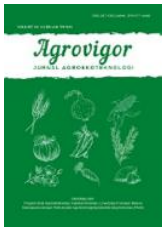
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Article

Seed Morphological Traits and Early Imbibition Dynamics of Three Local Madura Sorghum Accessions

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ABSTRACT

Sorghum is a cereal crop that is tolerant to dry conditions, making it potentially suitable for cultivation in drylands in Madura. This study aimed to describe seed morphological characteristics and early imbibition dynamics, and to evaluate the relationship between these two characteristics in three local Madura sorghums. The observed seed morphological characteristics included color, length, width, and thousand-seed weight, while the percentage of water absorption determined imbibition dynamics during the first 1–4 hours. The data were analyzed descriptively, followed by Pearson's correlation analysis and principal component analysis (PCA). Descriptive analysis revealed variation in seed morphological traits and early imbibition patterns among the three local Madura sorghum accessions. SPG2 showed a rapid early imbibition pattern, SPG1 exhibited a gradual increase in water uptake, whereas BKL displayed slow initial imbibition followed by a steady increase throughout the observation period. Positive correlations were observed among seed morphological traits, whereas negative correlations were found between seed morphological traits and early imbibition during the first three hours (IMB1–IMB3). PCA analysis showed that imbibition dynamics and thousand-seed weight were the traits that contributed the most to data diversity (PC1 = 71.4%). The results of this study provide basic information for characterizing local Madura sorghum germplasm.

INTRODUCTION

Sorghum (*Sorghum bicolor* [L.] Moench) is a cereal crop with high drought tolerance. It is considered suitable for cultivation in dry and semi-arid lands (Wang *et al*., 2025; Said *et al*., 2024). This potential is increasingly important considering that drought is one of the main abiotic stresses that impacts agricultural productivity, ecosystem stability, and global food security (Zhang *et al*., 2024). Compared with several other cereal crops, such as corn, sorghum has a better adaptation mechanism to water limitations, allowing it to maintain growth and productivity under stress conditions (Frantová *et al*., 2024). This condition makes sorghum a prospective commodity to support sustainable agricultural systems, especially in areas with low rainfall. In Indonesia, Madura Island is one of the areas dominated by dry land with limited water availability, so the use of local sorghum accessions has great potential as a genetic resource that supports the development of adaptive cultivation and regional food security.

Imbibition is the initial stage of germination that plays a crucial role in reactivating seed metabolism after dormancy. During imbibition, dry seeds rapidly absorb water, rehydrating cells and restoring membrane integrity disrupted during seed desiccation. This process reactivates cellular metabolism, initiates the activity of hydrolytic enzymes, and enables the mobilization of stored reserves to support embryo growth and subsequent radicle emergence (Nogoki, 2019). The success of the imbibition process is greatly influenced by the seed's ability to absorb water in the initial phase. Conversely, limited water availability can inhibit the imbibition process, reduce the activity of hydrolytic enzymes, such as α-amylase, and limit the utilization of seed nutrient reserves (Saha *et al*., 2022). These conditions result in decreased germination capacity, stunted early seedling growth, and increased sorghum seed mortality under drought stress conditions (Tounekti *et al*., 2020; Bobade *et al*., 2019).

Seed morphological characteristics play an important role in determining early imbibition dynamics during seed germination. Seed characteristics such as size, weight, shape, and seed coat properties can influence the rate and pattern of water uptake during imbibition by affecting the contact area between the seed and water as well as the permeability of the seed coat (Queiroz *et al*., 2019). Differences in these morphological characteristics cause each seed to have a different capacity and pattern of water uptake during the imbibition process. Variations in the rate of imbibition subsequently affect the rate of tissue rehydration, reactivation of seed metabolism, and the initiation of the germination process (Khokhar *et al*., 2025). Seed morphological characteristics are not only important as phenotypic characteristics of a genotype, but are also related to the initial response of the seed during germination. Understanding the relationship between seed morphological characteristics and early imbibition dynamics is important to explain variations in water absorption patterns between accessions and provide basic information for characterizing local sorghum germplasm (Yang *et al*., 2016).

Information on seed morphological traits, early imbibition dynamics, and their relationship in local Madura sorghum accessions remains limited, restricting a comprehensive understanding of seed characteristics among local accessions. This study is a preliminary study that describes seed morphological characteristics and initial imbibition dynamics in three local Madura sorghum accessions and evaluates the relationship between these two traits. The results of this study are expected to provide baseline data on variations in seed morphological characteristics, early imbibition patterns, and their relationship as part of the characterization of local Madura sorghum germplasm.

MATERIALS AND METHODS

The research was conducted at the Agroecotechnology Laboratory, Universitas Trunodjoyo Madura. The genetic material used was local Madura sorghum seeds consisting of three accessions: SPG1 (Sampang 1), SPG2 (Sampang 2), and BKL (Bangkalan). These accessions were obtained from local Madura germplasm collections. This study used a descriptive approach to examine seed morphological characteristics and early imbibition dynamics in three local Madura sorghum accessions. This approach aims to provide an overview of the variation in seed morphological characteristics, water absorption patterns during the early imbibition phase, and the relationship between the two characters. Each parameter was observed in three replications. Seed morphological traits included thousand-seed weight (TSW), seed length (SL), seed width (SW), seed thickness (ST), seed shape, and seed coat color.

Thousand-seed weight (TSW) was determined using an analytical balance with a precision of 0.01 g. Seed length (SL), seed width (SW), and seed thickness (ST) were measured using a digital caliper with a precision of 0.01 mm. Seed shape and seed coat color were recorded descriptively as qualitative supporting data.

Early imbibition dynamics were evaluated using 25 seeds per replicate. To obtain imbibition measurements at 1, 2, 3, and 4 h in a single sampling event, the seeds were immersed in distilled water at staggered starting times and removed simultaneously. After removal, the seeds were gently blotted with filter paper to remove excess surface water and immediately weighed to determine the fresh weight (Wt) at each observation time. The imbibition percentage (IMBt) was calculated as the increase in seed weight relative to the initial dry weight (W0) using the following equation:

$$\mathrm{IMB}_t(\%) = \frac{W_t - W_0}{W_0} \times 100$$

where:

- W_t= seed weight after th of soaking;
- W_0= initial seed weight before soaking.

The collected data were analyzed using descriptive, Pearson correlation, and principal component analyses (PCA). Descriptive analysis was performed to summarize the variation in seed morphological traits and imbibition percentages at 1, 2, 3, and 4 h (IMB1, IMB2, IMB3, and IMB4). Pearson correlation analysis was conducted to examine the relationships among the measured variables. Principal component analysis (PCA) was used to identify the major sources of variation and to visualize the multivariate relationships among seed morphological traits and imbibition characteristics.

RESULTS AND DISCUSSION

Morphological characteristics of local Madura sorghum seed accessions

Seed morphological characterization was conducted to describe the variation in seed size, shape, and weight among three local Madura sorghum accessions. The observed parameters included thousand-seed weight (TSW), seed length (SL), seed width (SW), and seed thickness (ST), together with seed shape and seed coat color. These morphological traits provide baseline information for characterizing local Madura sorghum germplasm and serve as the basis for evaluating their relationship with early imbibition dynamics. The descriptive results of the seed morphological characterization are presented in Tabel 1.

Table 1. Seed morphological traits of three local Madura sorghum accessions

Accession	Thousand seed weight (mm)	Seed length (mm)	Seed width (mm)	Seed thickness (mm)
SPG1	31.60	3.90	3.73	2.87
SPG2	19.30	4.00	2.83	2.30
BKL	30.20	4.00	3.60	2.65

SPG1: Sampang 1; SPG2: Sampang 2; BKL: Bangkalan.

Descriptive analysis showed variations in morphological characteristics in three local Madura sorghum accessions (Table 1). Accession SPG1 had the highest thousand-seed weight (TSW), followed by BKL and SPG2. This result suggests that SPG1 and BKL tended to produce heavier seeds than SPG2. In terms of seed dimensions, SPG2 and BKL have relatively longer seed lengths, while SPG1 has the largest seed width and thickness, resulting in a rounder seed shape. Conversely, SPG2 exhibited smaller seed width and thickness, resulting in a more elongated seed shape, whereas BKL showed a more balanced proportion of seed length and width. These variations in seed morphological characteristics may influence the dynamics of water uptake during the early imbibition phase because seed size and shape play important roles in determining the rate of water entry into seed tissues (Bose *et al*., 2018).



Fig. 1. Seed morphology of local Madura sorghum accessions. SPG1: Sampang 1; SPG2: Sampang 2; BKL: Bangkalan. Numbers (0–4) indicate seed soaking duration (h).

Overall, seed morphological characteristics showed variation among local Madura sorghum accessions, particularly in seed size, shape, and dimensional proportions. Accession SPG1 exhibited relatively large seeds with higher weight, a tendency toward a rounder shape, and greater seed width and thickness. Accession SPG2 had relatively smaller seeds with a slightly oval to oblong shape, whereas accession BKL exhibited medium-sized seeds with a more balanced proportion between seed length and width. These variations in seed morphological traits represent phenotypic variation among accessions and provide baseline information for characterizing local Madura sorghum germplasm. Differences in seed size and shape may also be associated with variations in water imbibition dynamics during the early stages of germination, as seed physical characteristics can influence the process of water entry into seed tissues (Paiva *et al*., 2022; Telodo *et al*., 2020).

Based on visual observations of seed color (Figure 1), the three local Madura sorghum accessions exhibited variation in seed color characteristics. SPG1 seeds showed a brownish-white color with a smooth and glossy surface. SPG2 exhibited a darker reddish-brown color with a slightly dull surface, whereas BKL showed a pale yellowish-brown color with a slightly rougher surface compared with SPG1. These variations in seed color represent differences in external morphological characteristics among the accessions. Seed color variation in sorghum is known to be associated with the presence of pigments in the pericarp layer, including phenolic compounds, which are generally higher in sorghum with darker-colored seeds (Lin *et al*., 2021).

Early Seed Imbibition Dynamics of Three Local Madura Sorghum Accessions

Early seed imbibition was evaluated to describe water uptake dynamics during the initial stage of germination in three local Madura sorghum accessions. The observed parameter was the imbibition percentage (IMB), calculated as the percentage increase in seed weight after 1, 2, 3, and 4 h of soaking, designated as IMB1, IMB2, IMB3, and IMB4, respectively. These measurements describe the pattern and rate of water uptake during the early imbibition phase. The descriptive results are presented in Figure 2.

The imbibition process exhibited distinct water uptake patterns among the three local Madura sorghum accessions (Figure 2). During the first hour of soaking, accession SPG2 showed the highest imbibition percentage, followed by SPG1, whereas BKL exhibited the lowest value. After 2 h of soaking, SPG2 continued to display rapid water uptake, while SPG1 showed a more gradual increase. In contrast, BKL exhibited relatively slow initial water uptake but showed a more pronounced increase after the second hour of soaking.

At 3 h of soaking, the increase in imbibition percentage slowed in all three accessions, suggesting that the initial rapid phase of water uptake had begun to level off. SPG2 maintained the highest imbibition percentage, followed by BKL and SPG1. After 4 h of soaking, BKL exhibited the highest imbibition percentage, whereas the values for SPG1 and SPG2 were lower than those observed during the earlier soaking periods. These results indicate distinct early imbibition patterns among the three local Madura sorghum accessions. SPG2 exhibited rapid water uptake during the initial soaking period, BKL showed a slower but more sustained increase in water uptake throughout the observation period, whereas SPG1

displayed a more gradual pattern with a lower increase during the later stages of imbibition.

Differences in early imbibition dynamics are mainly explained by variation in seed physical characteristics, especially seed size, shape, and seed coat properties, which affect how quickly water enters the seed tissues (Asropi *et al*., 2022). Previous studies have also shown that changes in seed moisture content and hardness during soaking are closely related to these physical characteristics, because differences in seed structure and surface properties influence water uptake (Asropi *et al*., 2022). Therefore, the distinct imbibition patterns observed among the three accessions indicate differences in seed characteristics and provide useful information for the characterization of local Madura sorghum germplasm.

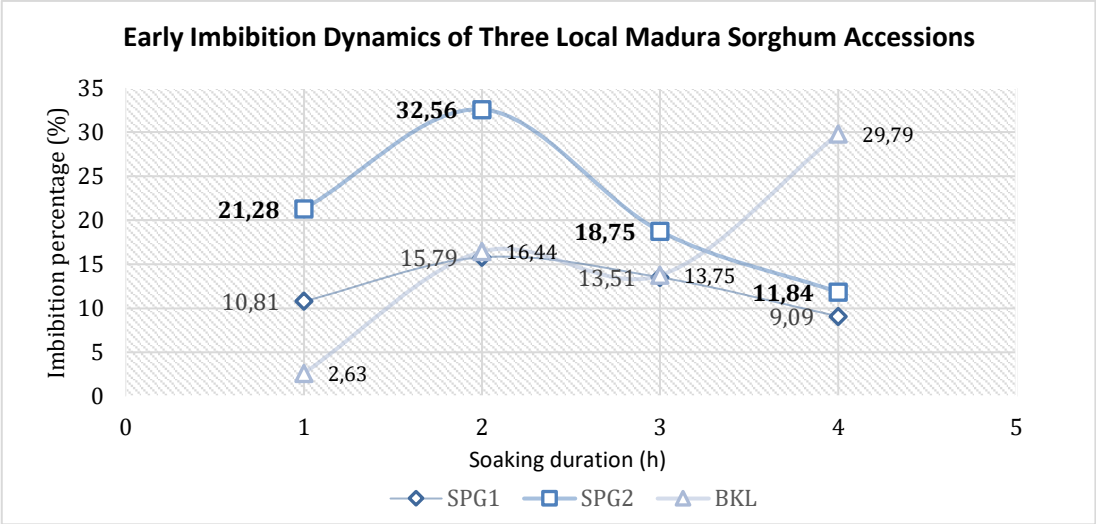


Fig 2. Early seed imbibition dynamics of three local Madura sorghum accessions. Imbibition percentage (%) was determined after 1, 2, 3, and 4 h of soaking. SPG1: Sampang 1; SPG2: Sampang 2; BKL: Bangkalan.

Visual observations after 24 h of soaking (Figure 1) showed that the rate of imbibition was associated with radicle emergence. All three accessions exhibited the highest imbibition rates during the initial hours of water uptake (Table 2), and after 24 h, IMB 3 and IMB 4 showed more uniform radicle emergence than IMB 1 and IMB 2. This pattern suggests that rapid water uptake during the early phase of imbibition promotes embryo rehydration, activates metabolic enzymes, and softens the tissues surrounding the embryo, thereby facilitating radicle protrusion (Asropi *et al*., 2022). These findings are consistent with previous studies reporting that rapid imbibition supports more uniform germination by accelerating the physiological processes required for germination, although successful germination is also influenced by seed viability, physiological condition, and environmental factors (Arief *et al*., 2024).

Correlation Heatmap Analysis of Seed Morphological Traits and Imbibition Parameters in Local Madura Sorghum Seeds

The correlation heatmap presented in Figure 3 illustrates the relationships between seed morphological traits and imbibition characteristics of local Madura sorghum accessions. The color gradient indicates the strength and direction of correlations, with blue representing positive relationships and red representing negative relationships. The analysis revealed variations in the associations among seed morphological parameters, including thousand seed weight (TSW), seed length (SL), seed width (SW), and seed thickness (ST), and imbibition parameters measured at different soaking periods (IMB1–IMB4). These relationships indicate that differences in seed morphology may contribute to variations in water uptake dynamics during the early phase of germination.

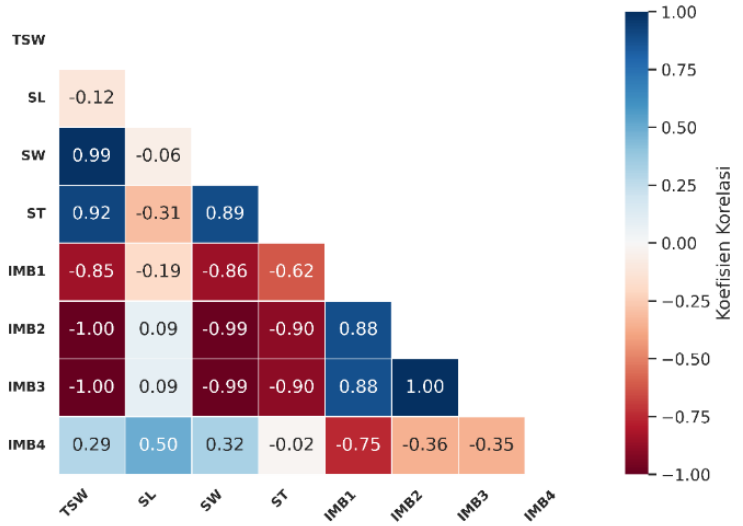


Fig. 3. Heatmap Correlation of Physiological and Morphological Traits in Local Madura Sorghum Seeds; blue color indicates strong positive correlation (r close to +1); while red color indicates strong negative correlation (r close to –1).

Seed morphological parameters showed strong positive correlations among thousand seed weight (TSW), seed width (SW), and seed thickness (ST), with correlation coefficients (r) of 0.99 and 0.92, respectively. The strong correlation among these traits indicates that variations in seed size, particularly seed width and thickness, were closely related to changes in seed mass. Seeds with greater size and thickness tended to have higher thousand seed weight, indicating a consistent relationship among morphological components within the evaluated local Madura sorghum accessions. In the present study, the observed correlation pattern indicates that seed mass was strongly related to seed morphological traits, where increases in seed width and thickness were accompanied by increases in seed weight. This relationship shows that morphological traits in local Madura sorghum accessions were closely related, forming a consistent pattern of variation among seed size characteristics.

The correlation analysis among imbibition parameters showed a consistent pattern of water uptake across different observation periods. The imbibition weights at the first, second, and third observation stages (IMB1, IMB2, and IMB3) showed strong positive correlations, indicating that water uptake during the early imbibition phase occurred consistently over time. This correlation pattern indicates that seeds with higher water uptake at the early observation stages tended to maintain higher imbibition levels in subsequent stages. Therefore, the positive correlations among IMB1, IMB2, and IMB3 indicate a continuous pattern of water absorption during the early imbibition period. The consistency among these parameters suggests that variation in early water uptake capacity was maintained throughout the early phase of seed hydration. This pattern shows differences in imbibition levels among local Madura sorghum accessions and highlights imbibition characteristics as an important physiological trait for describing early seed responses during germination.

A different correlation pattern was observed between seed morphological traits and water uptake capacity in local Madura sorghum accessions. Morphological parameters (TSW, SW, and ST) showed strong negative correlations with early imbibition parameters (IMB1–IMB3), with correlation coefficients ranging from −0.85 to −1.00. This pattern indicates that seeds with greater size and mass tended to exhibit lower water uptake during the early soaking phase. The negative correlation indicates that differences in seed morphological traits were related to variations in seed water uptake capacity, which may involve differences in seed structural properties, such as seed coat characteristics, tissue compactness, or internal organization. Overall, the correlation pattern observed in this study shows that variation in seed morphological traits among local Madura sorghum accessions is closely related to differences in seed water uptake capacity during the early stages of germination.

Principal Component Analysis of Seed Morphological Traits and Imbibition Characteristics

Principal component analysis (PCA) was performed to examine the relationships among seed morphological and imbibition traits and to identify the main characteristics differentiating the local Madura sorghum accessions. The PCA biplot (Fig. 4) provides a multivariate visualization of the relationships among variables and the distribution of the three accessions (SPG1, SPG2, and BKL), thereby facilitating the interpretation of trait associations and accession differentiation. The first two principal components (PC1 and PC2) explained 93.3% of the total variation, with PC1 accounting for 71.4% and PC2 accounting for 21.9%, indicating that the biplot adequately represents the overall variability of the measured traits.

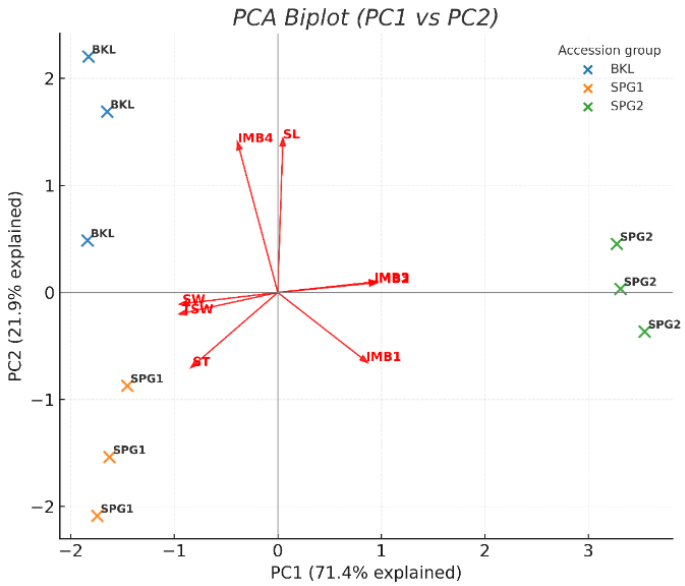


Fig. 4. Principal Component Analysis of Seed Morphological Traits and Imbibition Characteristics

The PCA biplot (Fig. 4) showed a clear separation among the three accessions based on the combination of seed morphological and imbibition traits. Principal component 1 (PC1) was primarily associated with thousand seed weight (TSW) and early to intermediate imbibition parameters (IMB1–IMB3), with IMB2 and IMB3 contributing most strongly to accession separation. SPG2 was positioned on the positive side of PC1, indicating relatively higher water uptake during the early and intermediate imbibition stages despite its smaller and more elongated seeds. In contrast, SPG1 was located on the negative side of PC1, suggesting lower water uptake capacity during the early imbibition phase. BKL was separated mainly along PC2, which was associated with the later imbibition stage (IMB4) and seed morphological traits, including seed length (SL), seed width (SW), and seed thickness (ST). This distribution indicates that SPG2 was characterized by rapid water uptake during the early to intermediate imbibition stages, whereas BKL exhibited relatively greater water uptake at the later imbibition stage and was associated with thicker and wider seeds

CONCLUSION

This study shows that local Madura sorghum accessions differ in seed morphological traits and early imbibition characteristics. Positive correlations occur among seed morphological traits, whereas negative correlations are observed between seed morphology and early imbibition. Principal component analysis identifies thousand-seed weight and early imbibition traits as the major contributors to variation among the evaluated accessions. These findings provide baseline information for the characterization of local Madura sorghum germplasm.

AUTHORS CONTRIBUTIONS

PAM conceptualized and designed the study, prepared, revised, and finalized the manuscript, and served as the corresponding author. YNA. conducted the data collection. ARH. performed the data analysis. SSW contributed to the final editing and refinement of the manuscript. All authors have read and approved the final manuscript.

CONFLICT OF INTEREST

The authors declare no conflict of interest.

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