PLANT SCIENCE TODAY
Vol 13(sp9): 01-14
https://doi.org/10.14719/pst.16543

eISSN 2348-1900
OPEN ACCESS

Research Article | Plant Breeding and Genetics 2026, Volume 13, Issue sp9, pp. 01-14

Genetic diversity and nutritional profiling of *Moringa oleifera* Lam. half-sib progenies

Mohit Kundal[1]*, Shweta[2], Robin[3], Neha Kumari[4], Thakur Narender Singh[5], Atul Gupta[6], Anita Kumari[1] & Shikha Thakur[1]

[1]Department of Tree Improvement and Genetic Resources, College of Forestry, Dr. Yashwant Singh Parmar University of Horticulture and Forestry, Nauni, Solan 173 230, Himachal Pradesh, India

[2]School of Agriculture, Baba Farid College of Engineering and Technology, Baba Farid Group of Institutions, Deon, Bathinda 151 001, Punjab, India

[3]Department of Agriculture, Sant Baba Bhag Singh University, Khiala, Jalandhar 144 030, Punjab, India

[4]School of Agriculture Sciences, Rayat Bahra University, Kharar-Mohali 140 301, Punjab, India

[5]Department of Horticulture, Dr. Khem Singh Gill Akal College of Agriculture, Eternal University, Baru Sahib 173 101, Himachal Pradesh, India

[6]Regional Horticulture Research and Training Station, Jachh, Kangra, Dr. Yashwant Singh Parmar University of Horticulture and Forestry, Nauni, Solan 173 230, Himachal Pradesh, India

***Correspondence:** mohitkundal1617@gmail.com

Abstract

Moringa oleifera Lam. ("Miracle tree") is a multi-purpose tropical bioresource valued for combating malnutrition. However, systematic evaluations monitoring proximate principles and mineral concentrations across wild genotypes during early nursery establishment remain limited. This study evaluated the nutritional profiles, proximate principles and biomass determinants of 35 half-sib genotypes collected from wild populations across five sub-Himalayan Indian states after one year of nursery growth. Mature seeds from seven geographical sources were evaluated to be deploying randomised block design. Leaf samples were analysed for total amino acids (TAA), proximate principles and 10 essential macro- and micro-minerals. Analysis of variance (ANOVA) revealed significant variation across all genotypes. Progeny P7 demonstrated target superiority, recording peak values for crude protein CP (27.49 %), TAA (19.12 %), nitrogen (N, 4397.87 mg/100 g) and zinc (Zn, 3.87 mg/100 g). Progeny P18 excelled in iron accumulation (49.60 mg/100 g), while P22 peaked in total ash (10.39 %) and phosphorus (P, 74.68 mg/100 g). Comparative values of phenotypic coefficient of variation (PCV) were higher than genotypic coefficient of variation (GCV) confirming strong genetic control. High broad-sense heritability and genetic advance were evaluated for crude fat, fibre, P, Zn, sulphur (S), iron (Fe) and manganese (Mn), indicating additive gene action. Principal component analysis (PCA) compressed total variance into four dominant components explaining 89.61 % of total variation. Path analysis revealed that zinc (β = 0.7590) and iron (β = 0.5490) exerted the strongest direct positive effects on fresh biomass. Substantial juvenile genetic variation indicates excellent potential for early selection. Systematic evaluations monitoring proximate principles and mineral concentrations across wild genotypes collected from north-west India, specifically during early nursery establishment have historically been limited. Additionally, there was a lack of data on juvenile genetic variation and early selection potential for nutritional traits among sub-Himalayan wild populations. This study addresses the selection of elite accessions (P7, P18 and P22) which could be advanced to multi-location field trials to confirm phenotypic stability for commercial and pharmacological production.

Keywords: clustering; correlation; genotypes; *Moringa oleifera*; principal component analysis; proximate principles

Received: 04 July 2026. **Accepted:** 07 September 2026. **Published:** 19 October 2026.

Cite this article: Mohit K, Shweta, Robin, Neha K, Thakur NS, Atul G, Anita K, Shikha T. Genetic diversity and nutritional profiling of *Moringa oleifera* Lam. half-sib progenies. Plant Science Today. 2026;13(sp9):01-14. https://doi.org/10.14719/pst.16543

Introduction

For centuries, medicinal and aromatic plants have been the backbone of the traditional health care systems throughout the world. Earliest records of medicinal plants are written in the ancient Indian texts like Rig-Veda, Charaka Samhita and Sushruta Samhita (1). According to the World Health Organisation (WHO), over 60 % of the world's population still rely on plant-based indigenous herbal plants for primary healthcare in the present world (2). *Moringa oleifera* Lam., widely known as moringa, the drumstick or miracle tree, has emerged as a promising multi-purpose tropical bioresource. It helps meet the increasing global demand for low-cost, non-narcotic and nutritious natural products to combat malnutrition and food insecurity (3).

It belongs to monogeneric family Moringaceae and is native to the sub-Himalayan

tracts of northern India. Morphologically it is a fast-growing, drought resistant, medium-sized tree with open crown (4). It is well adapted to varying agro-climatic zones, from hot drylands to humid tropics. It can tolerate a wide annual rainfall poor soil ranging from 250–3000 mm and a pH ranging from 5.0–9.0, respectively (5). The global market for moringa products (encompassing leaf powder, seed oil, teas and capsule supplements) is valued at approximately USD 10.01 billion to USD 11.09 billion, with aggressive compound annual growth rates (CAGR) ranging between 9.5 % and 10.8 % (6). With 38000 hectares of land under cultivation, India is the world's largest producer of moringa, yielding over 2.2 million tonnes of tender fruits per year (4).

Full plant utility, both raw and processed, is what gives its true value. Whole plant including roots, bark, pods, flowers and seeds, have therapeutic and practical qualities and are used to treat a variety of gastrointestinal, cardiovascular and inflammatory conditions (7, 8). The leaves constitute the most concentrated supply of macronutrients and micronutrients necessary for animal and human growth and nutrition (9, 10). Fresh *M. oleifera* leaves provide four times more calcium (Ca) than milk, four times more iron (Fe) than spinach, three times more potassium (K) than bananas, seven times more vitamin carbon (C) than oranges and four times more vitamin A than carrots (11). The protein quality is like that of milk and eggs. Dried moringa leaves represent a promising dietary supplement for improving nutritional security (12).

The physical and biochemical characteristics are greatly impacted by genetic composition, paternal lineage and environmental interactions, despite their enormous nutritional and commercial importance (13). To systematically domesticate, breed and scale up superior cultivars for the pharmaceutical and nutritional industries, it is imperative to assess available germplasm at an early developmental stage.

Evaluation during the nursery stage; evaluating genotypic and biochemical performances during a year of nursery growth; offers a crucial biological baseline for subsequent selection for field trials. This juvenile stage evaluation allows researchers and farmers to monitor vegetative vigour, environmental adaptability and stability of nutritional profiles prior to full-field transplantation, long-term perennial allocation and stability testing (14). The entire breeding cycle is accelerated through prescreening of genotypes. Therefore, consistent, high-quality yields for commercial extraction are ensured by choosing better phenotypes and identifying elite planting materials throughout the nursery phase (15).

While a lot of attention has been given on research work particularly in morphological, nutritional and molecular screening techniques to examine the wide range of botanical characteristics and genetic diversity of *M. oleifera* (13), there is scope for systematic assessments that monitor both proximate principles and specific nutrient concentrations across various domestic genotypes during early nursery establishment.

Hence, the current study was conducted to minimise the above-mentioned gap. The main goal of this study was to statistically profile and evaluate the nutritional properties of particular *Moringa* genotypes grown naturally in the wild, including crude protein (CP), carbs, crude fibre (CF), fat and important mineral/vitamin concentrations. This study intends to provide essential information for upcoming tree improvement initiatives, targeted germplasm conservation and high-efficiency agro-forestry deployments by identifying the most elite, nutrient-dense lines at one-year nursery stage.

Materials and Methods

Experimental site and agro-climatic conditions

The sub-Himalayan regions of the Indian states of Jammu, Himachal Pradesh, Punjab, Haryana and Uttarakhand were surveyed between November 2020 and February 2021 to determine the locations where this species grows in wild in abundance. Samba (Jammu), Dunera (Punjab), Siswa Dam (Punjab), Lamlehri (Himachal Pradesh), Tirla (Himachal Pradesh), Morni Hills (Haryana) and Vikasnagar (Uttarakhand) were the seven seed sources selected for the study (Table 1). For plus tree selection per location, a baseline criterion with massive total leaf biomass (kg), tree height up to 10–12 m and tree diameter of 35–45 cm at breast height was used. Five plus trees per mother location were chosen and tagged making it a total of 35 plus trees under study. From these 35 plus trees, mature pods were harvested and collected from all directions in the month of May 2021. These seeds collected from each plus tree were sown in 3 replications having 20 seeds sown per replication making it a total of 60 seedlings per plus tree. This experiment was conducted using one way analysis of variance (ANOVA) ($p \leq 0.05$) and deploying randomised block design.

The collected seeds were sown in polybags of size 5 × 7 inches at Regional Horticulture Research and Training Station, Jachh, Kangra under Dr. Yashwant Singh Parmar University of Horticulture and Forestry, Nauni, Solan, Himachal Pradesh. The station is located at 31.3674° N latitude, 77.3057° E longitude and 428 m above mean sea level. The experimental location accomplished mean annual rainfall of 1500 mm and mean annual temperature ranged from 29.3 °C in summer and 13.6 °C in winter. About 20 plants per replication were grown for each plus tree.

© The Author(s) 2026. Creative Commons CC BY 4.0. Published by Horizon e-Publishing Group.
https://doi.org/10.14719/pst.16543

Table 1. Selected seed sources of *Moringa oleifera*

Sl. No.	Location	District and State/UT	Latitude (°N)	Longitude (°E)	Altitude (above mean sea level)
1	Samba	Samba, Jammu and Kashmir	32.5603	75.1193	423
2	Dunera	Pathankot and Punjab	32.3593	75.7629	463
3	Vikasnagar	Dehradun and Uttarakhand	30.3463	77.9148	549
4	Lamlehri	Una and Himachal Pradesh	31.5232	76.3232	526
5	Tirla	Nalagarh and Himachal Pradesh	30.9239	76.9219	403
6	Siswa Dam	Sahibzada Ajit Singh Nagar and Punjab	30.8671	76.7487	351
7	Morni Hills	Panchkula and Haryana	30.6556	77.0831	516

By proportionately comparing it with its fresh weight, the total dry matter content of the leaves was calculated and written in percentage. Estimation of proximate principles viz., CP, ether extract (EE)/crude fat, CF, total ash content (AC) and nitrogen free extract (NFE) was done using standard official procedures (16, 17). Ninhydrin reagents and a colorimeter were used to estimate the total amino acid content using a methodology developed by previous researchers (18).

In this experiment, ten mineral nutrients viz., nitrogen (N), phosphorus (P), potassium (K), calcium (Ca), magnesium (Mg), sulphur (S), zinc (Zn), copper (Cu), iron (Fe) and manganese (Mn) were assessed. To estimate N, dried leaf samples were treated to wet and hot digestion using 98 % sulphuric acid for about one hour and cold digestion for 10–12 hr using a di-acid mixture (HNO_3 : $HClO_4$ in a 4 : 1 ratio) for the remaining mineral nutrients. The N was evaluated using the previous methodology and the microkjeldahl equipment (16). Phosphorus was measured using a UV-Visible Spectrophotometer and the yellow vanadomolybodate yellow colour technique (19). Using standard Flame Photometry calibrated against high-purity elemental working standards, K and Ca were directly measured (20). Ion chromatography was used to measure S (21). An Atomic Absorption Spectrophotometer (AAS) tuned at suitable wavelengths for each element was used to estimate Mg, Fe, Cu, Zn and Mn (22).

Statistical analysis

The ANOVA was conducted using OPSTAT to calculate statistically significant differences among the genotypes for various nutritional parameters (23). Further, various genetic parameters viz., genotypic coefficient of variation (GCV) (24), phenotypic coefficient of variation (PCV) (24), broad-sense heritability (h^2) (24) and genetic advance (24, 25) and genetic advance as a percentage of mean (25) were assessed to estimate the genetic component of variation among the genotypes. Genotypic and phenotypic correlation were worked using methods laid by previous researchers (26, 27). Principal component analysis (PCA) was calculated using method given by earlier researchers (28) and by using PAST 4.0 software (29). Path coefficient analysis was analysed using the previous procedure (30). Hierarchical cluster analysis was deployed using Ward's minimum variance method based on Euclidean distances and using PAST 4.0 software (29). Other than PAST 4.0 software used for certain parameters and the rest of the analysis was done using OPSTAT (23).

Results and Discussion

Divergence in proximate principles and amino acids

The ANOVA demonstrated significant variability for all analysed parameters across 35 half-sib genotypes under study. Highest CP content was observed in P7 (27.49 %) while highest EE (7.07 %) was observed in P19. Crude

© The Author(s) 2026. Creative Commons CC BY 4.0. Published by Horizon e-Publishing Group.
https://doi.org/10.14719/pst.16543

fibre content excelled in P3 (13.60 %). Total ash was highest in P22 (10.39 %) while N-free extract was observed highest in P34 (63.51 %). Total amino acids (TAA) content was also highest in P7 (19.12%) (Table 2).

Table 2. Variation in leaf dry matter content, proximate principles and biochemical estimates of leaf samples of *Moringa oleifera* progenies

Seed source	Progeny	Leaf dry matter content (%)	Crude protein (%)	Ether extract (%)	Crude fiber (%)	Total ash content (%)	Nitrogen free extract (%)	Total amino acids (%)
Samba	P1	19.06 (4.48)	22.52 (4.85)	4.88 (2.42)	8.40 (3.06)	7.81 (2.97)	56.38	15.51 (4.06)
	P2	19.22 (4.50)	19.11 (4.48)	3.79 (2.19)	10.91 (3.45)	7.09 (2.84)	59.10	13.16 (3.76)
	P3	18.89 (4.46)	19.61 (4.54)	3.02 (1.00)	13.60 (3.82)	8.05 (3.01)	55.71	13.55 (3.81)
	P4	19.08 (4.48)	24.07 (5.01)	3.63 (2.15)	11.85 (3.58)	8.67 (3.11)	51.79	16.67 (4.20)
	P5	19.01 (4.47)	20.44 (4.63)	5.55 (2.56)	8.00 (2.99)	6.73 (2.78)	59.28	14.13 (3.89)
Dunera	P6	19.58 (4.54)	26.26 (5.22)	6.21 (2.68)	10.09 (3.33)	7.73 (2.95)	49.72	18.14 (4.37)
	P7	18.72 (4.44)	27.49 (5.34)	3.20 (2.05)	13.51 (3.81)	9.23 (3.20)	46.56	19.12 (4.49)
	P8	18.83 (4.45)	20.70 (4.66)	3.47 (2.11)	13.39 (3.79)	9.29 (3.21)	53.15	14.22 (3.90)
	P9	19.25 (4.50)	26.98 (5.29)	4.32 (2.31)	8.61 (3.10)	6.65 (2.77)	53.44	18.63 (4.43)
	P10	19.02 (4.47)	26.67 (5.26)	3.74 (2.18)	11.92 (3.59)	7.65 (2.94)	50.02	18.42 (4.41)
Vikasnagar	P11	19.05 (4.48)	23.08 (4.91)	4.09 (2.25)	8.09 (3.01)	10.19 (3.34)	54.56	15.84 (4.10)
	P12	19.25 (4.50)	21.28 (4.72)	3.99 (2.23)	9.60 (3.26)	7.34 (2.89)	57.79	14.78 (3.97)
	P13	19.16 (4.49)	19.51 (4.53)	5.78 (2.60)	4.59 (2.36)	9.73 (3.27)	60.38	13.46 (3.80)
	P14	19.03 (4.48)	20.25 (4.61)	3.43 (2.10)	13.41 (3.80)	6.35 (2.71)	56.56	14.02 (3.88)
	P15	18.98 (4.47)	24.50 (5.05)	6.36 (2.71)	4.54 (2.35)	9.95 (3.31)	54.64	16.91 (4.23)
Lamlehri	P16	19.02 (4.47)	26.73 (5.27)	6.60 (2.75)	3.95 (2.22)	9.55 (3.25)	53.17	18.37 (4.40)
	P17	19.05 (4.48)	20.28 (4.61)	3.25 (2.06)	12.95 (3.74)	6.53 (2.74)	56.98	13.87 (3.86)
	P18	18.70 (4.44)	27.11 (5.30)	6.76 (2.78)	3.31 (2.08)	9.31 (3.21)	53.52	18.80 (4.45)
	P19	18.70 (4.44)	26.48 (5.24)	7.07 (2.84)	6.00 (2.65)	9.03 (3.16)	51.42	18.26 (4.39)
	P20	19.10 (4.48)	20.56 (4.64)	3.56 (2.13)	11.65 (3.56)	9.37 (3.22)	54.86	14.08 (3.88)
Tirla	P21	19.15 (4.49)	25.23 (5.12)	6.89 (2.81)	6.77 (2.78)	8.68 (3.11)	52.42	17.47 (4.30)
	P22	19.05 (4.48)	21.54 (4.75)	6.11 (2.67)	3.71 (2.17)	10.39 (3.37)	58.24	14.97 (4.00)
	P23	19.36 (4.51)	24.84 (5.08)	3.88 (2.21)	10.59 (3.40)	8.10 (3.01)	52.58	17.08 (4.25)
	P24	19.10 (4.48)	25.43 (5.14)	6.85 (2.80)	3.08 (2.02)	8.27 (3.04)	56.38	17.51 (4.30)
	P25	19.41 (4.52)	21.92 (4.79)	4.99 (2.45)	4.17 (2.27)	7.65 (2.94)	61.26	15.19 (4.02)

© The Author(s) 2026. Creative Commons CC BY 4.0. Published by Horizon e-Publishing Group.
https://doi.org/10.14719/pst.16543

Siswa dam	P26	19.16 (4.90)	24.71 (5.07)	5.41 (2.53)	7.34 (2.88)	7.59 (2.93)	54.95	16.99 (4.24)
	P27	18.82 (4.45)	22.22 (4.82)	4.52 (2.35)	10.24 (3.35)	9.50 (3.24)	53.51	15.44 (4.05)
	P28	19.30 (4.51)	25.89 (5.18)	4.79 (2.40)	6.58 (2.75)	8.72 (3.12)	54.02	17.68 (4.32)
	P29	19.47 (4.53)	25.10 (5.11)	5.16 (2.48)	7.21 (2.86)	8.22 (3.03)	54.31	17.32 (4.28)
	P30	19.01 (4.47)	24.00 (5.00)	5.94 (2.63)	9.21 (3.20)	8.20 (3.03)	52.65	16.52 (4.19)
Morni hills	P31	18.97 (4.47)	23.46 (4.95)	5.72 (2.59)	4.44 (2.33)	7.04 (2.83)	59.34	16.17 (4.14)
	P32	19.33 (4.51)	20.75 (4.66)	4.13 (2.26)	10.54 (3.40)	7.40 (2.90)	57.18	14.43 (3.93)
	P33	18.79 (4.45)	25.61 (5.16)	5.12 (2.47)	7.73 (2.95)	10.20 (3.34)	51.35	17.69 (4.32)
	P34	19.29 (4.50)	18.93 (4.46)	5.23 (2.50)	5.15 (2.48)	7.18 (2.86)	63.51	13.07 (3.75)
	P35	18.68 (4.44)	26.13 (5.21)	4.67 (2.38)	10.28 (3.36)	10.01 (3.32)	48.90	17.98 (4.36)
	Mean	19.07 (4.48)	23.41 (4.93)	4.92 (2.42)	8.44 (2.94)	8.38 (3.06)	54.85	16.16 (4.13)
	$CD_{0.05}$	NS	0.09	0.10	0.21	0.12	1.89	0.14
	CV		1.17	2.54	4.23	2.35	2.12	2.08

The observed variation among genotypes indicates a significant genetic contribution to proximate and mineral composition (31). Additionally, selections were made in selected domesticated lines having leaf CP levels reaching up to 28.9 g/100 g among *Moringa* germplasm (32).

Quantitative shifts in mineral micro- and macro-nutrients

Maximum N content was observed in P7 (4397.85 mg/100 g dried leaf sample) which was at par with P18, P9, P16, P10, P6, P35 and P28. Significantly maximum P content was observed in P22 (74.68 mg/100 g of dried leaf sample) which was statistically at par with P18 and P24. For K, a maximum value of 1761.02 mg/100 g dried leaf sample was observed in P22 which was statistically in line with P28, P33, P19, P22, P32, P4, P13, P16, P34, P1, P9, P30 and P24. Calcium had a maximum value in P20 (1.89 mg/100 g of dried moringa leaf sample) which was in accordance with P17, P18, P8, P14, P12, P2, P1 and P7. Statistically, P16 had the highest Mg content (777.88 mg/100 g dried leaf sample), followed by P21, P22, P25, P19, P18, P24, P15, P28 and P13. P7 has the highest S level (1279.19 mg/100 g dried leaf sample). P7 had the highest Zn level (3.87 mg/100 g dried moringa leaf sample), which was comparable to P14, P3 and P8.P14 and P18 had the highest Cu level (0.78 mg/100 g dried leaf sample each), which was statistically in line with P12, P11, P15, P20, P17 and P21. Finally, P22 exhibited the highest value of other Mn concentration (4.82 mg/100 g dried leaf sample). P22 was found to be comparable to P21, P18, P16, P29, P13, P24, P25, P19, P33, P15 and P28 in terms of Mn content (33).

Though the maximum at par values for the characteristics studied were distributed throughout the germplasm under study, particular half-sib genotypes, such as P7, P18 and P22, had the highest genetic superiority of all. This makes them elite trees for focused tree selection and tree further improvement programs (Table 3).

Significant differences in the mean values of proximate principles and mineral contents, especially Fe content, determined under this study and of that of the previous study was observed. This could be due to the superiority of genetic attributes of the genotypes as high genetic advance and heritability is observed in the genotypes under study. These results support the findings for dry matter content, proximate principles and mineral contents in *M. oleifera* (34). On the other hand, similar results for CF, Fe and Mn in *M. oleifera* (35). Similar results for crude fiber, Fe and Ca were found (36). Every portion of the moringa plant has therapeutic value and is used as a medication to treat a variety of illnesses (37).

Genetic parameters: Heritability and inter-trait correlations

The comparative PCV values were higher than the respective GCV expressions for all proximate, amino acids and mineral parameters evaluated indicating that while the environment influences these characters to a minor extent, phenotypic expressions under the study are largely governed by genetic factors.

© The Author(s) 2026. Creative Commons CC BY 4.0. Published by Horizon e-Publishing Group.
https://doi.org/10.14719/pst.16543

High broad-sense heritability coupled with significant genetic gain was calculated for EE, CF, Fe, P, S, Zn and Mn content. This pattern suggests that these nutritional traits are regulated primarily by additive gene action, making them responsive to direct selection methods (Table 4).

Table 3. Variation in mineral nutrient contents of leaf samples of *Moringa oleifera* progenies

Seed source	Progeny	Mineral nutrient content (mg/100 g)									
		N	P	K	Ca	Mg	S	Zn	Fe	Cu	Mn
Samba	P1	3603.20	49.16	1634.98	1.69	545.02	930.22	3.10	29.96	0.50	3.50
	P2	3057.07	44.33	1356.43	1.83	537.73	1095.17	3.54	26.76	0.65	3.49
	P3	3138.13	28.89	1425.95	1.79	394.92	1212.27	3.79	26.06	0.65	3.07
	P4	3850.67	37.26	1661.11	1.65	398.67	1179.14	3.62	41.87	0.49	3.30
	P5	3270.93	51.78	1362.37	1.78	601.56	839.62	2.95	28.76	0.61	3.94
Dunera	P6	4201.07	48.18	1535.54	1.77	551.97	980.35	3.27	29.08	0.62	3.63
	P7	4397.87	25.09	1471.26	1.81	340.45	1279.19	3.87	33.03	0.67	2.79
	P8	3311.47	26.58	1325.02	1.87	344.98	755.84	3.74	34.47	0.69	2.82
	P9	4317.33	50.89	1619.67	1.72	628.42	731.06	3.04	36.02	0.50	4.22
	P10	4267.73	36.12	1454.82	1.77	384.54	1152.03	3.58	35.08	0.63	3.47
Vikasnagar	P11	3692.80	49.92	1320.82	1.82	594.20	902.36	3.01	43.62	0.74	3.97
	P12	3405.33	41.30	1272.59	1.85	475.49	981.55	3.21	37.74	0.77	3.41
	P13	3122.13	55.21	1653.30	1.65	688.91	711.60	2.61	24.56	0.40	4.36
	P14	3240.53	31.53	1311.17	1.87	371.75	1206.60	3.84	32.41	0.78	3.44
	P15	3920.53	64.01	1417.00	1.87	673.18	944.96	2.68	30.89	0.74	4.27
Lamlehri	P16	4277.33	69.42	1647.14	1.64	777.88	623.09	2.41	25.70	0.43	4.39
	P17	3245.33	39.14	1416.99	1.88	446.31	1178.74	3.69	39.44	0.72	3.28
	P18	4337.07	74.63	1306.92	1.88	723.71	583.21	2.34	49.60	0.78	4.57
	P19	4236.27	66.15	1696.56	1.62	727.14	781.21	2.74	42.40	0.45	4.32
	P20	3289.60	40.08	1298.64	1.89	473.53	1062.88	3.50	37.12	0.74	3.15
Tirla	P21	4036.80	69.52	1393.42	1.86	775.16	826.16	2.77	25.13	0.72	4.59
	P22	3446.40	74.68	1695.45	1.62	758.94	617.06	2.39	42.65	0.37	4.82
	P23	3974.93	33.27	1378.15	1.78	377.73	1088.08	3.46	31.32	0.62	3.29
	P24	4068.27	70.73	1569.82	1.64	716.57	568.27	2.25	33.35	0.44	4.36
	P25	3507.73	65.07	1495.77	1.72	731.82	680.51	2.45	46.33	0.58	4.33
Siswa dam	P26	3954.13	54.48	1677.17	1.64	657.57	855.80	2.92	41.04	0.41	3.97
	P27	3555.73	46.47	1515.11	1.78	519.95	1010.08	3.33	48.80	0.59	3.49
	P28	4142.93	63.26	1708.04	1.59	672.63	652.39	2.53	46.89	0.35	4.27
	P29	4015.47	60.97	1761.02	1.58	649.37	1213.32	2.85	45.87	0.35	4.37
	P30	3839.47	51.68	1597.68	1.72	637.21	959.09	3.16	30.53	0.54	4.06
Morni hills	P31	3753.07	52.84	1470.96	1.75	596.20	813.91	2.66	42.14	0.61	4.06
	P32	3319.47	42.36	1675.46	1.65	484.26	1075.78	3.40	29.45	0.42	3.58
	P33	4097.60	57.87	1708.84	1.61	638.10	831.81	2.81	47.49	0.38	4.29
	P34	3028.80	45.84	1644.08	1.66	651.12	697.67	2.56	34.22	0.49	3.93
	P35	4181.33	61.06	1549.13	1.70	529.49	1043.56	3.37	38.31	0.55	3.57
	Mean	3745.84	50.85	1515.10	1.74	573.61	916.13	3.07	36.23	0.57	3.84
	$CD_{0.05}$	261.42	4.22	149.50	0.09	112.01	55.11	0.14	2.87	0.06	0.56
	CV	4.28	5.10	6.06	3.07	11.99	2.69	2.89	4.86	6.36	8.97

N: nitrogen; P: phosphorus; K: potassium; Ca: calcium; Mg: magnesium; S: sulphur; Zn: zinc; Fe: iron; Cu: copper; Mn: manganese; CD: critical difference; CV: coefficient of variation. Values are expressed as mg/100 g.

© The Author(s) 2026. Creative Commons CC BY 4.0. Published by Horizon e-Publishing Group.
https://doi.org/10.14719/pst.16543

Table 4. Genetic estimates for leaf proximate principles, leaf biochemical estimates and leaf mineral contents of *Moringa oleifera* progenies

Character	Range	Mean	CV	GCV	PCV	Heritability (broad sense) Percentage	Genetic advance	Genetic advance (%) of mean
Crude protein (%)	18.93-27.49	23.41	1.17	11.47	11.71	95.94	5.42	23.14
Ether extract (%)	3.02-7.07	4.92	2.54	24.51	25.36	93.41	3.00	48.79
Crude fibre (%)	3.08-13.60	8.44	4.23	38.79	39.76	95.15	6.58	77.94
Total ash content (%)	6.35-10.39	8.38	2.35	13.73	14.69	87.45	2.22	26.46
Nitrogen free extract (%)	46.56-63.51	54.85	2.12	6.58	6.91	90.63	7.08	12.91
Total amino acids (%)	13.07-19.12	16.16	2.08	11.28	12.08	87.17	3.50	21.69
Nitrogen (mg/100 g)	3028.80-4397.87	3745.84	4.28	11.28	12.07	87.40	813.65	21.72
Phosphorus (mg/100 g)	25.09-74.68	50.85	5.10	27.27	27.74	96.62	28.80	55.21
Potassium (mg/100 g)	1272.09-1761.02	1515.10	6.06	9.13	10.95	69.43	237.33	15.66
Calcium (mg/100 g)	1.58-1.89	1.74	3.07	5.30	6.13	74.81	0.16	9.44
Magnesium (mg/100 g)	340.45-777.88	573.61	11.99	22.27	25.29	77.54	231.49	40.39
Zinc (mg/100 g)	2.25-3.87	3.07	2.89	15.69	15.95	96.71	0.98	31.78
Sulphur (mg/100 g)	568.27-1279.19	916.13	2.69	22.57	22.87	97.39	420.31	45.88
Iron (mg/100 g)	24.56-49.60	36.23	4.86	20.42	20.99	94.63	14.82	40.91
Copper (mg/100 g)	0.35-0.78	0.57	6.36	23.63	24.47	93.24	0.27	47.00
Manganese (mg/100 g)	2.79-4.82	3.84	8.97	12.90	15.71	67.43	0.84	21.82

CV: coefficient of variation; GCV: genotypic coefficient of variation; PCV: phenotypic coefficient of variation.

Evaluation of open-pollinated progenies and F1 hybrids of *M. oleifera* established that major nutritional and physiological traits such as CP, CF and crude fat are highly heritable traits influenced primarily by genetic architecture rather than environmental fluctuations (38). Similar results for P, N, K, Mg, Ca, Fe and CP content were discovered in *M. oleifera* (39). Similar results from dry leaves of *M. oleifera* were reported for Ca, Fe and CF contents (36). In pumpkin, similar results for proximate principles and Fe, Ca, K, Mg and Zn were found (40).

The high broad-sense heritability and genetic advance observed for traits such as EE, CE, P, Zn, S, Fe and Mn indicate that these nutritional parameters are predominantly regulated by additive gene action rather than environmental influences. Because the PCV closely aligned with and remained higher than the GCV, it confirms that environmental modifications played only a minor role in phenotypic expression. This strong genetic control at the one-year nursery stage demonstrates that these physiological and biochemical pathways are fixed within the genetic architecture of the sub-Himalayan wild half-sib progenies, making them highly stable across generations and reliable targets for direct, early-stage phenotypic selection and genetic improvement.

Significant positive connections between the several factors under investigation were revealed via correlation matrices. Total ash, amino acids, N, K, Mg, P and Mn levels all showed strong positive correlations with EE. Sulfur, Ca and Cu contents were strongly and favourably correlated with crude fiber content. In leaf samples, manganese and iron content were strongly positively correlated (Table 5). Similar results were reported for correlation among calcium, iron, magnesium, CP and CF parameters (35).

Multivariate visualisations: Principal component analysis, path coefficient analysis and clustering

Principal component analysis compressed the nutritional variance into four dominant components with Eigen values > 1, explaining a cumulative 89.61 % of total variation. The PCA biplot identified several progenies including P9, P15, P16, P18, P19, P21, P26, P28, P29, P30, P33 and P35 as superior performers for these desirable proximate principles and mineral contents (Fig. 1, Table 6). The results are in accordance with the findings for leaf proximate principles and leaf mineral contents in cowpea, demonstrating that PCA is a highly sensitive technique for multi-trait selection in leafy crops (41).

On the other hand, to decouple the direct and indirect contributions of leaf proximate principles, TAA and mineral content toward the total fresh biomass of *M. oleifera* progenies, a path coefficient analysis was conducted. The path matrix's direct effects were

© The Author(s) 2026. Creative Commons CC BY 4.0. Published by Horizon e-Publishing Group.
https://doi.org/10.14719/pst.16543

shown by the diagonal bold values, but the remainder values showed how one parameter affected another indirectly. The residual effect of 0.5215 represented the proportion of unknown variations (Table 7). The different drivers, both positive and negative, according to their direct path coefficients are:

Primary positive determinants

Iron (β = 0.5490) and zinc (β = 0.7590) had the greatest overall positive direct effects on leaf fresh biomass. Both Fe and Zn functioned as strong positive drivers even though they often mediated negative indirect effects through one another and important macro-minerals. For the majority of proximate parameters, P demonstrated a significant positive direct effect (β = 0.6359) and acted as a major indirect channel. Sulfur then made a positive contribution (β = 0.2718). The main proximate principal drivers were EE (β = 0.3871), CP (β = 0.3282) and NFE (β = 0.3219), which demonstrated significant mutualistic positive indirect impacts through one another. A slight but substantial favourable direct effect was shown by TAA (β = 0.1713).

Negative direct contributors and suppressors

The high-impact suppressors (N and Ca): Total N (β = -0.6271) and Calcium (β = -0.5614) exhibited severe negative direct effects on fresh biomass. Paradoxically, both traits acted as vital indirect contributors; Nitrogen channeled positive indirect effects through organic proximate (CP, EE, CF, TAA), while Ca did so through major minerals. Potassium (β = -0.2804), Cu (β = -0.2694) and Mn (β = -0.1461) directly suppressed total biomass yield but maintained high positive indirect linkages across organic compounds.

Negligible biomass suppressors (Crude fibre and ash content)

Crude fibre (β = -0.0547) and total AC (β = -0.0315) exerted negligible negative direct impacts on biomass accumulation.

These intricate indirect associations and trade-offs mirror established literature on multi-purpose tree species. Previous researchers observed identical path complexities when evaluating vegetative properties (plant height, leaf area) and seed dynamics on *M. oleifera* oil content (35). Similarly, (42) demonstrated parallel interlocking influences of leaf proximate principles and morphology on the fresh biomass of *Grewia optiva* Drummond. Furthermore, the necessity of analysing compound traits as an integrated system rather than isolated variables aligns with previous reports in *Pongamia pinnata* (L.) Pierre, reinforcing that selection indices for *M. oleifera* (43). Progeny biomass must prioritise high Zn and P while balancing the indirect metabolic load of N and Ca.

Additionally, Hierarchical cluster analysis using Ward's method divided the progeny lines into two primary clusters containing 12 and 23 progenies, respectively. The progenies 16 and 21, 14 and 23, 1 and 6, 5 and 30, 26 and 31 were closest to each other individually while P15 and P31 were widest apart (Fig. 2). This grouping pattern demonstrates that genetic factors, rather than strict geographic proximity alone, play a significant role in determining nutritional traits. The results are in line with the findings of previous studies in *G. optiva* (42).

Conclusion

This study reveals substantial genetic variation in proximate principles and mineral content among *Moringa oleifera* progenies after one year of nursery growth. Specific lines demonstrated outstanding target superiority which are recommended to the end user/farmers for exploitation. High broad-sense heritability estimates for these traits indicate excellent potential for genetic improvement through early selection. These promising accessions should be advanced to multi-location field trials to confirm their stability and performance for commercial leaf-meal and pharmacological production. Based on the evaluation of the half-sib progenies, the following recommendations are made to maximise yields, nutritional quality and commercial value in end user:

- Prioritise elite progenies for cultivation: Farmers and nursery operators should prioritise superior half-sib lines identified in the study; specifically, P7, P18 and P22; for multi-location trials and mass propagation. Progeny P7 is ideal for high-protein and amino-acid-dense leaf production (recording peak crude protein (CP) at 27.49 % and zinc (Zn) at 3.87 mg/100 g). Progeny P18 is recommended for iron-rich biofortification strategies (reaching 49.60 mg/100 g of iron). Progeny P22 is best suited for mineral-rich biomass demands, showing peak total ash and phosphorus (P).
- Leverage early nursery selection: Because the study confirmed strong genetic control and high broad-sense heritability for essential traits like crude fat, fibre, P, Zn and iron (Fe), nursery managers can reliably perform early-stage selection at the one-year mark. This accelerates the breeding cycle without waiting for full-field maturity.
- Optimise soil and fertiliser management for biomass: Path coefficient analysis revealed that Zn and P are the strongest direct drivers of fresh biomass yield. Farmers should ensure targeted micronutrient management (particularly Zn and P fertilisation) during early establishment to maximise leaf yield.
- Balance nitrogen and calcium applications: While total nitrogen (N) and calcium (Ca) are vital for overall plant health, the study noted complex metabolic trade-offs where excessive levels exerted negative direct effects on fresh biomass. Growers should avoid over-applying nitrogen fertilisers in ways that hinder optimal growth balance.

© The Author(s) 2026. Creative Commons CC BY 4.0. Published by Horizon e-Publishing Group.
https://doi.org/10.14719/pst.16543

Table 5. Genotypic and phenotypic correlation coefficients for leaf proximate principles, leaf biochemical estimates and leaf mineral contents of *Moringa oleifera* progenies

		CP	EE	CF	AC	NFE	TAA	N	K	Mg	S	P	Ca	Zn	Fe	Cu	Mn
CP	G	1.000															
	P	1.000															
EE	G	0.398**	1.000														
	P	0.383**	1.000														
CF	G	-0.368**	-0.849**	1.000													
	P	-0.355**	-0.828**	1.000													
AC	G	0.249*	0.269**	-0.260**	1.000												
	P	0.238*	0.252**	-0.246*	1.000												
NFE	G	-0.693**	0.063^{NS}	-0.300**	-0.401**	1.000											
	P	-0.693**	0.049^{NS}	-0.307**	-0.405**	1.000											
TAA	G	0.920**	0.406**	-0.232*	0.307**	-0.789**	1.000										
	P	0.837**	0.351**	-0.205*	0.258**	-0.704**	1.000										
N	G	1.000**	0.398**	-0.368**	0.249*	-0.693**	0.920**	1.000									
	P	1.000**	0.383**	-0.355**	0.238*	-0.693**	0.837**	1.000									
K	G	0.339**	0.391**	-0.394**	0.177^{NS}	-0.090$^{N}_{S}$	0.289**	0.339**	1.000								
	P	0.263**	0.277**	-0.310**	0.113^{NS}	-0.051$^{N}_{S}$	0.263**	0.263**	1.000								
Mg	G	0.391**	0.904**	-0.953**	0.277**	0.206*	0.270**	0.391**	0.491**	1.000							
	P	0.364**	0.809**	-0.843**	0.233*	0.155^{NS}	0.200*	0.364**	0.328**	1.000							
S	G	-0.272**	-0.694**	0.822**	-0.244*	-0.263**	-0.141$^{N}_{S}$	-0.272**	-0.260**	-0.808**	1.000						
	P	-0.269**	-0.676**	0.803**	-0.238*	-0.242*	-0.126$^{N}_{S}$	-0.269**	-0.209*	-0.705**	1.000						
P	G	0.501**	0.866**	-0.887**	0.363**	0.031	0.388**	0.501**	0.423**	0.983**	-0.718**	1.000					
	P	0.482**	0.848**	-0.869**	0.345**	0.030	0.342**	0.482**	0.330**	0.871**	-0.697**	1.000					
Ca	G	-0.342**	-0.388**	0.476**	-0.156	0.001	-0.247*	-0.342**	-0.998**	-0.500**	0.355**	-0.449**	1.000				
	P	-0.280**	-0.308**	0.387**	-0.117	0.001	-0.237*	-0.280**	-0.857**	-0.365**	0.288**	-0.383**	1.000				
Zn	G	-0.392**	-0.850**	0.997**	-0.266**	-0.286**	-0.259**	-0.392**	-0.431**	-0.982**	0.866**	-0.917**	0.515**	1.000			
	P	-0.371**	-0.800**	0.946**	-0.246*	-0.251**	-0.216*	-0.371**	-0.343**	-0.841**	0.822**	-0.856**	0.429**	1.000			
Fe	G	0.403**	0.009	-0.207*	0.246*	-0.215*	0.254**	0.403**	0.185	0.164	-0.173	0.274**	-0.218*	-0.256**	1.000		
	P	0.375**	0.003	-0.200*	0.225*	-0.191	0.250*	0.375**	0.157	0.145	-0.155	0.266**	-0.200*	-0.233*	1.000		
Cu	G	-0.268**	-0.331**	0.410**	-0.152	-0.016	-0.184	-0.268**	-0.998**	-0.469**	0.345**	-0.409**	0.932**	0.458**	-0.158	1.000	
	P	-0.243*	-0.317**	0.389**	-0.142	-0.019	-0.176	-0.243*	-0.819**	-0.381**	0.329**	-0.382**	0.877**	0.427**	-0.141	1.000	
Mn	G	0.470**	0.913**	-0.969**	0.254**	0.162	0.308**	0.470**	0.493**	0.865**	-0.779**	0.813**	-0.516**	-0.806**	0.243*	-0.484**	1.000
	P	0.367**	0.696**	-0.781**	0.211*	0.142	0.290**	0.367**	0.348**	0.771**	-0.617**	0.788**	-0.402**	-0.765**	0.202*	-0.389**	1.000

CP: crude protein; EE: ether extract; CF: crude fibre; AC: ash content; NFE: nitrogen-free extract; TAA: total amino acids; N: nitrogen; K: potassium; Mg: magnesium; S: sulphur; P: phosphorus; Ca: calcium; Zn: zinc; Fe: iron; Cu: copper; Mn: manganese; G: genotypic correlation coefficient; P: phenotypic correlation coefficient;** significant at 1 % level; * significant at 5 % level.

© The Author(s) 2026. Creative Commons CC BY 4.0. Published by Horizon e-Publishing Group.
https://doi.org/10.14719/pst.16543

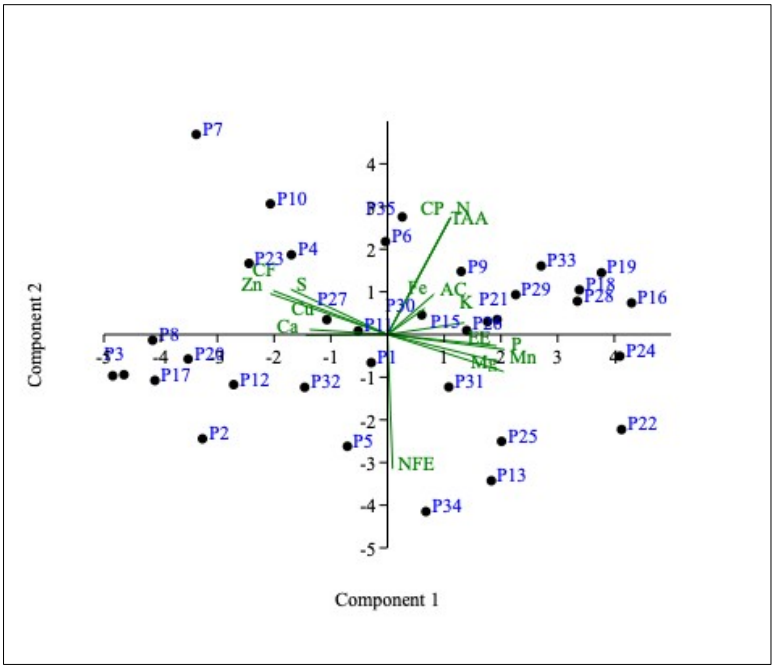


Fig. 1. Distribution and grouping of progenies of *Moringa oleifera* across first two principal components for leaf proximate principles, leaf biochemical estimates and leaf mineral contents using scatter plot.

Table 6. Principal component analysis of leaf proximate principles, leaf biochemical estimates and leaf mineral contents of *Moringa oleifera* progenies

	PC 1	PC 2	PC 3	PC 4
CP	0.180	0.442	0.077	-0.119
EE	0.312	-0.043	0.186	-0.244
CF	-0.326	0.166	-0.137	-0.001
AC	0.133	0.153	0.088	0.514
NFE	0.015	-0.509	-0.024	0.005
TAA	0.179	0.443	0.079	-0.119
N	0.180	0.442	0.078	-0.119
P	0.334	-0.057	0.152	0.039
K	0.219	0.044	-0.529	-0.052
Ca	-0.233	-0.003	0.518	0.011
Mg	0.331	-0.141	0.118	-0.059
Zn	-0.335	0.155	-0.113	-0.029
S	-0.276	0.171	-0.155	-0.052
Fe	0.106	0.098	-0.033	0.788
Cu	-0.222	0.018	0.536	0.025
Mn	0.331	-0.109	0.101	-0.031
Eigenvalue	7.64	3.59	2.08	1.03
% variance	47.73	22.42	13.00	6.46

CP: crude protein; EE: ether extract; CF: crude fibre; AC: ash content; NFE: nitrogen-free extract; TAA: total amino acids; N: nitrogen; P: phosphorus; K: potassium; Ca: calcium; Mg: magnesium; Zn: zinc; S: sulphur; Fe: iron; Cu: copper; Mn: manganese; PC: principal component.

© The Author(s) 2026. Creative Commons CC BY 4.0. Published by Horizon e-Publishing Group.
https://doi.org/10.14719/pst.16543

Table 7. Path coefficient analysis showing direct and indirect effects of leaf proximate principles, leaf biochemical estimates and leaf mineral contents on total fresh biomass of *Moringa oleifera* progenies

	CP	EE	CF	AC	NFE	TAA	N	K	Mg	S	P	Ca	Zn	Fe	Cu	Mn
CP	0.3282	0.1540	0.0202	-0.0078	-0.2229	0.1576	-0.6271	-0.0950	-0.0200	-0.0740	0.3187	0.1920	-0.2973	0.2212	0.0722	-0.0687
EE	0.1305	0.3871	0.0465	-0.0085	0.0203	0.0695	-0.2494	-0.1096	-0.0462	-0.1887	0.5509	0.2176	-0.6450	0.0049	0.0890	-0.1334
CF	-0.1209	-0.3288	-0.0547	0.0082	-0.0966	-0.0397	0.2310	0.1106	0.0486	0.2233	-0.5638	-0.2671	0.7643	-0.1136	-0.1104	0.1415
AC	0.0816	0.1042	0.0143	-0.0315	-0.1292	0.0525	-0.1559	-0.0495	-0.0142	-0.0663	0.2310	0.0874	-0.2016	0.1349	0.0410	-0.0371
NFE	-0.2273	0.0245	0.0164	0.0127	0.3219	-0.1352	0.4343	0.0251	-0.0105	-0.0714	0.0200	-0.0004	-0.2170	-0.1181	0.0043	-0.0237
TAA	0.3020	0.1570	0.0127	-0.0097	-0.2541	0.1713	-0.5770	-0.0809	-0.0138	-0.0385	0.2467	0.1385	-0.1969	0.1394	0.0497	-0.0450
N	0.3282	0.1540	0.0202	-0.0078	-0.2229	0.1576	-0.6271	-0.0950	-0.0200	-0.0740	0.3187	0.1920	-0.2973	0.2212	0.0722	-0.0687
K	0.1112	0.1513	0.0216	-0.0056	-0.0288	0.0494	-0.2125	-0.2804	-0.0251	-0.0707	0.2692	0.5601	-0.3275	0.1015	0.2768	-0.0720
Mg	0.1285	0.3500	0.0521	-0.0087	0.0663	0.0462	-0.2455	-0.1378	-0.0511	-0.2196	0.6248	0.2808	-0.7456	0.0901	0.1263	-0.1556
S	-0.0893	-0.2688	-0.0450	0.0077	-0.0845	-0.0242	0.1706	0.0729	0.0413	0.2718	-0.4566	-0.1996	0.6570	-0.0950	-0.0930	0.1139
P	0.1645	0.3354	0.0485	-0.0115	0.0101	0.0665	-0.3143	-0.1187	-0.0502	-0.1952	0.6359	0.2520	-0.6962	0.1504	0.1101	-0.1480
Ca	-0.1122	-0.1500	-0.0260	0.0049	0.0002	-0.0423	0.2144	0.2798	0.0255	0.0966	-0.2854	-0.5614	0.3908	-0.1197	-0.2779	0.0754
Zn	-0.1286	-0.3290	-0.0551	0.0084	-0.0920	-0.0444	0.2456	0.1210	0.0502	0.2353	-0.5832	-0.2890	0.7590	-0.1405	-0.1235	0.1470
Fe	0.1322	0.0035	0.0113	-0.0077	-0.0693	0.0435	-0.2526	-0.0518	-0.0084	-0.0470	0.1743	0.1224	-0.1943	0.5490	0.0425	-0.0355
Cu	-0.0880	-0.1280	-0.0224	0.0048	-0.0052	-0.0316	0.1681	0.2882	0.0239	0.0938	-0.2599	-0.5793	0.3480	-0.0867	-0.2694	0.0707
Mn	0.1544	0.3536	0.0530	-0.0080	0.0522	0.0528	-0.2950	-0.1383	-0.0544	-0.2119	0.6440	0.2898	-0.7638	0.1334	0.1303	-0.1461

CP: crude protein; EE: ether extract; CF: crude fibre; AC: ash content; NFE: nitrogen-free extract; TAA: total amino acids; N: nitrogen; K: potassium; Mg: magnesium; S: sulphur; P: phosphorus; Ca: calcium; Zn: zinc; Fe: iron; Cu: copper; Mn: manganese. Residue: 0.52147.

© The Author(s) 2026. Creative Commons CC BY 4.0. Published by Horizon e-Publishing Group.
https://doi.org/10.14719/pst.16543

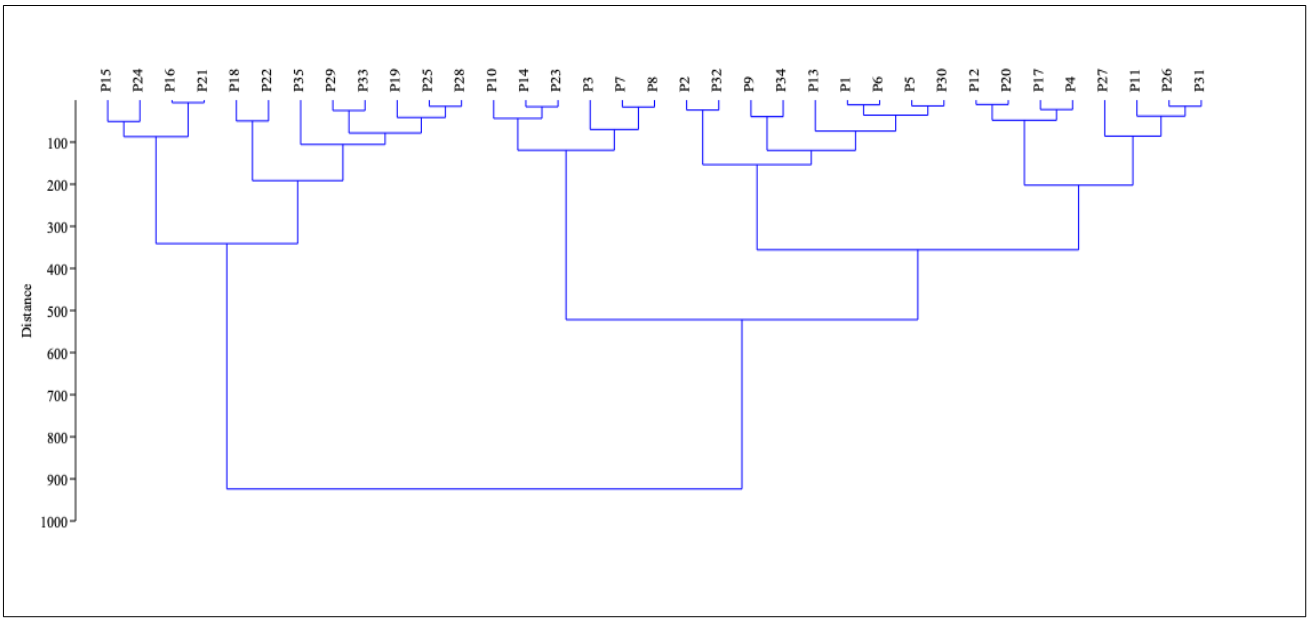


Fig. 2. Cluster analysis of *Moringa oleifera* progenies based on leaf proximate principles, leaf biochemical estimates and leaf mineral contents.

Commercialising these lines requires aligning production with lucrative market price points within the rapidly expanding global moringa leaf powder industry, prioritising high-margin sectors that value verified biochemical profiles over generic commodity leaf-meal. While general biomass is important, breeding efforts must focus on premium functional markers specifically high CP concentrations, exceptional antioxidant activity like total phenols and flavonoids and elevated bioavailable micronutrients such as Fe and Zn with progenies like P7 and P18 directly addressing these industrial requirements. Prior to widespread market release, these candidate genotypes must be systematically benchmarked against established commercial cultivars in field trials to prove they match or exceed industry standards for uniformity, disease resistance and environmental adaptability. Furthermore, strict post-harvest protocols must be enforced to preserve their superior nutritional profiles; because heat-sensitive vitamins, amino acids and antioxidant compounds degrade under improper conditions; operations should utilise controlled shade-drying or low-temperature dehydration techniques rather than direct sun exposure to prevent nutrient degradation and oxidation prior to milling.

Acknowledgements

The authors acknowledge Dr. Jyoti Dhiman for her assistance with biochemical analysis and Dr. Aman Deep Ranga for his guidance in statistical analysis. The authors also thank the Forest Range Officers, Forest Guards and their assistants for their assistance with the survey and selection of *Moringa oleifera* Lam. trees during the difficult circumstances of the COVID-19 pandemic. The authors further acknowledge their department for providing the equipment, chemicals and other necessary assistance for conducting this study.

Authors' contributions

MK and AG designed the experiment and conducted the survey and sample collection. MK, S, AK and ST contributed to the biochemical analysis of leaf samples. RS, NK and TNS assisted MK with statistical analysis and contributed to the final framing of the manuscript. All authors have read and approved the final manuscript.

Compliance with ethical standards

Conflict of interest

Authors do not have any conflict of interests to declare.

Ethical issues

None

References

1. Kirtikar KR, Basu BD. Indian medicinal plants. 2nd ed. Allahabad (India): Lalit Mohan Basu; 1934.
2. World Health Organization. WHO traditional medicine strategy: 2014–2023. Geneva: World Health Organization; 2013.
3. Akshay K, Heena V, Singh R, Rohit K. Phytochemical and pharmacological profile of *Moringa oleifera* Lam. Int J Pharm Sci Rev Res. 2014;28(1):121–7.

© The Author(s) 2026. Creative Commons CC BY 4.0. Published by Horizon e-Publishing Group.
https://doi.org/10.14719/pst.16543

https://doi.org/10.13040/IJPSR.0975-8232.11(12).5968-73

4. Panova N, Gerasimova A, Gentscheva G, Nikolova S, Makedonski L, Velikova M, et al. *Moringa oleifera* Lam.: A nutritional powerhouse with multifaceted pharmacological and functional applications. Life. 2025;15(6):881. https://doi.org/10.3390/life15060881
5. Morton JF. The horseradish tree, *Moringa oleifera* (Moringaceae): A boon to arid lands? Econ Bot. 1991;45(3):318–33. https://doi.org/10.1007/BF02887070
6. Fortune Business Insights. Moringa products market size, share & global industry analysis, by product (leaf & leaf powder, tea, oil, seeds), by distribution channel, and regional forecast, 2026–2034. Fortune Business Insights Report; 2026.
7. Siddhuraju P, Becker K. Antioxidant properties of various solvent extracts of total phenolic constituents from three different agroclimatic origins of drumstick tree (*Moringa oleifera* Lam.) leaves. J Agric Food Chem. 2003;51(8):2144–55. https://doi.org/10.1021/jf020444
8. Abbas RK, El-Shereef AA, Khan FA, Hazimi AH. Nutritional values of *Moringa oleifera*, total protein, amino acid vitamins, minerals, carbohydrates, total fat and crude fiber, under the semi-arid environment of Sudan. J Agric Sci. 2018;10(4):136–44. https://doi.org/10.4172/1948-5948.1000396
9. Lockett CT, Calvert CC, Grivetti LE. Energy and micronutrient composition of dietary and medicinal wild plants consumed during drought: study of rural Fulani, Northeastern Nigeria. Int J Food Sci Nutr. 2000;51(3):195–208. https://doi.org/10.1080/09637480050029700
10. Freiberger CE, Vanderjagt DJ, Pastuszyn A, Glew RS, Mounkaila G, Millson M, et al. Nutrient content of the edible leaves of seven wild plants from Niger. Plant Foods Hum Nutr. 1998;53(1):57–69. https://doi.org/10.1023/A:1008080508028
11. Fahey JW. *Moringa oleifera*: A review of the medical evidence for its nutritional, therapeutic, and prophylactic properties. Part 1. Trees Life J. 2005;1:1–15. https://doi.org/10.1201/9781420039078.ch12
12. Ruiz-Hernández R, Pérez-Vázquez A, Hernández-Rodríguez M, García-Pérez E, Morales-Trejo F, Soto-Hernández RM. Genetic diversity of *Moringa oleifera* Lam. in Southeastern Mexico. Agrociencia. 2024;58(6). https://doi.org/10.47163/agrociencia.v58i6.3101
13. Rani B, Devi T, Kumari N, Rani P, Duhan J, Lavisha. A comprehensive overview of nutritional and bioactive compounds of *Moringa oleifera* seeds. Int J Adv Biochem Res. 2025;9(8):315–23. https://doi.org/10.33545/26174693.2025.v9.i8e.5172
14. Wahid N, Lamhamedi MS, Beaulieu J, Margolis HA, Deblois J. Genetic parameters and clonal variation in growth and nutritional traits of containerized white spruce somatic seedlings. Acta Bot Gallica. 2012;159(3):373–84. https://doi.org/10.1080/12538078.2012.721226
15. Muniandi SK, Ariff FFM, Pisar MM, Harun ST, Abdullah MZ, Abdullah F, et al. Crop improvement of *Moringa oleifera* L. through genotype screening for the development of clonal propagation techniques of high-yielding clones in Malaysia. Biology. 2024;13(10):785. https://doi.org/10.3390/biology13100785
16. AOAC International. Official methods of analysis AOAC International. Vol. 1, 26th ed. Washington, DC: Association of Official Analytical Chemists; 1995. p. 4.1–4.20.
17. Sankaram A. A laboratory manual of agricultural chemistry. Madras: Asia Publishing House; 1966. p. 252–63.
18. Lee YP, Takahashi T. An improved colorimetric determination of amino acids with the use of ninhydrin. Anal Biochem. 1966;14:71–7. https://doi.org/10.1016/0003-2697(66)90057-1
19. Tatina R. A colorimeter for measuring phosphorus in solution. Am Biol Teach. 2009;63:190–3. https://doi.org/10.2307/4451075
20. Harve GN. The flame photometric determination of sodium, potassium and calcium in plant extracts with special reference to interference effects. Anal Chim Acta. 1961;25:557–66. https://doi.org/10.1016/0003-2670(61)80134-7
21. Chen ML, Ye ML, Zeng XL, Fan YC, Yan Z. Determination of sulphur anions by ion chromatography-postcolumn derivation and UV detection. Chin Chem Lett. 2009;20:1241–4. https://doi.org/10.1016/j.cclet.2009.05.003
22. Antunes GA, dos Santos HS, da Silva YP, Silva MM, Piatnicki CMS, Samios D. Energy Fuels. 2017;31:2944–50. https://doi.org/10.1021/acs.energyfuels.6b03360
23. Sheoran OP, Tonk DS, Kaushik LS, Hasija RC, Pannu RS. Statistical software package for agricultural research workers [Internet]. Hisar: Department of Mathematics and Statistics, CCS Haryana Agricultural University; 1998.
24. Burton GW, Devane EM. Estimation of heritability in tall fescue. Agron J. 1953;45:478–81. https://doi.org/10.2134/agronj1953.00021962004500100005x
25. Johnson HW, Robinson HF, Comstock RE. Estimates of genetic and environmental variability in soybean. Agron J. 1955;47:314–18. https://doi.org/10.2134/agronj1955.00021962004700070009x
26. Robinson HF, Comstock RE, Harvey PH. Genotypic and phenotypic correlations in corn and their implications in selection. Agron J. 1951;43:282–7. https://doi.org/10.2134/agronj1951.00021962004300060007x
27. Searle SR. Phenotypic, genotypic and environmental correlations. Biometrics. 1961;17:474–80. https://doi.org/10.2307/2527838
28. Pearson K. On lines and planes of closest fit to systems of points in space. Lond Edinb Dubl Philosophical Mag J Sci. 1901;2:559–72. https://doi.org/10.1080/14786440109462720
29. Hammer O, Harper D, Ryan P. PAST: Paleontological Statistics Software Package for Education and Data Analysis. Palaeontol Electron. 2001;4:1–9.
30. Dewey DR, Lu KH. Correlation and path coefficient analysis of components of crested wheat grass seed production. Agron J. 1959;51:515–18. https://doi.org/10.2134/agronj1959.00021962005100090002x
31. Ndhlala AR, Tshabalala T. Diversity in the nutritional values of some *Moringa oleifera* Lam. cultivars. Diversity. 2023;15(7):834. https://doi.org/10.3390/d15070834
32. Olson ME, Sankaran RP, Fahey JW, Grusak MA, Odee D, et al. Leaf protein and mineral concentrations across the "Miracle Tree" genus Moringa. PLoS One. 2016;11(7):e0159782. https://doi.org/10.1371/journal.pone.0159782
33. Okiki PA, Osibote IA, Balogun O, Oyinloye BE, Idris OO, Adelegan O, et al. Evaluation of proximate, minerals, vitamins and phytochemical composition of *Moringa oleifera* Lam. cultivated in Ado Ekiti, Nigeria. Adv Biol Res. 2015;9:436–43. https://doi.org/10.5829/idosi.abr.2015.9.6.96112

© The Author(s) 2026. Creative Commons CC BY 4.0. Published by Horizon e-Publishing Group.
https://doi.org/10.14719/pst.16543

34. Offor IF, Ehiri RC, Njoku CN. Proximate nutritional analysis and heavy metal composition of dried *Moringa oleifera* leaves from Oshiri Onicha L.G.A, Ebonyi State, Nigeria. IOSR J Environ Sci Toxicol Food Technol. 2014;8:57–62. https://doi.org/10.9790/2402-08115762

35. Selvakumari P. Assessment of morphological, biochemical and molecular diversity in moringa (*Moringa oleifera* Lam.) with special reference to its industrial applications [master's thesis]. Periyakulam: Horticultural College and Research Institute, Tamil Nadu Agricultural University; 2013. 194 p.

36. Balaguru P, Sathiyamurthy VA, Janavi GJ, Sangtha S. Variability in perennial moringa (*Moringa oleifera* Lam.) genotypes for quantitative and qualitative traits. Electron J Plant Breed. 2020;11:515–20. https://doi.org/10.37992/2020.1102.087

37. Singh HP. Exploring R&D potential of Moringa for nutrition and healthcare. Indian Hortic [Internet]. 2011.

38. Dhakad AK, Kamboj R, Ranjan R. Genetic variability, character association and heterosis studies in intraspecific F1 hybrids and open-pollinated progenies of *Moringa oleifera* for seed germination, seedling growth and nutritional characteristics. Indian J Plant Genet Resour. 2025;38(3):357–67.

39. Tak M. Survey, evaluation and genetic characterization of drumstick (*Moringa oleifera* Lam.) genotypes in Rajasthan [master's thesis]. Bikaner: Rajasthan Agricultural University; 2012.

40. Okon UI, Silver EO, Emeka NG. Genetic variability in proximate, mineral, vitamin, carotene and anti-nutrients content of fluted pumpkin (*Telfairia occidentalis* Hook F). Int J Trend Sci Res Dev. 2022;6:962–70. Paper ID: IJTSRD52001.

41. Udensi OU, Edu NE. Evaluation and identification of genetic variation pattern in cowpea [*Vigna unguiculata* (L.) Walp] accessions using multivariate analyses. J Basic Appl Sci. 2015;11:149–58. https://doi.org/10.6000/1927-5129.2015.11.22

42. Bhagta S, Sankhyan HP, Sharma D, Ashine T. Correlation and path coefficient analysis in *Grewia optiva* Drummond. Int J Chem Stud. 2017;7:746–9.

43. Pavithra HR, Gowda B, Prasanna T, Shivanna MB. Pod and seed traits in candidate plus trees of *Pongamia pinnata* (L.) Pierre from Southern Peninsular India in relation to provenance variation and genetic variability. J Crop Sci Biotechnol. 2013;16:131–42. https://doi.org/10.1007/s12892-012-0052-8

Additional information

Peer review: Publisher thanks the Sectional Editor and anonymous reviewers for their contribution to the peer review of this work.

Reprints & permissions information: Available at https://horizonepublishing.com/journals/index.php/PST/open_access_policy.

Publisher's Note: Horizon e-Publishing Group remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.

Indexing: See https://horizonepublishing.com/journals/index.php/PST/indexing_abstracting.

Copyright: © The Author(s). This is an open-access article distributed under the Creative Commons Attribution License CC BY 4.0.

Publisher information: Plant Science Today is published by Horizon e-Publishing Group with support from Empirion Publishers Private Limited, Thiruvananthapuram, India.

© The Author(s) 2026. Creative Commons CC BY 4.0. Published by Horizon e-Publishing Group.

https://doi.org/10.14719/pst.16543