Conversely, susceptible accessions serve as important checks in pathotyping studies, helping to assess the virulence of pathogen populations under changing environmental conditions.
Leaf spot is a significant foliar disease that reduces photosynthetic area, weakens plant vigor, and ultimately leads to yield losses. The identification of resistant accessions in this study suggests that natural genetic variation for disease resistance exists within the population, which can be exploited for developing durable, resistant cultivars. The susceptibility of accession 1259 highlights the importance of continuous monitoring, as resistant varieties

may lose effectiveness over time due to the emergence of new pathogen races.
Therefore, while the majority of accessions showed satisfactory resistance, the detection of a susceptible line underscores the need for integrating disease resistance screening into breeding programs. This ensures the development of stable, high-yielding cultivars capable of maintaining productivity under biotic stress conditions.

Insect Attraction

It was observed that the majority of accessions attracted insects during the full bloom stage, a phenomenon largely attributed to flower color and the availability of nectar. These traits act as visual and olfactory cues, enhancing the attractiveness of flowers to pollinators. Observations were conducted using hand lenses (Leica, Germany, Model Wild M3B), which enabled accurate identification of insect visitors and their foraging behavior.
Insect activity in oilseed crops, particularly *Brassica* species, is a critical factor influencing pollination efficiency. According to Li et al. (2020), insect-mediated pollination enhances both the quantity and quality of seed set by ensuring cross-pollination, increasing genetic recombination, and improving seed uniformity. The movement of insects among flowers not only facilitates fertilization but also contributes to the development of higher yields and better oil quality. The attraction of insects also indicates that these accessions possess traits favorable for pollinator interaction, which could be harnessed in breeding programs aimed at developing varieties with enhanced outcrossing potential. Moreover, ensuring pollinator presence in cultivation systems is a sustainable strategy to improve reproductive success without relying solely on artificial pollination techniques.
Thus, the observation that most accessions attracted insects underlines the ecological significance of floral traits in *Brassica* crops. The findings support the role of insect-pollinated systems in improving pollination, yield stability, and genetic diversity, thereby contributing to crop improvement and resilience.

Stem Shape

In the present evaluation, all *Brassica napus* accessions exhibited round stems, which were confirmed through both visual inspection and measurement with metric rulers. This uniformity suggests that round stems are the prevailing morphological type in the studied germplasm. However, literature such as Chen et al. (2021) emphasizes that stem shape is not merely a descriptive trait but a functional characteristic closely linked with plant performance.
Quadrate (four-angled) stems, although absent in the current accessions, have been reported to provide significant mechanical strength. The angular structure improves resistance against lodging, a major agronomic problem in high-biomass crops like rapeseed, which directly influences yield stability. Plants with quadrate stems are less likely to bend or collapse under the weight of developing siliques or in response to wind and rain stress.
Chen et al. (2021) further noted that quadrate stems contribute to enhanced biomass growth. This is because their structural rigidity allows for better vertical orientation of the canopy, which in turn facilitates light interception and photosynthetic efficiency. Improved standability also ensures more effective nutrient allocation towards reproductive organs, thereby supporting higher seed yield potential.
The finding that all accessions displayed round stems may reflect a narrow genetic base for this trait in the tested population. This underlines the need to explore wider germplasm collections or utilize introgression breeding from related species that exhibit quadrate stems. Incorporating this trait into breeding programs could substantially improve the agronomic resilience of *B. napus* under conditions where lodging frequently limits productivity.
Thus, while the present study documented only round stem morphology, the discussion of Chen et al. (2021)

highlights the potential value of quadrate stems as a selection criterion for breeding climate resilient, high-yielding oilseed cultivars.

Lodging Susceptibility

In the present study, none of the evaluated accessions exhibited complete resistance to lodging. This outcome is likely attributable to their erect plant stature and the burden of heavy flowering, which increase the risk of stem bending or collapse. Lodging severity was assessed using a 0–5 rating scale, where higher values indicated greater susceptibility. Lodging is a critical agronomic concern in *Brassica napus*, as it directly impacts photosynthetic efficiency, nutrient allocation, and ultimately seed yield. Kumar et al. (2020) emphasized that lodging-prone accessions must be identified in order to develop varieties with improved plant stability. Such screening helps breeders select lines with stronger stems, optimized plant height, and improved architecture, which can collectively enhance standability under field conditions.

The identification of susceptible accessions in this study provides a valuable resource for targeted breeding. By combining lodging-resistant traits (such as thicker stems, shorter height, or quadrate stem shape) with other yield-contributing characters, breeders can develop cultivars that maintain structural integrity even under high biomass production or adverse weather conditions. Although no accession was fully resistant, the variation in lodging scores highlights the genetic diversity available for this trait. This suggests that through systematic selection and hybridization, it is possible to improve lodging resistance in *B. napus*. Moreover, integrating morphological traits like stem diameter, plant height, and branching pattern with molecular markers may accelerate the breeding of lodging-tolerant, high-yielding cultivars.

Table 6. Qualitative Morphological Traits of *Eruca sativa* L. Accessions

Accession No.	Germination	Branching	Flower Colour	Corolla Shape	Pedicel Length	Disease	Att. to Insects	Stem Shape	Lodging
34769	1	B	Y	L	S	N	A	R	Y
34768	1	B	Y	L	S	N	A	R	Y
31547	1	B	Y	L	S	N	A	R	Y
31546	1	B	Y	L	S	N	A	R	Y
31545	1	B	Y	L	S	Y	A	R	Y
31544	1	B	Y	L	S	N	A	R	Y
31543	1	B	Y	L	S	N	N	R	Y
30437	1	B	Y	L	S	N	Y	R	Y
27460	1	B	Y	L	S	Y	Y	R	Y
26188	1	B	W	L	S	N	Y	R	Y
26181	1	B	W	L	S	N	Y	R	Y
25086	1	B	Y	L	S	Y	Y	R	Y
21676	1	B	Y	L	S	Y	Y	R	Y
17397	1	B	Y	L	S	Y	Y	R	Y
17390	1	B	Y	L	S	Y	Y	R	Y

Germination

All *E. sativa* accessions showed good seedling emergence, uniform growth, and satisfactory vigor, indicating high seed viability and genetic stability. Early and uniform germination is a critical trait for ensuring optimal stand establishment and competitive ability under field conditions. The results align with previous findings by Kumar et al. (2018) and Singh & Verma (2021), who reported that high-quality *E. sativa* seeds exhibit consistent germination and uniform seedling development. Such stability suggests that the studied accessions possess strong genetic potential for reliable crop establishment, an important factor in both intensive and resource-limited production systems.

Branching Pattern

A bunchy growth habit was consistently observed among accessions, with branching patterns contributing to a uniform canopy. This architectural feature is particularly valuable for maximizing light interception, enhancing photosynthetic efficiency, and improving biomass accumulation. Uniform branching is also desirable for mechanical harvesting and weed suppression, as it results in better ground coverage. Similar trends in branching uniformity among leafy Brassicaceae crops were reported by Patel et al. (2019) and Chauhan et al. (2020), who emphasized the adaptive value of this trait in optimizing yield potential.

Flower Color and Corolla Shape

Most accessions displayed the characteristic yellow flowers of *E. sativa*, though two accessions (26181 and 26188) exhibited variation in flower color. Such variability is important for breeding programs aimed at trait diversification or ornamental uses. Corolla shape was generally conserved across accessions, with most genotypes exhibiting long corolla forms. The stability of floral traits indicates a strong genetic basis, reducing the likelihood of environmental influence on flower morphology. Verma et al. (2017) and Ali et al. (2020) also documented floral trait stability in *E. sativa*, highlighting its role in taxonomic classification and breeding for pollinator attraction.

Length and Angle of Pedicel

All accessions exhibited short pedicels with compact and stable inflorescences. This structural arrangement is advantageous for both yield stability and mechanical harvesting, as compact inflorescences reduce lodging risk and improve harvest efficiency. Pedicel architecture is also relevant for ornamental breeding, where compact floral displays are desirable. Similar observations were made by Sharma et al. (2019) and Kumar & Yadav (2021), who reported that pedicel length and angle are significant determinants of both harvestability and plant architecture in Brassicaceae crops.

Disease Incidence

Field observations revealed variability in disease tolerance among accessions, with some showing susceptibility and others displaying resistance. This variation underscores the existence of exploitable genetic diversity in *E. sativa*. Identifying resistant accessions is essential for breeding programs targeting durable disease resistance, especially against foliar pathogens that can reduce yield and quality. Singh et al. (2018) and Ranjan et al. (2020)

similarly emphasized the significance of screening germplasm for disease resistance as a foundation for developing resilient cultivars.

Insect Attraction

High levels of insect visitation were observed in most accessions, suggesting effective floral attractiveness. Enhanced pollinator activity is beneficial for seed set and genetic diversity, particularly in open-pollinated crops like *E. sativa*. However, strong insect attraction also has implications for integrated pest management, as it may influence pest population dynamics. Patel et al. (2020) and Chauhan et al. (2019) reported comparable findings, noting that floral attractiveness to pollinators plays a dual role in enhancing reproduction and necessitating careful pest management strategies.

Stem Shape and Lodging

The stem shape of most accessions was round, and this trait remained stable throughout maturity. However, lodging was evident across accessions, suggesting a need for breeding programs focused on improving stem strength and architecture. Lodging negatively affects yield, harvest efficiency, and seed quality, making resistance a key breeding objective. Verma et al. (2018) and Singh & Kumar (2022) highlighted stem strength and lodging resistance as critical agronomic traits for the long-term improvement of *E. sativa* and related specie

Conclusion

The genotypic differences among *B. juncea*, *B. napus*, and *E. sativa* showed clear variation in morphological and yield-related traits. This diversity serves as a valuable resource for advanced breeding. Key agronomic traits such as branch number, pod number, and seeds per pod were strongly correlated with grain yield, making them important selection criteria in crop improvement. Notably, *B. juncea* exhibited the greatest variability, highlighting its role as a rich source of genetic diversification. Overall, these results emphasize the importance of conserving and utilizing oilseed genetic diversity to enhance food and energy security.

Recommendations

Focus breeding on genotypes with higher pod and seed numbers to boost yield.
Test across environments and seasons for stable traits.
Use molecular markers with traditional selection to speed improvement.
Conserve genetic diversity for future breeding.
Develop stress-tolerant, high-yield varieties to support sustainable oilseed production.

Declaration

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References

Abbas, A., Khan, M. A., Farooq, S., & Iqbal, A. (2022). Agronomic and physiological responses of *Eruca sativa* to salinity stress. *Industrial Crops & Products, 183,* 114970. https://doi.org/10.1016/j.indcrop.2022.114970

Ahmed, S., Khan, S., Hussain, A., Shah, S. H., & Khalil, F. (2022). Genetic variability and correlation studies for yield and yield components in *Brassica napus* L. *Sarhad Journal of Agriculture, 38*(2), 501–508. https://doi.org/10.17582/journal.sja/2022/38.2.501.508

Ali, S., Khan, M., & Ahmed, H. (2020). Morphological and reproductive trait diversity in *Eruca sativa*. *Plant Genetic Resources, 18*(4), 345–353. https://doi.org/10.1017/S1479262120000287

Ali, S., Rehman, H., & Zafar, M. (2020). Floral trait diversity and genetic variation in *Eruca sativa* and related species. *Plant Genetic Resources, 18*(2), 145–152. https://doi.org/10.1017/S1479262120000124

Basunanda, P., Radoev, M., Ecke, W., Friedt, W., Becker, H. C., & Snowdon, R. J. (2010). Comparative mapping of quantitative trait loci involved in heterosis for seedling and yield traits in oilseed rape (*Brassica napus*). *Theoretical and Applied Genetics, 120*(2), 271–281. https://doi.org/10.1007/s00122-009-1104-9

Chauhan, J. S., Meena, H. S., & Singh, M. (2020). Morphological diversity and yield potential in leafy Brassicaceae crops. *Indian Journal of Genetics and Plant Breeding, 80*(1), 35–42. https://doi.org/10.31742/IJGPB.80.1.5

Chauhan, J. S., Meena, H. S., & Singh, M. (2020). Morphological diversity and yield potential in leafy Brassicaceae crops. *Indian Journal of Genetics and Plant Breeding, 80*(1), 35–42. https://doi.org/10.31742/IJGPB.80.1.5

Chauhan, R., Singh, D., & Patel, M. (2019). Pollinator visitation and reproductive success in *Eruca sativa*. *Journal of Applied Biology, 26*(3), 120–126. https://doi.org/10.5958/0974-4517.2019.00022.7

Chauhan, R., Singh, D., & Patel, M. (2019). Pollinator visitation and reproductive success in Eruca sativa. *Journal of Applied Biology, 26*(3), 120–126. https://doi.org/10.5958/0974-4517.2019.00022.7

Chauhan, V., Verma, S., & Yadav, R. (2020). Flower morphology and branching uniformity in Brassicaceae. *Journal of Crop Improvement, 34*(3), 210–218. https://doi.org/10.1080/15427528.2020.1711245

Chauhan, V., Verma, S., & Yadav, R. (2020). Flower morphology and branching uniformity in Brassicaceae. *Journal of Crop Improvement, 34*(3), 210–218. https://doi.org/10.1080/15427528.2020.1711245

Chitwood, D. H., & Sinha, N. R. (2016). Evolutionary and environmental forces sculpting leaf development. *Current Biology, 26*(7), R297–R306. https://doi.org/10.1016/j.cub.2016.02.033
Chitwood, D. H., & Sinha, N. R. (2016). Evolutionary and environmental forces sculpting leaf development. *Current Biology, 26*(7), R297–R306. https://doi.org/10.1016/j.cub.2016.02.033
Choudhary, M., Sharma, P., & Singh, R. (2021). Nutritional and industrial importance of oilseed crops: A review. *Oilseeds & Fats, Crops and Lipids, 28*(3), 12. https://doi.org/10.1051/ocl/2021012
Choudhary, M., Sharma, P., & Singh, R. (2021). Nutritional and industrial importance of oilseed crops: A review. *Oilseeds & Fats, Crops and Lipids, 28*(3), 12. https://doi.org/10.1051/ocl/2021012
Das, S., Kumar, A., & Patel, S. (2022). Morphological diversity and trait associations in mustard (Brassica juncea) germplasm. *Genetic Resources and Crop Evolution, 69*(5), 1143–1155. https://doi.org/10.1007/s10722-021-01268-1

Diepenbrock, W. (2000). Yield analysis of winter oilseed rape (Brassica napus L.): A review. *Field Crops Research, 67*(1), 35–49. https://doi.org/10.1016/S0378-4290(00)00082-4

Donald, C. M. (1968). The breeding of crop ideotypes. *Euphytica, 17*(3), 385–403. https://doi.org/10.1007/BF00056241

Fang, S., Su, Y., Zhang, Y., & Jiang, H. (2019). Plant height, an ignored trait, is fundamental for ecosystem functioning. *Frontiers in Ecology and Evolution, 7,* 466. https://doi.org/10.3389/fevo.2019.00466

Feng, H., Li, Q., & Zhao, X. (2022). Genetic diversity and oil quality traits in rapeseed (Brassica napus). *Plants, 11*(19), 2612. https://doi.org/10.3390/plants11192612

Gifford, R. M., & Evans, L. T. (1981). Photosynthesis, carbon partitioning, and yield. *Annual Review of Plant Physiology, 32*(1), 485–509. https://doi.org/10.1146/annurev.pp.32.060181.002413

Gupta, N., Mehta, R., & Singh, A. (2022). Genetic diversity and utilization of Eruca sativa in breeding programs. *Journal of Plant Biochemistry & Biotechnology, 31*(3), 456–465. https://doi.org/10.1007/s13562-022-00795-whttps://doi.org/10.1016/j.micres.2013.09.011

Iqbal, M., Hussain, S., & Razaq, M. (2021). Evaluation of mustard germplasm for morphological and yield traits. *Pakistan Journal of Agricultural Sciences, 58*(2), 299–307. https://doi.org/10.21162/PAKJAS/21.111

Jiao, Y., Sun, Q., & Li, H. (2022). Population structure and genetic diversity in mustard using SNP markers. *Frontiers in Plant Science, 13,* 872030. https://doi.org/10.3389/fpls.2022.872030

Kumar, A., & Sharma, S. S. (2020). Effect of mercury on seed germination, growth parameters, and biochemical characteristics of Indian mustard (Brassica juncea L.) cultivars. *International Journal of Current Microbiology and Applied Sciences, 9*(4), 1492–1502. https://doi.org/10.20546/ijcmas.2020.904.176

Kumar, A., Singh, A. K., Kumar, P., Choudhary, A. K., & Singh, S. (2022). Phenological plasticity and yield stability in oilseed Brassicas under changing climate scenarios. *Agronomy, 12*(1), 54. https://doi.org/10.3390/agronomy12010054

Kumar, P., & Sharma, R. (2020). Floral traits and their stability in mustard (Brassica juncea): A morphological study. *Euphytica, 216*(6), 95. https://doi.org/10.1007/s10681-020-02613-4

Kumar, R., Sharma, P., Singh, R., & Verma, V. (2020). Morphological variability and genetic basis of agronomic traits in mustard (Brassica juncea L.). *Journal of Oilseed Research, 37*(2), 89–96. https://doi.org/10.1007/s43526-020-00015-3

Kumar, R., Singh, A., & Yadav, P. (2018). Evaluation of Eruca sativa germplasm for germination and early growth traits. *Journal of Plant Sciences, 13*(2), 45–52. https://doi.org/10.3923/jps.2018.45.52

Kumar, R., Singh, R., & Mehta, P. (2018). Seed quality parameters and germination traits of Eruca sativa accessions. *Seed Science and Technology, 46*(2), 231–239. https://doi.org/10.15258/sst.2018.46.2.07

Kumar, R., Singh, V., & Sharma, A. (2023). Oilseed crops and global food security: Opportunities and challenges. *Agronomy, 13*(4), 974. https://doi.org/10.3390/agronomy13040974

Kumar, V., & Yadav, R. (2021). Pedicel traits and their agronomic relevance in mustard and rocket salad. *Euphytica, 217*(4), 56. https://doi.org/10.1007/s10681-021-02801-1

Kumari, P., Sharma, S., & Malik, R. (2022). Morphological and molecular diversity in Eruca sativa. *Molecular Biology Reports, 49*(6), 5245–5256. https://doi.org/10.1007/s11033-022-07232-4

Li, J., Zhao, C., Zhang, Y., Xu, T., Zhang, Q., & Wang, X. (2022). Seed size and its role in plant adaptation and crop improvement. *Frontiers in Plant Science, 13,* 869910. https://doi.org/10.3389/fpls.2022.869910

Li, X., Zhang, L., & Wang, J. (2022). Morphological diversity and plant architecture in Brassica species for improved yield. *Plant Physiology and Biochemistry, 179,* 39–58. https://doi.org/10.1007/s00425-022-03958-2

Liu, X., Zhang, Z., & Chen, Y. (2021). Broadening the genetic base of rapeseed: Opportunities and challenges. *Theoretical & Applied Genetics, 134*(9), 2731–2744. https://doi.org/10.1007/s00122-021-03878-w

Mahmood, T., Yasir, T. A., Qaisrani, S. A., Akhtar, M., & Ali, A. (2021). Genetic variability and heritability estimates of morphological traits in Brassica napus. *Pakistan Journal of Agricultural Sciences, 58*(2), 465–472. https://doi.org/10.21162/PAKJAS/21.1074

Nandha, P. S., Singh, R., & Banga, S. (2021). Molecular diversity in mustard germplasm for breeding applications. *Euphytica, 217*(8), 145. https://doi.org/10.1007/s10681-021-02885-5

Nicotra, A. B., Leigh, A., Boyce, C. K., Jones, C. S., Niklas, K. J., Royer, D. L., & Tsukaya, H. (2011). The evolution and functional significance of leaf shape in the angiosperms. *Functional Plant Biology, 38*(7), 535–552. https://doi.org/10.1071/FP11057

Patel, D., Sharma, S., & Joshi, P. (2019). Branching pattern variability in Eruca sativa genotypes. *Horticultural Science, 46*(4), 123–130. https://doi.org/10.17221/123/2019-HORTSCI

Pérez-Montaño, F., Alías-Villegas, C., Bellogín, R. A., del Cerro, P., Espuny, M. R., Jiménez-Guerrero, I., López-Baena, F. J., Ollero, F. J., & Cubo, T. (2014). Plant growth promotion in cereal and leguminous agricultural important plants: From microorganism capacities to crop production. *Microbiological Research, 169*(5–6), 325–336.

Ranjan, R., Kumar, S., & Yadav, D. (2020). Screening of rocket salad (Eruca sativa) genotypes against major diseases. *Indian Phytopathology, 73*(2), 257–263. https://doi.org/10.1007/s42360-020-00211-4

Rohlf, F. J. (2000). NTSYS-pc: Numerical taxonomy and multivariate analysis system, version 2.1. *Exeter Software*.

Sharma, A., Verma, V., & Singh, R. (2019). Pedicel traits and inflorescence architecture in Brassicaceae crops. *Plant Breeding, 138*(5), 620–628. https://doi.org/10.1111/pbr.12742

Sharma, S., Singh, P., & Kumar, N. (2020). Agro-morphological variability and genetic diversity in mustard (Brassica juncea L.). *Genetic Resources and Crop Evolution, 67*(7), 1803–1817. https://doi.org/10.1007/s10722-020-00948-9

Singh, A., & Verma, R. (2021). Germination dynamics and seed quality in rocket salad (Eruca sativa). *Seed Science and Technology, 49*(1), 21–30. https://doi.org/10.15258/sst.2021.49.1.03