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GENETIC VARIABILITY AND CHARACTER ASSOCIATION STUDIES IN *Moringa oleifera* Lam. SEED SOURCES FOR VEGETATIVE GROWTH AND BIOMASS

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Moringa oleifera Lam. belongs to monogeneric family Moringaceae which is commonly known as Drumstick, *Sohanjna* and *Sahjan* and native to the foothills of the Himalayas in north-western India (Lalas *et al.,* 2012). The genus *Moringa* comprises 13 species, of which *Moringa oleifera* is widely cultivated and adapted by local communities across the globe. It is found evergreen in nature in tropical climatic conditions, while deciduous in nature in sub-tropical climatic conditions (Folkard *et al.,* 1999). *M. oleifera* has high amount of nutrients and mineral supplements, for example, proteins, K, Ca, Fe, etc. with a quality equivalent to that of meat, milk and eggs (Fuglie, 2005), carbohydrates, fat, fiber, essential amino acids and minerals. Besides, it has shown outstanding performance as an alternative protein source for animal feed to increase milk and meat quantity and quality (Su and Chen, 2020). Digestibility score of essential amino acids present in *M. oleifera* plant parts are more than the standards given by WHO, FAO and UNO for small children (Fuglie, 2005) and thus used in different ways which improves human health and his surrounding environment. It is broadly used in traditional system of phytomedicine and showed a high degree of safety without having any adverse effects on human health (Saini *et al.,* 2016).

It is an established fact that concentration of photochemical ingredients, nutrients and minerals varies with the geographical area and locality (Dahakd *et al.,* 2019). The variability in biomass, fruit yield and phytochemical composition is strongly dependent on the different agro-climatic conditions, genetic factors, growth stage and cultivation techniques (Leone *et al.,* 2015). With wide range of uses of moringa, most of the research studies are focused mainly either on nutritional or medicinal values. Since, *M. oleifera* normally grows in different environmental conditions; huge variations for growth yield and phytochemical ingredients are reported. For maximum utilization of the crop, proper characterization especially at the morphological level is very important for the identification of accessions with superior agromorphological traits. Even though *M. oleifera* is cultivated under various agro-ecological systems, large-scale commercial plantations are still not reported in Indian subcontinent except four south Indian states possibly due to less availability of scientific research database for morphological growth and productivity potential. Thus, morphological characterization of *M. oleifera* is needed before recommending it at commercial scale in subtropical climatic conditions of Punjab.

The experiment was conducted at Department of Forestry and Natural Resources, Punjab Agricultural University, Ludhiana during 2020-21. The study area falls in central zone of Punjab and characterized by sub-tropical to tropical, semi-arid type of climate. The minimum temperature may go down to 4°C or even less,while the maximum temperature may be as high as more than 45°C during summer season. Occurrence of frost is not common. The soils are deep, well drained, sandy loam in texture with low humus content. The soil pH is neutral. The average annual rainfall in Ludhiana is 760 mm, about three-fourth of which is contributed by south-west monsoon during July to September.

The experiment was carried out in field evaluation trial established since August 2017 at spacing of 3.5×2.0m in three replications with plot size of 5 plants following complete randomized block design (CRBD). A total of 15 seed sources collected from the different geographical regions belonging to 10 states comprised the base experimental material for present investigation (Table 1, Fig. 1). Recommended fertigation regimes and management practices were performed as per schedule. The data on vegetative, leaf morphological characteristics and green biomass were recorded during first week of October, 2020 on the 3-years-old plants. The data for leaf traits were recorded as per procedure laid down for AVRDC-GRSU characterization record sheet developed by the World Vegetable Centre, Taiwan. The observations for vegetative growth traits and leaf characteristics were recorded on plants having 2-months old vegetative growth after summer harvesting (July, 2020) for green biomass. Data for leaf and leaflet traits were recorded on thirty randomly selected leaves in three replicates. Only healthy, mature and complete leaves were subjected to data collection and further

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Table 1. Geographical details of *Moringa oleifera* seed sources

Code	Seed sources	Status	Locality	Latitude (°N)	Longitude (°E)
S1	Bhagya	NRV	UHS Bagalkot, Karnataka	16.16369	75.61728
S2	Konkan Ruchira	NRV	Dapoli, Maharastra	17.76883	73.19098
S3	Dantiwara	LSS	Gujarat	24.32191	72.31774
S4	PAU-1	LSS	Ludhiana, Punjab	30.90111	75.80712
S5	PAU-2	LSS	Ludhiana, Punjab	30.90111	75.80712
S6	PAU-3	LSS	Ludhiana, Punjab	30.90111	75.80712
S7	PKM-1	NRV	Tamil Nadu	11.01234	76.93541
S8	PKM-2	NRV	Tamil Nadu	11.01234	76.93541
S9	ODC-3	NRV	Tamil Nadu	8.187868	77.61255
S10	Jodhpur	LSS	Rajasthan	26.26309	72.99730
S11	Mysore	LSS	Karnataka	12.32137	76.61818
S12	Kadapa	LSS	Andhra Pradesh	14.48165	78.82783
S13	Ranchi	LSS	Jharkhand	23.44160	85.31822
S14	Jabalpur	LSS	Madhya Pradesh	23.09951	79.98904
S15	Pilibhit	LSS	Uttar Pradesh	28.70562	80.06157

Note: NRV-National released variety; LSS-Local seed source

evaluation. Green biomass was measured for 5 trees in three replicates. The mixture of leaves and tender twigs of each plant was taken collectively and weighted to estimate the green biomass.

The data collected from the seed sources of *M. oleifera* on different parameters were subjected to statistical analysis. Coefficient of variability at phenotypic and genotypic level, heritability (%) in narrow-sense, genotypic and phenotypic correlation parameters were estimated using OPSTAT software. Path analysis was carried out using the genotypic and phenotypic correlation coefficients to know the direct and indirect effects of the components on green biomass. SPSS software, version 16.0 was used to perform principal component analysis on data recorded for vegetative, leaf morphological characteristics and green biomass. The latent root criterion (Eigen values greater than unity) was applied for estimating the number of principal components. Bi-plot displays of the first three principal components were used for grouping genotypes illustrating the relationship between genotypes and indices using JMP Pro 10.0 software.

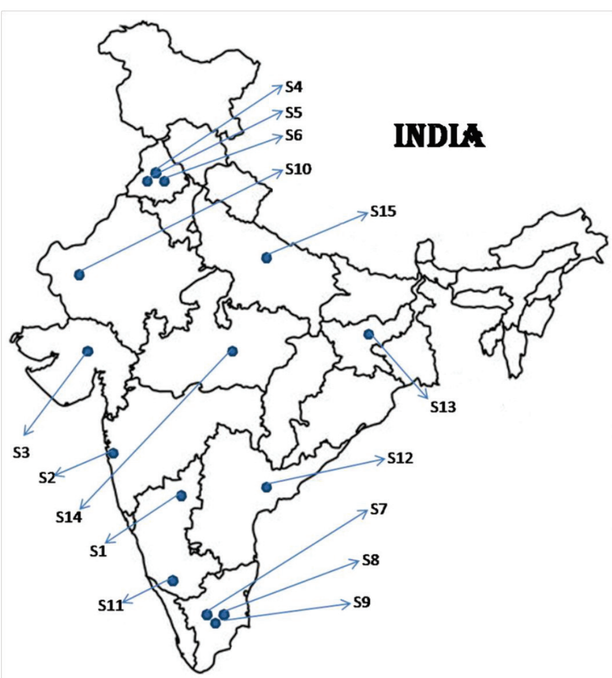

Fig. 1. Geographical locations of *Moringa oleifera* seed sources representing the distribution

A key to progress in tree improvement and breeding programme is the degree and the extent of variation present in a species germplasm (Zobel, 1981). Variation observed in the traits was mainly due to the seed sources and environmental conditions; hence estimation of these genetic parameters is important in the present study. Variability and genetic parameters were estimated for vegetative, leaf morphological traits and green biomass among seed sources (Table 2). Factors of locality has very less influence on leaf length, leaf width, leaf weight, number of pinnae, number of leaflets, terminal leaflet length and dry biomass due to less difference between phenotypic and genotypic coefficient of variation. However, number of pollarded shoots, pollarded shoot's length, number of leaves, petiolule length and leaflet weight have greatly affected either by environment factors or management practices. It was observed that green biomass was severely

Table 2. Genetic variability estimates for vegetative, morphological and biomass characteristics of *Moringa oleifera* seed sources

Characters	Mean	Range		Coefficient of variation		Heritability (%)	Genetic Advance	Genetic gain (% of mean)
		Min.	Max.	Phenotypic (%)	Genotypic (%)			
PH	316.29	250.00	363.33	12.09	10.14	70.40	55.40	17.53
SG	43.65	30.96	49.67	12.45	11.05	78.72	8.80	20.19
NOPS	15.40	8.53	19.67	27.69	23.20	70.20	6.20	40.04
PSL	134.29	68.00	181.33	28.47	23.89	70.40	55.40	41.29
LL	567.75	469.89	674.47	11.97	11.50	92.22	129.10	22.75
LW	457.02	358.24	533.44	13.49	13.02	93.10	118.30	25.88
NOL	12.70	11.67	14.20	6.50	3.97	37.30	0.60	4.99
LWt	14.81	11.18	20.79	20.71	20.25	95.56	6.00	40.77
PL	138.06	121.20	152.05	8.67	7.70	78.94	19.50	14.09
PLL	30.45	25.46	34.38	11.10	7.05	40.35	2.80	9.23
IL	95.07	78.22	107.22	8.47	6.94	67.12	11.10	11.72
NOP	15.43	11.85	19.89	17.67	17.26	95.48	5.40	34.74
LLL	24.94	22.99	26.87	5.59	3.92	49.10	1.40	5.65
LLW	15.84	14.00	17.24	7.67	5.62	53.55	1.30	8.47
NOLL	434.75	229.13	769.13	40.69	40.08	97.06	353.70	81.35
LLWt	63.84	49.40	79.60	18.91	13.18	48.57	12.10	18.92
TLLL	28.44	24.11	41.75	16.86	16.35	94.13	9.30	32.69
TLLW	18.65	14.50	26.31	18.35	17.32	89.09	6.30	33.67
GB	8.73	6.35	11.29	27.31	11.39	17.40	0.90	9.79

Note: PH - Plant Height, SG - Stem girth, NOPS - Number of pollarded shoots, PSL - Pollarded shoot length, LL - Leaf length, LW - Leaf width, NOL - Number of leaves/1m shoot length, LWt - Leaf weight, PL - Petiole length, PLL - Petiolule length, IL - Internodal length, NOP - Number of pinnae, LLL - Leaflet length, LLW - Leaflet width, NOLL - Number of leaflets per leaf, LLWt - Leaflet weight, TLLL - Terminal leaflet length, TLLW - Terminal leaflet width, GB - Green biomass

affected by environmental conditions. The value obtained for phenotypic coefficient of variation was higher than the corresponding genotypic coefficient of variation for all the characters which indicated that the traits were influenced by the environment conditions. High and moderate phenotypic coefficient of variation is indicative of the existence of substantial variability pointing ample scope for their improvement through selection (Salihu *et al.,* 2017). Greater improvement, therefore, could be obtained for these characters. Comparatively, low phenotypic coefficient of variation indicated the high stable nature of these characters among different genotypes studied and less scope of improvement in these characters in *M. oleifera* by Selvakumari and Ponnuswami (2017).

Heritability and genetic advance give information of total variations present in planting material as well as environmental influences on the traits. The components of variance with high genetic gain and high heritability can be undertaken to generate an idea and scope for response of selection to various characters (Chauhan *et al.,* 2020). Estimate of heritability (narrow-sense) revealed that the range of heritability for character under study was from 17.40% (green biomass) to 97.06% (number of leaflets per leaf) for vegetative growth and leaf traits. Number of leaflets (97.06%), leaf weight (95.56%), number of pinnae (95.48%), terminal leaflet length (94.13%), leaf width (93.10%) and leaf length (92.22%) had very high heritability indicating that the variability existing for these traits is tightly linked with their genetic constitution. Genetic advance was found highest for number of leaflets/leaf (353.70%) which was followed by leaf length (129.10%), while lowest (0.6%) for genetic advance was observed for number of leaves/1m shoot length. Genetic gain was observed maximum (81.35%) for number of leaflets/leaf and followed by 41.29% for pollarded shoot length, whereas minimum was recorded 4.99% for number of leaves/1m shoot length. Very high heritability coupled with high genetic advance was observed for the characters namely number of leaflets per leaf (97.06% with 81.35%) and leaf weight (95.56% with 40.77%).

Green biomass had very low heritability *i.e.* 17.40% which means there is a high environmental influence.

It might be due to the effect of either management practices like planting density, pollarding height and frequency (Mabapa *et al.,* 2017) or environmental factors like soil type and fertigation regimes (Singh, 2021). High heritability reflects the effectiveness of selection based on phenotypic performance but it does not ensure high genetic gain for a specific character. Therefore, selection encompassing heritability and expected genetic gain gives more realistic results (Johnson *et al.,* 1955) as they reflect the additive type of gene action. Heritability values were high than those of genetic advance for most of the traits which indicated that they were least influenced by the environment and their phenotypes acted as true representative of their genotypes and selection based on these types of phenotypic performance would be reliable in annual moringa (Raja and Bagle, 2008) and in perennial moringa (Karunakar *et al.,* 2018).

In general, genotypic correlation coefficients were higher than corresponding phenotypic correlation coefficients for most of the traits (Table 3). Green biomass at genotypic level had positive significant correlation with stem girth, number of pollarded shoots, leaf weight and internode length, while at phenotypic level only with stem girth. Plant height showed negative correlation with stem girth at genotypic level. Number of leaves/1m shoot length had only significant but negative correlation with number of pollarded shoots among vegetative traits at genotypic level. Leaf length exhibited significantly positive correlation with stem girth but negative correlation with pollarded shoot length. Leaf length exhibited high significant and positive correlation with leaf width, leaf weight, petiole length, number of pinnae and number of leaflets/ leaf, while highly significant negative correlation exhibited with internode length. Leaf width revealed high significant positive correlation with leaf weight, petiole length, number of pinnae and number of leaflets but negative correlation with internode length. Internode length, petiolule length and petiole length had no correlation with the leaflet traits except petiole length to number of leaflet and leaflet weight at phenotypic level. Such associations were also reported by Verma *et al.* (2019) in perennial moringa.

Genotypic and phenotypic path coefficient analysis was carried out considering green biomass as dependent character and remaining traits were considered as independent characteristics. The direct and indirect effects of various characters were worked out from correlation matrix and are presented in Table 4 and Table 5 at genotypic and phenotypic level, respectively. Path coefficient analysis revealed that the highest positive direct effect contributing to green biomass was observed due to plant height (r = 4.343) followed by leaf weight (r = 2.610), number of pollarded shoot (r = 2.336) and leaflet weight (r = 2.114) at genotypic level, while leaf width (r = 1.573) and plant height (1.166) at phenotypic level; hence direct selection for these traits may be advantageous. At genotypic level, pollarded shoot length exhibited positive indirect effect contributing to green biomass was observed due to petiole length (r = 10.309), leaf width (r = 7.777), leaf length (r = 7. 465), number of leaflets (r = 6.905), terminal leaflet length (r = 5.703), leaflet weight (r = 5.638), terminal leaflet width (r = 5.008), number of pinnae (r = 4.863), petiolule length (r = 3.447) and stem girth (r = 3.415). Number of pinnae showed positive indirect effect contributing to green biomass was observed due to plant height (r = 4.310) followed by internode length (r = 3.987), number of leaves / 1 m shoot length (r = 3.808) and pollarded shoot length (3.361). At phenotypic level, leaf width exhibited positive indirect effect contributing to green biomass was observed due to leaf length (r = 1.472), followed by number of leaflets (r = 1.071), leaf weight (r = 0.937), petiole length (r = 0.882), number of pinnae (r = 0.759), and pollarded shoot length through plant height (r = 1.084). Unexplained effects are treated as residual effects. Very low magnitudes of residual effects at genotypic and phenotypic level indicated that the traits included in present investigation accounted for most of the variation present in dependent variable, *i.e.* green biomass. These results are in agreement with the results obtained by Verma *et al.* (2019) and Singh (2021).

The present study identified five principal components (PCs) with eigenvalues greater than one, which collectively accounted for over 86.5% of the total observed variability (Table 6). The biplots of PC1 versus PC2, PC3, and PC2 versus PC3 are presented in Figure 2 (Yang and Kang, 2003). Of the nineteen components examined, five exhibited eigenvalues exceeding unity, explaining 86.51% of the total variation. The first principal component (λ1 = 6.346) explained 33.40% of the total variation, with the highest loading observed for petiole length (0.929). The second component (λ2 = 4.014) explained 21.13% of the variation, with the greatest loading for terminal leaflet length (0.908). The third component (λ3 = 2.557) accounted for 13.46% of the variation, with the highest loading recorded for internode length (0.756). The fourth component (λ4 = 2.246) explained 11.82% of the variation, with leaflet width (0.784) showing the highest loading. The fifth component (λ5 = 1.273) explained 6.70% of the variation, with the maximum loading for leaflet weight (0.473).

Based on the PCA analysis, the nineteen morphological characters were clustered into five distinct groups, with a clustering variance proportion of 0.71 (Table 7). The most representative traits were plant height, leaf length, internode length, leaflet width,

Table 3. Correlations coefficients among the vegetative, morphological and biomass characteristics of *Moringa oleifera* seed sources

	PH	SG	NOPS	PSL	LL	LW	NOL	LWt	PL	PLL	IL	NOSR	LLL	LLW	NOLL	LLWt	TLLL	TLLW	GB
PH		-0.088^{NS}	0.363*	0.929**	-0.477**	-0.517**	0.058^{NS}	-0.134^{NS}	-0.543**	-0.014^{NS}	0.111^{NS}	-0.228^{NS}	-0.002^{NS}	0.105^{NS}	-0.478**	-0.336*	-0.348*	-0.195^{NS}	0.315^{NS}
SG	-0.452**		0.511**	-0.142^{NS}	0.330*	0.332*	0.085^{NS}	0.150^{NS}	0.259^{NS}	-0.014^{NS}	-0.109^{NS}	0.366*	0.099^{NS}	0.108^{NS}	0.244^{NS}	-0.130^{NS}	0.069^{NS}	0.104^{NS}	0.502**
NOPS	0.468**	0.713**		0.373*	0.094^{NS}	-0.029^{NS}	-0.117^{NS}	0.143^{NS}	-0.134^{NS}	-0.110^{NS}	0.048^{NS}	0.347*	0.101^{NS}	0.160^{NS}	-0.113^{NS}	-0.178^{NS}	-0.252^{NS}	-0.075^{NS}	0.277^{NS}
PSL	1.107**	-0.348*	0.439**		-0.553**	-0.574**	0.024^{NS}	-0.167^{NS}	-0.589**	-0.014^{NS}	0.156^{NS}	-0.326^{NS}	-0.082^{NS}	0.038^{NS}	-0.594**	-0.410*	-0.432**	-0.289^{NS}	0.206^{NS}
LL	-0.899**	0.478**	0.003^{NS}	-0.760**		0.936**	-0.201^{NS}	0.631**	0.532**	0.072^{NS}	-0.198^{NS}	0.644**	0.060^{NS}	-0.034^{NS}	0.699**	0.109^{NS}	-0.139^{NS}	-0.114^{NS}	0.155^{NS}
LW	-0.913**	0.420*	-0.179^{NS}	-0.792**	0.955**		-0.009^{NS}	0.596**	0.560**	0.107^{NS}	-0.089^{NS}	0.482**	-0.018^{NS}	-0.129^{NS}	0.681**	0.091^{NS}	-0.146^{NS}	-0.170^{NS}	0.238^{NS}
NOL	-0.185^{NS}	-0.113^{NS}	-0.533**	-0.110^{NS}	-0.201^{NS}	-0.012^{NS}		-0.378*	-0.086^{NS}	0.205^{NS}	0.407*	-0.287^{NS}	-0.059^{NS}	-0.024^{NS}	-0.053^{NS}	-0.070^{NS}	0.001^{NS}	-0.110^{NS}	0.117^{NS}
LWt	-0.268^{NS}	0.123^{NS}	0.194^{NS}	-0.218^{NS}	0.713**	0.661**	-0.694**		0.479**	-0.135^{NS}	-0.385*	0.699**	-0.045^{NS}	-0.200^{NS}	0.620**	0.174^{NS}	-0.362*	-0.364*	0.139^{NS}
PL	-1.204**	0.534**	-0.063^{NS}	-1.050**	0.887**	0.876**	-0.299^{NS}	0.621**		0.073^{NS}	-0.171^{NS}	0.576**	-0.101^{NS}	-0.223^{NS}	0.643**	0.428**	0.307^{NS}	0.184^{NS}	-0.013^{NS}
PLL	-0.419*	0.056^{NS}	0.129^{NS}	-0.351*	0.074^{NS}	0.069^{NS}	0.422*	-0.374*	-0.058^{NS}		0.309^{NS}	0.022^{NS}	0.043^{NS}	0.067^{NS}	0.141^{NS}	0.020^{NS}	0.121^{NS}	0.196^{NS}	0.061^{NS}
IL	0.428**	-0.037^{NS}	-0.121^{NS}	0.327^{NS}	-0.825**	-0.603**	1.004**	-0.769**	-0.460**	1.257**		-0.276^{NS}	-0.150^{NS}	-0.053^{NS}	-0.248^{NS}	0.016^{NS}	0.047^{NS}	0.062^{NS}	0.049^{NS}
NOSR	-0.635**	0.432**	0.435**	-0.495**	0.802**	0.642**	-0.561**	0.742**	0.831**	0.014^{NS}	-0.587**		0.207^{NS}	0.056^{NS}	0.628**	0.344*	-0.044^{NS}	-0.063^{NS}	0.070^{NS}
LLL	-0.445**	-0.316^{NS}	0.266^{NS}	-0.275^{NS}	0.342*	-0.101^{NS}	-0.927**	-0.269^{NS}	0.027^{NS}	0.958**	-0.115^{NS}	0.335*		0.922**	-0.108^{NS}	0.222^{NS}	0.227^{NS}	0.266^{NS}	0.042^{NS}
LLW	-0.124^{NS}	-0.097^{NS}	0.372*	-0.012^{NS}	0.063^{NS}	-0.307^{NS}	-0.623**	-0.479**	-0.252^{NS}	0.973**	0.134^{NS}	0.050^{NS}	0.956**		-0.212^{NS}	0.036^{NS}	0.231^{NS}	0.310^{NS}	0.111^{NS}
NOLL	-0.862**	0.331*	-0.163^{NS}	-0.703**	0.898**	0.924**	0.035^{NS}	0.660**	0.882**	0.424**	-0.331*	0.680**	-0.159^{NS}	-0.329^{NS}		0.239^{NS}	-0.023^{NS}	-0.094^{NS}	0.005^{NS}
LLWt	-0.698**	-0.258^{NS}	-0.311^{NS}	-0.574**	0.224^{NS}	0.096^{NS}	-0.241^{NS}	0.222^{NS}	0.545**	0.284^{NS}	-0.125^{NS}	0.574**	0.440**	0.138^{NS}	0.305^{NS}		0.417*	0.232^{NS}	-0.125^{NS}
TLLL	-0.711**	-0.063^{NS}	-0.445**	-0.581**	-0.153^{NS}	-0.184^{NS}	-0.136^{NS}	-0.406*	0.397*	0.331*	0.260^{NS}	-0.082^{NS}	0.385*	0.373*	-0.034^{NS}	0.506**		0.840**	-0.207^{NS}
TLLW	-0.658**	0.080^{NS}	-0.317^{NS}	-0.510**	-0.125^{NS}	-0.174^{NS}	-0.200^{NS}	-0.418*	0.266^{NS}	0.388*	0.292^{NS}	-0.138^{NS}	0.653**	0.711**	-0.129^{NS}	0.479**	0.984**		-0.197^{NS}
GB	-0.171^{NS}	0.545**	0.721**	0.104^{NS}	0.298^{NS}	0.470**	0.102^{NS}	0.172^{NS}	-0.067^{NS}	0.284^{NS}	0.991**	0.104^{NS}	-0.751**	-0.682**	-0.031^{NS}	-0.860**	-0.831**	-0.494**	

Note: Genotypic correction coefficient is at left lower side of the table and phenotypic correction coefficient is at right upper side of the table

PH - Plant Height, SG - Stem girth, NOPS - Number of pollarded shoots, PSL - Pollarded shoot length, LL - Leaf length, LW - Leaf width, NOL - Number of leaves/1m shoot length, LWt - Leaf weight, PL - Petiole length, PLL - Petiolule length, IL - Internodal length, NOP - Number of pinnae, LLL - Leaflet length, LLW - Leaflet width, NOLL - Number of leaflets per leaf, LLWt - Leaflet weight, TLLL - Terminal leaflet length, TLLW - Terminal leaflet width, GB - Green biomass

Table 4. Estimates of direct and indirect effects at genotypic level of different characters on green biomass of *Moringa oleifera* seed sources

	PH	SG	NOPS	PSL	LL	LW	NOL	LWt	PL	PLL	IL	NOSR	LLL	LLW	NOLL	LLWt	TLLL	TLLW
PH	**4.342**	-0.649	1.093	-10.87	0.545	1.694	0.139	-0.699	-1.536	-0.686	-0.103	4.310	-0.517	0.132	0.999	-1.477	1.798	1.311
SG	-1.963	**1.435**	1.666	3.415	-0.290	-0.779	0.085	0.321	0.681	0.092	0.009	-2.935	-0.367	0.103	-0.383	-0.545	0.159	-0.159
NOPS	2.033	1.024	**2.336**	-4.314	-0.002	0.332	0.400	0.507	-0.080	0.211	0.029	-2.955	0.309	-0.396	0.189	-0.658	1.125	0.631
PSL	4.806	-0.499	1.026	**-9.820**	0.461	1.469	0.082	-0.570	-1.339	-0.574	-0.079	3.361	-0.319	0.013	0.815	-1.214	1.469	1.017
LL	-3.905	0.686	0.008	7.465	**-0.606**	-1.771	0.151	1.862	1.132	0.122	0.199	-5.445	0.397	-0.066	-1.040	0.474	0.387	0.250
LW	-3.967	0.603	-0.418	7.777	-0.578	**-1.855**	0.009	1.726	1.118	0.114	0.146	-4.359	-0.117	0.326	-1.071	0.203	0.466	0.348
NOL	-0.801	-0.162	-1.245	1.079	0.122	0.022	**-0.751**	-1.812	-0.382	0.690	-0.243	3.808	-1.076	0.662	-0.040	-0.510	0.343	0.398
LWt	-1.162	0.176	0.454	2.144	-0.432	-1.227	0.521	**2.610**	0.793	-0.613	0.186	-5.040	-0.313	0.509	-0.764	0.468	1.028	0.833
PL	-5.230	0.767	-0.146	10.309	-0.538	-1.626	0.225	1.622	**1.276**	-0.095	0.111	-5.638	0.032	0.268	-1.022	1.152	-1.004	-0.530
PLL	-1.819	0.081	0.301	3.447	-0.045	-0.129	-0.317	-0.977	-0.074	**1.637**	-0.304	-0.093	1.113	-1.034	-0.491	0.601	-0.839	-0.774
IL	1.857	-0.053	-0.282	-3.207	0.500	1.119	-0.754	-2.007	-0.587	2.057	**-0.242**	3.987	-0.134	-0.142	0.384	-0.264	-0.658	-0.582
NOSR	-2.757	0.621	1.017	4.863	-0.486	-1.191	0.421	1.938	1.059	0.022	0.142	**-6.788**	0.389	-0.053	-0.788	1.213	0.206	0.275
LLL	-1.932	-0.453	0.621	2.700	-0.207	0.187	0.695	-0.703	0.035	1.568	0.028	-2.275	**1.161**	-1.016	0.184	0.931	-0.973	-1.301
LLW	-0.539	-0.140	0.870	0.118	-0.038	0.569	0.467	-1.251	-0.322	1.592	-0.032	-0.337	1.110	**-1.063**	0.381	0.292	-0.943	-1.418
NOLL	-3.745	0.475	-0.381	6.905	-0.544	-1.714	-0.026	1.722	1.125	0.694	0.080	-4.615	-0.184	0.349	**-1.159**	0.645	0.086	0.256
LLWt	-3.033	-0.370	-0.727	5.638	-0.136	-0.179	0.181	0.578	0.695	0.465	0.030	-3.894	0.511	-0.147	-0.354	**2.114**	-1.279	-0.955
TLLL	-3.087	-0.090	-1.039	5.703	0.093	0.341	0.102	-1.061	0.506	0.543	-0.063	0.553	0.447	-0.396	0.039	1.069	**-2.530**	-1.961
TLLW	-2.856	0.114	-0.740	5.008	0.076	0.323	0.150	-1.090	0.339	0.635	-0.071	0.935	0.758	-0.756	0.149	1.013	-2.488	-1.994

Note: Residual effect is 0.38539

Note: PH - Plant Height, SG - Stem girth, NOPS - Number of pollarded shoots, PSL - Pollarded shoot length, LL - Leaf length, LW - Leaf width, NOL - Number of leaves/1m shoot length, LWt - Leaf weight, PL - Petiole length, PLL - Petiolule length, IL - Internodal length, NOP - Number of pinnae, LLL - Leaflet length, LLW - Leaflet width, NOLL - Number of leaflets per leaf, LLWt - Leaflet weight, TLLL - Terminal leaflet length, TLLW - Terminal leaflet width, GB - Green biomass.

Table 5. Estimates of direct and indirect effects at phenotypic level of different characters on green biomass of *Moringa oleifera* seed sources

	PH	SG	NOPS	PSL	LL	LW	NOL	LWt	PL	PLL	IL	NOSR	LLL	LLW	NOLL	LLWt	TLLL	TLLW
PH	**1.166**	-0.050	-0.046	-0.772	0.595	-0.814	-0.016	0.014	0.024	-0.002	-0.008	-0.040	0.002	0.105	0.166	-0.099	0.031	0.060
SG	-0.103	**0.570**	-0.065	0.118	-0.412	0.523	-0.024	-0.015	-0.012	-0.002	0.008	0.063	-0.096	0.108	-0.085	-0.038	-0.006	-0.032
NOPS	0.423	0.291	**-0.126**	-0.310	-0.117	-0.045	0.033	-0.015	0.006	-0.015	-0.004	0.060	-0.098	0.160	0.039	-0.052	0.022	0.023
PSL	1.084	-0.081	-0.047	**-0.831**	0.690	-0.904	-0.007	0.017	0.027	-0.002	-0.011	-0.057	0.079	0.038	0.207	-0.121	0.038	0.088
LL	-0.556	0.188	-0.012	0.459	**-1.247**	1.472	0.057	-0.064	-0.024	0.010	0.015	0.112	-0.057	-0.034	-0.243	0.032	0.012	0.035
LW	-0.603	0.189	0.004	0.477	-1.167	**1.573**	0.002	-0.061	-0.025	0.015	0.007	0.084	0.017	-0.129	-0.237	0.027	0.013	0.052
NOL	0.067	0.048	0.015	-0.020	0.251	-0.013	**-0.286**	0.038	0.004	0.028	-0.030	-0.050	0.057	-0.024	0.018	-0.021	0.000	0.034
LWt	-0.156	0.086	-0.018	0.138	-0.787	0.937	0.108	**-0.102**	-0.022	-0.019	0.028	0.121	0.043	-0.199	-0.216	0.051	0.032	0.111
PL	-0.633	0.148	0.017	0.490	-0.664	0.882	0.025	-0.049	**-0.045**	0.010	0.013	0.100	0.097	-0.222	-0.224	0.126	-0.027	-0.056
PLL	-0.016	-0.008	0.014	0.012	-0.090	0.168	-0.058	0.014	-0.003	**0.139**	-0.023	0.004	-0.042	0.067	-0.049	0.006	-0.011	-0.060
IL	0.129	-0.062	-0.006	-0.130	0.247	-0.141	-0.116	0.039	0.008	0.043	**-0.073**	-0.048	0.144	-0.053	0.086	0.005	-0.004	-0.019
NOSR	-0.266	0.208	-0.044	0.271	-0.803	0.759	0.082	-0.071	-0.026	0.003	0.020	**0.174**	-0.199	0.056	-0.218	0.101	0.004	0.019
LLL	-0.003	0.057	-0.013	0.068	-0.074	-0.028	0.017	0.005	0.005	0.006	0.011	0.036	**-0.963**	0.918	0.038	0.065	-0.020	-0.081
LLW	0.123	0.062	-0.020	-0.032	0.043	-0.203	0.007	0.020	0.010	0.009	0.004	0.010	-0.887	**0.996**	0.074	0.011	-0.020	-0.095
NOLL	-0.557	0.139	0.014	0.494	-0.872	1.071	0.015	-0.063	-0.029	0.020	0.018	0.109	0.104	-0.211	**-0.348**	0.070	0.002	0.029
LLWt	-0.392	-0.074	0.022	0.341	-0.136	0.144	0.020	-0.018	-0.019	0.003	-0.001	0.060	-0.214	0.036	-0.083	**0.294**	-0.037	-0.071
TLLL	-0.405	0.039	0.032	0.359	0.173	-0.230	0.000	0.037	-0.014	0.017	-0.003	-0.008	-0.219	0.230	0.008	0.123	**-0.088**	-0.257
TLLW	-0.227	0.060	0.010	0.240	0.142	-0.268	0.031	0.037	-0.008	0.027	-0.005	-0.011	-0.256	0.309	0.033	0.068	-0.074	**-0.306**

Note: Residual effect is 0.29078

Note: PH - Plant Height, SG - Stem girth, NOPS - Number of pollarded shoots, PSL - Pollarded shoot length, LL - Leaf length, LW - Leaf width, NOL - Number of leaves/1m shoot length, LWt - Leaf weight, PL - Petiole length, PLL - Petiolule length, IL - Internodal length, NOP - Number of pinnae, LLL - Leaflet length, LLW - Leaflet width, NOLL - Number of leaflets per leaf, LLWt - Leaflet weight, TLLL - Terminal leaflet length, TLLW - Terminal leaflet width, GB - Green biomass.

Table 6. Percentage of variance explained by different principal components in *Moringa oleifera* seed sources

Characters	Component				
	PC1	PC2	PC3	PC4	PC5
PH	-0.82932	-0.39641	-0.16400	0.26809	0.07495
SG	0.40165	-0.24353	0.40783	0.21469	-0.63856
NOPS	0.02885	-0.51143	0.50986	0.47448	0.15762
PSL	-0.82932	-0.39641	-0.16400	0.26809	0.07495
LL	0.91166	-0.21785	0.07107	0.19589	-0.01523
LW	0.86639	-0.29373	0.18747	-0.05987	-0.03832
NOL	-0.25472	-0.10074	0.70614	-0.46750	0.19052
LWt	0.67176	-0.49367	-0.39001	0.10757	0.16758
PL	0.92924	0.10820	0.03313	-0.21948	-0.07525
PLL	0.05248	0.30158	0.71383	0.23881	0.36664
IL	-0.44820	0.13215	0.75667	-0.14785	0.18997
NOP	0.80327	-0.15794	-0.08786	0.37578	0.15507
LLL	0.11560	0.56999	-0.03859	0.75689	0.09691
LLW	-0.09554	0.55955	0.09936	0.78405	-0.04040
NOLL	0.86479	-0.18907	0.16738	-0.12493	0.24342
LLWt	0.44243	0.50030	-0.11924	-0.05431	0.47357
TLLL	0.15196	0.90831	0.05922	-0.22494	-0.19853
TLLW	0.09374	0.89551	0.12006	0.00854	-0.30604
GB	0.01545	-0.54381	0.47285	0.18518	-0.36721
Eigen value	6.346	4.014	2.557	2.246	1.273
Percent of variability	33.401	21.129	13.458	11.824	6.698
Cumulative percent of variability	33.401	54.530	67.988	79.812	86.510

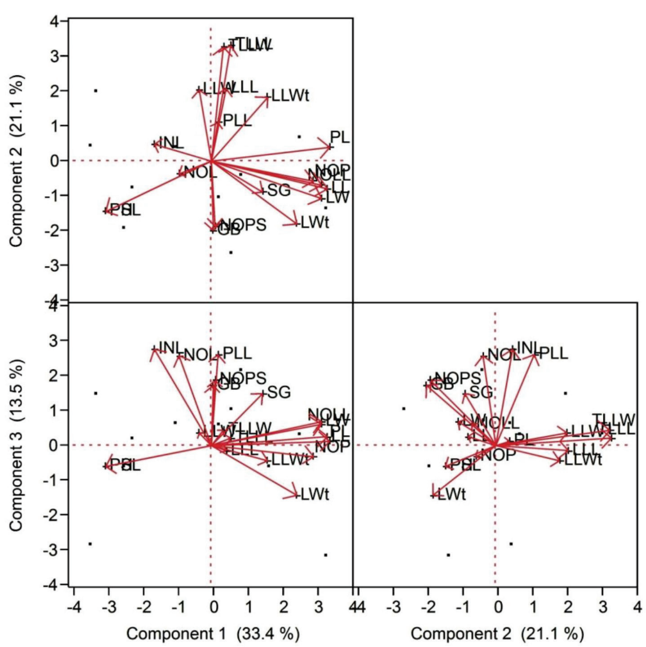

Fig. 2. Bi-plot analysis for *Moringa oleifera* seed sources for first three principal components

and terminal leaflet length. These findings suggest that traits contributing the most to variation should be prioritized in breeding programs (Jagdev *et al.*, 1991). In this study, leaflet weight accounted for 96.6% of the variation in divergence. The PCA results indicate that five principal components are sufficient to characterize *M. oleifera* seed sources, possibly reducing the need for a larger number of traits. In line with this, Yilmaz *et al.* (2012) demonstrated that 21 morphological traits were sufficient for the characterization of apricot, compared to the use of 57 traits. Similar PCA studies on Moringa were conducted by Papoola *et al.* (2016).

In conclusion, the *Moringa oleifera* seed sources exhibited substantial variability in morphometric traits, offering significant potential for genetic improvement and conservation efforts. Traits such as the number of leaflets (97.06% heritability with 81.35% genetic gain) and leaf weight (95.56% heritability with 40.77% genetic gain) demonstrated very high heritability and genetic gain, suggesting their suitability for direct selection in breeding programs. In contrast, green biomass showed low heritability, indicating a strong

Table 7. Variable clustering summary

Cluster	Number of variables	Most representative variable	Proportion of variation explained	Proportion of variation explained by clustering
1	6	LL	0.682	0.71
2	4	INL	0.547	
3	4	TLLL	0.623	
4	2	LLW	0.966	
5	3	PH	0.931	

influence of environmental factors and management practices on this trait. The inter-character correlations provide a valuable basis for designing hybridization strategies aimed at enhancing genotypic selection. Path coefficient analysis indicated that plant height, leaf weight, number of pollarded shoots, leaflet weight, and leaf width had the highest positive direct effects on green biomass. Thus, direct selection for these traits could be advantageous for improving biomass productivity in future breeding programs. Based on principal component analysis (PCA), the most representative traits for Moringa were plant height, leaf length, internode length, leaflet width, and terminal leaflet length. These traits could be leveraged for further selection efforts to optimize the productivity of elite Moringa sources. Additionally, selection strategies focused on biomass production should consider these key traits, as they have both direct and indirect impacts on biomass yield in *M. oleifera.*

Authors' contribution

Conceptualization of research work and designing of experiments (AKD); Resources availability (AKD, GPS), Execution of field/lab experiments and data collection (NS, AKD); Analysis of data and interpretation (AKD, GPS); Writing original draft (AKD, NS), Review & editing (AKD, GPS). All authors have read and agreed to the published version of the manuscript.

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