Evaluating pod variability and allometric growth dynamics in Moringa oleifera progenies

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Abstract

Moringa oleifera is a globally significant multipurpose crop, yet the physiological linkages between maternal reproductive investment and progeny fitness remain insufficiently characterized to enable high-precision breeding. This study evaluated the ontogenetic parameters and allometric growth patterns of ten genotypes (MO-11 to MO-20) and their corresponding progenies (P-11 to P-20) to identify elite germplasm for industrial and nutritional applications. Maternal phenotypic analysis revealed significant sink-strength variability; accession MO-11 exhibited maximized pod robusticity (length: 47.81; weight: 13.10 g), while MO-16 recorded the peak 100-seed weight (19.14 g). A pronounced reproductive trade-off was observed in MO-20, where high seed prolificacy (21.60 seeds/pod) inversely correlated with individual seed mass and subsequent germination vigor (64.42).

Progeny evaluation through 90 days after sowing (DAS) highlighted a critical decoupling between initial establishment and long-term structural vigor. While P-15 demonstrated superior initial germination, P-16 emerged as the elite line for structural acceleration, nearly tripling its Shoot Vigour Index (SVI) to 46.03 by 90 DAS. Biomass partitioning analysis further identified P-19 as a superior candidate for nutrient conversion efficiency, recording the maximum dry matter accumulation (20.77 g). Multivariate analysis (PCA and Hierarchical Clustering) successfully categorized the progenies, identifying P-16 and P-19 as elite lines with superior growth profiles. Correlation analysis demonstrated that SVI is primarily driven by shoot and total length (r = 0.99), whereas germination percentage showed a weaker relationship with overall vigor. The high stability and low phenotypic plasticity of 100-seed weight (C.V. = 2.07) and 90-day structural traits validate these parameters as robust bio-morphological markers. These findings provide a quantitative framework for genomic-assisted selection, classifying MO-11 for vegetable yield and MO-16/P-16 for industrial oil extraction and high-density silvicultural systems.

1. Introduction

Moringa oleifera Lam., a member of the monogeneric family Moringaceae, is a versatile tree species recognized globally for its nutritional, medicinal, and industrial value. It is known by various regional vernacular names, including *dandalonbin* (Burmese), *shajna* (Hindi), *murungai* (Tamil), and *muringa* (Malayalam), reflecting its deep-rooted integration into diverse agro-climatic regions. The species exhibits significant phenotypic plasticity, maintaining an evergreen habit in tropical humid zones while becoming deciduous in sub-tropical climates (Folkard et al., 1999 [2]). It demonstrates remarkable ecophysiological resilience, thriving within an optimal thermal range of 25 to 35°C, yet capable of surviving extreme drought conditions with temperatures reaching 48°C and occasional winter frosts (Price, 2000 [7]). The species is currently cultivated in over 60 countries as a multi-purpose crop (Mridha, 2015 [5]). Among the thirteen known species within the genus, *M. oleifera* and *M. peregrina* hold the greatest economic significance due to their extensive agricultural applications (Leone et al., 2015 [4]). In India, *Moringa* is a major commercial vegetable crop, primarily grown for its edible pods and leaves, with the potential to produce approximately 580 t/ha of fresh biomass annually. However, actual crop yields are highly contingent upon seasonal fluctuations, climatic variables, genotype selection, and fertilization regimes. National production in India ranges from 2.20 to 2.40 million tons of tender fruits annually from an estimated area of 38,000 hectares, representing an average productivity of 63 t/ha. Production is geographically concentrated in southern states, with Andhra Pradesh (15,665 ha) ranking first, followed by Tamil Nadu (13,250 ha) and Karnataka (10,280 ha) (Sekhar et al., 2018 [8]).

The botanical characteristics of *Moringa* include zygomorphic, bisexual flowers that are yellowish-white in color, featuring five thin, unequal, and veined petals. While numerous regional landraces exist—such as Moolanur, Valayapatti, and Jaffna types—commercial cultivation throughout India and globally is dominated by improved, high-yielding varieties like PKM-1 and PKM-2. Despite the prevalence of these cultivars, significant natural variability exists among "plus trees" within indigenous populations. Understanding the relationship between pod morphology and progeny vigor is essential for advancing breeding programs and improving nursery management. Consequently, the present study was designed to evaluate natural pod variability and the performance of progenies from selected plus trees, with a specific focus on seed germination kinetics and early seedling morphological characteristics.

2. Materials and methods

2.1 Experimental Site and Climatic Conditions

The study was conducted at the nursery of the College of Agriculture, Chaudhary Charan Singh Haryana Agricultural University, Bawal, Haryana, India (28.08°N latitude, 76.58°E longitude; 266 m above mean sea level). The regional climate is characterized as semi-arid with low and erratic annual precipitation ranging between 350 and 550 mm, primarily occurring during the monsoon season (July to September). The site experiences extreme thermal fluctuations, with mean maximum temperatures reaching 46°C during the peak summer months (May–June) and minimum temperatures dropping to 0°C during the winter (December–January).

2.2 Germplasm Collection and Selection of Plus Trees

A total of ten accessions were identified and selected based on phenotypic superiority from ten distinct geographical locations in Rajasthan (Table 1). Each accession comprised five "plus trees" (genotypically superior individuals). Mature pods were harvested from these selected trees to evaluate natural variability and progeny performance.

2.3 Morphological Characterization of Pods

To assess pod variability, a total of 150 pods (50 pods per replication) were randomly selected for each accession. The following morphological parameters were recorded for pod morphometrics, including pod length (cm), pod diameter (mm), total pod weight (g), and seed characteristics such as Number of seeds per pod and 100-seed weight (g).

Following morphological assessment, the pods were subjected to uniform sun-drying. Seeds were manually extracted and processed for subsequent nursery establishment.

2.4 Nursery Establishment and Experimental Design

The extracted seeds were sown in the nursery to evaluate progeny performance. The experiment was laid out in a Completely Randomized Design (CRD) with three replications. Standard nursery management practices, including irrigation and weeding, were uniformly applied to ensure optimal seedling development. Observations regarding the growth and vigor of the progenies were recorded at two critical growth stages: 45 and 90 days after sowing (DAS). Seedling parameters such as Germination percentage (%), Shoot length (cm), root length (cm), total seedling length (cm), collar diameter (mm), and the number of leaves per seedling. Seedling fresh weight (g) and dry weight (g), Seedling Vigor Index (SVI) and Root Vigor Index (RVI) were calculated to determine the comparative physiological strength of the accessions.

2.5 Statistical Analysis

The recorded data were subjected to Analysis of Variance (ANOVA) to determine the significance of variance among the accessions, following the statistical procedure outlined by Panse and Sukhatme,1961 [6]. Mean values were derived from the three replications. All statistical computations, including the determination of Critical Difference (CD) at a 5% level of significance, were performed using the OPSTAT statistical software (CCS HAU, Hisar) [10].

Table 1
Provenance and Collection Details of Twenty-Four *Moringa oleifera* Genotypes

Samples	Location	State	Cultivars	Co-ordinates
MO-11	Kundansinghpura, Neemrana	Rajasthan, India	Cultivated	27º59´48″ N 76º22´00″ E
MO-12	Neemrana	Rajasthan, India	Wild	27º58´42″ N 76º23´42″ E
MO -13	Behrorjat, Distt. Alwar	Rajasthan, India	Wild	27º58´04″ N 76º26´23″ E
MO -14	Baghana, Distt. Alwar	Rajasthan, India	Wild	28º01´41″ N 76º40´22″ E
MO -15	Jhajharpur, Distt. Alwar	Rajasthan, India	Wild	27º51´23″ N 76º26´53″ E
MO -16	Dhelawas, Distt. Alwar	Rajasthan, India	Cultivated	28º15´00″ N 76º32´24″ E
MO -17	Bansur, Distt. Alwar	Rajasthan, India	Wild	27º40´09″ N 76º21´25″ E
MO -18	Hajipur, Distt. Alwar	Rajasthan, India	Wild	27º41´15″ N 76º26´53″ E
MO -19	Badlidhani, Mandawar, Distt. Alwar	Rajasthan, India	Wild	27º46´43″ N 76º32´23″ E
MO -20	Pehal, Mandawar, Distt. Alwar	Rajasthan, India	Wild	27º48´58″ N 76º33´18″ E

3. Results

3.1. Variability in Pod Morphological Traits

Significant variation was observed among the ten evaluated genotypes for all pod-related morphological traits (Table 2). Multivariate analysis was employed to consolidate these traits into a holistic performance profile..The length of the pod ranged from 31.40 (MO-16) to 47.81 cm (MO-11), with a grand mean of 39.41 cm. Genotype MO-11 was identified as the superior performer for pod length, significantly outperforming the mean and other genotypes like MO-15 (34.83 cm) and MO-19 (34.60 cm).

The pod diameter followed a similar trend, with MO-11 recording the maximum significant diameter (19.14 mm). In contrast, the minimum diameter was recorded in MO-17 (11.42 mm). The pod weight showed a substantial range of 5.67g (MO-17) to 13.10 g (MO-11). It is noteworthy that MO-11 and MO-12 exhibited significantly higher pod weights (13.10 g and 11.25g, respectively) compared to the overall mean of 7.58 g, suggesting their potential for high-biomass selection. The number of seeds per pod and 100-seed weight are critical determinants of yield, and both showed significant genotype-dependent differences. The number of seeds per pod varied from 11.40 (MO-15) to a maximum of 21.60 (MO-20). Genotypes MO-20, MO-17, MO-12, and MO-11 were statistically at par, all producing more than 20 seeds per pod (Table 1).

Interestingly, a distinct pattern was observed for 100-seed weight. While MO-11 and MO-20 had high seed counts, their 100-seed weights were moderate (11.45 g and 11.96 g, respectively). The highest 100-seed weights were recorded in MO-16 (19.14 g) and MO-15 (18.50 g), which were significantly higher than the grand mean of 13.13 g.

The PCA biplot accounted for a significant portion of the total variance, illustrating a strong positive correlation between Pod Length, Pod Diameter, and Pod Weight. This suggests that breeding for any one of these physical dimensions will likely lead to a concurrent increase in the others. However, a distinct trade-off was observed between Number of Seeds per Pod and 100-Seed Weight (Fig. 1). The 100-seed weight showed the lowest C.V. (2.07), indicating high precision and stability of this trait across replicates (Table 2). Conversely, the number of seeds per pod exhibited the highest C.V. (23.25), suggesting a greater degree of environmental influence or inherent biological variability in seed set among the genotypes.

Under multivariate chart (Fig. 2), outer boundary represents the maximum performance across the group. MO-11 (Blue line) stretches furthest toward the top and right, showing it is a "physical giant" in this group. MO-16 and MO-15 stretch toward the left, indicating they prioritize seed density/weight over pod size.

Genotypes	Length of pod (cm)	Pod diameter (mm)	Pod weight(g)	Number of seeds per pod	100 seed weight
MO-11	47.81 ± 0.70	19.14 ± 1.52	13.10 ± 0.23	20.67 ± 1.01	11.45 ± 0.05
MO-12	39.93 ± 1.01	14.98 ± 0.55	11.25 ± 0.40	20.73 ± 1.04	8.71 ± 0.11
MO -13	37.89 ± 1.16	12.53 ± 0.23	6.05 ± 0.38	16.93 ± 1.24	12.37 ± 0.09
MO -14	37.89 ± 0.65	14.40 ± 0.50	6.53 ± 0.47	14.27 ± 0.64	16.62 ± 0.33
MO -15	34.83 ± 0.33	14.80 ± 0.37	6.57 ± 0.19	11.40 ± 0.72	18.50 ± 0.21
MO -16	31.40 ± 1.64	16.22 ± 0.38	6.87 ± 0.75	14.53 ± 6.42	19.14 ± 0.17
MO -17	43.14 ± 0.88	11.42 ± 0.35	5.67 ± 0.37	21.13 ± 0.57	8.63 ± 0.09
MO -18	42.79 ± 0.68	11.79 ± 0.08	5.84 ± 0.04	20.53 ± 1.33	9.33 ± 0.18
MO -19	34.60 ± 4.52	13.41 ± 0.90	6.48 ± 1.63	13.27 ± 2.71	14.59 ± 0.05
MO -20	43.81 ± 0.15	13.07 ± 0.33	7.48 ± 0.28	21.60 ± 0.31	11.96 ± 0.06
Mean	39.41	14.18	7.58	17.51	13.13
C.D.	4.95	1.94	1.89	6.98	0.47
C.V.	7.33	7.97	14.50	23.25	2.07

Heatmap analysis uses Z-scores (standardization) where MO-11 is the top performer for physical dimensions (Length, Diameter, Weight), while MO-16 dominates in 100-seed weight despite having the shortest pods (Fig. 3).

Table 3
Germination percentage, collar diameter of different progenies of Moringa at 45 and 90 DAS in nursery

Progenies	Germination percentage (%)	Collar diameter (cm)		Number of leaves	
		45 DAS	90 DAS	45 DAS	90 DAS
P-11	75.62	2.88 ± 0.28	4.47 ± 0.28	77.67 ± 2.40	97.33 ± 4.33
P-12	72.32	3.95 ± 0.16	5.92 ± 0.45	59.00 ± 3.06	108.00 ± 4.58
P-13	68.96	2.52 ± 0.12	5.36 ± 0.34	32.67 ± 3.18	116.67 ± 4.10
P-14	73.27	2.63 ± 0.28	4.07 ± 0.45	34.00 ± 1.73	87.67 ± 3.18
P-15	75.83	3.63 ± 0.19	3.89 ± 0.33	58.33 ± 2.03	100.67 ± 0.88
P-16	65.92	3.17 ± 0.41	4.38 ± 0.17	72.33 ± 2.91	113.67 ± 4.33
P-17	74.43	2.72 ± 0.29	3.86 ± 0.35	56.33 ± 2.03	109.00 ± 4.04
P-18	70.36	2.46 ± 0.16	3.88 ± 0.20	41.67 ± 1.20	110.67 ± 6.36
P-19	73.73	2.45 ± 0.16	4.52 ± 0.23	56.33 ± 2.33	95.67 ± 1.67
P-20	64.42	2.10 ± 0.05	4.97 ± 0.38	46.33 ± 3.28	100.67 ± 2.96
Mean (x)	71.49	2.85	4.53	53.47	104
C.D.	**--**	**0.69**	0.98	7.43	11.68
C.V.	--	14.02	12.60	8.10	6.55

3.2. Progeny Germination and Early Growth Performance

The distribution boxplot highlights the variability within the dataset for each standardized parameter, where most traits are relatively well-distributed (Fig. 4). The boxplot analysis highlighted that while germination rates were relatively stable across the population (low standard deviation), traits like SVI and Shoot Length exhibited high plasticity, offering a significant window for selection in breeding programs.

Early growth, measured by collar diameter and number of leaves, demonstrated distinct developmental trajectories (Table 3). At 45 days after sowing (DAS), P-12 recorded the maximum collar diameter (3.95 cm), a lead it maintained through to 90 DAS (5.92 cm). This performance was significantly higher than the grand mean of 4.53 cm. The number of leaves per plant served as a proxy for the photosynthetic capacity of the progenies. At 45 DAS, P-11 showed the most vigorous leaf production (77.67), outperforming all other lines. However, by 90 DAS, a shift in growth dynamics was observed, with P-13 achieving the highest leaf count (116.67). The variability for leaf count at 90 DAS was notably low (C.V. = 6.55), indicating that once the progenies passed the initial establishment phase, their growth became highly uniform across replicates. Five progenies had greater values than the grand mean (104).

The PCA plot (Fig. 5) reduces the complexity of the 10 traits into two main dimensions (PC1 and PC2). PC1 explains 56.0% of the variance and is largely defined by length and biomass traits. The plot clearly demarcated P-16 and P-19 as distinct outliers from the main cluster, positioned on the far right of the PC1 axis, which is heavily weighted by length-based traits and vigor indices, indicating they have distinct growth characteristics compared to others.

Figure 5: Principal Component Analysis (PCA) biplot depicting the multivariate distribution of progenies

3.3. Shoot and Root System Architecture

The analysis of root and shoot development provided deeper insights into the vigor of the progenies (Table 4). At 90 DAS, shoot length showed dramatic differentiation, ranging from 23.67 cm (P-14) to a striking 69.83 cm in P-16. Similarly, root length at 90 DAS was maximized in P-16 (20.00 cm), which was significantly higher than the mean of 13.7 cm.

The total seedling length at 90 DAS highlighted P-16 (89.83 cm) and P-19 (77.33 cm) as the most vigorous lines, both significantly outperforming the grand mean of 49.98 cm. It is important to note that P-15, which excelled in early germination, also maintained high shoot and root length at 45 DAS, suggesting it is a "fast-starter" in the nursery phase.

Table 4
Shoot length, Root length of different progenies of Moringa at 45 and 90 DAS in nursery

Progenies	Shoot length (cm)		Root length (cm)		Total length (cm)	
	45 DAS	90 DAS	45 DAS	90 DAS	45 DAS	90 DAS
P-11	17.86 ± 0.14	27.00 ± 1.53	8.07 ± 0.52	10.80 ± 1.04	25.92 ± 0.40	37.80 ± 2.08
P-12	20.10 ± 0.49	35.17 ± 1.32	9.23 ± 0.15	12.33 ± 0.44	29.33 ± 0.44	47.50 ± 1.66
P-13	18.33 ± 0.44	29.37 ± 1.48	9.13 ± 0.58	11.30 ± 0.79	27.47 ± 0.73	40.67 ± 2.14
P-14	21.50 ± 0.93	23.67 ± 0.76	9.50 ± 0.29	12.97 ± 0.90	31.00 ± 0.64	36.63 ± 1.37
P-15	22.73 ± 0.39	59.00 ± 2.31	11.87 ± 0.59	12.73 ± 0.82	34.60 ± 0.55	39.37 ± 1.39
P-16	20.56 ± 0.32	69.83 ± 1.42	9.93 ± 0.64	20.00 ± 0.58	30.50 ± 0.55	89.83 ± 1.75
P-17	19.77 ± 0.65	28.67 ± 1.20	10.13 ± 0.20	13.57 ± 0.99	29.90 ± 0.81	42.23 ± 2.13
P-18	19.83 ± 0.60	31.67 ± 2.19	10.53 ± 0.38	13.23 ± 1.18	30.37 ± 0.92	44.90 ± 2.08
P-19	20.00 ± 0.29	26.63 ± 0.58	11.37 ± 0.32	18.33 ± 1.76	31.37 ± 0.45	77.33 ± 3.71
P-20	20.87 ± 0.70	31.77 ± 0.39	10.53 ± 0.26	11.73 ± 0.89	31.40 ± 0.86	43.50 ± 1.04
Mean (x)	20.16	36.28	10.03	13.70	30.19	49.98
C.D.	1.61	4.30	1.27	2.97	1.96	6.11
C.V.	4.65	6.90	7.36	12.65	3.78	7.13

3.4. Dynamic Assessment of Seedling Vigour Indices

The Seedling Vigour Indices (SVI and RVI) provided a multi-dimensional assessment of progeny robustness (Table 5). Under Initial Vigour, i.e., 45 DAS; Progeny P-15 exhibited the highest initial Shoot Vigour Index (17.24) and Root Vigour Index (9.00), likely due to its high germination rate and rapid initial root penetration. Whereas by 90 DAS, a significant shift in vigor dominance was observed. P-16 emerged as the elite line for Shoot Vigour, recording a peak SVI of 46.03, which was nearly 1.8x higher than the grand mean (25.73). For Root Vigour, P-19 reached the maximum RVI of 13.52, followed closely by P-16 (13.18). This synergy between root and shoot systems contributed to its outlier status in the SVI.

The dramatic increase in SVI for P-16 between 45 and 90 DAS (from 13.55 to 46.03) suggests a late-stage growth acceleration that distinguishes it from "early-starter" lines like P-14, which remained relatively stagnant (15.75 to 17.34). Conversely, P-14 and P-11 showed restricted vertical growth, with total lengths of 36.63 cm and 37.80 cm, respectively, which correlated with their lower overall vigour indices.

Table 5
Shoot Vigour Index (SVI) Root Vigour Index (RVI) of different progenies of Moringa at 45 and 90 DAS in nursery

Progenies	Shoot Vigour Index (SVI)		Root Vigour Index (RVI)	
	45 DAS	90 DAS	45 DAS	90 DAS
P-11	13.50 ± 0.11	20.42 ± 1.16	6.10 ± 0.40	8.17 ± 0.79
P-12	14.54 ± 0.36	25.43 ± 0.96	6.68 ± 0.11	8.92 ± 0.32
P-13	12.64 ± 0.30	20.25 ± 1.02	6.30 ± 0.40	7.79 ± 0.55
P-14	15.75 ± 0.68	17.34 ± 0.56	6.96 ± 0.21	9.50 ± 0.66
P-15	17.24 ± 0.30	20.20 ± 0.44	9.00 ± 0.45	9.66 ± 0.62
P-16	13.55 ± 0.21	46.03 ± 0.93	6.55 ± 0.42	13.18 ± 0.38
P-17	14.71 ± 0.48	21.34 ± 0.89	7.54 ± 0.15	10.10 ± 0.74
P-18	13.96 ± 0.42	22.28 ± 1.54	7.41 ± 0.26	9.31 ± 0.84
P-19	14.75 ± 0.21	43.50 ± 1.70	8.38 ± 0.24	13.52 ± 1.30
P-20	13.44 ± 0.45	20.47 ± 0.25	6.79 ± 0.17	7.56 ± 0.57
Mean (x)	14.41	25.73	7.17	9.77
C.D. at 5%	**1.15**	3.09	0.91	2.15
C.V.	4.64	7.00	7.35	12.85

3.5. Biomass accumulation

The analysis of fresh and dry weights provided a quantitative and significant variation in total biomass accumulation (Table 6). Fresh Weight of P-14 consistently outperformed other lines in fresh biomass accumulation at both 45 DAS (3.87 g) and 90 DAS (22.27 g), significantly exceeding the grand mean of 15.18 g. Interestingly, while P-14 led in fresh weight, P-19 exhibited the highest dry matter accumulation at 90 DAS (20.77 g), suggesting a higher water-use efficiency and nutrient conversion rate compared to the mean (14.70 g).

The trait profile radar chart (Fig. 6), showed a fingerprint comparison for top-performing progenies (P-16, P-19, P-12). P-16 demonstrated a specialized profile for vertical growth and biomass accumulation

(Dry/Fresh Weight), while P-12 maintained a more balanced profile with high Collar Diameter despite lower total length.

Figure 6: Normalized performance profiles of the top three performing progenies

Table 6
Fresh weight of seedling (g), Dry weight of seedling (g) of different progenies of Moringa at 45 and 90 DAS in nursery

Progenies	Fresh weight of Seedling(g)		Dry weight of Seedling (g)	
	45 DAS	90 DAS	45 DAS	90 DAS
P-11	2.90 ± 0.12	16.50 ± 0.32	2.62 ± 0.18	15.31 ± 0.81
P-12	2.57 ± 0.32	19.60 ± 0.21	2.34 ± 0.33	18.99 ± 0.21
P-13	2.75 ± 0.27	12.93 ± 0.18	2.22 ± 0.43	11.96 ± 0.86
P-14	3.87 ± 0.07	22.27 ± 0.78	2.62 ± 0.16	10.51 ± 0.31
P-15	3.50 ± 0.31	18.92 ± 0.36	2.91 ± 0.61	16.62 ± 0.87
P-16	2.83 ± 0.19	17.18 ± 1.22	2.07 ± 0.10	16.61 ± 0.52
P-17	2.37 ± 0.22	17.50 ± 0.72	2.06 ± 0.05	15.61 ± 1.78
P-18	3.37 ± 0.19	17.70 ± 0.16	3.11 ± 0.16	15.27 ± 4.18
P-19	3.57 ± 0.23	10.77 ± 0.44	3.31 ± 0.29	20.77 ± 0.67
P-20	3.30 ± 0.30	15.18 ± 0.23	3.05 ± 0.27	14.70 ± 0.27
Mean (x)	3.10	16.86	2.63	15.63
C.D.	0.70	1.68	--	4.57
C.V.	13.07	5.81	19.98	17.06

3.6. Hierarchical Clustered Dendrogram and Heatmap Analysis

The analysis of trait clustering and correlations reveals clear groupings among the studied parameters. A highly cohesive seedling vigor cluster is formed by Seedling Vigor Index (SVI), shoot length, total length, root length, and Relative Vigor Index (RVI), indicating that these traits are strongly correlated and exhibit a nearly identical performance pattern across progenies. Similarly, fresh weight and dry weight of seedlings form a closely associated cluster, reflecting a predictable biological relationship between these biomass traits (Fig. 7). In contrast, germination percentage, collar diameter, and number of leaves behave as relatively independent variables, forming distinct branches that merge with the larger clusters only at higher distance levels.

The progeny classification further highlights variation in performance. Cluster I comprises high-performing elite progenies, namely P-16 and P-19, which consistently exhibit high positive values across most vigor and growth parameters, particularly SVI, shoot length, and total length. Cluster II, which includes the remaining eight progenies, represents moderate to low-performing groups and shows greater diversity. This cluster is further subdivided into two sub-clusters: Sub-cluster IIa includes P-11, P-15, P-17, and P-18, characterized by moderate overall performance but relatively higher germination percentages, especially in P-11 (1.04) and P-15 (1.09). Sub-cluster IIb consists of P-13, P-20, and P-12, where P-12 stands out with

the highest collar diameter (2.00) and strong performance in fresh and dry weights, while P-13 and P-20 exhibit comparatively lower values for most growth traits (Fig. 7). Additionally, P-14 appears as an outlier within Cluster II due to its notably low fresh weight (-1.85) and dry weight (-1.71) values, distinguishing it from other progenies.

Figure 7: Hierarchical clustering and standardized (Z-score) heatmap analysis of progeny phenotypic profiles

3.7. Correlation Heatmap

The correlation heatmap revealed strong synergistic relationships between several growth parameters. The figure illustrates the relationships between different growth parameters; SVI exhibited a near-perfect positive correlation with Total Length (r = 0.99), Shoot Length (r = 0.99), and Root Length (r = 0.94) as indicated in Fig. 8. These results indicate that shoot and root elongation are the primary drivers of seedling vigor in this population, suggesting that these traits are highly interdependent in these progenies. Conversely, Collar Diameter and Number of Leaves showed weak correlations with SVI (r = 0.04 and r = 0.17, respectively), indicating they are secondary contributors to overall vigor at this stage of growth. Fresh weight and Dry weight also showed a very high correlation (r = 0.97).

4. Discussion

4.1. Genotypic Variation and Maternal Resource Partitioning

The significant differences observed in maternal pod morphology (Table 1) indicate a high degree of genetic divergence within the evaluated *Moringa oleifera* germplasm. The superior performance of genotype MO-11 (pod length: 47.81 cm; pod weight: 13.10 g) suggests a robust genetic architecture for biomass accumulation. Such variation in fruit dimensions is a critical selection criterion for the vegetable market, as highlighted by Selvakumari and Ponnuswami, 2017 [9], who established that pod robusticity is often linked to efficient maternal resource translocation. Similar to findings by Singh et al. (2018) [11] in cowpea research, pod length and pod weight are often governed by similar genetic clusters, making them easy to improve simultaneously through mass selection.

A primary finding in this study is the apparent trade-off between reproductive quantity and quality. Genotype MO-20 achieved the highest seed prolificacy (21.60 seeds per pod), yet its 100-seed weight (11.96 g) was significantly lower than that of MO-16 (19.14 g). This relationship aligns with the offspring size-number trade-off theory (Smith and Fretwell model [12]), which posits that plants partition a finite pool of nutrients between the number of offspring and the investment in each individual seed. Genotypes like MO-16 appear to prioritize resource "quality", which is often linked to higher seedling vigor and oil content, whereas genotypes like MO-20 prioritize "quantity", a strategy aimed at maximizing the potential number of progenies. The high 100-seed weight in MO-16 likely explains the subsequent vigor observed in its progeny, as heavier seeds typically possess larger endosperm reserves required for early autotrophic transition. The positive correlation observed between pod length, diameter, and weight suggests that selection for larger pod size effectively increases total biomass.

4.2. Ontogenetic Growth Dynamics

The transition from seed to seedling revealed distinct growth strategies. Initial vigor (45 DAS) was maximized in P-15, which showed the highest germination percentage (75.83%) and initial Shoot Vigour Index (17.24). However, monitoring through 90 DAS revealed a significant ontogenetic shift. P-16 emerged as the elite line for structural acceleration, nearly tripling its Shoot Vigour Index to 46.03. This indicates that while lines like P-15 are "early-starters," genotypes such as P-16 possess superior long-term growth potential, suggesting that seedling developmental vigor and initial germination capacity may be governed by different genetic or physiological mechanisms in these progenies.

This acceleration is further supported by the architectural development of the progenies. By 90 DAS, P-12 achieved the maximum collar diameter (5.92 cm) and P-13 produced the most extensive canopy (116.67 leaves). As noted by Balaguru et al. (2020) [1], such shifts in growth dominance between 45 and 90 DAS suggest that after the depletion of maternal seed reserves, the progeny's inherent photosynthetic efficiency and nutrient uptake capacity become the primary drivers of vigor. Similar results were observed by Yadav et al. (2026) [13] and Gupta, N. (2026)[3].

The integration of vertical growth and root penetration via the SVI and RVI provided a multi-dimensional assessment of plant robustness. The maximum Root Vigour Index (RVI) recorded in P-19 (13.52) and P-16 (13.18) at 90 DAS points toward a strategic allocation of resources into deep root systems. In *Moringa*, deep root penetration (20.00 cm in P-16) is a vital adaptation for drought resilience and nutrient foraging in semi-arid environments.

The low Coefficient of Variation (C.V.) observed for the 90-day SVI (7.0%) and total seedling length (7.13%) confirms that these vigor traits are highly stable. This stability suggests high heritability, making them effective markers for selection in advanced breeding programs aimed at producing high-density silvicultural systems.

The analysis of fresh and dry weights revealed significant differences in dry matter accumulation—a trait of paramount importance for the leaf powder and pharmaceutical industries. While P-14 achieved the highest fresh weight (22.27 g), P-19 exhibited the maximum dry matter accumulation at 90 DAS (20.77 g). This indicates that P-19 possesses superior water-use efficiency and a higher rate of nutrient conversion compared to its peers. Based on this study, we can recommend MO-11 as the elite germplasm for the vegetable industry, while MO-16 and its progeny P-16 represent superior genetic resources (Table 7).

The PCA Biplot effectively separated the progenies into distinct performance tiers. The positioning of P-16 and P-19 on the extreme end of the PC1 axis—which was heavily weighted by length and weight traits—confirms their status as high-performing genotypes. The hierarchical clustering further supported this by grouping P-16 and P-19 into a distinct "high-vigor" clade. This categorization is vital for breeding programs, as it allows researchers to select parent lines that are genetically distinct yet possess complementary superior traits. The radar chart analysis of the top performers (P-16, P-19, and P-12) revealed that while P-16 is ideal for rapid canopy establishment, P-12 might offer better structural stability, a factor that could be explored in future studies regarding wind resistance or drought tolerance.

The high positive correlation between SVI and length-based parameters (Total Length and Shoot Length) underscores the importance of rapid vertical development during the early growth stages. The near-perfect correlation (r = 0.99) suggests that measuring shoot length can serve as a reliable, non-destructive proxy for estimating the Seed Vigor Index in these progenies. In contrast, the weak correlation between collar diameter and SVI indicates that during the initial stages of development, these plants prioritize apical dominance and vertical growth over radial expansion.

Table 7
Targeted Utilization of Specific Germplasm Based on Phenotypic and Physiological Traits

Economic/Scientific sector	**Recommended Germplasm**	**Physiological rationale**
Vegetable Industry	MO-11 and MO-12	Pod production due to superior maternal dimensions
Industrial Oil and Seed	MO-16 and MO-15	"Ben oil" extraction based on superior 100-seed weights
Biomass and Fodder	P-19 and P-12	High-density planting
Restoration Forestry	P-16	Due to deep root penetration
Genetic Improvement	MO-20	Valuable genetic resource for increasing the sink capacity

5. Conclusion

The longitudinal evaluation of ten *Moringa oleifera* accessions revealed profound intraspecific phenotypic variability, establishing a decisive maternal-progeny performance continuum that defines the species' reproductive strategy. Initial analysis of maternal pod and seed architecture indicated significant diversity in resource partitioning, where genotype MO-11 emerged as the superior performer for sink-strength, recording maximized pod length (47.81 cm) and individual pod weight (13.10 g). However, a distinct physiological trade-off was observed between reproductive quantity and quality; while MO-20 achieved the highest seed prolificacy (21.6 seeds/pod), it resulted in the lowest germination percentage (64.42%) and moderate seedling vigor.

In contrast, maternal genotypes with higher 100-seed weights, specifically MO-16 (19.14 g), produced progenies (P-16) with significantly superior structural establishment and biomass accumulation. The transition from maternal reserves to independent growth highlighted a distinct ontogenetic shift between 45 and 90 days after sowing (DAS). The Seedling Vigour Indices (SVI and RVI) confirmed a decoupling between initial establishment and long-term growth; while P-15 excelled in early germination, P-16 and P-19 emerged as the elite lines for structural vigor, reaching a peak SVI of 46.03 at 90 DAS. This structural establishment was further characterized by the developmental stability of P-12, which achieved the maximum collar diameter of 5.92 cm, and P-13, which exhibited optimized photosynthetic capacity through a peak leaf count of 116.67.

Biomass partitioning and dry matter allocation provided further quantitative evidence of genotypic differentiation in resource utilization. While P-14 led the population in fresh weight accumulation (22.27 g at 90 DAS), progeny P-19 demonstrated the highest dry matter accumulation (20.77 g), indicating exceptional water-use efficiency and a high rate of nutrient conversion. The synergy between vertical extension and root architecture was most pronounced in P-16, which reached a total seedling length of 89.83 cm, supported by a deep root penetration of 20.00 cm. Furthermore, the strong correlation between shoot length and SVI offers a simplified monitoring tool for researchers to assess vigor in large-scale nursery operations. This root-shoot synergy, captured by the high Root Vigour Index (RVI) in P-19 and P-16, highlights these genotypes as premier candidates for carbon sequestration and reforestation in arid bioclimates where deep-rooting traits are essential for survival. Our analysis confirms that seedling vigor in this population is more closely tied to elongation and biomass accumulation than to initial germination percentage. Among all germplasms, MO-11 as the elite germplasm for vegetative yield, while MO-16 and its progeny P-16 represent superior genetic resources for industrial oil extraction and structural biomass.

Declarations

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Ethics Approval

All field studies and collection of tree material *Moringa oleifera* complied with relevant institutional, local, and national guidelines. Verbal permissions were obtained from landowners and government official to collect the tree specimens**.** The plant material was formally authenticated and identified by Naresh Kaushik, Dean and principal scientist at Atal College of Agriculture, Bawal. A voucher specimen of the collected wild tree was prepared and is stored at the Department of Forestry, Chuadhary Charan Singh Haryana Agricultural University, Hisar.

Ethical declaration statement

Not applicable.

Conflict of interest

The authors of this research declare that they have no relevant conflicts of interest.

Consent to Participate declaration

Not applicable.

Consent to Publish declaration

Not applicable.

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Figures

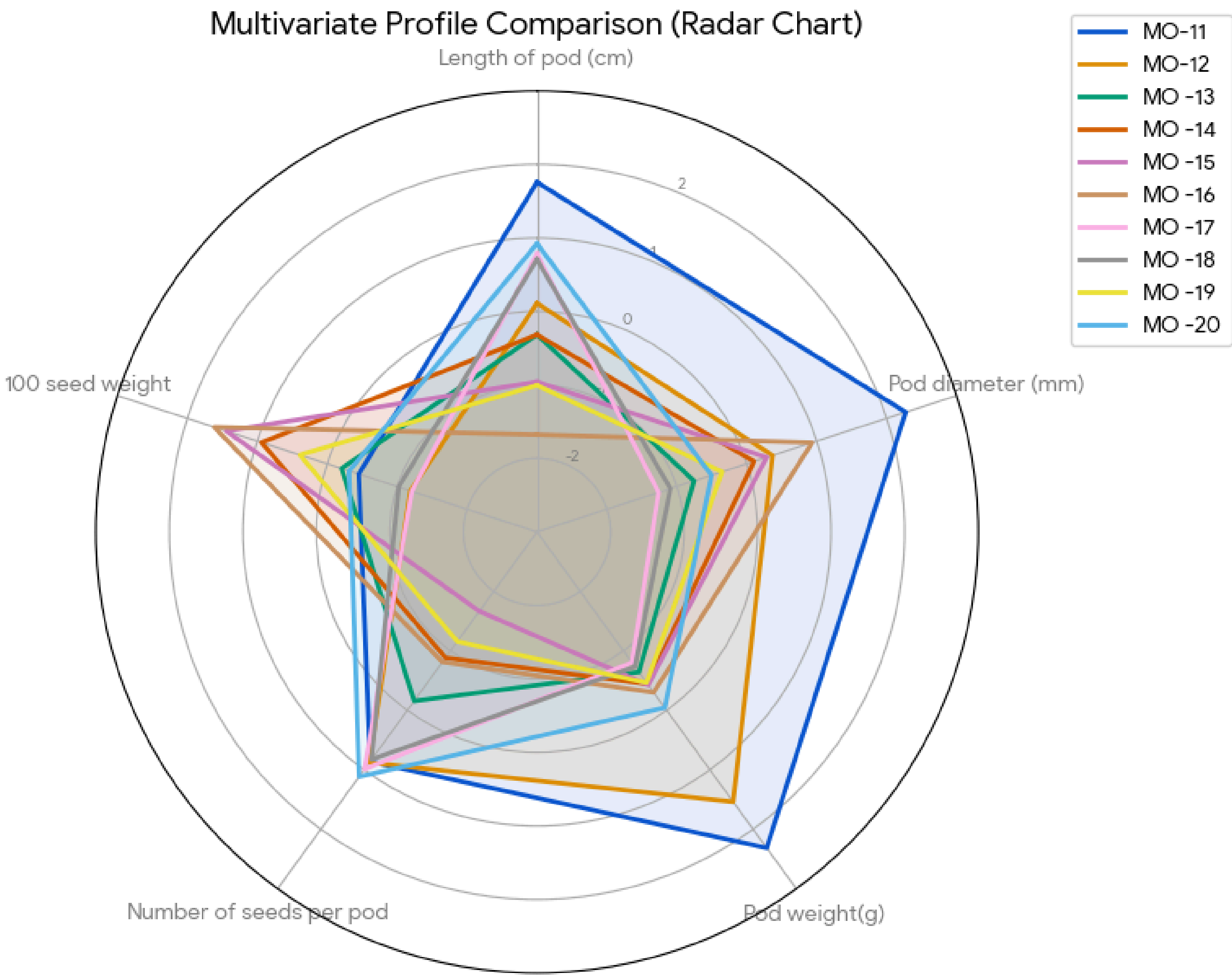

Figure 1

Principal Component Analysis (PCA) Biplot of Trait-Genotype Interactions

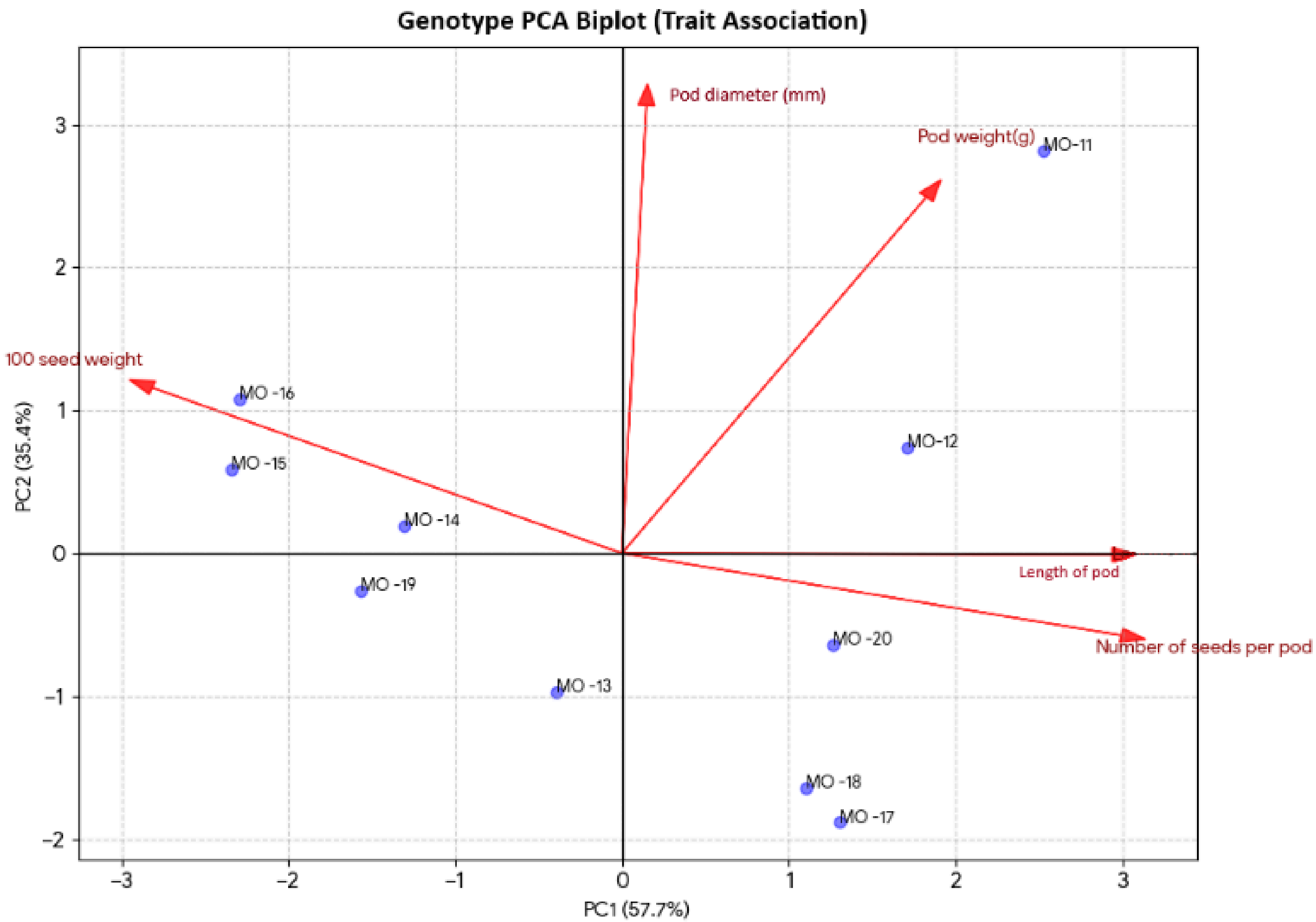

Figure 2

Multivariate Radar Profile of Genotypic Performance

Figure 3

Heatmap of Standardized Phenotypic Traits Across Ten Genotypes

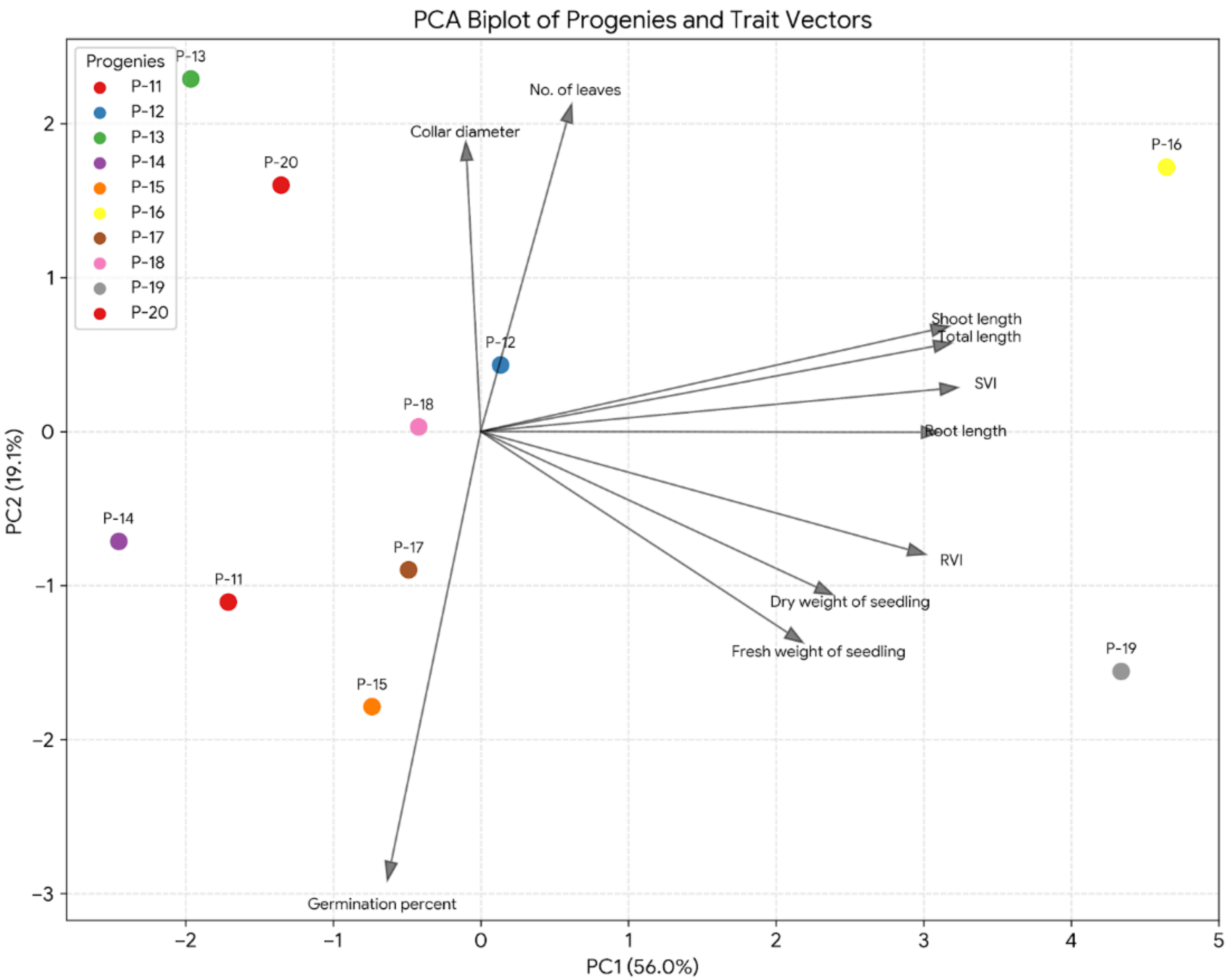

Figure 4

Principal Component Analysis (PCA) biplot depicting the multivariate distribution of progenies

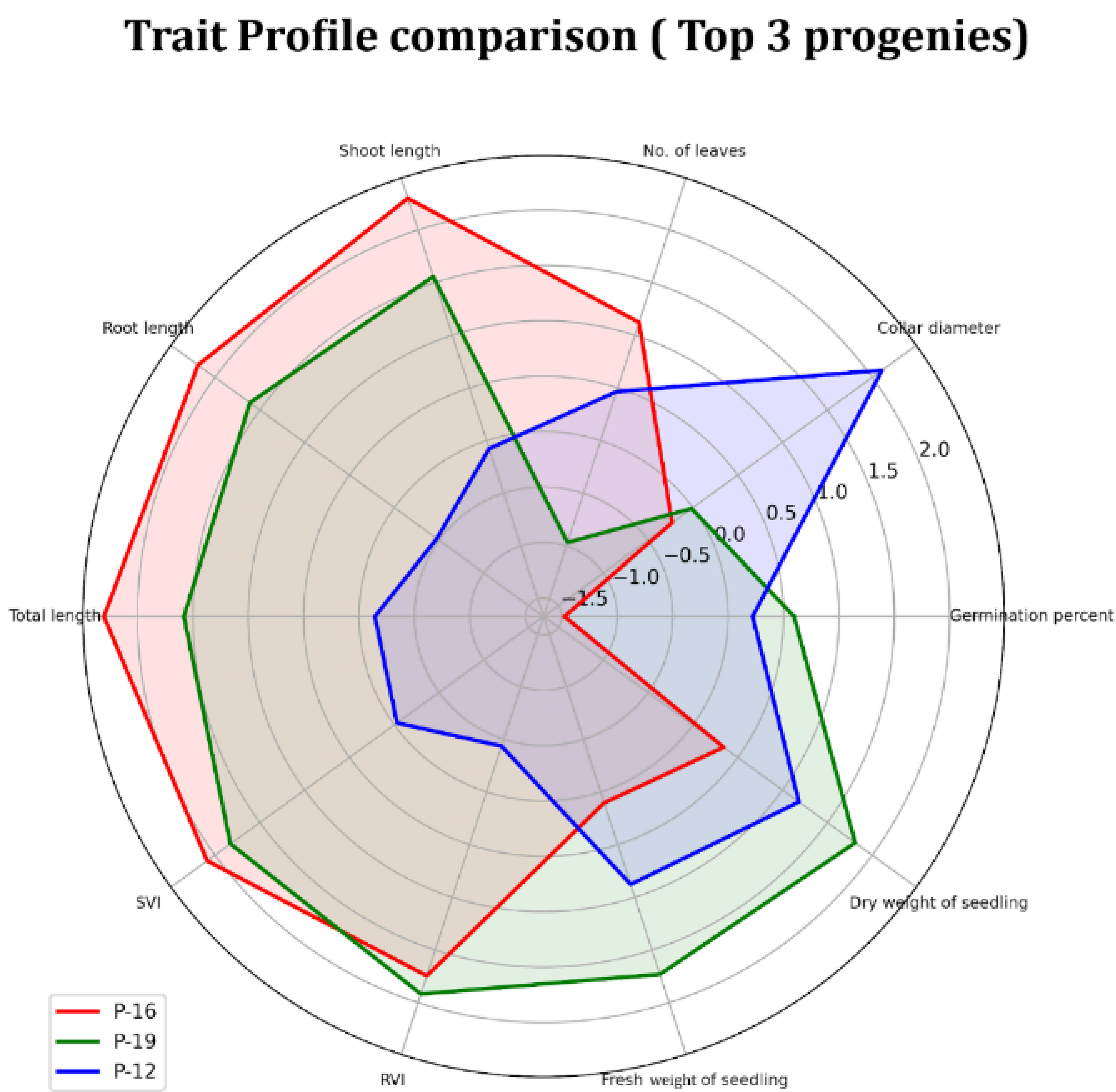

Figure 5

Normalized performance profiles of the top three performing progenies

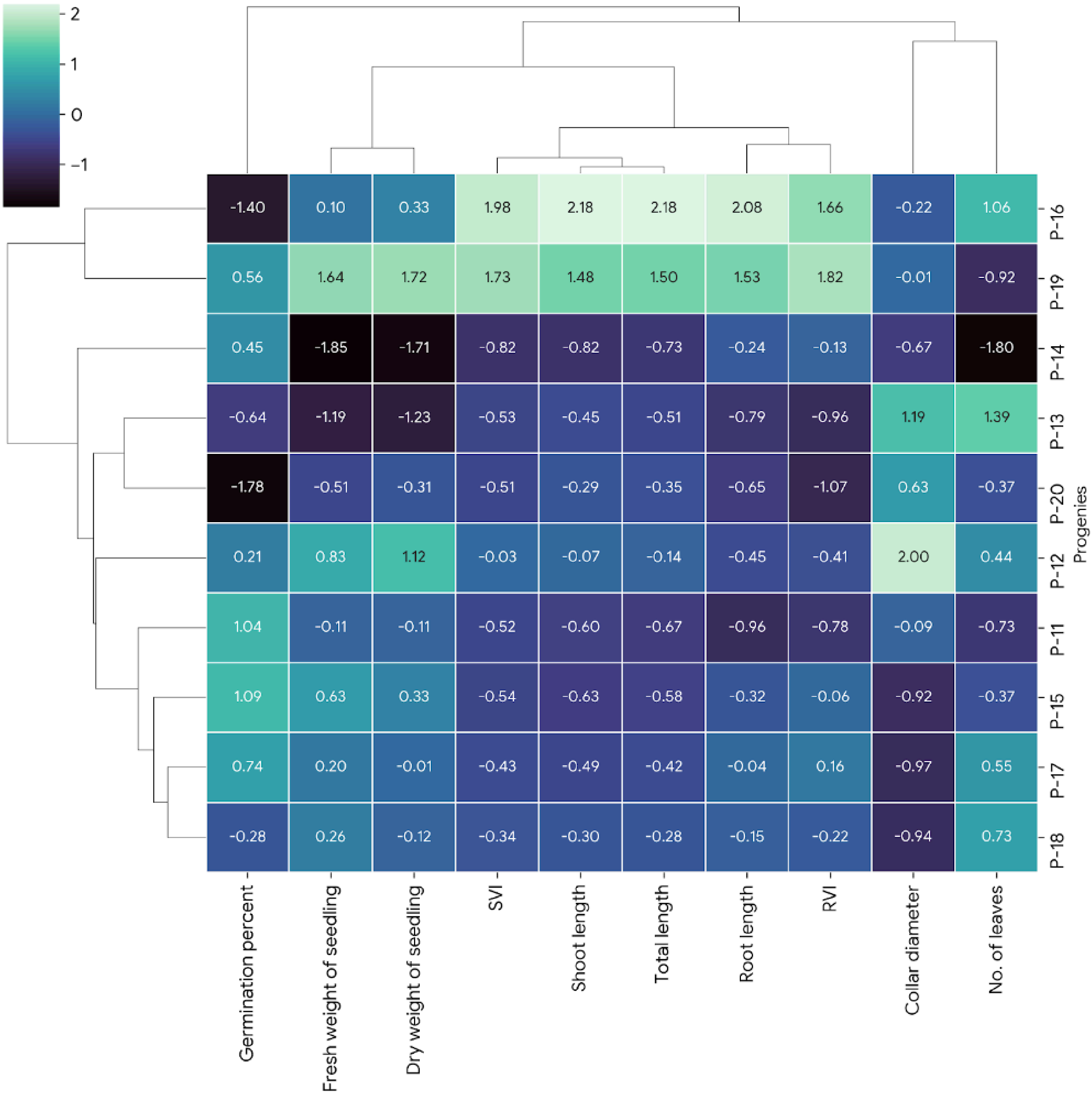

Figure 6

Hierarchical clustering and standardized (Z-score) heatmap analysis of progeny phenotypic profiles

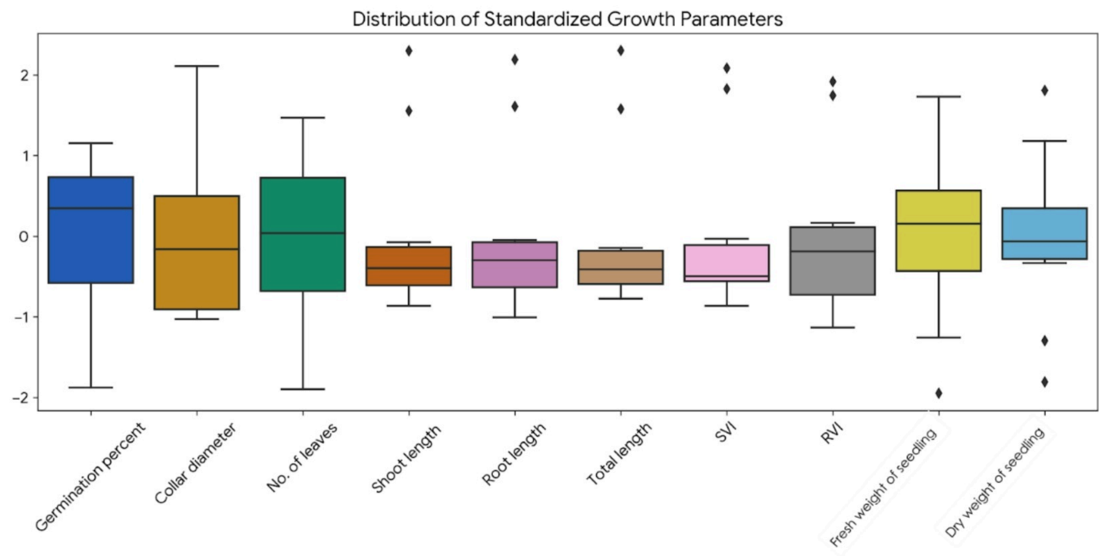

Figure 7

Distribution and variability analysis (box-and-whisker plots) of seedling parameters

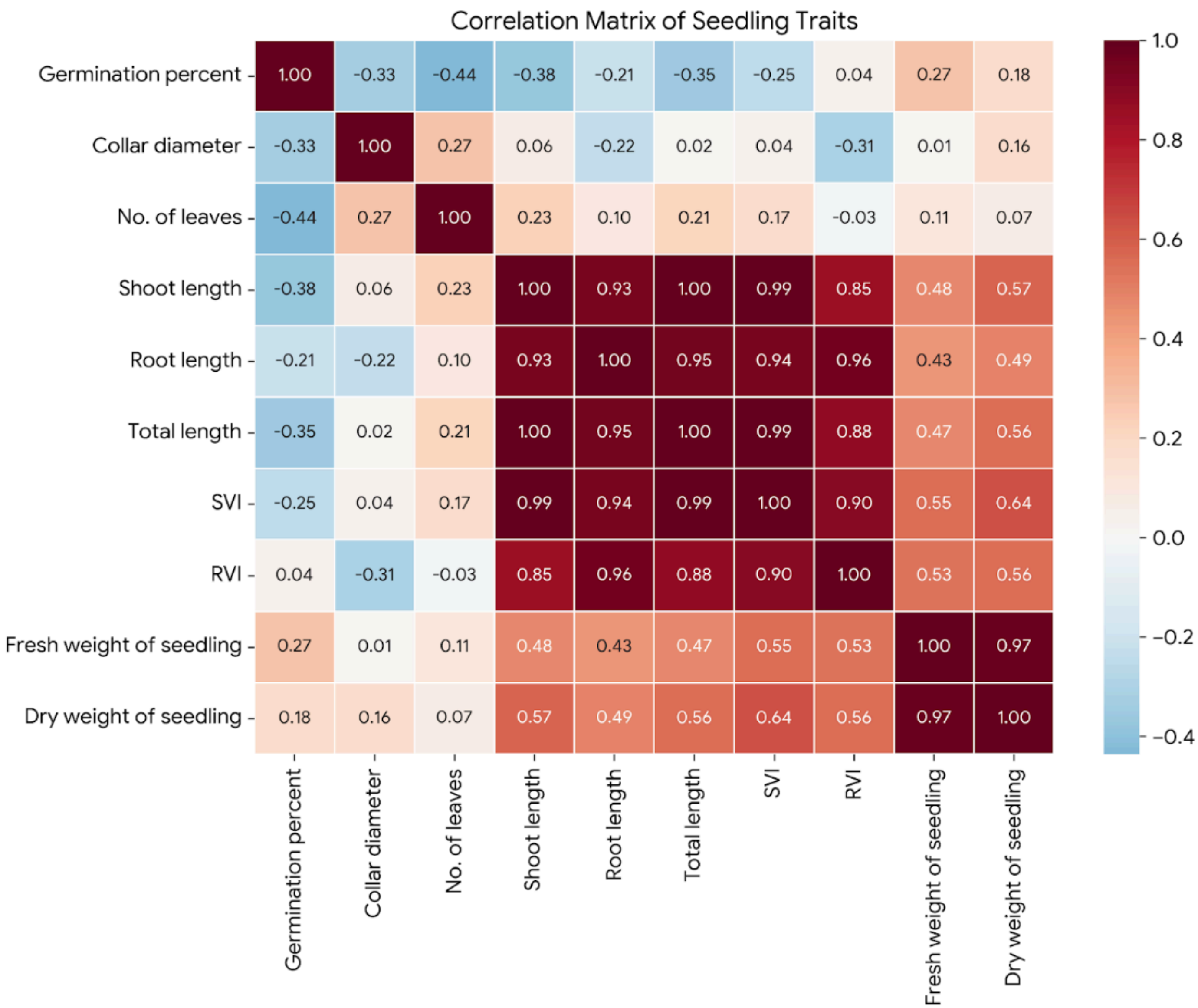

Figure 8

Pearson correlation coefficient matrix illustrating the inter-relationships among seedling growth parameters

Supplementary Files

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