Original Research Article

Evaluation of seed diversity ~~morphological characters~~ of landraces and improved varieties of rice through morphological characters using image analyzer

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ABSTRACT

Aims: Rice (*Oryza sativa* L.) serves as a staple food for over half of the global population, with traditional landraces playing a critical role in maintaining genetic diversity and adaptability. This study aimed to evaluate the morphological variation of seeds among 169 rice landraces and 24 improved varieties using Biovisimage analyzer. **Study design**: ?? **Place and Duration of Study**?? **Methodology** ?? Seed traits including length, width, length-to-width ratio, area, and other attributes were measured. **Results:** Analysis of variance (ANOVA) revealed significant variation among the genotypes. The results showed that traits like seed length ranged from 3.43 mm to 10.29 mm, while the length-to-width ratio (L/W) varied significantly, classifying the grains into slender, medium, and bold types. High heritability estimates for traits such as seed length (70.35%) and area (67.93%) suggest that these traits are primarily governed by genetic factors, making them ideal candidates for selection in breeding programs. Additionally, the study found that most landraces exhibited medium grain size (5.51–6.60 mm) and shape (L/W ratio of 2.1–3.0). These findings underscore the importance of rice landraces as reservoirs of genetic diversity, essential for future breeding programs and food security efforts. **Conclusion:** The study provides a foundation for the conservation and utilization of rice landraces in improving agricultural productivity and resilience.

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Keywords: Rice landraces, Genetic diversity, Morphological traits, Image analysis, Grain size, Grain shape

1. INTRODUCTION

Rice (*Oryza sativa* L.) is a one of the major and staple food for over half of the global population. Nearly 90% of the world's rice is cultivated and consumed in Asia, where it serves as the primary food source for 50% of the people (Tenorio *et al*., 2013). As the population grows and food demand rises, breeding efforts are increasingly focused on developing high-yielding rice varieties. Although traditional varieties or landraces, typically produce lower yields, they are considered to be better adapted to local conditions and hold significant symbolic, social, and economic value (Rijal, 2010). Rice landraces serve as reservoirs for genetic potential and numerous resistant genes against both biotic and abiotic stresses, a quality often lacking in modern varieties (Tiwari*et al*., 2018). Landraces exhibit a greater adaptation to

UNDER PEER REVIEW

local conditions, increasing their likelihood of survival and successful reproduction, thereby transmitting their characteristics to subsequent generations (dan Heritabilitas, 2020).

Rice landraces represent a vital gene pool for current and future genetic improvement efforts (Wang and Han, 2022). However, since domestication and through the development of modern cultivars, the genetic diversity of domesticated rice has decreased by approximately 80% compared to its wild progenitors (Allaby*et al*., 2019; Londo *et al*., 2006). If this trend continues, it may deprive mankind of the genetic diversity in rice necessary to address unforeseen challenges such as diseases, pests, agronomic adaptation, and climate change (Raza *et al*., 2019). Traditional farmers around the world prefer landraces for their proven adaptations to local climates and specific traits (Marone *et al*., 2021; Roy *et al*., 2016). Therefore, it is essential to conduct detailed profiling of these landraces, including agro-morphological characterization (Choudhury *et al*., 2013). The genetic diversity within heterogeneous populations provides resilience and adaptive traits to the species (Vanlalsanga and Singh, 2019). Traditional landraces, characterized by distinct morphological traits and locally popular names due to their unique features, represent an intermediate stage between wild ancestors and modern cultivars, acting as reservoirs of valuable genes (Elkelish, 2021).

Over an extensive period of domestication, ancient varieties have evolved under various climatic, management, and cultural influences, leading to the development of genetic resilience to climatic disruptions (Henry, 2014). The intra-varietal variation present within landraces provides genetic plasticity, enabling them to adapt to local field conditions and marginal environments (Kyratzis*et al*., 2019). Multiple studies validate that locally adapted crops and their landraces are time-tested and deeply seated in local livelihood systems, requiring minimal inputs, offering superior nutrition, and demonstrating resilience to prevalent abiotic and biotic stresses, especially in marginal areas (Ramanatha and Hodgkin, 2002). Hence, it is worthwhile to enhance farmers' genetic resources, not just to meet indigenous needs but also to improve traits in other ecosystems. (dan Heritabilitas, 2020). Nevertheless, it's important to note that while all landraces, regardless of their potential usefulness in the future, may be conserved under on-farm conditions by farmers themselves, challenges such as low yields in heterogeneous form, as well as issues concerning seed purity and availability, need to be addressed (Hour *et al*., 2020). Recent reports indicate that both natural evolution and artificial selection can lead to speciation in rice (Mi*et al*., 2020). Traditional landraces have been reshaped through the interplay of adaptation to local environments and the selective practices of farmers, aligning with their agro-ecological and cultural needs and preferences. In contrast, wild rice populations thrive due to their invasive characteristics and their ability to outcompete other species under natural conditions (Thomson *et al*., 2009). The precise interaction between these events and their impact on shaping the population genetics and intra-varietal structure of a landrace over time and space remains unclear (Kyratzis*et al*., 2019; Islam*et al*., 2019). Despite the dynamic nature of landraces genetically, there is a lack of comprehensive reports on the systematic characterization and quantification of intra-varietal diversity in their hotspot areas (Roy *et al*., 2016). Thorough characterization

UNDER PEER REVIEW

and exploration of various traits, as well as the selection of desirable types within landraces, could be crucial for comprehending evolutionary trajectories, discovering traits, and enhancing crop improvement efforts (Li *et al*., 2014).

To harness the potential of landraces in breeding programs, it's essential to comprehend their genetic variability. Analyzing the extent and patterns of genetic divergence in rice genotypes offers insights and understanding into their genetic variability (Bhati*et al*., 2015). Genetic diversity data aids in selecting parents from vast landraces or germplasm collections. Assessing genetic divergence and distance among parent lines helps evaluate potential heterotic combinations before crossbreeding attempts, thus optimizing breeding strategies and conserving time and resources (Acquaah, 2012).Understanding the morphological variation within rice landraces is crucial for their conservation and utilization in breeding programs aimed at enhancing productivity, resilience, and nutritional quality. Morphological traits, especially those linked to seed characteristics, are key indicators of genetic diversity and adaptation to specific environments. Globally, there is a growing demand for rice varieties with superior grain quality, as cooking and eating qualities are crucial for market and consumer acceptance. Rice grain quality is influenced by both physical and physico-chemical properties where, physical appearance is determined by grain shape and size (Dixit *et al*., 2022).

In recent years, advances in technology have facilitated the objective and precise evaluation of morphological traits in rice seeds. Image analyzers offer a non-destructive and efficient method for quantifying various seed characteristics, enabling researchers to explore the intricate morphological diversity present within rice landraces comprehensively. By utilizing image analysis techniques, researchers can accurately measure traits such as seed size, shape, surface texture etc, providing valuable insights into the genetic makeup and potential agronomic traits of different landrace varieties. Moreover, the classification of rice seeds into distinct categories based on their morphological attributes, such as fine, medium, and bold grains, holds significance for both agricultural practices and consumer preferences. Understanding the distribution and frequency of these seed types within rice landraces can inform breeding strategies aimed at developing varieties tailored to specific market demands and culinary preferences. For instance, while some consumers may prefer rice with fine grains for its delicate texture and faster cooking time, others may favor bold grains for their chewier consistency and enhanced visual appeal (Khush, 2005).

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Thus, this study aims to evaluate the morphological characters of rice landrace seeds using an image analyzer, shedding light on the diversity and distribution of seed types within these traditional varieties. By elucidating the morphological variation present in rice landraces and its implications for both agricultural practices and consumer preferences, this finding contributes to the broader goals of genetic conservation, crop improvement, and food security.

2. MATERIAL AND METHODS

UNDER PEER REVIEW

2.1 Details of rice landraces

The material used for the study comprised of 169 landraces collected from different parts of Karnataka and 24 improved varieties. Seedlings were transplanted in College of Agriculture, Mandya. Seeds were harvested and used for further studies.

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2.2 Trait measurements

Seed morphological characters viz., area, length, width, aspect (length to width ratio),diameter, perimeter, density, roundness, compactness and roughness were measured by taking ten seeds as ten replications using Biovis image analyser and some characters were grouped into different categories. Based on seed length (size) they were grouped as extra-long (>7.5 mm), long (6.61–7.5 mm), medium (5.51–6.60 mm), and short (<5.5mm). Grain shape was determined based on the length-width ratio (L/W). Based on the L/W ratio, rice grains were further classified into slender (>3.0), medium (2.1–3.0), bold (1.1–2.0), and round (<1.1) grain types (IRRI 2013).

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Biovis seed image analyzer was used which has an efficient and time-saving image processing program. The analyzer is maintained at the National Seed Project, University of Agricultural Sciences, GKVK, Bangalore.

2.3 Statistical analysis

Analysis of variance (ANOVA) among genotypes and genetic parameters for all the traits was implemented in the package 'variability' in R studio. Besides, Welch's two sample ‘t’ test was conducted in R, to test for differences between landraces and varieties. Violin plots were constructed with "ggplot2" package in R.

2.4 Genetic Variability parameters

Phenotypic and genotypic coefficient of variation (PCV and GCV) were calculated by the formula given by Burton and DeVane (1953).

$$\mathrm{PCV}\ (\%) = \frac{\sqrt{\sigma_p^2}}{\bar{X}} \times 100$$

$$\mathrm{GCV}\ (\%) = \frac{\sqrt{\sigma_g^2}}{\bar{X}} \times 100$$

where, $\bar{X}$ = Grand mean

σ_g^2 = genotypic variance

σ_p^2= phenotypic variance

UNDER PEER REVIEW

Broad sense heritability (H) was estimated using the following formula (Allard, 1960).

$$H= \frac{\sigma_g^2}{\sigma_p^2} \times 100$$

where, σ_g^2= genotypic variance,

σ_p^2 = phenotypic variance

Expected Genetic advance (GA) was calculated by the following formula (Allard, 1960).

$$\mathrm{GA} = k \times h_b^2 \times \sqrt{\sigma_p^2}$$

where, k = selection differential (2.06) at 5% selection intensity

$\sqrt{\sigma_p^2}$ = phenotypic standard deviation

The genetic advance as a percentage of the mean was estimated as:

$$\mathrm{GAM} = \frac{GA}{\bar{\mathrm{X}}} \times 100,$$

Where, GA= genetic advance; $\bar{\mathrm{X}} =$ grand mean

3. RESULTS AND DISCUSSION

3.1 Significant Genetic Diversity in Seed Morphological Traits Among Rice Genotypes Revealed by ANOVA Analysis

The analysis of variance (ANOVA) results for the ten traits i.e., area, length, width, aspect (length/width ratio), diameter, perimeter, density, roundness, compactness and roughness are presented in the T~~t~~able 1. Across the evaluated rice genotypes, a broad range of variation was observed for each trait, highlighting inherent genetic differences among genotypes. Genotypes showed highly significant differences for area (mean sum of squares = 27.90, $p < 0.001$), indicating substantial genetic diversity. Similarly, significant genetic variation was observed for length (3.35, $p < 0.001$) and width (0.70, $p < 0.001$) further underscoring the diversity among genotypes. The aspect ratio also exhibited highly significant genetic differences (1.28, $p < 0.001$), with no notable variation among replicates, emphasizing the genotypic influence on shape characteristics. Significant genotypic effects were also shown by diameter (1.06, $p < 0.001$) and perimeter (16.48, $p < 0.001$) revealing considerable variability across genotypes. Similarly, high levels of genotypic variation were displayed by density (2352.20, $p < 0.001$), roundness (0.035, $p < 0.001$), compactness (29.36, $p < 0.001$), and roughness (0.0009, $p < 0.001$) with replication effects remaining non-significant. The low residual variation across all traits suggests that the model effectively accounted for the observed variability.

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The results reveal considerable genetic diversity among the rice genotypes for all evaluated seed morphological traits. The highly significant differences in area, length, and width ($p < 0.001$) suggest

UNDER PEER REVIEW

substantial genetic variation impacting seed size. This aligns with findings that highlight seed morphology as a heritable trait with potential variability among rice genotypes, which can affect agronomic performance and market preference. The highly significant variation in aspect ratio (length/width) emphasizes genotypic influence on seed shape, a crucial characteristic for consumer preference and post-harvest processing. Similarly, the substantial genotypic effects observed for diameter and perimeter underscore genetic differences in both size and surface characteristics of seeds, which may impact seed packaging and milling yield.

Density and compactness, displaying high genotypic variation, are critical traits tied to grain quality. Genotypic differences in density may reflect variation in grain filling and could relate to nutritional quality, while compactness influences grain hardness, an important trait for rice milling and cooking properties. Roundness and roughness also showed high genotypic variability. Roundness can influence cooking quality and grain appearance, while roughness could relate to husk adhesion or milling efficiency. The non-significant replication effects and low residual variance suggest that the model effectively captured these differences, reinforcing the reliability of these traits for selection in breeding programs. This variability among genotypes offers a valuable basis for selecting traits aligned with specific breeding objectives, such as improving grain quality, marketability, or processing efficiency.

3.2 Comprehensive Statistical Analysis of Trait Variability, Heritability, and Genetic Potential

In plant breeding, a thorough understanding of statistical parameters such as maximum and minimum values, mean, genotypic coefficient of variation (GCV), phenotypic coefficient of variation (PCV), broad-sense heritability, genetic advance, and genetic advance as a percentage of the mean (GAM) is essential for the effective selection of superior genotypes and the enhancement of desired traits. The Table 2 presents data on these parameters for area, length, width, aspect (length/width ratio), diameter, perimeter, density, roundness, compactness and roughness providing valuable insights into the variability, heritability, and potential genetic progress for each trait under consideration.

UNDER PEER REVIEW

Table 1. Analysis of variance for seed morphological traits of rice landraces and improved varieties

		Mean sum of square									
Source of variation	**Degrees of freedom**	**Area (sq mm)**	**Length (mm)**	**Width (mm)**	**Aspect (Length/Width)**	**Diameter(mm)**	**Perimeter (mm)**	**Density (gray)**	**Roundness**	**Compactness**	**Roughness**
Replication	9	5.62 ***	0.33 *	0.20 ***	0.06	0.12 *	2.70 ***	106.99	0.003	1.84	0.0003
Genotype	192	27.90 ***	3.35 ***	0.70***	1.28 ***	1.06 ***	16.48***	2352.20 ***	0.035 ***	29.36***	0.0009***
Residuals	1728	1.26	0.14	0.05	0.08	0.06	0.69	144.52	0.002	1.65	0.0002

*** Significant at P=0.001; ** Significant at P=0.01, *Significant at P=0.05

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UNDER PEER REVIEW

Table 2. Descriptive statistics and genetic variability parameters for seed morphology traits of rice landraces and improved varieties

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	Area (sq mm)	Length (mm)	Width (mm)	Aspect (Length/ width ratio)	Diameter (mm)	Perimeter (mm)	Density (gray)	Roundness	Compactness	Roughness
Maximum	23.18	10.29	5.29	5.61	5.34	29.64	181.99	0.93	37.90	1.57
Minimum	4.62	3.43	1.32	1.32	2.29	8.12	52.57	0.33	13.49	1.02
Grand Mean	11.28	5.92	2.42	2.49	3.83	14.13	123.62	0.71	17.89	1.04
Genotypic Coefficient of Variance	14.47	9.58	10.56	13.93	8.25	8.89	12.02	8.08	9.31	0.96
Phenotypic Coefficient of Variance	17.56	11.42	14.16	17.79	10.29	10.66	15.46	10.34	11.76	1.66
Heritability (Broad Sense)	0.68	0.70	0.56	0.61	0.64	0.70	0.60	0.61	0.63	0.33
Genetic Advance	2.77	0.98	0.39	0.56	0.52	2.16	23.79	0.09	2.71	0.01
Genetic Advance as percentage of mean	24.57	16.55	16.21	22.47	13.64	15.29	19.25	13.02	15.18	1.14

UNDER PEER REVIEW

3.2.1 Mean performance

The grand mean reflects the overall average performance of all genotypes for a specific trait. The area ranged from a minimum of 4.62 sq mm to a maximum of 23.18 sq mm, with an average of 11.27 sq mm (Table 2). Similar studies for mean was done by Anuradha *et al*. (2012). The length varied between 3.43 mm and 10.29 mm, with a mean length of 5.92 mm. The width spanned from 1.32 mm to 5.28 mm, averaging 2.42 mm. The aspect (length/width ratio) had a minimum of 1.31 and a maximum of 5.60 with a mean of 2.49. Similar studies were done by Varnamkhasti *et al*. (2008), Lahkar and Tanti (2017), Panda *et al*. (2024), Sinha *et al*. (2015), Saha *et al*. (2022), Roy *et al*. (2016), Bhargavi *et al*. (2021), Touthang *et al*. (2023), Adhikari *et al*. (2018), Duraiswamy *et al*. (2023), Dey *et al*. (2019).

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The diameter ranged from 2.29 mm to 5.34 mm, with an average diameter of 3.83 mm. Similar study was conducted by Varnamkhasti *et al*. (2008). The perimeter measurements varied from 8.11 mm to 29.63 mm, with a mean of 14.12 mm. Density values ranged from a minimum of 52.56 gray to a maximum of 181.99 gray, with an average of 123.61 gray. The roundness varied between 0.33 and 0.93, with an average of 0.71. Compactness ranged from 13.49 to 37.89, with a mean of 17.88. Roughness ranged from 1.01 to 1.57, with an average of 1.04. Similar findings were reported by Anuradha *et al*. (2012).

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3.2.2 Genotypic and phenotypic coefficients of variation

The genotypic coefficient of variation (GCV) measures the proportion of genetic variation for a trait relative to the mean, expressed as a percentage. A high GCV indicates substantial genetic variability, enhancing the potential for trait improvement through selection, as it focuses specifically on the genetic component of total variance. Likewise, the phenotypic coefficient of variation (PCV) captures the overall variation for a trait, including both genetic and environmental influences. When the PCV is notably higher than the GCV, it indicates strong environmental impact on the trait, making selection more challenging. The results revealed that the Genotypic Coefficient of Variation (GCV) was slightly lower than the Phenotypic Coefficient of Variation (PCV) for each trait analyzed, indicating that environmental factors had minimal influence on phenotypic expression (Table 2). This suggests that selecting based on phenotype could be an effective strategy for improving these traits.

Moderate GCV values were observed for area (14.47%), width (10.55%), aspect (length/width ratio) (13.92%), and density (12.01%). Lower GCV values were recorded for traits such as length (9.58%), average diameter (8.25%), perimeter (8.89%), roundness (8.08%), compactness (9.30%), and roughness (0.95%). For PCV, moderate values were found for area (17.55%), length (11.42%), width (14.16%), aspect (17.78%), average diameter (10.28%), perimeter (10.65%), density (15.40%), roundness (10.34%), and compactness (11.75%). The lowest PCV value was recorded for roughness at 1.65%. Genetic variability for GCV and PCV for length, width, and aspect (length/width ratio) were also

UNDER PEER REVIEW

assessed by Phukon*et al*. (2019), Bhargavi et al. (2021), Touthang *et al*. (2023), Duraiswamy *et al*. (2023), Dey *et al*. (2019).

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The study's results on genotypic coefficient of variation (GCV) and phenotypic coefficient of variation (PCV) provide valuable insights into the genetic variability of seed morphological traits in rice. Across all traits analyzed, GCV values were slightly lower than the corresponding PCV values, indicating that environmental influence on phenotypic expression was minimal. This minimal environmental impact suggests that selecting phenotypically superior genotypes could be effective in improving these traits, as the observed variability largely reflects genetic differences rather than environmental factors.

The moderate GCV values observed for area (14.47%), width (10.55%), aspect (length/width ratio) (13.92%), and density (12.01%) indicate a reasonable level of genetic variability, which is promising for selection efforts aimed at these traits. The relatively higher genetic variation for area and aspect ratio suggests these traits could respond well to selection, facilitating genetic improvements. Traits such as width and density, although showing moderate genetic variation, still exhibit enough variability to warrant consideration in breeding programs.In contrast, lower GCV values were recorded for length (9.58%), average diameter (8.25%), perimeter (8.89%), roundness (8.08%), compactness (9.30%), and particularly roughness (0.95%). These lower GCV values imply limited genetic variability for these traits, meaning that achieving substantial gains through selection may be more challenging. For instance, roughness, with a very low GCV, appears to be a trait with limited genetic variation and, therefore, a low potential for improvement through selection based solely on phenotypic expression.

For PCV, moderate values for area (17.55%), length (11.42%), width (14.16%), aspect (17.78%), average diameter (10.28%), perimeter (10.65%), density (15.40%), roundness (10.34%), and compactness (11.75%) align closely with their respective GCV values, reinforcing that environmental effects on these traits are not substantial. The lowest PCV value observed for roughness (1.65%) further supports the finding that roughness has low phenotypic variability, largely consistent with its minimal genetic variation.

In summary, these results highlight the potential for effective selection in traits with moderate GCV values, particularly area and aspect ratio, while traits with lower GCV values may require alternative strategies or be of lower priority in breeding programs. The alignment between GCV and PCV values further confirms the stability of these traits, supporting phenotype-based selection as a practical approach for rice improvement in these seed morphological traits.

3.2.3 Heritability and genetic advance over percent mean

Heritability estimates serve as predictive tools, indicating the reliability of phenotypic values for trait selection. High heritability is particularly beneficial for efficient selection of traits. According to Johnson *et al.* (1955), heritability is categorized as low (below 30%), medium (30-60%), and high (above 60%). In this study, the traits exhibited moderate to high heritability, ranging from 33.33% to 70.35%

UNDER PEER REVIEW

(Table 2). High heritability was observed for traits like length (70.35%), perimeter (69.63%), area (67.93%), diameter (64.33%), compactness (62.65%), aspect (61.31%), roundness (61.11%), and density (60.44%). Moderate heritability was found for width (55.57%) and roughness (33.33%).

Genetic advance is an important measure for predicting the expected improvement from selection within a population. When combined with heritability, it provides a more accurate indicator of selection potential (Johnson et al., 1955). The highest genetic advance as a percentage of the mean was observed for area (24.56%), followed by aspect (22.46%). Moderate genetic advance values were recorded for length (16.55%), width (16.21%), average diameter (13.63%), perimeter (15.28%), diameter (19.24%), roundness (13.01%), and compactness (15.17%). Roughness showed the lowest genetic advance at 1.13%. Similar studies regarding heritability and genetic advance as a percentage of the mean for length, width, and aspect (length/width ratio) were done by Phukon *et al*. (2019), Bhargavi *et al*. (2021), Touthang *et al*. (2023), Duraiswamy *et al*. (2023), Dey *et al*. (2019).

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All these traits except roughness having higher or moderate heritability accompanied with higher or moderate GAM indicated presence of additive gene action and their selection will be highly beneficial. High heritability with low genetic advance was observed for roughness. It suggested non-additive gene action for the expressions of this character. The high heritability was exhibited due to favorable influence of environment rather than genotype and selection for such traits might not be rewarding.

3.3 Comparison between landraces and improved varieties

Comparing seed morphological traits between landraces and improved varieties is essential for identifying genetic diversity and understanding trait stability in rice breeding. Landraces, with their unique adaptation to local conditions, often exhibit considerable genetic variation, particularly in traits like area, length, width, and aspect ratio, which influence yield and market preferences. In contrast, improved varieties are selectively bred for specific traits, typically showing optimized performance in traits such as density, compactness, and roundness. By analyzing these traits across both groups, breeders can identify valuable genetic resources within landraces that may enhance or stabilize traits in improved varieties, particularly in challenging environments or for specialty markets. Additionally, understanding differences in traits like perimeter, diameter, and roughness can inform post-harvest processing and quality assessment, guiding breeding efforts toward varieties that meet both agronomic and consumer demands. This comparison ultimately supports a more resilient and diversified breeding pipeline, preserving beneficial landrace traits while advancing crop improvement goals. From all 10 traits, 8 traits were significant ($p < 0.05$) indicating substantial significant difference between rice landraces and improved varieties (Table 3).

Table 3.T test results for comparison between rice landraces and improved varieties

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	Area (sq mm)	Length (mm)	Width (mm)	Aspect (length/	Diameter (mm)	Perimeter (mm)	Density (gray)	Roundness	Compactness	Roughness

UNDER PEER REVIEW

				width)						
P-Value	1.26×10^{-14}	0.5385	$<2.2 \times 10^{-16}$	1.90×10^{-15}	1.47×10^{-5}	0.003848	$<2.2 \times 10^{-16}$	5.94×10^{-15}	3.98×10^{-13}	0.6495

The violin plots in figure 1 illustrates the distribution and variability of these traits between rice landraces and improved varieties. Overall, the plots reveal distinct patterns in several traits, highlighting substantial morphological differences between these two groups. For traits like area, length, and aspect ratio, landraces demonstrate a broader distribution, suggesting a high degree of genetic diversity. This variation in landraces could be due to their adaptation to diverse environmental conditions, which has led to a broader genetic base. In contrast, improved varieties show more consistent distributions for traits like density, roundness, and compactness, indicating selective breeding's role in stabilizing these attributes for uniformity in commercial production. Notably, traits such as perimeter, diameter, and roughness also exhibit distinct patterns, with improved varieties tending towards narrower distributions and more optimized values.These highlights breeding efforts focused on traits advantageous for processing and market preferences. With eight out of ten traits showing statistically significant differences ($p < 0.05$), these results underscore the importance of landraces as a valuable genetic reservoir for breeding programs. Incorporating these diverse traits from landraces can contribute to the development of rice varieties that are both resilient and tailored to meet specific agronomic and consumer demands.

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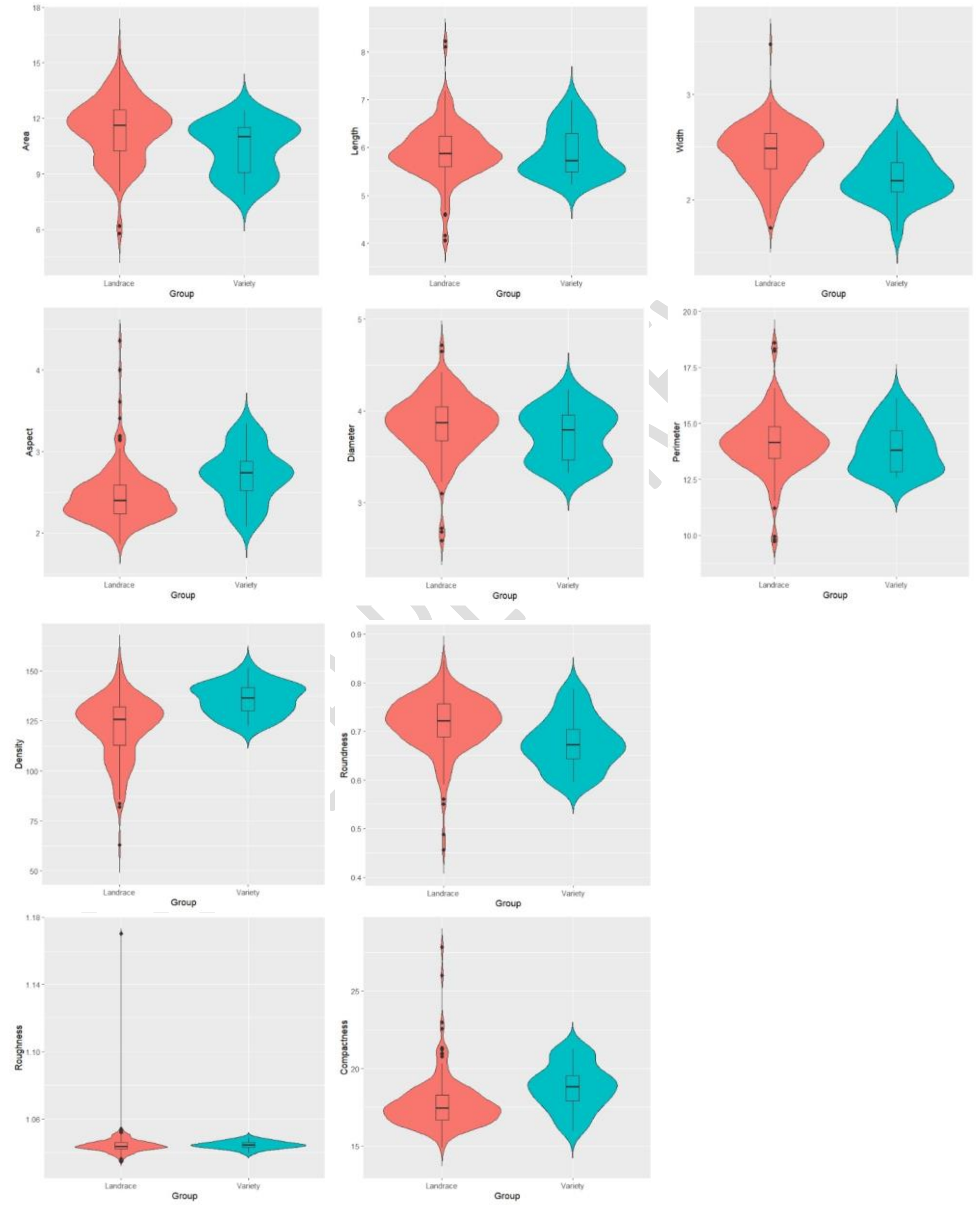
UNDER PEER REVIEW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Density
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Roughness
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Figure 1. Violin plots depicting variation in different traits in rice landraces and improved varieties.

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3.4 Grain dimensions

3.4.1 Grain size

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Based on grain length, ~~2~~ two landraces, but none of the improved varieties, were classified as extra-long (>7.5 mm)~~.~~ and ~~10~~ ten landraces and ~~3~~ three improved varieties fell into the long category (6.6–7.5 mm) (Table 2). A majority of 129 landraces and 14 improved varieties were categorized as medium (5.51–6.6 mm), while 28 landraces and ~~7~~ seven improved varieties were classified as short (≤5.5 mm), as shown in Table 4. The findings highlight distinct trends in grain length across rice landraces and improved varieties, reflecting the different selective pressures and breeding objectives shaping these groups. The presence of only two landraces with extra-long grains and the absence of any improved varieties in this category suggest unique genetic traits retained in traditional varieties. This indicates that certain landraces were potentially preserved in regions where longer grains were preferred culturally or economically. Improved varieties, on the other hand, might emphasize traits like yield and adaptability over grain elongation, as extreme lengths may not align with broader breeding goals.

The predominance of medium-grain rice in both landraces and improved varieties, with 129 landraces and 14 improved varieties in this category, suggests that medium length may represent a stable, adaptable trait. The distribution across categories, from long to short grains, illustrates a balance between traditional diversity and breeding interventions to meet specific consumer preferences or functional needs. Shorter grains in some varieties could also reflect adaptation to specific environmental conditions or culinary uses, such as traditional dishes that favor compact grains. Together, these patterns show how both genetic diversity and human selection shape grain length in rice, with implications for market demands, cooking properties, and environmental adaptability.

Table 4. Classification of rice landraces and improved varieties based on grain size (length)

Grain size				
Scale	**Size category/length**	**Value(mm)**	**Landraces**	**Improved varieties**
1	Extra long	>7.5	2	0
3	Long	6.6-7.5	10	3
5	Medium	5.51-6.6	129	14
7	Short	≤5.5	28	7
		Total	169	24

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3.4.2 Grain shape

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The length-to-width ratio of rice grains was used to determine their shape, showing significant variation across the different varieties (Table 5). Based on the IRRI classification of grain shape, the study found that ~~9~~ nine landraces and ~~4~~ four improved varieties were slender (> 3.0), 147 landraces and 19 improved varieties were classified as medium (2.1-3.0), 13 landraces and ~~1~~ one improved variety were bold (1.1-2.0), while none were identified as round. The findings on rice grain shape, classified using the length-to-width ratio, underscore distinct patterns between landraces and improved varieties, reflecting varying breeding focuses and natural selection effects. The identification of nine landraces and four improved varieties as slender suggests that while elongated shapes exist across both groups, improved varieties may prioritize other agronomic traits over achieving slender profiles. This shape might be favored in traditional contexts, where longer, slender grains are culturally valued, indicating that natural diversity within landraces retains this desirable trait.

With the majority of both landraces and improved varieties classified as medium shape (147 landraces and 19 improved varieties), medium grain shapes appear to offer a balanced trait favored in both natural and selective breeding processes. Bold grains, found in 13 landraces and one improved variety, further illustrate that bolder shapes are rare and may serve niche applications or specific culinary uses. The absence of round grains across all genotypes suggests limited preference or suitability for extremely compact grains in both traditional and modern breeding contexts, likely due to consumer preferences and market demands that align better with medium and slender profiles. Overall, these findings reveal how grain shape diversity has been preserved in landraces and strategically selected in improved varieties to meet practical, cultural, and market expectations.

Table 5. Classification of rice landraces and improved varieties based on grain shape (length/width ratio)

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Grain shape				
Scale	**Shape category**	**Value(mm)/ratio**	**Landraces**	**Improved varieties**
1	Slender	>3.0	9	4
3	Medium	2.1 to 3.0	147	19
5	Bold	1.1 to 2.0	13	1
9	Round	<1.1	0	0
		Total	169	24

Similar studies related to grain size and shape were conducted by Dixit *et al*. (2022), Muhammad *et al*. (2024), Venkatesan *et al.* (2023), Sinha *et al*. (2015),Umarani *et al*. (2017), Surje *et al*. (2018), Rawte and Saxena (2018), Tran *et al*. (2021), Dewan and Sangeeta (2018).Pokhrel *et al.* (2020) found that grain shape and size significantly impact rice cooking quality, and similar results were observed in their study of Nepalese landraces.

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4. CONCLUSION

Seed features in rice are crucial for enhancing productivity, quality, and adaptability. Traits such as seed size, shape, and weight directly impact yield by promoting higher germination rates and robust early growth, which can ultimately increase crop output. Physical characteristics, including grain size, length-to-width ratio, and texture, are essential quality indicators, influencing consumer preferences and market value due to their effects on cooking and eating qualities. So, our study sheds light on the significant morphological diversity present among rice landraces in comparison to improved varieties. The results reveal the genetic variability among landraces, underscoring their potential as valuable genetic reservoirs for future breeding efforts.

The analysis of variance (ANOVA) confirmed highly significant differences across all measured traits, suggesting that the inherent genetic diversity within these landraces can be utilized to develop new varieties better suited to various environmental conditions. Traits like grain area, length, width, and aspect demonstrated moderate to high heritability and genetic advance, indicating that selection based on these phenotypic traits could be highly effective for crop improvement programs. When comparing landraces and improved varieties, a clear distinction was noted. Although improved varieties often offer higher yields, landraces demonstrate a broader range of seed sizes and shapes, with two landraces classified as extra-long and a large proportion falling into the medium size category. The classification based on grain shape also revealed that most landraces exhibit a medium grain shape, which is valuable for breeding programs aiming to meet diverse consumer preferences.

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Overall, this study highlights the importance of conserving rice landraces due to their genetic diversity and potential to contribute to breeding programs focused on enhancing resilience, nutritional quality, and productivity. By preserving these landraces and incorporating them into modern breeding strategies, researchers and farmers can better address future agricultural challenges, including climate change, disease resistance, and food security.

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