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MORPHOPHYSIOLOGICAL CHARACTERIZATION OF BUCKWHEAT LANDRACES TOWARD THE DEVELOPMENT OF GERMPLASM IN BANGLADESH

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SUMMARY

The morphological analysis of buckwheat (*Fagopyrum esculentum*) is crucial in developing germplasm resources. The study used 19 local common buckwheat landraces to characterize their morphophysiological and yield-related traits for germplasm development. The analysis of variance revealed no statistically significant variations in most morphophysiological and agronomic features, except for plant height and chlorophyll content (SPAD Value). Landraces L_7 and L_{14} stood out for their superior morphological and yield-related traits, while L_2 had the highest grain yield per raceme. Employing principal component analysis helped identify key morphological and yield-related traits. The first six principal components accounted for 99% of the total variance, with the first component having the highest Eigenvalues. Cluster analysis assessed the similarities among landraces based on their morphophysiological and agronomic traits. Notably, the distribution of landraces from similar locations often appeared across different clusters, indicating diverse genetic variability. These findings are crucial for selecting suitable landraces for germplasm development in common buckwheat. Additionally, the insights gained into morphophysiological and yield-related variations can help enhance buckwheat breeding programs in Bangladesh.

Keywords: Buckwheat, diversity, germplasm, morphological markers, PCA

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Key findings: Landraces L_{14} and L_7 contributed the highest variation among the buckwheat's (*Fagopyrum esculentum*) 14 morphophysiological and yield-contributing traits. The principal component analysis showed that the first six principal components comprised 99% of the total variation. Dendrogram data demonstrated that the various landraces reached different cluster groupings based on morphophysiological and yield variations.

INTRODUCTION

The common buckwheat (*Fagopyrum esculentum* Moench) has a pseudo-cereal classification and belongs to the family Polygonaceae. Its cultivation is predominantly in the winter season (November-March) across northern regions of Bangladesh, including Dinajpur, Thakurgaon, Panchagarh, Nilphamari, Lalmonirhat, Kurigram, and Rangpur districts. Initially, it is stated that buckwheat originated in Siberia and Northern China, but recent research has identified Yunnan province in Southern China as the actual birthplace of buckwheat (Yao *et al*., 2023).

The distribution of common buckwheat extends from Sichuan Province to eastern Tibet and further to Bhutan and the Himalayan regions of Nepal. Additionally, it spreads from Yunnan Province across Northern Myanmar to the Naga Hills in Nagaland, Meghalaya, and the Indian Himalayan regions, extending to Bhutan and Nepal (Ohsako and Li, 2020). Reports also revealed buckwheat existed in Darjeeling, India, which is geographically close to the Panchagarh district in Bangladesh. It is plausible that buckwheat distribution from Darjeeling extends through Nilphamari to Panchagarh and further to Thakurgaon and Dinajpur, as facilitated by farmers, traders, or even through the flow of the Teesta River.

Buckwheat thrives in low to medium-textured soils with good drainage and can tolerate slightly acidic conditions (up to pH 5) (Shen, 2003). Although it does not demand high-quality soil, buckwheat is sensitive to environmental factors like frost, extreme temperatures, dry winds, and droughts (Germ and Gaberščik, 2016). Buckwheat plants are typically erect and slender, reaching heights of up to one meter (Arduini *et al*., 2016). They have a branching growth habit that allows them to utilize available space effectively. This growth pattern is particularly beneficial in intercropping systems and in marginal lands where space is limited.

Buckwheat plants have heart-shaped or triangular leaves with prominent veins arranged alternately along the stems, enhancing their lush appearance and aiding in efficient photosynthesis and water use (Aubert *et al.,* 2021). Their small white to pink flowers form clusters at stem tips, each with five petals and green sepals, attracting pollinators and supporting biodiversity (Sokoloff *et al.,* 2023). Post-pollination, these flowers develop into groats, enclosed in solid and dark hulls. The triangular, grooved seeds aid in dispersal and are visually distinctive (Grahić *et al.,* 2022).

With a short lifecycle of 10–12 weeks under ideal conditions, buckwheat matures quickly, making it suitable for short-season crops and as a cover crop. Its unique features, such as slender growth, distinctive leaves, flowers, and seeds, define its identity as a pseudocereal (Song *et al.,* 2022). These traits, with adaptability and nutritional benefits, have made buckwheat popular worldwide. Additionally, its soft, reddish stems are consumable as green leafy vegetables, rich in antioxidants and flavonoids (Cawoy *et al.,* 2009).

Both green leaves and bloomed flowers are sources of rutin, a compound used in medicine to treat various ailments, including cancer and edema (Sayed *et al*., 2015; Islam *et al*., 2016; Abedin *et al*., 2020; Abedin *et al*., 2021). The plant can recover from rain damage during its immature stage by sprouting from the lower leaf axils (Ahmed *et al*., 2014). Each buckwheat plant typically has 20–30 long internodes (pedicels) averaging around 7 cm in length (Arduini *et al*., 2016). The plant produces two distinct flower types: thrum (short-styled, short pistil, and long stamen) and pin (long-styled, long pistil, and short stamen) flowers, which occur on separate plants (Matsui and Yasui, 2020). Germplasm conservation is crucial for preserving the genetic diversity of species, which in turn, supports food security and biodiversity conservation (Priyanka *et al*., 2021).

Analyzing morphophysiological and yield-related traits, like plant height, maturity period, and 1000-grain weight, serves as valuable markers for assessing different genotypes. This information is instrumental in characterizing germplasm resources and establishing buckwheat germplasm collections. This study aimed to develop germplasm of common buckwheat landraces based on agro-morphological and physiological traits.

MATERIALS AND METHODS

Plant materials

The 19 buckwheat landraces (denoted as "L") collected from different districts in the Rangpur division of Bangladesh, specifically Dinajpur, Nilphamari, Panchagarh, Thakurgaon, and Lalmonirhat (Table 1). These landraces cultivation ensued at the field laboratory of the Department of Biochemistry and Molecular Biology, Hajee Mohammad Danesh Science and Technology University (HSTU) in Dinajpur (25° 38′N latitude, 88° 38′E longitude) from December 2020 to April 2021, under rainfed and minimally irrigated conditions.

Experimental procedure

The field experiment followed a randomized complete block design (RCBD) with three replications, utilizing soil properties previously described for the Dinajpur district in Bangladesh (Badaruddin *et al*., 2000). Each plot measured 4 m × 2 m (8 m^2), spaced 0.5 m apart. Cow dung, urea, TSP, and MOP applications had rates of 10 t/ha, 220 kg/ha, 120 kg/ha, and 100 kg/ha, respectively. Urea treatment continued 15 and 30 days after sowing. Standard crop management practices ensured healthy crop growth, evaluating the landraces based on agro-morphological and physiological traits.

Assessment of morphophysiological and yield-related traits

Morphophysiological and yield-related traits assessment focused on several parameters: grain-forming racemes per plant, grains per raceme, total grains per plant, 1000-seed weight (g), and grain weight per plot (kg). The grain-setting racemes per plant determination progressed by counting the racemes on five plants from each plot and then averaging the count. Counting one large and one small raceme grain from five plants in each plot ascertained the number of grains per raceme. The 1000-seed weight (g) measurement ensued after sun drying, ensuring a moisture content of 12%–14%. Seed weight was recorded per plot (kg) used a digital balance after drying the seeds in sunlight. Morphological assessments of the landraces included measurements of plant height (cm), distance to the first node (cm), number of branches per plant, number of inflorescences, number of flowers per inflorescence, raceme length (cm), leaf length, and leaf area (mm^2). SPAD readings were taken from the middle of the flag leaf of five main shoots at the reproductive stage (95 days after sowing) using a SPAD meter

Table 1. Lists of common buckwheat landraces and collection sites used in this study with their geographical coordinates.

District	No. of landraces	Landrace’s name	Location Latitude	Longitude
Nilphamari	01	L_1	25° 56′ 30.12″	88° 50′ 39.84″
Panchagarh	04	L_2, L_3, L_4, L_5	26° 20′ 0.17″	88° 33′ 27.97″
Thakurgaon	08	L_6, L_7, L_8, L_9, L_{10}, L_{11}, L_{12}, L_{13}	26° 2′ 30.6204″	88° 25′ 41.7432″
Lalmonirhat	06	L_{14}, L_{15}, L_{16}, L_{17}, L_{18}, L_{19}	25° 54′ 58.3128″	89° 27′ 2.088″
Dinajpur	01	L_{20}	25° 38′ 11.6664″	88° 38′ 10.7592″

(Chlorophyll Meter SPAD 502). Leaf length and area measuring used a portable leaf area meter (BLAM-1 BLAM-2) at the reproductive stage.

Statistical analysis

The scrutiny of 14 quantitative traits incurs analysis of variance (ANOVA). Descriptive statistics, including mean, standard deviation, coefficient of variation, and range, reached calculation using R version 4.1.3, as detailed in Nadeem *et al*. (2020). Principal component analysis (PCA), biplot graphical display, dendrogram creation with agglomerative clustering, and cluster analysis continued using RStudio version 4.1.3, following the methods described by Evgenidis *et al*. (2011).

RESULTS AND DISCUSSION

Morphological and physiological characteristics

The morphological, physiological, and yield-contributing traits of buckwheat cultivars' characterization engaged the previously described method by Sugiyama *et al*. (2023). Descriptive statistics for these morphophysiological characteristics appear in Table 2.

The analysis revealed no significant variations among all landraces except for plant height and chlorophyll content. In contrast, Facho *et al*. (2016) identified variations in morphological parameters among three common buckwheat genotypes. A study has shown that plant height, number of branches, stem diameter, stem thickness, and yield-enhancing parameters decrease with increasing seed rate (Debnath *et al*., 2008). Such relationships could arise due to plants' competition for nutrients, space, and light (Mondal *et al*., 1992). This research observed three distinct flower colors among the 19 buckwheat landraces (Figure 1), indicating morphophysiological variations. Some landraces exhibited promising results in yield-contributing traits. Study findings showed that the number of grains per plant ranged from 72 (L_{19}) to 246 (L_{14}) among the 19 common buckwheat landraces.

A comparable number of grains per plant (238–472) in common buckwheat came from Baniya *et al*. (1995). The highest grain yield (1.05 kg/8 m^2) was apparent in landrace L_7, equivalent to approximately 1300 kg/ha. Morphophysiological data indicated no statistically significant variation among the buckwheat landraces, except for plant height and chlorophyll content. Variations in morphological and physiological data could refer to cultural practices, such as weeding and irrigation (Facho *et al*., 2016). The morphological and physiological characteristics of buckwheat landraces reveal considerable disparity, which may be due to genetic diversity, environmental factors, and geographic origins.

The tallest plant height was visible in L_7, originating from Bairati, Thakurgaon, reaching 81.60 cm. It suggests that L_7 has a robust growth habit and may have adapted well to its native environment. In contrast, the distance of the first node, an indicator of internode length, was highest in L_{14} at 3.80 cm and lowest in L_{20} at 2.40 cm (Aubert *et al*., 2021). This variation in internode length can influence plant architecture, affecting lodging resistance and light interception. L_5 exhibited the highest number of branches at 5.40, implying a bushy growth habit, whereas L_{20} had 3.66 branches. Flowering characteristics also varied among the landraces, with L_8 having the highest fluorescence number at 105.80 and L_{20} the lowest at 44.93.

Similarly, the number of flowers per fluorescence was optimum in L_{11} (19.06) and minimum in L_4 (12.73). These variations in flowering can affect pollination efficiency and, ultimately, seed set. For raceme characteristics, raceme length was longest in L_{20} (4.75 cm) and shortest in L_{17} (3.01 cm).

Leaf area, a crucial factor for photosynthesis, was the largest in L_8 (2440.29 mm^2) and smallest in L_{17} (1053.97 mm^2). Leaf length followed a similar trend, with L_8 having extended leaves (63.99 mm) and L_{20} the shortest (33.45 mm) (Aubert *et al*., 2021). Chlorophyll content, an indicator of photosynthetic capacity, varied between

Table 2. Performance of 19 buckwheat landraces in response to morphophysiological and yield-contributing traits.

	DFN (cm)	PH (cm)	NB	NF	NFF	RL (cm)	GRP	NGR	TGP	TSW (g)	SW/Plot (kg)	LA (mm^2)	LL (mm)	CC (SPAD value)
L_1	2.75 ± 0.13 a	57.46 ± 4.42 ab	4.20 ± 0.20 a	87.73 ± 22.21 a	12.80 ± 2.22 a	4.40 ± 0.17 a	67.26 ± 25.74 a	6.66 ± 0.80 a	202.6 ± 39.15 a	1.42 ± 0.19 a	0.34 ± 0.07 a	1349.88 ± 728.81 a	39.26 ± 13.63 a	44.74 ± 1.42 ab
L_2	3.28 ± 0.88 a	69.13 ± 20.69 ab	4.66 ± 0.50 a	68.20 ± 10.47 a	14.33 ± 2.70 a	3.84 ± 1.07 a	47.13 ± 15.31 a	9.73 ± 1.67 a	114.73 ± 61.78 a	1.48 ± 0.28 a	0.49 ± 0.35 a	1619.28 ± 143.3 a	47.41 ± 9.33 a	44.31 ± 0.79 ab
L_3	2.70 ± 0.45 a	65.93 ± 14.80 ab	4.26 ± 0.23 a	76.80 ± 17.11 a	13.93 ± 2.41 a	3.11 ± 0.38 a	58.26 ± 34.03 a	4.33 ± 2.31 a	156.53 ± 93.28 a	1.57 ± 0.26 a	0.46 ± 0.32 a	1782.9 ± 1013.91 a	48.86 ± 18.22 a	45.47 ± 2.57 ab
L_4	2.71 ± 0.51 a	68.13 ± 16.57 ab	5.26 ± 1.30 a	104 ± 46.99 a	12.73 ± 0.80 a	4.19 ± 1.05 a	45.53 ± 18.22 a	5.80 ± 3.46 a	142.93 ± 60.52 a	1.50 ± 0.36 a	0.72 ± 0.25 a	1660.61 ± 372.25 a	54.97 ± 5.44 a	48.56 ± 0.54 a
L_5	2.61 ± 0.60 a	78.66 ± 2.80 ab	5.40 ± 1.24 a	83.66 ± 28.56 a	13.86 ± 3.28 a	3.46 ± 0.15 a	36.26 ± 13.49 a	4.46 ± 2.54 a	102.26 ± 29.37 a	1.44 ± 0.04 a	0.78 ± 0.45 a	1240.97 ± 649.41 a	41.01 ± 14.57 a	48.09 ± 3.15 a
L_6	3.31 ± 0.16 a	76.20 ± 11.53 ab	4.40 ± 0.60 a	94.33 ± 9.36 a	13.86 ± 3.28 a	3.88 ± 1.02 a	43.80 ± 20.57 a	7.06 ± 0.61 a	118.8 ± 56.95 a	1.30 ± 0.13 a	0.75 ± 0.51 a	1577.88 ± 215.3 a	47.7 ± 4.47 a	46.33 ± 2.70 ab
L_7	3.36 ± 0.48 a	81.60 ± 2.70 a	4.20 ± 0.20 a	72.53 ± 23.28 a	13.0 ± 2.0 a	3.93 ± 1.44 a	59.46 ± 29.26 a	7.6 ± 4.54 a	133.86 ± 34.23 a	1.74 ± 0.14 a	1.05 ± 0.85 a	1973.02 ± 325.97 a	56.13 ± 5.80 a	46.44 ± 2.44 ab
L_8	2.63 ± 0.53 a	77.46 ± 0.75 ab	4.00 ± 0.52 a	105.80 ± 6.63 a	13.26 ± 2.83 a	3.70 ± 0.27 a	33.46 ± 23.82 a	3.93 ± 1.44 a	133.2 ± 84.51 a	1.41 ± 0.07 a	0.33 ± 0.08 a	2440.29 ± 920.64 a	63.99 ± 11.35 a	45.39 ± 3.25 ab
L_9	3.06 ± 0.70 a	79.73 ± 13.84 ab	4.33 ± 0.50 a	82.60 ± 6.63 a	14.0 ± 1.50 a	4.33 ± 0.56 a	50.66 ± 17 a	8.6 ± 0.87 a	184.73 ± 85.49 a	1.46 ± 0.17 a	0.52 ± 0.45 a	1734.75 ± 875.79 a	51.4 ± 13.57 a	46.42 ± 2.81 ab
L_{10}	2.78 ± 0.24 a	80.53 ± 8.92 a	4.93 ± 0.64 a	86.13 ± 7.73 a	15.13 ± 3 a	3.36 ± 0.41 a	55.66 ± 24.90 a	6.06 ± 2.88 a	163 ± 97.81 a	1.52 ± 0.08 a	0.75 ± 0.37 a	1778.28 ± 756.9 a	54.1 ± 15.14 a	48.11 ± 2.05 a
L_{11}	2.97 ± 0.40 a	71.00 ± 7.93 ab	4.93 ± 1.00 a	81.26 ± 6.81 a	19.06 ± 4.08 a	3.54 ± 0.41 a	41.60 ± 6.93 a	5.0 ± 1.24 a	143.13 ± 32.39 a	1.58 ± 0.33 a	0.94 ± 0.41 a	1392.9 ± 862.7 a	46.24 ± 14.68 a	46.06 ± 3.61 ab
L_{12}	3.39 ± 0.27 a	71.20 ± 6.80 ab	4.53 ± 0.61 a	80.46 ± 33.90 a	15.40 ± 5.04 a	3.37 ± 0.77 a	33.20 ± 20.78 a	5.93 ± 0.61 a	131.93 ± 104.3 a	1.51 ± 0.12 a	0.54 ± 0.11 a	1884.31 ± 397.07 a	58.17 ± 8.74 a	42.20 ± 2.09 ab
L_{14}	3.80 ± 0.51 a	71.20 ± 13.16 ab	3.80 ± 0.34 a	76.06 ± 15.72 a	14.13 ± 2.31 a	4.44 ± 0.95 a	75.80 ± 0.34 a	8.33 ± 3.92 a	246.66 ± 23.8 a	1.65 ± 0.23 a	0.81 ± 0.68 a	1482.88 ± 655.8 a	46.54 ± 13.21 a	47.40 ± 3.33 a
L_{15}	3.50 ± 0.21 a	80.20 ± 9.36 ab	4.22 ± 0.32 a	73.93 ± 16.28 a	15.33 ± 2.71 a	3.21 ± 0.49 a	51.46 ± 1.47 a	4.80 ± 1.05 a	202.26 ± 47.56 a	1.47 ± 0.14 a	0.64 ± 0.53 a	1907.15 ± 682.62 a	54.68 ± 10.91 a	46.53 ± 2.56 ab
L_{16}	3.45 ± 0.89 a	81.33 ± 7.14 a	4.60 ± 0.72 a	89.00 ± 32.00 a	18.53 ± 2.41 a	3.96 ± 0.20 a	45.53 ± 31.13 a	6.60 ± 0.8 a	136.4 ± 90.87 a	1.30 ± 0.10 a	0.49 ± 0.20 a	1215.8 ± 200.91 a	42.17 ± 1.81 a	46.51 ± 0.51 ab
L_{17}	2.73 ± 0.81 a	67.20 ± 5.20 ab	4.40 ± 0.60 a	56.20 ± 12.50 a	14.26 ± 2.05 a	3.01 ± 0.18 a	37.46 ± 23.79 a	8.30 ± 4.94 a	107.73 ± 45.13 a	1.32 ± 0.23 a	0.40 ± 0.17 a	1053.97 ± 49.98 a	36.64 ± 6.28 a	45.02 ± 2.88 ab
L_{18}	2.82 ± 0.31 a	68.73 ± 6.02 ab	4.26 ± 0.61 a	61 ± 29.59 a	14.46 ± 0.94 a	4.06 ± 1.15 a	34.60 ± 13.75 a	8.66 ± 3.72 a	95.66 ± 52.23 a	1.47 ± 0.21 a	0.72 ± 0.39 a	1598.8 ± 1370.63 a	47.41 ± 26.33 a	44.57 ± 2.56 ab
L_{19}	2.63 ± 0.68 a	63.93 ± 2.00 ab	4.40 ± 0.40 a	63.80 ± 16.06 a	14.26 ± 2.02 a	3.63 ± 1.20 a	26.73 ± 3.53 a	6.86 ± 3.28 a	72.66 ± 28.61 a	1.21 ± 0.05 a	0.46 ± 0.17 a	1137.83 ± 245.95 a	42.75 ± 8.32 a	45.62 ± 1.92 ab
L_{20}	2.40 ± 0.62 a	51.33 ± 6.70 b	3.66 ± 0.23 a	44.93 ± 7.07 a	15.26 ± 2.34 a	4.75 ± 0.27 a	28.26 ± 22.59 a	6.2 ± 3.07 a	85.66 ± 74.38 a	1.32 ± 0.13 a	0.41 ± 0.17 a	1619.28 ± 143.3 a	33.45 ± 16.88 a	39.44 ± 2.74 b

Legends: DFN: distance of first node, PH: plant height, NB: number of branches, NF: number of fluorescence, NFF: number of flowers per fluorescence, RL: raceme length, GRP: grain setting racemes, NGR: number of grains per raceme, TGP: total grains per plants, TSW: thousand seed weight, SW/plot: seed weight per plot, LA: leaf area, LL: leaf length, CC: chlorophyll content.

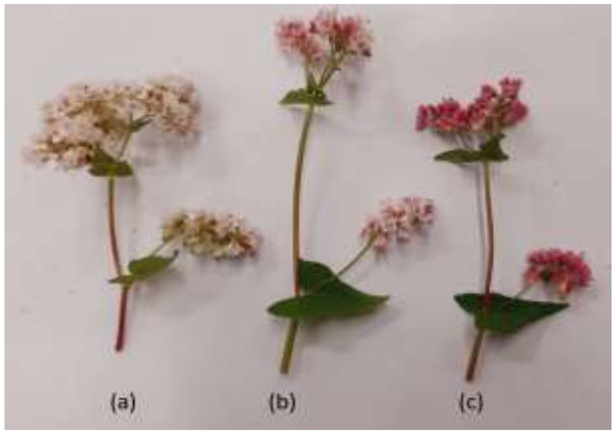


Figure 1. Different colors of buckwheat flower (a) white, (b) mixture of white and pink, and (c) pink.

landraces. L_4 exhibited the highest chlorophyll content (SPAD value 48.566), and L_{20} had the lowest (SPAD value 39.44). This variation could influence the overall photosynthetic efficiency and plant growth and yield. Regarding grain setting, L_{14} and L_{19} showed contrasting results in raceme per plant, with L_{14} having the highest (75.80) and L_{19} the lowest (26.73). The number of grains per raceme was maximum in L_2 (9.73) and minimum in L_8 (3.93) (Grahić *et al*., 2022).

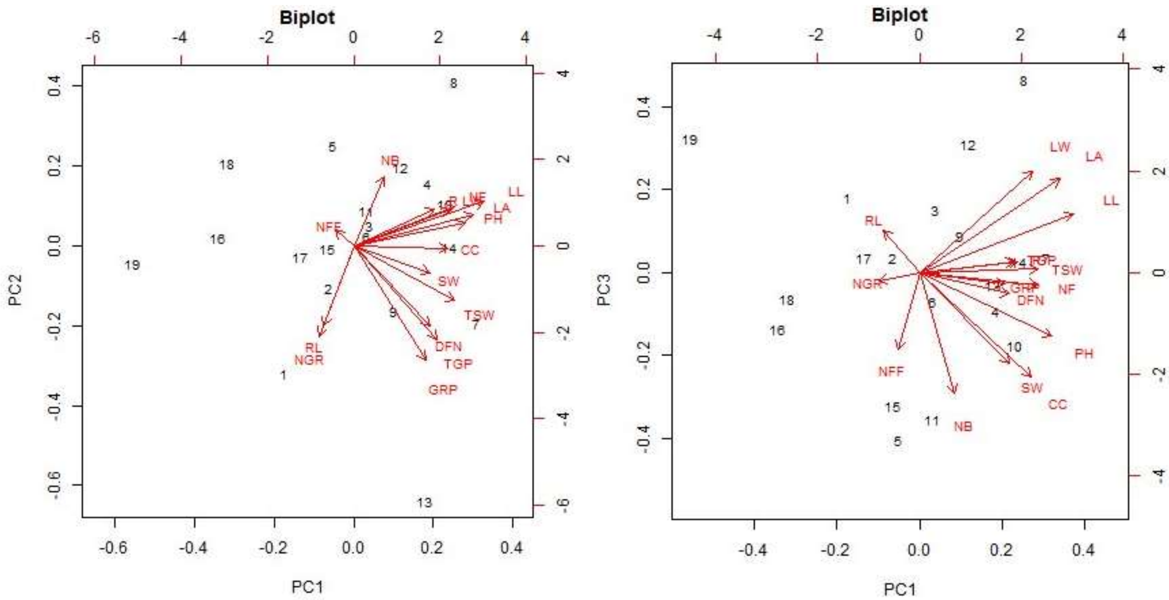
Interestingly, the total number of grains per plant was highest in L_{14} (246.66) and lowest in L_{19} (72.66). 1000-seed weight was higher in L_7 (1.74 g) and minimum in L_{19} (1.21 g). Additionally, the total weight of buckwheat seeds per plot was higher in L_7 (1.05 kg) and lowest in L_8 (0.33 kg) (Grahić *et al*., 2022). The observed morphophysiological variations among the buckwheat landraces highlight these plants' genetic diversity and adaptability. These variations can further influence breeding programs in developing improved buckwheat varieties with desirable traits, such as high yield, stress tolerance, and nutritional quality.

Principal component analysis (PCA)

The Principal Component Analysis (PCA) effectively highlighted the genetic diversity within the buckwheat landraces. A cumulative variance of 7.23%, explained by the first six components, each with an Eigenvalue exceeding one, underscores the significant morphophysiological and yield-related variations among the landraces. Table 3 displays the Principal Component (PC) values and variation percentages for 14 parameters across 19 buckwheat landraces. Consistent with findings by Ding *et al*. (2010), the landraces dispersed widely across different quadrants, emphasizing the importance of the first three principal components in capturing variation patterns among landraces Ding *et al*., 2010 and Joshi *et al*., 2010).

The first three components of the PCA accounted for over 3.5% of the total variation. The first principal component, representing 2.2% of this variation, incurred negative influences from traits like total grains per plant, seed weight, and distance of the first node. In contrast, attributes such as raceme length, plant height, chlorophyll content, and leaf area positively contributed to this component (Figure 2).

The second principal component represented 0.15% of the total variation and sustained positive effects from traits, such as, plant height, leaf area, and chlorophyll content. Conversely, qualities like raceme length, seed weight, and distance of the first node negatively influenced this component. For the third principal component, plant height and seed weight negatively influenced it, while raceme length and leaf area made positive contributions.



(a) **(b)**

Figure 2: Biplot analysis - a) PC1 between PC2 and b) PC1 between PC3

Table 3. Principal component (PC) values and percentage of variation for corresponding 14 parameters in 19 buckwheat landraces.

Parameter	Principle components					
	PC-I	PC-II	PC-III	PC-IV	PC-V	PC-VI
Distance of first node (cm)	0.2235	-0.3278	-0.0812	-0.2707	-0.3079	0.3042
Plant height (cm)	0.3293	0.0938	-0.2425	-0.1433	-0.0732	0.2614
Number of branches	0.0874	0.2841	-0.4604	0.1508	0.1177	-0.1492
Number of fluorescence	0.2952	0.1636	-0.0454	0.3487	0.1561	0.3453
Number of flowers per fluorescence	-0.0546	0.0642	-0.2942	-0.3223	-0.5318	0.2190
Raceme length (cm)	-0.0895	-0.3286	0.1628	-0.0692	0.4495	0.2327
Grain setting raceme per plant	0.2118	-0.4690	-0.0434	0.2913	-0.0478	-0.0803
Number of grains per raceme	-0.1023	-0.3722	-0.0294	-0.3145	0.2523	0.1586
Total number of grains per plant	0.2452	-0.3831	0.0417	0.3118	-0.2105	0.1178
1000 seed weight(gm)	0.2962	-0.2258	0.0132	0.1110	-0.0303	-0.5764
Seed weight/plot (kg)	0.2249	-0.1113	-0.3450	-0.3061	0.1455	-0.4064
Leaf area (mm)	0.3503	0.1299	0.3564	-0.0708	0.0241	-0.0223
Leaf length (mm)	0.3837	0.1521	0.2235	-0.1222	0.0521	0.0335
Chlorophyll content (SPAD value)	0.2767	0.1815	-0.3951	0.2547	0.2286	0.1247
Standard deviation	2.2643	0.1498	1.4853	1.2189	1.1196	1.0017
Proportion of variance	0.3204	-0.0110	0.1379	0.0929	0.0783	0.0627
Cumulative proportion	0.3204	0.4835	0.6214	0.7142	0.7926	0.8553
Eigenvalues	5.1270	2.6086	2.2062	1.4858	1.2534	1.0034

The fourth principal component accounted for 1.21% of the total variation with an Eigenvalue of 1.41, primarily influenced by traits like chlorophyll content and number of fluorescence, followed by grain-setting racemes per plant. The fifth and sixth components represented 1.11% and 1.04% of the variation, with raceme length and chlorophyll content being chief contributors. Together, the six components explained 0.85% of the total variation. Key traits like plant height, the number of grains per plant, and the seed weight were crucial, explaining 40% of this variation in the first two components. These findings support buckwheat germplasm development, aligning with the past study on Japanese common buckwheat (Mikami *et al*., 2018).

Morphophysiological traits assessment by cluster analysis

Agglomerative cluster analysis helped differentiate and categorize genotypes based on their variations in variables, as described by Khodadadi *et al*. (2011). In this research, 19 buckwheat landraces' evaluation and clustering depended on 14 agronomical and morphophysiological traits. The resulting cluster analysis categorized these landraces into three distinct clusters with the corresponding dendrogram illustrated in Figure 3. The mean values for various morphological traits across these clusters are available in Table 4.

Cluster III exhibited the highest mean values for traits, such as distance of the first node, plant height, raceme length, grain setting per raceme, grain-setting racemes per plant, the total number of grains per plant, 1000-seed weight, the grain yield per plot, leaf area, leaf length, and chlorophyll content. Conversely, Cluster II had the highest mean values for the number of branches, fluorescence, and flowers per fluorescence. Landraces in Clusters II and III generally showed higher means than those in Cluster I, suggesting that they could be superior genotypes to those in Cluster I, which had lower means. Interestingly, landraces from the exact geographic locations showed inconsistent groupings in the cluster analysis.

Notably, landraces from the Panchagarh district incurred clustering, indicating high genetic diversity within this group. This finding is consistent with the

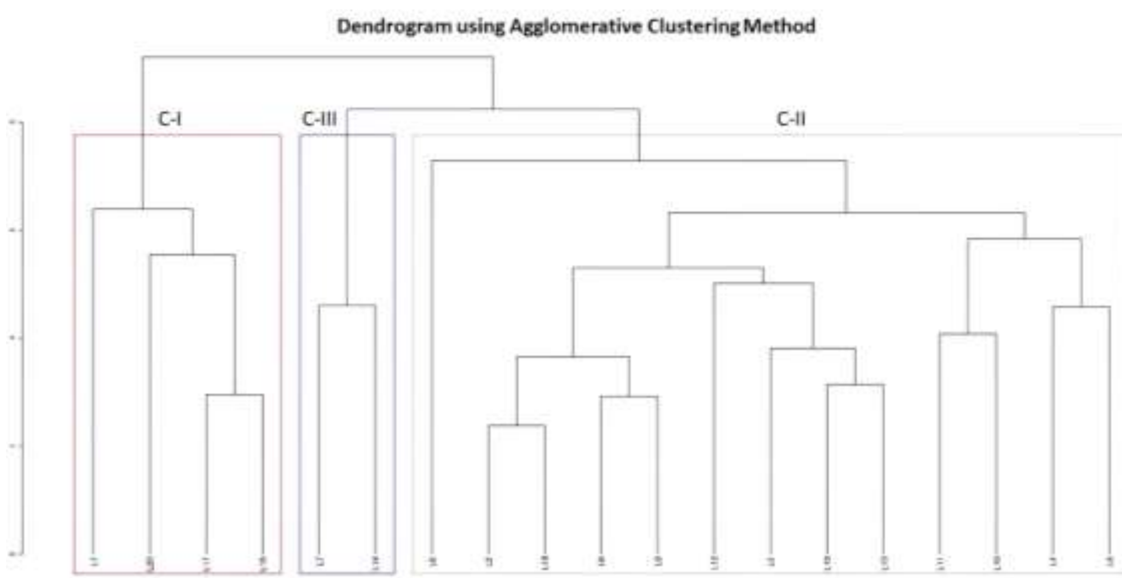


Figure 3. Dendrogram using agglomerative clustering method based on the morpho-physiological and agronomical traits showing different landraces under three clusters. Cluster I (L_1, L_{17}, L_{19}, L_{20}), Cluster II (L_2, L_3, L_4, L_5, L_6, L_8, L_9, L_{10}, L_{11}, L_{12}, L_{15}, L_{16}, L_{18}), and Cluster III (L_7, L_{14}).

Table 4. Cluster means of 14 parameters of buckwheat landraces.

Parameter	Clusters		
	C-I	C-II	C-III
Distance of first node (cm)	2.63	3.02	3.59
Plant height (cm)	59.98	74.48	76.40
Number of branches	4.17	4.60	4.00
Number of fluorescence	63.16	83.63	74.30
Number of flowers per fluorescence	14.15	14.92	13.57
Raceme length (cm)	3.95	3.70	4.19
Grain setting raceme per plant	39.94	44.40	67.63
Number of grains per raceme	7.01	6.23	7.96
Total number of grains per plant	117.17	140.43	190.27
1000 seed weight (gm)	1.32	1.47	1.69
Seed weight/plot (kg)	0.40	0.63	0.94
Leaf area (mm)	1173.19	1679.54	1727.95
Leaf length (mm)	38.03	50.63	51.34
Chlorophyll content (SPAD)	43.71	46.07	46.92

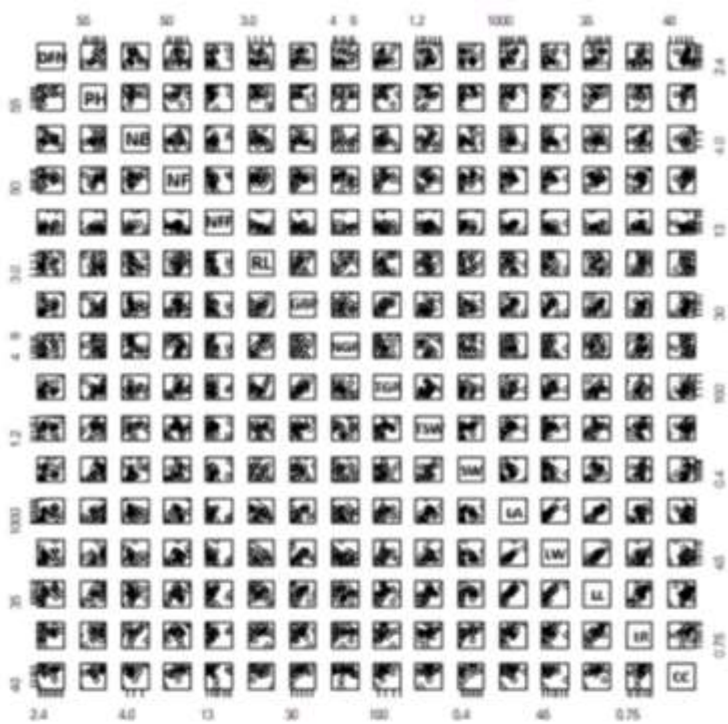


Figure 4. Scatterplot matrix of dendrogram analysis.

observations by Facho *et al*. (2016), who grouped 20 indigenous buckwheat genotypes from Pakistan into two species and three clusters based on morphological characteristics rather than geographical origin. They also found significant variations in most of the traits analyzed. Similarly, Debnath *et al*. (2008) analyzed clustering on 21 buckwheat genotypes and categorized them into five clusters based on morphological and yield-contributing traits. Their findings also supported the notion that landraces from identical locations do not necessarily belong to a single cluster, further emphasizing the importance of considering multiple traits for accurate categorization.

Table 5. Distance matrix of dendrogram analysis.

Lines	L_1	L_2	L_3	L_4	L_5	L_6	L_7	L_8	L_9	L_{10}	L_{11}	L_{12}	L_{14}	L_{15}	L_{16}	L_{17}	L_{18}	L_{19}	L_{20}
L_1	0	5.29	4.50	6.33	6.23	5.26	7.40	7.82	4.71	6.44	6.98	6.72	5.78	6.39	6.18	5.40	5.61	6.11	6.38
L_2	5.29	0	4.55	4.94	5.39	3.33	4.78	6.46	3.06	4.40	5.04	4.63	5.32	4.86	4.45	4.13	2.37	4.26	6.33
L_3	4.50	4.55	0	5.02	4.82	4.41	5.33	5.32	4.35	3.80	4.97	4.36	6.02	3.64	5.70	5.00	4.68	5.46	7.14
L_4	6.33	4.94	5.02	0	4.57	4.00	5.09	5.17	4.30	3.23	5.17	5.94	6.38	5.25	5.84	6.95	5.05	5.86	8.68
L_5	6.23	5.39	4.82	4.57	0	4.16	6.52	7.28	5.42	4.23	4.52	6.31	7.67	5.64	4.99	4.85	4.98	4.81	7.94
L_6	5.26	3.33	4.41	4.00	4.16	0	4.69	5.48	2.91	3.64	4.69	4.67	5.42	3.95	3.60	4.89	3.42	4.30	7.19
L_7	7.40	4.78	5.33	5.09	5.09	4.69	0	6.34	4.21	3.99	5.67	5.56	4.59	4.41	6.72	7.55	4.80	7.45	9.19
L_8	7.82	6.46	5.32	5.17	5.17	5.48	6.34	0	5.42	5.16	7.19	5.13	8.22	5.17	7.19	8.22	6.39	7.01	9.07
L_9	4.71	3.06	4.35	4.30	4.30	2.91	4.21	5.42	0	3.58	5.39	4.73	4.30	3.76	4.42	5.55	3.64	5.52	7.45
L_{10}	6.44	4.40	3.80	3.23	3.23	3.64	3.99	5.16	3.58	0	3.86	5.01	5.63	3.14	4.78	6.11	4.65	5.89	8.83
L_{11}	6.98	5.04	4.97	5.17	5.17	4.69	5.67	7.19	5.39	3.86	0	5.60	6.39	4.86	4.07	5.93	4.66	5.69	7.60
L_{12}	6.72	4.63	4.36	5.94	5.94	4.67	5.56	5.13	4.73	5.01	5.60	0	7.29	4.13	6.06	6.56	5.13	6.47	7.85
L_{14}	5.78	5.32	6.02	6.38	6.38	5.42	4.59	8.22	4.30	5.63	6.39	7.29	0	5.13	6.13	7.48	5.88	7.85	8.90
L_{15}	6.39	4.86	3.64	5.25	5.25	3.95	4.41	5.17	3.76	3.14	4.86	4.13	5.13	0	4.91	6.37	5.29	6.45	8.81
L_{16}	6.18	4.45	5.70	5.84	5.84	3.60	6.72	7.19	4.42	4.78	4.07	6.06	6.13	4.91	0	5.11	4.82	4.85	7.36
L_{17}	5.40	4.13	5.00	6.95	6.95	4.89	7.55	8.22	5.55	6.11	5.93	6.56	7.48	6.37	5.11	0	3.94	2.94	5.54
L_{18}	5.61	2.37	4.68	5.05	5.05	3.42	4.80	6.39	3.64	4.65	4.66	5.13	5.88	5.29	4.82	3.94	0	3.41	5.22
L_{19}	6.11	4.26	5.46	5.86	5.86	4.30	7.45	7.01	7.01	5.89	5.69	6.47	7.85	6.45	4.85	2.94	3.41	0	4.90
L_{20}	6.38	6.33	7.14	8.68	8.68	7.19	9.19	9.07	9.07	8.83	7.60	7.85	8.90	8.81	7.36	5.54	5.22	4.90	0

This study also employed two complementary analytical approaches, the distance matrix of dendrogram analysis and the scatterplot matrix of dendrogram analysis, which comprehensively explored the relationships and patterns within the dataset of buckwheat landraces (Table 5, Figure 4). The distance matrix provided a quantitative measure of the dissimilarities between pairs of data points, serving as the foundation for this study's hierarchical clustering analysis depicted by the dendrogram (Figure 3). This dendrogram visually represented the clustering structure, highlighting the natural groupings or clusters within the data based on the calculated distances of 19 buckwheat landraces. On the other hand, the scatterplot matrix offered a pairwise visualization of the relationships between variables within the dataset of buckwheat landraces (Aubert *et al*., 2021). The analysis revealed significant genetic and morphological diversity among the buckwheat landraces. It emphasizes the importance of comprehensive evaluations when categorizing and selecting genotypes for breeding and germplasm conservation efforts (Woo and Adachi, 1997; Mangkita *et al*., 2005; Shaimerdenova *et al*., 2022).

CONCLUSIONS

In conclusion, prioritizing the analysis of vital morphophysiological and yield-contributing traits, such as those identified in this study, can guide targeted germplasm development and crop improvement strategies for buckwheat. This approach can ultimately contribute to the sustainability and productivity of buckwheat cultivation, benefiting farmers and ensuring food security.

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