Volume 1 Issue 1, 2025 | Page: 5 - 14

Genetics, Plant Breeding and Seed Science

pISSN: 3102-0089 eISSN: 3102-0151

Journal homepage: https://plantbreeding.org.np/page/journal.html

Research article

Phenotypic Diversity in Nepalese Finger Millet (*Eleusine coracana* (L.) Gaertn.) Landraces

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ARTICLE INFO

Keywords:

Agro-morphological traits, finger millet, landraces, multivariate analysis, phenotypic diversity

Article history:

Received 21 Jan 2025
Revised 24 Jun 2025
Accepted 24 Jun 2025

ABSTRACT

Finger millet (*Eleusine coracana* (L.) Gaertn.), a nutritionally rich and climate-resilient crop, remains underutilized in modern breeding programs despite its broad agroecological adaptability and genetic diversity. This study aimed to characterize phenotypic diversity among 72 finger millet landraces collected from 19 districts of Nepal. Field evaluation was conducted at the National Agriculture Genetic Resources Centre, Khumaltar, during the 2021–2022 growing season using an augmented block design with two replications. A total of 23 quantitative and 9 qualitative traits were assessed following the IBPGR descriptors. Statistical analyses of the collected dataset included descriptive statistics, the Shannon–Weaver diversity index (H′), principal component analysis (PCA), K-means clustering, and phenotypic path analysis. Substantial variability was observed across agro-morphological traits, with CV ranging from 3.98% to 37.99% and H′ from 0.59 to 0.93 for quantitative traits, and from 0.18 to 0.98 for qualitative traits. PCA revealed that the first seven components (eigenvalue >1) explained 76.8% of total phenotypic variation, with PC1 and PC2 contributing 43.83%. Cluster analysis based on the average method and Euclidean distance delineated three clusters, with Cluster 1 comprising 93% of accessions characterized by superior yield traits including fingers per ear (7.10), ear weight (10.20 g), thousand-seed weight (2.88 g), and grain yield (2.47 t/ha). Path coefficient analysis indicated that fourth leaf breadth and flag leaf length exerted strong positive direct effects on grain yield, while the area of the fourth leaf and finger width had negative effects. Promising landraces including CO12712 (3.89 t/ha), CO12570 (3.62 t/ha), and CO13039 (3.59 t/ha) were identified as potential candidates for future varietal improvement. The findings underscore the high phenotypic diversity and agronomic potential of Nepalese finger millet landraces. Integrating phenotypic, molecular, and multi-environment data is suggested to improve the genetic potential of finger millet in breeding programs.

Introduction

Finger millet (*Eleusine coracana* (L.) Gaertn.) is a short-day, self-pollinating, annual crop with an allotetraploid genome (2n = 4x = 36), classified under the subfamily Chloridoideae of the Poaceae family (Kerr 2014). The genus *Eleusine* comprises 10 species distributed across tropical and subtropical regions of Africa, Asia, and South America (Hilu and Wet 1976), with nine species native to East Africa, the primary center of diversity (Phillips 1972). The cultivated subspecies *E. coracana* subsp. *coracana* was domesticated from *E. coracana* subsp. *africana*, a polyploid derivative of *E. indica* (2n = 18) (Sood et al. 2019)advanced plant phenomics and genomics methods enhanced genetic gain and understanding of important agronomic, adaptation and nutritional traits in finger millet. Finger millet (Eleusine coracana L. Gaertn. Domestication began around 5000 BCE in Western Uganda and the Ethiopian highlands, reaching India around 3000 BCE (Padulosi et al. 2009, Hilu et al. 1979).

Globally, finger millet ranks fourth among millets, following sorghum, pearl millet, and foxtail millet (Gupta et al. 2012). In Nepal, it is also the fourth most important cereal crop after rice, maize, and wheat, covering 227,934 hectares and yielding 310,847 metric tons annually (MoALD 2023). Its resilience to drought and adaptability to a wide range of agroecological zones, including altitudes up to 3,100 m, make it suitable for climate-resilient agriculture (Ghimire et al. 2023, Rurinda et al. 2014). Locally known as "Kodo," it thrives in marginal soils under erratic rainfall, earning its place among 'Future Smart Foods' (Joshi et al. 2020).

Finger millet's nutritional profile contributes to its growing popularity. It contains high levels of calcium (0.38%), protein (6–13%), dietary fiber (18%), carbohydrates (65–75%), and minerals (2.5–3.5%), along with health-promoting compounds such as phytates (0.48%), tannins (0.61%), phenolics (0.3–3%), and trypsin inhibitors (Chandra et al. 2016). These components contribute to its anti-diabetic, anti-tumor, anti-diarrheal, anti-ulcer, anti-inflammatory, antioxidant, antimicrobial, and anti-atherosclerotic properties (Devi et al. 2014).

Landraces, shaped through centuries of farmer-led selection and adaptation, possess valuable traits for pest, disease, and abiotic stress resistance (Villa et al. 2005). Despite their significance, such genetic resources remain underutilized in modern breeding. As global food demand is expected to rise with a projected population exceeding 9 billion by 2050, genetic diversity must be prioritized to achieve sustainable development goals (Godfray et al. 2010). Nepal's National Agricultural Genetic Resources Centre (NAGRC), also known as the Gene Bank, conserves over 1,000 finger millet accessions; however, detailed agro-morphological characterization is limited (Kandel et al. 2019, Ghimire et al. 2017). Although improved cultivars like "Okhle-1" and "Rato Kodo" have been developed from local landraces, the full genetic potential of NAGRC's collections remains untapped (Ghimire et al. 2023). This study aimed to evaluate the phenotypic variability among Nepalese finger millet landraces collected from diverse regions. By analyzing both qualitative and quantitative traits, we sought to identify unique accessions and prioritize promising candidates for future breeding efforts.

Materials and Methods

Experimental design and plant materials

The experiment was conducted from July 2021 to January 2022 at the breeding field of the National Agricultural Genetic Resources Centre (NAGRC), Khumaltar, Lalitpur, Nepal (27°40′N, 85°20′E; elevation: 1,360 masl). The geographic coordinates were recorded using the mobile application 'My GPS Coordinates' version 6.35 (Mystic Mobile Apps LLC, Dover). An augmented block design with two replications was employed, with treatments randomized across plots measuring 3 m × 1 m. A total of 72 finger millet accessions, collected from 19 districts across Nepal, were evaluated (Table 1). Three check varieties, CO12205 (Kalo Kodo), CO10552 (Pahelo Kodo), and CO12570 (Sthaniya Kodo), were included for comparison. Field preparation involved single plowing followed by harrowing and leveling to achieve uniform tilth. Seeds were directly sown in four-row plots with 16 plants per row. Recommended fertilizers and standard agronomic practices were applied uniformly. At physiological maturity, crops were harvested manually using sickles, sun-dried, hand-threshed, and cleaned by winnowing. Grain weight was measured using a calibrated electronic balance.

Table 1. Details of finger millet collections used in the experiment as per the database in the National Agricultural Genetic Resources Centre (Gene Bank), Khumaltar, Nepal.

S.N.	Collection code	Local name	District	Latitude	Longitude	Altitude, m
1	CO10047	Bhotange Kodo	Udayapur	26. 42	86. 73	628
2	CO10385	Dalle Kodo	Bajura	29.31	81.43	1500
3	CO10489	Pangdure Kodo	Sindhuli	27.22	85.57	721
4	CO10552	Pahelo Kodo	Ramechhap	27. 55	86. 36	2005
5	CO10557	Kesare Kodo	Ramechhap	27. 55	86. 36	180
6	CO10561	Dalle Kodo	Ramechhap	27. 59	86. 26	1350
7	CO10848	Dalle Kodo	Ramechhap	27. 59	86. 26	1350
8	CO10980	Nangkatuwa Kodo	Ramechhap	27. 55	86. 36	180
9	CO10991	Dalle sthaniya Kodo	Ramechhap	27. 55	86. 36	2005
10	CO11140	Jhope Kodo	Myagdi	28. 41	83. 44	2097

S.N.	Collection code	Local name	District	Latitude	Longitude	Altitude, m
11	CO11694	Sthaniya Kodo	Nuwakot	27.96	85.15	935
13	CO11696	Rato Kodo	Nuwakot	27.96	85.11	1294
14	CO11698	Sthaniya Kodo	Nuwakot	27.96	85.15	967
15	CO11699	Miney Kodo	Nuwakot	27.95	85.11	1348
16	CO11700	Chaudey Kodo	Nuwakot	27.95	85.11	1154
17	CO11701	Chaurey Kodo	Rasuwa	27.95	85.11	1152
18	CO11702	Dalle Kodo	Rasuwa	27.95	85.11	1152
19	CO11704	Jhapre Kodo	Rasuwa	28.01	85.21	1900
20	CO11705	Dalle Kodo	Rasuwa	28.01	85.21	1900
21	CO11707	Sthaniya Kodo	Dhading	27.93	84.98	1276
22	CO11708	Kartike Kodo	Dhading	27.93	84.98	1276
23	CO11711	Sthaniya Kodo	Makawanpur	27.66	85.10	1952
24	CO11712	Sthaniya Kodo	Makawanpur	27.66	85.10	1952
25	CO11714	Sthaniya Kodo	Makawanpur	27.61	85.15	1567
26	CO11942	Dalle Kodo	Mugu	29.32	82.09	2400
27	CO11943	Ghar Kodo	Mugu	29.23	82.31	1900
28	CO12039	Nangkatuwa Kodo	Khotang	27. 19	86. 62	1345
29	CO12075	Sthaniya Kodo	Khotang	27. 21	86. 79	1523
30	CO12136	Acchame Kodo	Khotang	27.10	82.42	915
31	CO12143	Nangkatuwa Kodo	Khotang	27.10	82.82	915
32	CO12177	Dalle Kodo	Tanahun	27.97	84.07	453
33	CO12202	Lekali Kodo	Tanahun	27.96	84.14	744
34	CO12205	Kalo Kodo	Tanahun	27.96	84.14	744
35	CO12230	Muddke Kodo	Tanahun	27.92	84.16	1105
36	CO12246	Seto Kodo	Tanahun	27.92	84.17	1034
37	CO12276	Sthaniya Kodo	Tanahun	27.95	84.09	728
38	CO12298	Rato Kodo	Tanahun	27.91	84.05	799
39	CO12327	Seto Kodo	Tanahun	27.88	83.99	715
40	CO12435	Sthaniya Kodo	Tanahun	27.97	84.03	845
41	CO12460	Dudey Kodo	Tanahun	27.95	84.00	923
42	CO12478	Kailo Kodo	Tanahun	27.96	84.00	921
43	CO12510	Dalle Kodo	Tanahun	27.93	83.98	871
44	CO12570	Sthaniya Kodo	Syanja	27.98	83.96	1137
45	CO12594	Kalo Kodo	Syanja	28.00	83.94	1090
46	CO12657	Sthaniya Kodo	Tanahun	28.00	83.91	879
47	CO12712	Sthaniya Kodo	Okhaldhunga	27.19	86.30	1937
48	CO12722	Nangkatuwa Kodo	Solukhumbu	27.26	86.38	2150
49	CO12759	Seto Pangdure Kodo	Okhaldhunga	27.19	86.30	1937
50	CO12781	Kalo Pangdure Kodo	Okhaldhunga	27.19	86.30	1937
51	CO12789	Nang Chinney Kodo	Okhaldhunga	27.19	86.30	1937
52	CO12803	Nangkatuwa Kodo	Solukhumbu	27.26	86.38	2150
53	CO12869	Pahelo Kodo	Solukhumbu	27.26	86.38	2150
54	CO12937	Nang Chinnuwa Kodo	Solukhumbu	27.26	86.38	2150
55	CO13026	Muddke Kodo	Nawalpur	27.11	84.40	184
56	CO13039	Kartike Kodo	Nawalpur	27.11	84.40	184
57	CO13048	Larkani Kodo	Nawalpur	27.76	84.31	208
58	CO13226	Seto Kodo	Dhankuta	27. 00	86. 31	1485
59	CO13252	Muddke Kodo	Dhankuta	27. 00	87. 31	1530

S.N.	Collection code	Local name	District	Latitude	Longitude	Altitude, m
60	CO13266	Dalle Kodo	Dhankuta	27. 00	87. 31	1490
61	CO13308	Dalle Kodo	Dhankuta	27. 00	87. 30	1431
62	CO13324	Pangdure Kodo	Dhankuta	27. 99	87. 30	1419
63	CO13344	Khairokalo Kodo	Dhankuta	27. 00	87. 30	1380
64	CO13385	Khairo Kodo	Dhankuta	27. 03	87. 10	1521
65	CO13407	Kalo mudey Kodo	Kaski	28. 28	83. 81	1639
66	CO13408	Kodo Seto ursi	Kaski	28. 28	83. 81	1639
67	CO13497	Muddke Kodo	Paachthar	26. 86	87. 66	1699
68	CO13519	Seto Kodo	Paachthar	26. 86	87. 66	1623
69	CO13535	Dalle Kodo	Paachthar	26. 86	87. 66	1623
70	CO13292	Sthaniya Kodo	Dhankuta	27.01	87.30	1597
71	CO10588	Rato Kodo	Ramechhap	27.19	86.07	1410
72	CO13342	Seto Kodo	Dhankuta	27.00	87.308	1380

Measurement of agro-morphological traits

Quantitative data were collected from five randomly selected plants within a 1 m² ring thrown into the plot, while qualitative traits were assessed by observing the entire plot. A total of 23 quantitative traits (Table 2) and 9 qualitative traits (Table 3) were recorded following the standard finger millet descriptor (IBPGR 1985).

Measurements of yield and yield-attributing traits

Total yield, biomass of different plant parts, plant height, number of tillers, leaf sheath length, peduncle length, number of leaves, flag leaf length, flag leaf breadth and area, fourth leaf length, breadth and area, number of fingers, ear head length, finger length, finger width, and ear weight were recorded as described in the finger millet descriptor (IBPGR 1985). Thousand seed weight (TSW) was determined following ISTA Rules, Chapter 10 (ISTA 2023)the International Rules for Seed Testing (ISTA Rules, using eight replicates of 100 pure seeds at a seed moisture content of 10 ± 0.35%. Grain moisture content was recorded for each sample, and the Nepal standard of 11% was used to adjust TSW. Variation in seed traits was assessed using IBPGR descriptors (IBPGR 1985). A digital balance (PFB 200-3, Kern and Sohn GmbH, Germany) was used to measure related weights. Grain yield per plot was converted to tons per hectare (t/ha). Observed traits such as the fourth leaf in finger millet denotes the shift to the vegetative stage and guides key agronomic decisions, hence was purposively selected for the analysis.

Data analysis

Descriptive statistics, including mean, maximum and minimum values, coefficient of variation (CV), and Shannon-Weaver diversity index (H′) (Shannon 1948), were calculated using Microsoft Excel. Inferential statistical analyses were performed in R version 4.4.3 (R Core Team 2023). Principal component analysis (PCA) was conducted using the R packages Factoextra, FactoMineR, and Gridextra. Phenotypic path analysis was performed with the Metan package. A circular hierarchical cluster dendrogram was generated using the average linkage method and Euclidean distance through the Dendextend and Circlize packages. K-means clustering was executed using Factoextra, and the optimal number of clusters was determined using the NbClust package (Charrad et al. 2014)

Table 2. List of twenty-three quantitative characters studied among the finger millet landraces

S.N.	Quantitative traits	Unit	Description of character
1	Plant height	cm	From ground level to the tip of the inflorescence(ear) at the dough stage
2	Number of tillers	count	Number of basal tillers that bear mature ears
3	Leaf sheath length	cm	Measured from the node to the ligule of the flag leaf from the top
4	Peduncle length	cm	From top topmost node to the base of the thumb finger
5	Number of leaves	count	The total count of leaves present on the main tiller at the flowering stage
6	Flag leaf length	cm	Measured from ligule to tip of fourth blade from top at flowering
7	Flag leaf breadth	cm	Measured across the center of the fourth leaf from the top at flowering
8	Area of the flag leaf	cm^2	Product of flag leaf length and flag leaf breadth
9	Length of the 4th leaf	cm	Measured from the ligule to the tip of the fourth leaf from the top at flowering
10	Breadth of the 4th leaf	cm	Measured across the center of the fourth leaf from the top at the flowering stage
11	Area of the 4th leaf	cm^2	The product of the length and breadth of the fourth leaf from the top at flowering
12	Number of fingers	count	The number of fingers present in the main ear at the dough stage was counted
13	Ear head length	cm	From the base tip of the inflorescence to the top of the inflorescence at the dough stage
14	Finger length	cm	From the base tip of the longest spike from the main tiller at the dough stage
15	Finger width	cm	Measured across the center of the longest finger at the dough stage
16	Ear weight	g	Weight taken after harvesting
17	Days to 50% heading	count	The number of days from sowing until 50% of the plants have visible panicles emerging from the boot
18	Days to 50% flowering	count	From sowing to the stage when ears have emerged from 50% of the main tillers
19	Days to 50% seed fill	count	The number of days from sowing to the stage when half of the grains in the ear head have started to fill
20	Days to 80% maturity	count	From sowing to the stage when 80% of the main tillers have mature ears
21	Days to harvest	count	From sowing to the stage when 50% of the main tillers have mature ears
22	Thousand-seed weight	g	The weight of a random sample of 1000 seeds from the total harvest of an accession was expressed in grams
23	Grain yield	t/ha	The grain yield was adjusted to 11% moisture and converted to t/ha

Table 3. List of nine qualitative characters studied among the finger millet landraces

S.N.	Qualitative traits	Description of character
1	Orientation of the head	The positioning of the ear head (inflorescence) on the plant
2	Pigmentation	Presence or absence of anthocyanin pigmentation on plant parts at the flowering stage
3	Glume color	The color of the glumes (outer husks) enclosing the grain
4	Stem cull branching	Number of culm branches at maturity
5	Seed shattering	The tendency of seeds to detach from the ear head when fully mature
6	Glume cover	The extent of glume coverage over the grain
7	Lodging	The extent to which plants fall over at maturity at maturity
8	Seed color	The color of mature seeds after the post-harvest stage
9	Seed shape	The shape of harvested seeds at the post-harvest stage

Results

Quantitative traits

Descriptive statistics and Shannon-Weaver diversity indices (H′) for 23 quantitative traits are summarized. The CV ranged from 3.98% to 37.99%, indicating substantial phenotypic variation. Days to 50% flowering ranged from 89 to 121 days (mean: 101), while days to 50% heading ranged from 86 to 110 days (mean: 97). Days to 50% seed filling varied from 96 to 150 days (mean: 117). Days to 80% maturity ranged from 131 to 176 days (mean: 164). Tiller number per plant ranged from 1 to 7 (mean: 4). TSW varied between 2.34 and 3.65 g (mean: 2.86 g), and grain yield ranged from 0.9 to 3.89 t/ha (mean: 2.44 t/ha) (Table 4).

Shannon-Weaver indices for quantitative traits ranged from 0.59 to 0.93, indicating moderate to very high diversity. High diversity (H′ ≥ 0.80) was observed in ear weight (0.93), peduncle length (0.92), number of leaves (0.92), grain yield (0.90), days to 50% heading (0.89), plant height (0.88), finger width (0.86), and flag leaf breadth (0.85). Moderate diversity (0.59 ≤ H′ < 0.80) was found for traits such as days to 50% flowering (0.72) and days to harvest (0.59) (Table 4).

Table 4. Quantitative traits variability among 72 finger millet landraces

S.N.	Variables	Min	Max	Mean ± SEM	STD	CV (%)	H'
1	Plant height (cm)	73.5	125.3	102.35±1.04	8.79	8.59	0.88
2	Number of tillers	1	7	4±0.16	1.34	37.99	0.86
3	Leaf sheath length (cm)	7.15	14.9	11.69±0.15	1.29	11.07	0.82
4	Peduncle length (cm)	10.18	23.3	16.92±0.32	2.70	15.98	0.92
5	Number of leaves	6.5	16.5	12.43±0.24	2.01	16.17	0.92
6	Flag leaf length (cm)	21.8	44.7	33.79±0.48	4.07	12.05	0.84
7	Flag leaf breadth (cm)	0.71	1.31	1.04±0.01	0.10	9.51	0.85
8	Area of flag leaf ($cm^{2)}$	18.3	55.9	35.35±0.76	6.46	18.26	0.81
9	Length of 4th leaf (cm)	31.3	54.7	43.25±0.54	4.59	10.61	0.89
10	Breadth of 4th leaf (cm)	0.91	2.34	1.19±0.02	0.18	15.14	0.76
11	Area of 4th leaf ($cm^{2)}$	26.022	118.956	51.95±1.45	12.30	23.68	0.8
12	Number of fingers	4.7	10.6	7.06±0.12	1.02	14.44	0.89
13	Ear head length (cm)	5.09	14.44	7.65±0.24	2.01	26.23	0.78
14	Finger length (cm)	4.8	11.94	7.25±0.20	1.74	23.96	0.76
15	Finger width (cm)	0.81	1.34	1.05±0.01	0.09	8.85	0.86
16	Ear weight (g)	6	14	10.00±0.21	1.80	17.98	0.93
17	Days to 50% heading	86	110	96.05±0.72	6.10	6.35	0.89
18	Days to 50% flowering	89	121	100.99±0.75	6.37	6.31	0.72
19	Days to 50% seed fill	96	150	118.26±1.01	8.55	7.23	0.76
20	Days to 80% maturity	131	176	163.79±0.79	6.69	4.09	0.82
21	Days to harvest	158	186	179.33±0.84	7.13	3.98	0.59
22	Thousand seed weight (g)	2.34	3.65	2.86±0.04	0.35	12.08	0.82
23	Grain yield (t/ha)	0.9	3.89	2.44±0.10	0.82	10.34	0.90

Min = minimum, Max = maximum, Mean ± SEM= standard error of mean, STD = standard deviation, CV (%) = coefficient of variation, H'= notation for Shannon-Weaver diversity index

Qualitative traits

Shannon-Weaver indices for nine qualitative traits ranged from 0.18 to 0.98. The highest diversity was found in seed shape (H′ = 0.98), which varied across round (26.39%), reniform (29.17%), and ovoid (44.44%) types. Orientation of the head also showed high diversity (H′ = 0.96), with five distinct forms: fist-type (16.67%), compact (25%), semi-compact (25%), open (25%), and droopy (8.33%) (Table 5).

Table 5. Qualitative traits diversity among 72 finger millet landraces

S. N	Parameters	Descriptor states	Frequency (n)	Percentage (%)	H′
1	Orientation of the head	1-Fist type	12	16.67	0.96
		3-Compact	18	25	
		5-Semi compact	18	25	
		7-Open	18	25	
		9-Droopy	6	8.33	
2	Pigmentation	0-Absent	52	52	0.85
		1-Present	20	20	
3	Glume color	3-Light green	23	31.94	0.96
		5-Dark green	9	12.50	
		7-Light purple	21	29.17	
		9-Dark purple	19	26.39	
4	Stem cull branching	0-Absent	10	13.89	0.58
		1-Present	62	86.11	
5	Seed shattering	0-Absent	70	97.22	0.18
		1-Present	2	2.78	
6	Glume cover	2-Enclosed	53	73.61	0.63
		4-Intermediate	16	22.22	
		6-Exposed	3	4.16	
7	Lodging	1-Zero	44	61.11	0.70
		3-Low	13	18.06	
		5-Intermediate	6	8.33	
		7-High	8	11.11	
		9-Very high	1	1.39	
8	Seed color	1-White	2	2.78	0.77
		2-Light brown	27	37.50	
		3-Coper brown	35	48.61	
		4-Purple brown	8	11.11	
9	Seed shape	1-Round	19	26.39	0.98
		3-Reniform	21	29.17	
		5-Ovoid	32	44.44	

Glume color displayed wide variation, light green (31.94%), dark green (12.50%), light purple (29.17%), and dark purple (26.39%), with an H′ of 0.96. Seed color ranged from white (2.79%) to copper brown (48.61%), with an H′ of 0.77. Seed shattering had the lowest diversity (H′ = 0.18), as 97.22% of accessions exhibited no shattering. Moderate diversity was recorded for stem cull branching (H′ = 0.58), glume cover (H′ = 0.63), and lodging (H′ = 0.70) (Figures 1 and 2).

Figure 1. Head orientation diversity among 72 finger millet landraces of Nepal

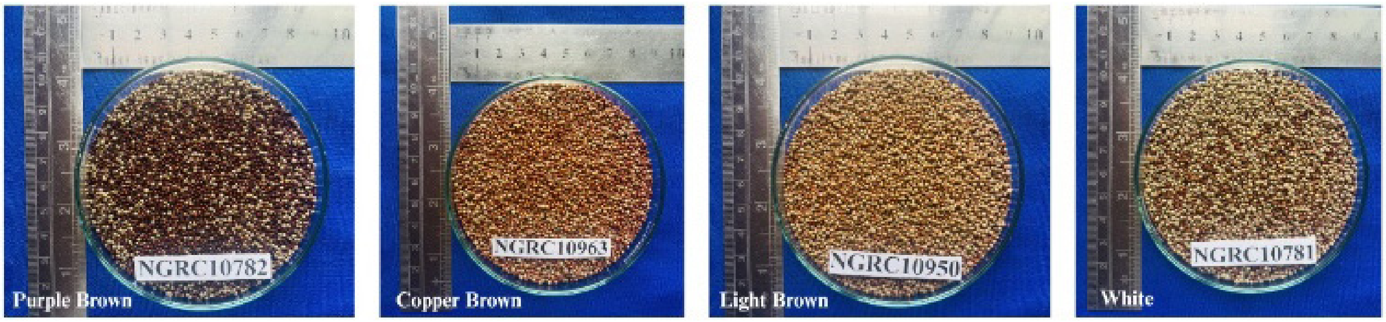

Figure 2. Seed color diversity among 72 finger millet landraces of Nepal

Principal component analysis

Seven principal components with eigenvalues greater than one accounted for 76.80% of the total phenotypic variation. The first principal component (PC-1) explained 26.37% of the variance and was associated with traits such as days to 50% heading, flowering, seed fill, number of leaves, flag leaf length and area, and ear head length (Figure 3). The second component (PC-2) explained 17.46% of the variance, associated with traits such as flag leaf and 4th leaf dimensions, ear head length, finger length, and peduncle length. PC-3 contributed 10.06% of the total variance and was driven by ear weight, peduncle length, finger width, number of fingers, TSW, days to maturity, flag leaf length, and tiller number.

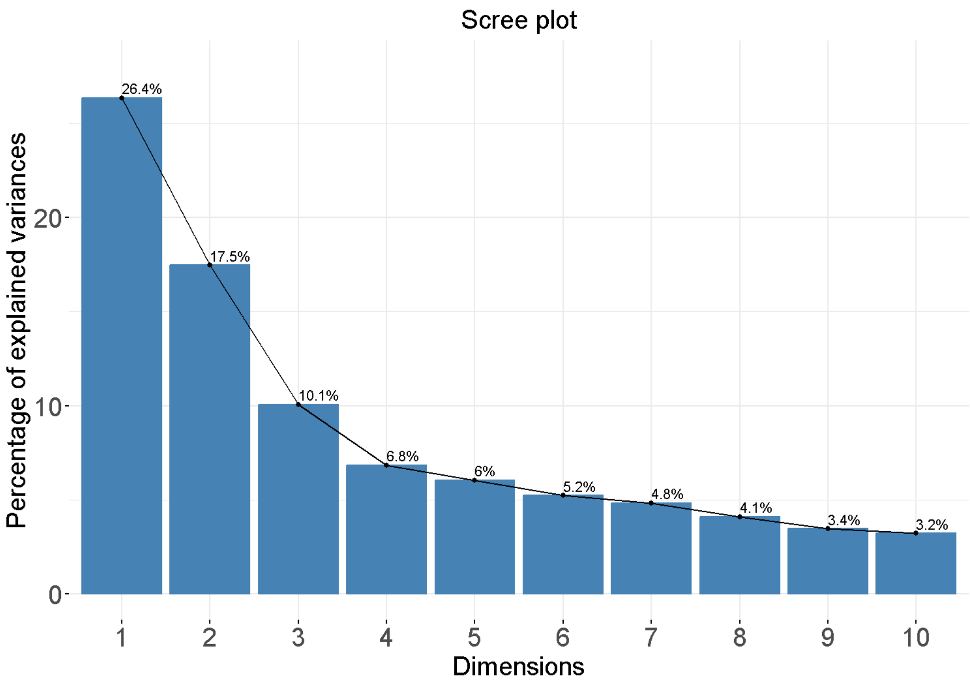

Figure 3. Scree plot of principal component analysis showing dimension-wise percentage of explained variances

The first two principal components (PC-1 and PC-2) collectively accounted for 43.83% of the total phenotypic variation, with PC-1 explaining 26.37% and PC-2 contributing 17.46%. The first PC-1 was strongly associated with developmental and seed-related traits, including days to 50% heading, days to 50% flowering, length of the 4th leaf, days to 50% seed fill, area of the 4th leaf, number of leaves, flag leaf length, ear head length, days to 80% maturity, flag leaf area and finger length. The second Principal component analysis (PC-2) primarily reflected seed and vegetative related traits such as; flag leaf breadth, flag leaf area, breadth of the 4th leaf, area of the 4th leaf, ear head length, days to 50% seed filling, finger length, flag leaf length, days to 80% maturity, and peduncle length. The third principal component (PC-3) explained 10.05% of the total variance, with primary contributions from ear weight, peduncle length, finger width, number of fingers, thousand seed weight, days to 80% maturity, flag leaf length, and number of tillers (Table 6).

Table 6. Principal component analysis of 23 quantitative traits. PC-1 to PC-7 indicate seven principal components.

Dimensions	PC-1	PC-2	PC-3	PC-4	PC-5	PC-6	PC-7
Eigenvalue	6.07	4.02	2.31	1.57	1.39	1.20	1.11
Variance (%)	26.37	17.46	10.06	6.84	6.03	5.22	4.81
Cumulative variance (%)	26.37	43.83	53.89	60.74	66.77	71.99	76.80
Variables	**Co-efficient vectors**						
Plant height (cm)	-0.191	0.115	-0.009	-0.126	-0.405	-0.447	0.125
Number of tillers	0.014	0.096	-0.232	-0.190	0.211	0.307	0.298
Leaf sheath length (cm)	0.023	-0.106	0.096	-0.528	-0.129	-0.238	0.296
Peduncle length (cm)	-0.089	-0.224	-0.395	0.100	-0.044	-0.158	0.106
Number of leaves	-0.243	0.126	0.123	0.163	-0.212	0.117	0.167
Flag leaf length (cm)	-0.237	-0.255	-0.271	-0.025	0.177	-0.050	-0.001
Flag leaf breadth (cm)	-0.125	-0.357	0.082	0.156	0.054	0.215	-0.194
Area of flag leaf (cm^2)	-0.220	-0.357	-0.138	0.082	0.144	0.097	-0.103
Length of 4th leaf (cm)	-0.328	-0.165	-0.012	-0.082	-0.065	-0.170	0.055
Breadth of 4th leaf (cm)	-0.186	-0.294	0.149	0.091	0.186	-0.119	0.095
Area of 4th leaf (cm^2)	-0.266	-0.285	0.090	0.028	0.123	-0.190	0.120
Number of fingers	-0.146	-0.103	0.298	0.002	-0.447	0.273	-0.228
Ear head length (cm)	-0.224	0.285	-0.110	0.305	0.010	-0.222	-0.043
Finger length (cm)	-0.216	0.258	-0.138	0.384	0.005	-0.196	-0.043
Finger width (cm)	0.184	-0.137	0.301	0.020	0.183	-0.305	0.295
Ear weight (g)	-0.102	-0.095	0.494	0.128	-0.101	0.034	0.049
Days to 50% heading	-0.338	0.118	0.034	-0.171	-0.025	0.162	0.057
Days to 50% flowering	-0.330	0.088	0.038	-0.201	-0.030	0.189	0.037
Days to 50% seed fill	-0.303	0.265	-0.081	-0.107	0.017	-0.021	-0.078
Days to 80% maturity	-0.166	0.253	0.109	-0.259	0.410	0.025	-0.066
Days to harvest	-0.221	0.137	0.275	-0.128	0.358	0.018	-0.109
Thousand seed weight (g)	0.050	0.154	0.281	0.352	0.254	-0.078	0.230
Grain yield (t/ha)	-0.083	0.013	-0.076	0.200	-0.111	0.385	0.685

K-means clustering

Using PC -1 and PC-2 (explaining 47.06% of the variation), 72 landraces were grouped into three distinct clusters. Cluster 1 (red) comprised 26 accessions, mostly on the positive PC-1 axis. Cluster 2 (green) contained 43 genetically distinct accessions in an isolated group. Cluster 3 (blue) included three accessions located on the negative PC-1 axis (Figure 4).

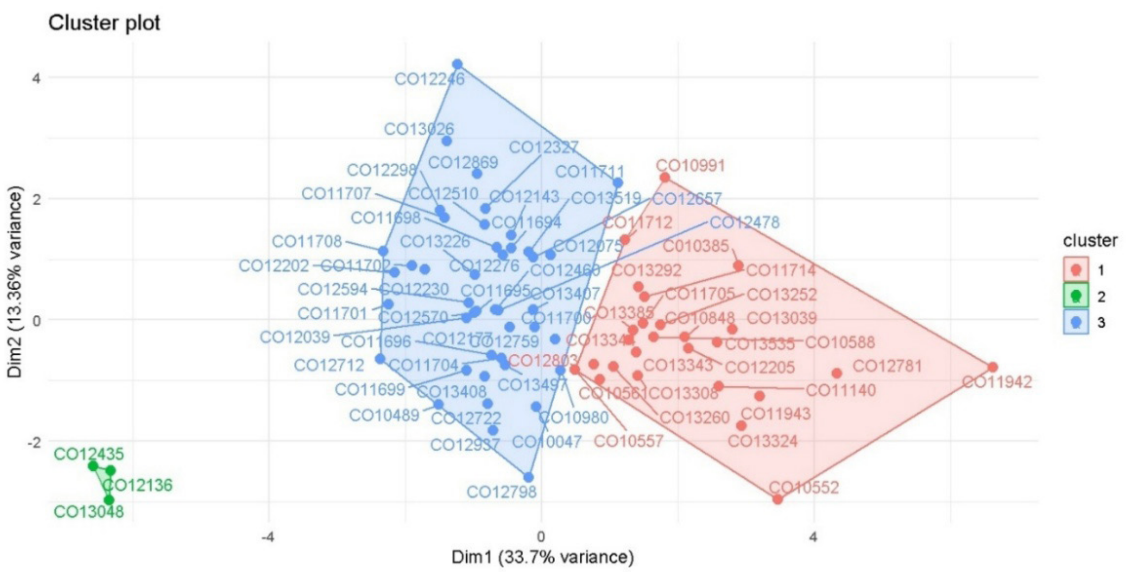

Figure 4. A cluster plot showing the grouping of finger millet collections based on K-mean values

Hierarchical cluster dendrogram

The optimal number of clusters was determined using the average Silhouette method in R, which identified three clusters at 80% similarity. A hierarchical dendrogram was constructed using the average linkage method and Euclidean distance, based on 23 quantitative traits measured across 72 finger millet landraces. Clusters 1, 2, and 3 are represented by red, blue, and green, respectively, in Figure 5.

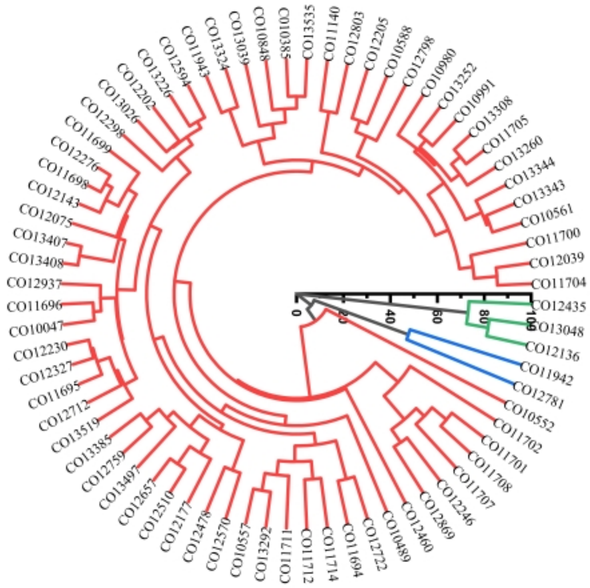

Figure 5. Circular cluster dendrogram with Euclidean distance and average method

The number of accessions and cluster-wise trait characteristics are summarized in Table 7. Cluster 1 is the largest, comprising 67 accessions (93.05%). Landraces in this cluster exhibited superior performance in yield-related traits, including fingers per ear (7.10), ear weight (10.20 g), thousand seed weight (2.88 g), and grain yield (2.47 t/ha). Notably, accession CO12246 had the highest finger number and ear weight, CO13026 recorded the highest thousand seed weight, and CO12712 showed the highest grain yield. Cluster 2, with 2 accessions (2.77%), consisted of early-maturing landraces characterized by shorter phenological durations including days to 50% heading (86.5), flowering (89), seed filling (101), and harvest maturity (161). Accession CO11942 also exhibited wider fingers (1.21 cm), distinguishing it from accessions in other clusters. Cluster 3 included 3 accessions (4.16%), marked by taller plant stature, longer ear heads, and higher tiller numbers. Among these, CO12435 had the tallest plants (125 cm) and the longest ear heads (14.44 cm), while CO13408 exhibited the highest tiller count (7).

Table 7. Cluster means of 13 quantitative traits

Variable	1	2	3
No of accessions	67	2	3
Plant height (cm)	101.94	92.83	117.99
Number of tillers	3.56	1.95	3.93
Number of fingers	7.10	6.35	6.70
Ear head length (cm)	7.45	5.83	13.41
Finger length (cm)	7.10	5.73	11.53
Finger width (cm)	1.05	1.21	0.83
Ear weight (g)	10.20	7.80	7.07
Days to 50% heading	95.75	86.50	109.00
Days to 50% flowering	100.82	89.50	112.33
Days to 80% maturity	163.99	140.00	175.17
Days to harvest	179.60	161.00	185.67
Days to 50% seed fill	117.43	101.00	148.33
Thousand seed weight (g)	2.88	2.60	2.57
Grain yield (t/ha)	2.47	1.22	2.34

Table 8. Phenotypic path analysis

	PH	NOT	LSH	PL	NOL	FLL	FLW	FLA	LFL	BFL	AFL	NOF	EHL	FL	FW	EWT	DTF	DTH	DSF	DTM	DOH	TGW	linear
PH	0.10	-0.02	0.02	-0.03	0.11	0.04	0.02	0.01	0.04	0.01	-0.17	-0.05	-0.16	0.14	0.09	0.01	0.16	-0.03	-0.19	-0.04	-0.02	-0.03	0.02
NOT	-0.01	0.23	-0.01	-0.02	-0.02	0.01	0.03	0.02	-0.01	-0.12	0.11	0.03	-0.02	0.03	0.04	-0.05	0.01	0.00	-0.02	-0.05	0.00	-0.05	0.15
LSH	0.02	-0.01	0.12	0.00	-0.04	0.02	0.00	0.00	0.01	0.03	-0.06	0.00	0.11	-0.14	-0.09	0.02	0.00	0.00	0.04	-0.01	0.01	-0.06	-0.04
PL	0.02	0.02	0.00	-0.20	0.01	0.30	-0.05	-0.11	0.03	0.14	-0.22	0.03	0.01	0.02	0.06	-0.06	0.01	-0.01	0.02	0.07	0.03	-0.07	0.05
NOL	0.04	-0.02	-0.02	-0.01	0.30	0.04	-0.01	-0.02	0.03	0.08	-0.16	-0.06	-0.19	0.16	0.10	0.06	0.26	-0.04	-0.21	-0.07	-0.03	0.04	0.25
FLL	0.01	0.00	0.00	-0.10	0.02	0.58	-0.06	-0.18	0.06	0.28	-0.46	0.00	-0.05	0.05	0.10	-0.01	0.14	-0.03	-0.11	-0.01	-0.01	-0.10	0.13
FLW	-0.02	-0.05	0.00	-0.07	0.03	0.24	-0.14	-0.16	0.03	0.36	-0.36	-0.08	0.09	-0.07	0.00	0.07	0.04	-0.01	0.08	0.05	-0.01	-0.03	0.01
FLA	-0.01	-0.02	0.00	-0.10	0.03	0.51	-0.11	-0.21	0.05	0.38	-0.49	-0.04	0.02	0.00	0.07	0.04	0.11	-0.03	-0.03	0.03	-0.01	-0.08	0.10
LFL	0.05	-0.01	0.01	-0.07	0.09	0.40	-0.05	-0.13	0.09	0.34	-0.59	-0.09	-0.10	0.10	0.11	0.07	0.25	-0.05	-0.19	-0.04	-0.03	-0.06	0.11
BFL	0.00	-0.04	0.01	-0.04	0.03	0.23	-0.07	-0.11	0.04	0.72	-0.71	-0.06	0.02	0.00	-0.05	0.07	0.10	-0.02	0.01	0.01	-0.02	-0.04	0.09
AFL	0.02	-0.03	0.01	-0.06	0.06	0.35	-0.07	-0.13	0.07	0.66	-0.77	-0.07	-0.03	0.04	0.01	0.07	0.17	-0.03	-0.06	-0.01	-0.03	-0.05	0.11
NOF	0.02	-0.03	0.00	0.02	0.08	0.01	-0.05	-0.04	0.03	0.17	-0.23	-0.23	0.02	-0.01	0.08	0.12	0.12	-0.02	-0.03	0.02	-0.02	-0.04	0.02
EHL	0.04	0.01	-0.03	0.00	0.12	0.07	0.03	0.01	0.02	-0.03	-0.05	0.01	-0.45	0.40	0.18	0.01	0.20	-0.03	-0.29	-0.10	-0.03	0.04	0.12
FL	0.04	0.02	-0.04	-0.01	0.11	0.07	0.02	0.00	0.02	0.00	-0.07	0.00	-0.43	0.41	0.19	0.01	0.17	-0.03	-0.26	-0.08	-0.03	0.04	0.15
FW	-0.02	-0.02	0.02	0.03	-0.07	-0.12	0.00	0.03	-0.02	0.07	0.01	0.04	0.17	-0.17	-0.45	0.07	-0.18	0.03	0.22	0.07	0.01	0.09	-0.18
EWT	0.01	-0.05	0.01	0.05	0.07	-0.02	-0.05	-0.03	0.02	0.20	-0.23	-0.12	-0.02	0.01	-0.13	0.23	0.05	-0.01	0.02	-0.02	-0.03	0.06	0.04
DTF	0.04	0.00	0.00	0.00	0.17	0.18	-0.01	-0.05	0.05	0.15	-0.28	-0.06	-0.19	0.15	0.17	0.03	0.46	-0.08	-0.35	-0.11	-0.05	-0.02	0.19
DTF	0.04	0.01	0.00	-0.01	0.15	0.19	-0.02	-0.06	0.05	0.15	-0.27	-0.06	-0.16	0.13	0.17	0.04	0.44	-0.09	-0.32	-0.12	-0.05	-0.03	0.17
DSF	0.05	0.01	-0.01	0.01	0.14	0.15	0.03	-0.01	0.04	-0.02	-0.10	-0.02	-0.30	0.25	0.23	-0.01	0.37	-0.06	-0.43	-0.16	-0.05	-0.01	0.09
DTM	0.01	0.04	0.01	0.05	0.07	0.01	0.03	0.02	0.01	-0.02	-0.03	0.02	-0.16	0.12	0.12	0.01	0.19	-0.04	-0.24	-0.28	-0.07	0.05	-0.06
DOH	0.02	0.01	-0.01	0.05	0.10	0.04	-0.01	-0.02	0.03	0.16	-0.22	-0.04	-0.13	0.10	0.05	0.06	0.23	-0.04	-0.21	-0.18	-0.10	0.06	-0.05
TGW	-0.01	-0.04	-0.02	0.04	0.03	-0.19	0.02	0.06	-0.02	-0.09	0.12	0.03	-0.06	0.05	-0.13	0.04	-0.02	0.01	0.01	-0.05	-0.02	0.31	0.09

PH= Plant height, NOT= Numbers of tiller/s, LSH=Leaf sheath length, PL= Peduncle length, NOL= Numbers of leaves, FLL= Flag leaf length, FLW= Flag leaf width, FLA= Flag leaf area, LFL=Length of 4th Leaf, BFL= Breadth of 4th leaf, AFL= Area of 4th leaf, NOF= Numbers of fingers, EHL= Ear head length, FL=Finger length, FW= Finger width, EWT= Ear weight, DTF= Days to 50% flowering, DTH= Days to 50% headings= Days to 50% seed filling, DTM= Days to 80% maturity, DOH= Days of harvest, TGW= Thousand grain weight, GY= Grain yield

Phenotypic path analysis

Path coefficient analysis revealed that 22 quantitative traits collectively explained 31% of the variation in grain yield (R^2 = 0.31). The breadth of the fourth leaf had the highest positive direct effect (0.719), followed by flag leaf length (0.584), both contributing directly to yield improvement. In contrast, the area of the fourth leaf (–0.773) and finger width (–0.453) had the strongest negative direct effects. Although the number of leaves and days to 50% flowering and heading had moderate direct effects, their total contribution to yield was limited (Table 8).

Discussion

Finger millet landraces exhibited substantial genetic variation in both qualitative and quantitative traits, reaffirming their potential for crop improvement. Despite their wide adaptability and resilience to abiotic stresses, these landraces remain underutilized in breeding programs and have received limited attention in terms of systematic phenotypic characterization (Bastola et al. 2015). The Shannon-Weaver diversity index revealed a broad range of variation; traits with low H′ values reflected uneven frequency distributions, indicating limited diversity, as previously noted by Perry and McIntosh (1991).

Tiller number ranged from 1 to 7 (H′ = 0.86), likely a result of long-term farmer-driven selection, which may have facilitated genetic differentiation across populations (Ghimire et al. 2020). Variation in days to 80% maturity (131–176 days) suggests adaptation strategies whereby early-maturing landraces can escape terminal droughts at higher altitudes, while late-maturing types offer higher biomass and straw yield for livestock use (Patel 2017).

The observed variability in thousand seed weight (2.34–3.65 g) likely reflects high heritability and the influence of additive gene action (Priyadharshini et al. 2011). Grain yield diversity (0.9–3.89 t/ha, H′ = 0.90) may be attributed to genotypic differences in grain filling duration and assimilate partitioning between grain and biomass, as noted in previous studies (Bastola et al. 2015). The predominance of copper brown seed color aligns with consumer preferences for traditional food and beverage products (Sapkota and Joshi 2023). Notably, white seed coat accessions (CO12327, CO12246), while rare, are culturally and commercially valued (Bhusal 2023). Dark-colored seeds may also confer reduced bird predation due to lower visibility (Owere et al. 2014).

Non-shattering types, such as CO12478 and CO11712, are advantageous for late harvests and improved yield stability. Over 60% of landraces were lodging-resistant, a farmer-preferred trait that reduces mechanical loss and enhances harvest efficiency (Dhami et al. 2018). Most accessions displayed enclosed glumes, which confer protection against pests and environmental exposure—traits associated with higher marketability and storability (Ghimire et al. 2023). The dominance of compact and semi-compact head orientation types further suggests their selection for reduced seed loss and bird damage (Louis et al. 2023, Bastola et al. 2015). Although this study did not include detailed seed morphology, the observed variation in seed coat features aligns with previous reports highlighting their utility in varietal identification and genotype delimitation (Mundada et al. 2020).

PCA efficiently captured major trait variation, allowing dimensional reduction without significant information loss. The current study's clustering pattern (three distinct groups) is consistent with prior findings. Naik et al. (2021)character association and diversity among twenty diverse genotypes of finger millet for seven different agronomic traits. The genotypic mean square values were highly significant for all the characters studied, which indicates the suitability of cultivars and improved varieties selected for study. Higher estimates of PCV and GCV were recorded for the characters number of productive tillers per plant (29.04% and 24.33% identified two clusters among 10 genotypes, while Ghimire et al. (2023) delineated four clusters across 300 landraces. Such clustering provides a basis for selecting genetically distinct parents in hybridization programs (Thapa et al. 2019). Although multi-environment trials were not conducted, PCA allowed effective reduction of redundancy in trait analysis and minimized multiple testing errors, as recommended by Lever et al. (2017).

Hybridization between accessions from Cluster 1 (high yield, seed weight, and finger number) and Cluster 3 (greater plant height, tiller number, and finger length) could generate transgressive segregants. This finding aligns with Luitel et al. (2020), who reported that subtropical zones with moderate climates are optimal for finger millet cultivation. Similarly, Adhikari et al. (2018) observed improved performance for key agronomic traits under such conditions. Phenotypic path analysis identified fourth leaf breadth, flag leaf length, and tiller number as key traits with positive direct effects on yield. These results highlight their potential as selection indices in early-generation breeding.

Among the identified genotypes, Cluster 1 accessions such as CO12246 excelled in finger number and ear weight, CO13026 (Nawalpur) in TSW, and CO12712 (Okhaldhunga) in grain yield. Cluster 2 genotypes like CO11942 (Mugu) were early-maturing, making them suitable for short-season environments. Cluster 3 accessions, such as CO12435 (Tanahun), exhibited superior plant height and ear head length, while CO13408 (Kaski) had the highest tiller number, traits of agronomic and economic importance. These findings provide a foundation for trait-based selection and targeted improvement of finger millet in Nepal and similar agroecologies.

Conclusion

This study revealed significant phenotypic variability among 72 Nepalese finger millet landraces, underscoring their value as genetic resources for crop improvement. The observed diversity across both quantitative and qualitative traits, particularly in yield components, phenology, and leaf morphology, highlights the adaptive potential of these landraces to diverse agroecological zones. Multivariate analyses, including PCA and clustering, effectively differentiated accessions, identifying clusters with superior agronomic performance and early-maturing traits. Phenotypic path analysis further pinpointed specific traits, such as fourth leaf breadth and flag leaf length, with strong direct effects on grain yield, offering useful selection criteria for breeding programs. The identification of high-yielding landraces such as CO12712, CO12570, and CO13039 emphasizes the potential for direct utilization in varietal development. However, the study also indicates the need for integrating phenotypic evaluation with molecular marker-assisted characterization and multi-environment trials to capture genotype × environment interactions and ensure trait stability. The findings reinforce the importance of conserving and characterizing indigenous germplasm to broaden the genetic base of finger millet and support sustainable, climate-resilient agriculture in marginal environments.

Acknowledgement

We sincerely acknowledge the NARC head office for funding this research and extend our gratitude to the staff and all the research interns of the National Genebank for their valuable support.

Author responsibility

P Thapa: Conceptualized and designed the experiments, conducted the research, analyzed and interpreted the data, and drafted the manuscript

S Bohora, S Acharya, A Adhikari, A Kawar, P Shrestha, B K Joshi: Contributed to data analysis and drafting manuscript.

D Poudyal: Revised the manuscript, provided critical input to align it with the reviewers' comments

Conflict of interest declaration

The authors declare that there are no conflicts of interest regarding the publication of this manuscript.

Data availability commitment

The data that support the findings of this study are available on reasonable request.

Declaration on the use of generative AI tools

The author(s) confirm that no artificial intelligence (AI) tools were used in the writing, editing, or content generation of this article. All work is the original effort of the author(s).

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