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UNIVARIATE–MULTIVARIATE INTEGRATION TO ASSESS THE CONSISTENCY OF AGRONOMIC PERFORMANCE AND SUSTAINABILITY POTENTIAL OF *SORGHUM BICOLOR* (L.) MOENCH ‘KELLER’ FROM MAIN TO SECOND RATOON CROPS

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ABSTRACT

Comprehensive analysis highlights sorghum ‘Keller’ capacity to sustain agronomic performance and sustainability across main and second ratoon crops. To identify sorghum ‘Keller’ as a superior variety and evaluate its sustainability potential through univariate–multivariate integration. This research comprised two stages on dry land in Sindang Jaya Village, Bengkulu, Indonesia. The first study compared four sorghum varieties (B100, Keller, Numbu, Wray). The second tested Keller and B100 up to second ratoon using univariate–multivariate analyses (ANOVA, Tukey HSD, PCA, biplot, PERMANOVA, Pearson). The results showed that in the first study, PCA score plot and biplot highlighted Keller’s superior profile, strongly associated with leaf area, stem, leaf, and root weights, clearly separating it from other varieties. In the second study, K-means clustering consistently distinguished varieties and phases, with Keller forming stable clusters and B100 showing higher variability. Keller declined in ratoon-1 vegetative traits but partially recovered in ratoon-2, while reproductive traits decreased gradually. Conversely, B100 showed significant increases in seed weight and spikelet length but sharp vegetative decline without recovery. Pearson correlation indicated strong positive associations among vegetative traits and negative correlations with seed weight, suggesting a potential trade-off, likely influenced by ratoon data. Nevertheless, Keller maintained strong capacity and higher stability in sugar content (18.0→15.0→13.0%) compared to B100’s fluctuation (8.7→13.0→8.0%). The integration of statistical approaches effectively identified ‘Keller’ as a highly adaptive variety for sustainable ratooning systems, offering valuable insights for agronomic selection strategies.

Keywords: Biomass, PCA, PERMANOVA, Stability, Sustainable

1. INTRODUCTION

Sorghum (*Sorghum bicolor* (L.) Moench) is an important cereal crop with great potential to support food security (Tan et al., 2024), especially amid global challenges such as limited fertile land and the impact of climate change (Negri et al., 2024). This plant is known to be able to grow on marginal land with low inputs and has good resistance to heat and drought. These adaptive advantages make sorghum a strategic commodity in addressing food availability issues in the era of global warming. Additionally, sorghum has a wide range of multifunctional uses, from food (De Oliveira et al., 2022), animal feed, to bioenergy sources, further strengthening its position as a promising crop for development (Zhou et al. 2022).

In order to improve and develop sorghum varieties, agronomic evaluation is a crucial aspect for determining variety excellence criteria (Mercyana et al., 2023). To date, most sorghum experiments have relied on a univariate approach (Apriyanto et al. 2014; Kurniasari, et al., 2023). This approach typically focuses on one or a few key parameters. This approach often makes it difficult to determine the best criteria. This is because the superiority of a sorghum variety is fundamentally shaped by the interaction of many interrelated factors. Therefore, the integration of multivariate analysis becomes highly relevant (Enciso-Alfaro et al., 2023). Multivariate approach allows for the comprehensive combination of various agronomic parameters. The result, it can produce evaluation outcomes that are more representative of the plant's overall performance (Mittal and Kumar 2022).

Additionally, one of the advantages from sorghum plant is its “ratooning” ability (Harmini et al., 2021). The ratoon system has the potential to increase cultivation efficiency by extending the production period with lower inputs compared to new plantings. Most sorghum research focuses on evaluation up to the first ratoon phase. Studies examining sorghum performance up to the second ratoon are still very limited, even though this information is important for understanding long-term productivity consistency (Zubaidi et al. 2024). In fact, ratoon utilization can be an important strategy in increasing the productivity and efficiency of sorghum farming (Mahpuzah et al., 2025; Zhou et al. 2022).

This study was performed to comprehensively assess the consistency and stability of the agronomic performance of sorghum varieties from the main crop to the second ratoon. The second ratoon is a crucial aspect of sustainability because it reflects the ability of varieties to remain productive in the next cropping cycle. By combining univariate and multivariate analyses, this study provides a comprehensive overview of the growth dynamics and yield of sorghum in the ratoon system. This stability assessment is important to support sustainable cultivation practices and to determine adaptive superior varieties. Through this approach, it is hoped that a more complete understanding of the dynamics of sorghum growth and yield in the ratoon system will be obtained.

2. MATERIALS AND METHOD

This study was conducted on dry land in Sindang Jaya Village, East Curup Subdistrict, Rejang Lebong Regency, Bengkulu Province, Indonesia. The first planting was part of a variety exploration study conducted by Apriyanto et al. (2014) in 2014. Subsequently, the planting for the second study was focused on observations from the main growth phase to the second ratoon. It was carried out in 2016 in the same area. In the first study, multivariate analysis was not conducted, as the primary focus was limited to exploring differences between varieties in a single planting. The second test was conducted until the first and second ratoon systems to evaluate sustainability aspects. This study used the Keller and B100 varieties as test materials.

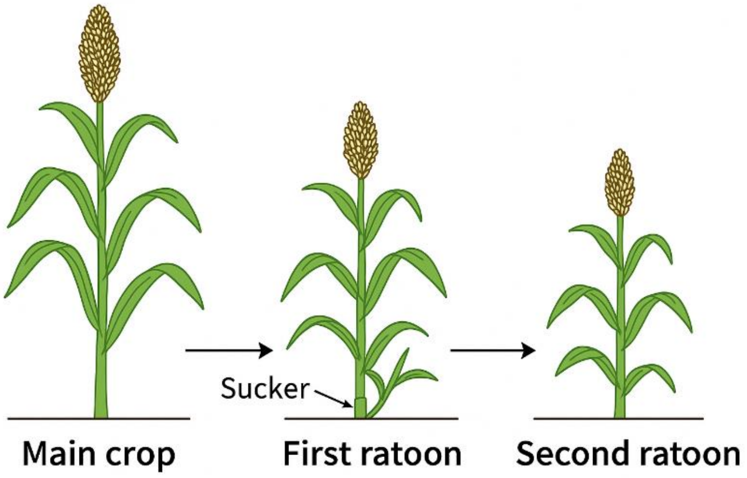

Figure 1: The ratoon process in sorghum plants. The main crop produces panicles and after harvesting, side shoots (suckers) emerge from the base of the stem and develop into the first ratoon. After the first ratoon is harvested, new shoots grow back from the base of the stem and form the second ratoon

The first study used a completely randomized block design (CRBD) experimental design with three replicates. The factor tested was sorghum varieties consisting of Keller (V1), Numbu (V2), B100 (V5), and Wray (V4). The second study was a continuation of the previous study using a CRBD design. The factor tested was varieties, namely B100 and Keller, with three replicates. The fertilizer used was 160 kg of urea, 120 kg of SP-36, and 80 kg of KCl per hectare, with 50% applied at planting and the rest 30 days after planting (30 DAP). The planting distance used was 60 × 20 cm. Agronomic management practices, including fertilizer application rates, planting density, and crop management, were maintained consistently between the first study (2014) and the second study (2016) to ensure comparability of agronomic performance across cropping cycles.

The dry weight parameter was observed by drying the plants in an oven at 70 °C for three days until they reached a constant weight. The sugar content of sorghum cane sap was measured using a hand refractometer and expressed in °Brix.

The analyses used in this study include multivariate and univariate analyses. Multivariate analysis was performed using the MetaboAnalyst 6.0 platform in the first study and in the second study. Multivariate tests in this study consisted of PCA, biplot, K-graph, and PERMANOVA. PCA was applied to reduce the data dimensions and visualize the patterns of agronomic performance variation between varieties and ratoon cycles. Biplot was used to describe the contribution of agronomic variables to the diversity formed in the main components, thereby facilitating the interpretation of the dominant parameters. K-graph analysis is used to evaluate the proximity between samples based on multivariate distance. The principle of this method is to connect each sample with a number of its closest neighbors (K-nearest neighbors) or to group them into K clusters based on agronomic similarities. Thus, K-graph strengthens the PCA results by showing the pattern of relationships between samples in more detail, while confirming the separation between the main crop, ratoon-1, and ratoon-2. Next, PERMANOVA (Permutational Multivariate Analysis of Variance) with 999 permutations was used in both studies to test the significance of differences between groups based on PCA results. PERMANOVA was chosen because it is capable of evaluating differences in multivariate structures between treatments simultaneously through distance matrices without having to meet normal distribution assumptions. In the context of this study, PERMANOVA played an important role in assessing the consistency of agronomic performance between sorghum varieties and between ratoon cycles. This combined approach was considered appropriate given the complex nature of the agronomic data, involving many response variables, and often not meeting parametric assumptions, thus producing a more robust interpretation of the stability and consistency of variety performance from the main crop to the second ratoon.

In addition, the second study also conducted a bivariate analysis using Pearson correlation to assess the linear relationship between agronomic parameters in pairs. The correlation results were visualized in the form of a heatmap, thereby strengthening the interpretation of the relationship patterns between variables that supported the findings from the multivariate analysis.

Univariate analysis was conducted to assess the differences in each agronomic parameter individually, including stem diameter, plant height, leaf area, fresh weight of organs (stem, leaves, and roots), panicle length, and seed weight. The data were analyzed using Analysis of Variance (ANOVA), and if significant differences were found, they were followed by Tukey's Honest

Significant Difference (HSD) test at a significance level of 5%. In addition, the data were visualized using boxplots to describe the distribution of values and the percentage change was calculated to assess the increasing or decreasing trends in the main crop, ratoon-1, and ratoon-2.

3. RESULTS AND DISCUSSION

3.1. Variety exploration

Until now, agronomic testing on crops has generally relied on a univariate approach, particularly through analysis of variance (ANOVA) adapted to conventional experimental designs. This approach is commonly used because it is simple, easy to interpret, and has become the standard in agricultural research. However, the use of univariate analysis has limitations, mainly because each parameter is tested separately and only highlights the main production aspects. In reality, the agronomic performance of a variety is the result of complex interactions between various factors (Philibert, et al., 2012; Young, et al., 2021). Agronomic research systems are inherently multivariate, yet most reported analyses remain univariate (Yeater and Villamil 2018). Therefore, the application of multivariate analysis is highly relevant to complement univariate testing. Multivariate analysis allows the integration of multiple parameters simultaneously (Abrar, et al., 2024), thereby providing a more comprehensive understanding of the consistency and advantages of a variety. Thus, multivariate analysis can offer new perspectives and enhance the accuracy of assessments in the selection of superior varieties including sorghum.

Apriyanto et al. (2014) revealed that several sorghum varieties, namely B100, Keller, Numbu, and Wray, exhibited different growth performances. The results of the study indicate that the Keller variety has superior growth and higher sugar content compared to other varieties. However, the study was limited to a single growing season and only assessed the early growth phase using a univariate approach. Therefore, prior research did not sufficiently capture the consistency of sorghum's agronomic performance throughout successive ratoon cycles. This situation necessitates further comprehensive research utilizing data from the main crop to the second ratoon, and integrating univariate and multivariate analyses. With this approach, the study is expected to address fundamental questions regarding the consistency of agronomic performance of the Keller variety.

Based on the first study, the results of PCA (Fig. 2A) showed that Keller and Numbu had agronomic patterns that were clearly different from B100 and Wray. PCA analysis shows that two principal components (PC) are able to explain most of the agronomic data diversity, with PC1 contributing 59.8% and PC2 contributing 32.3%, bringing the total explained diversity to 92.1%. PC1 describes the main variation that distinguishes agronomic performance between varieties, while PC2 adds supporting variation that complements these differences. The PERMANOVA results showed a value of $F = 242.69$ with $R^2 = 0.989$, meaning that 98.9% of the data variation could be explained by sorghum variety factors. The value of p = 0.001 (based on 999 permutations) confirmed that the differences between varieties were statistically significant and did not occur by chance. Keller (green) is consistently grouped and separated from other varieties, indicating its agronomic performance stability. B100 (red) and Numbu (dark blue) form their own group, while Wray (light blue) is far separated on the PC1 axis, indicating significant differences in agronomic characteristics.

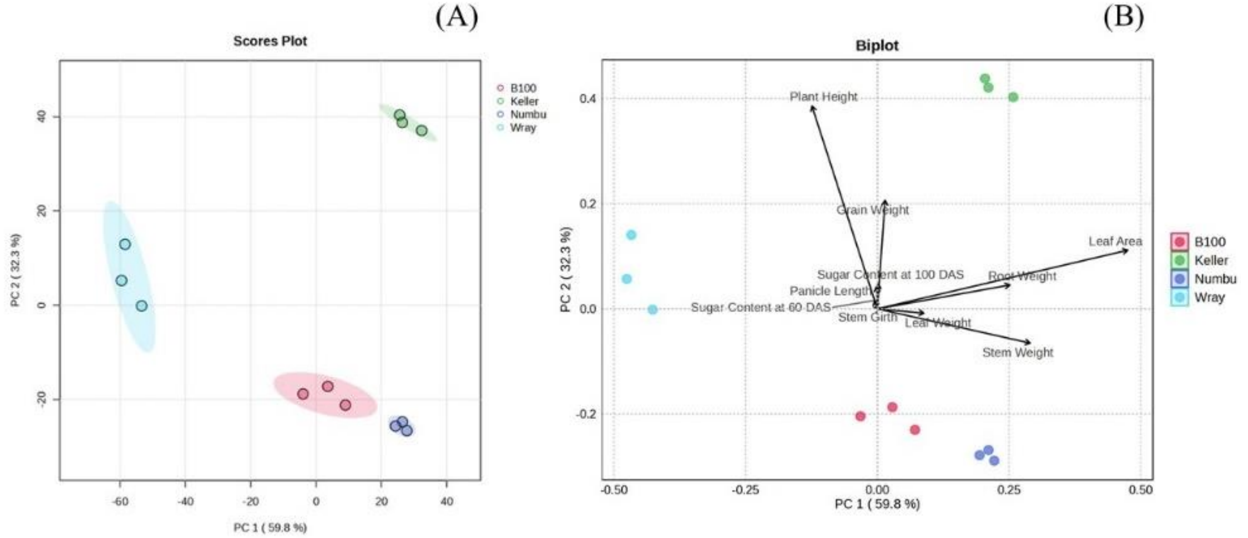

Figure 2: Principal component analysis (PCA) of agronomic traits of four sorghum varieties (B100, Keller, Numbu, and Wray). (A) The score plot shows the grouping of varieties based on the similarity of agronomic traits, with Keller and Numbu clearly separated from B100 and Wray. (B) The biplot illustrates the contribution of agronomic variables

Furthermore, plotting was performed using principal component analysis biplot (Fig. 2B) to show clear separation between sorghum varieties based on the observed agronomic parameters. The Keller variety (green) is located in the upper-right quadrant and is strongly associated with the variables plant height, seed weight, leaf area, and root weight, indicating that this variety has superior compared to other varieties. Conversely, the B100 variety (red) is concentrated in the lower quadrant and far from the main parameter vectors, indicating that its performance is relatively low in almost all observed traits. The Numbu variety (purple) tends to be associated with vegetative parameters such as stem weight, leaf weight, and stem circumference, indicating that its advantage lies more in vegetative growth than in yield productivity. The Wray variety (blue) is located on the left side of the biplot, relatively far from most parameter vectors, indicating a smaller agronomic contribution and less consistent performance. Keller stands out for its association with leaf area, stem weight, leaf weight, and root weight, which are the main factors driving its performance in a multivariate manner. In contrast, plant height, although significant in univariate analysis (Apritanyo et al., 2014), is not a major determinant in group separation. These findings indicate that Keller has a unique agronomic profile, making it worthy of further investigation.

Multivariate analysis has proven effective in distinguishing between cultivar groups. This approach has also been applied to other agricultural commodities, such as organic tomatoes (Araujo et al. 2016). The results of this study indicate that combining univariate and multivariate procedures is more beneficial because it provides a more comprehensive agronomic evaluation.

3.2. Consistency of Keller varieties in ratoon systems

Based on the results of initial exploration, this study then focused on the Keller variety, which showed the most outstanding potential, with the B100 variety used as a comparison. B100 was selected as the control based on its tendency to perform poorly in almost all agronomic parameters, thus providing a clear contrast for a more objective assessment of Keller's superiority. This study was conducted to examine whether the Keller variety can maintain consistent agronomic performance when grown under a ratoon system up to the second ratoon, thereby testing the sustainability of this variety.

The results of principal component analysis (PCA) in Fig. 3A show that the PC1 (95.2%) and PC2 (3.4%) axes explain most of the agronomic data diversity in Keller (K) and B100 (B) sorghum varieties grown using the ratoon system. The score plots show a clear separation between the main cropping groups (Main), first ratoon (Ratoon-1), and second ratoon (Ratoon-2). This distribution pattern confirms that each growth phase has distinct agronomic characteristics, enabling consistent variety performance to be observed across planting cycles.

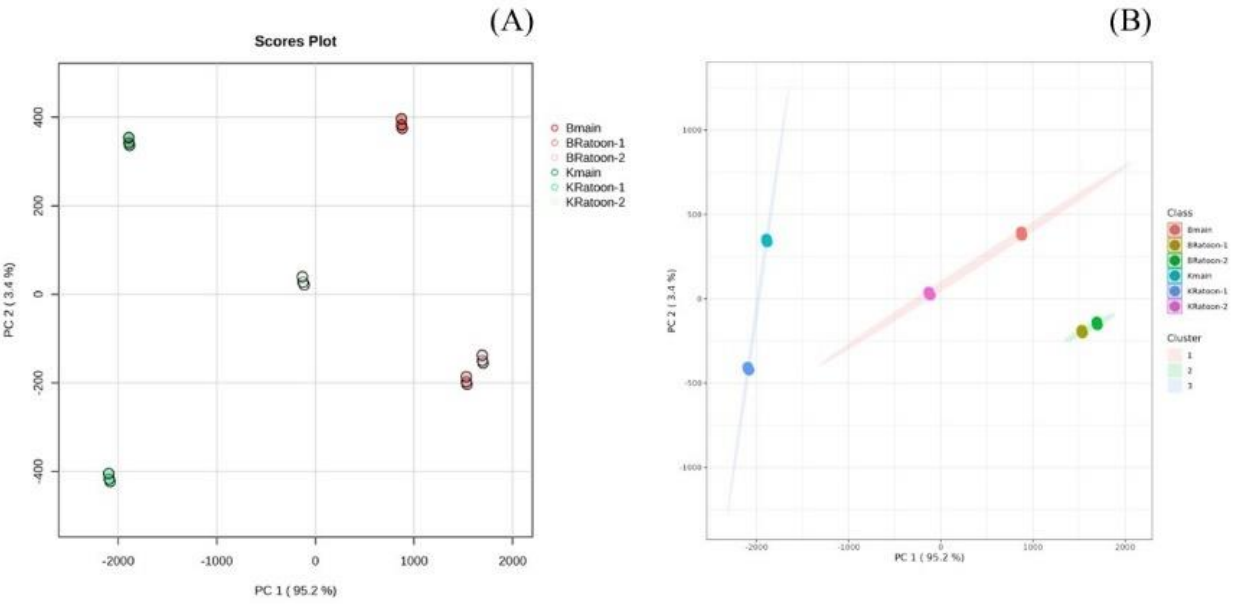

Figure 3: Principal component analysis (PCA) and clustering of Keller (K) and B100 (B) sorghum varieties using the ratoon system. (A) The score plot shows the distribution of data on PC1 (95.2%) and PC2 (3.4%), which separates the main planting group (Main) from the first ratoon (Ratoon-1) and the second ratoon (Ratoon-2). (B) Cluster analysis based on PCA results shows a clear separation between B Main, B Ratoon-1, B Ratoon-2, K Main, K Ratoon-1, and K Ratoon-2, with three main clusters formed according to the agronomic characteristics of each growth phase

The PCA scores plot shows that PC1 (95.2%) as the dominant axis consistently separates the varieties, with Keller (Kmain, KRatoon-1, KRatoon-2) entirely on the negative side and B100 (Bmain, BRatoon-1, BRatoon-2) on the positive side, so that both maintain the main direction of variation throughout the cycle. Meanwhile, PC2 (3.4%) shows a vertical shift that emphasizes phase changes, where Keller shows a large shift from Kmain (positive PC2) to KRatoon-1 (negative PC2), then moves closer to the midpoint at KRatoon-2, indicating a partial recovery in performance, although not back to the level of the main crop. This shows that after a sharp decline in the first ratoon, Keller did not continue to decline but was able to maintain its performance in the second ratoon in a relatively consistent pattern. In B100, a similar pattern was also seen, with a large shift from Bmain to BRatoon-1, but BRatoon-1 and BRatoon-2 were very close together, making them more stable between ratoons, although they did not show signs of recovery as in Keller. Thus, Keller showed stability in the form of consistency in the direction of variation on PC1 and a tendency to maintain performance until the second ratoon. B100 showed local stability between ratoons without any recovery in performance.

To further examine the results of data separation from PCA, cluster analysis was performed using the K-means clustering method (Fig. 3B). K-means clustering is a multivariate analysis method that works by grouping data into *k* specific clusters, where each data point is placed in the cluster with the nearest centroid. This algorithm calculates the distance between data points and the centroid, then updates the position of the centroid until the most stable condition is achieved. Thus, K-means can separate groups of data that are highly similar within a cluster while distinguishing them from other more heterogeneous groups. In this study, the K-means results showed the formation of three main clusters that consistently separated the B Main, B Ratoon-1, B Ratoon-2, K Main, K Ratoon-1, and K Ratoon-2 phases. This pattern confirms that the combination of agronomic parameters can systematically classify varieties and planting phases. Keller tends to be consolidated in stable clusters, indicating that variations between cropping cycles are relatively small. Conversely, B100 is more dispersed and enters different cluster positions, reflecting higher agronomic variability between cropping phases.

K-means analysis is important in this context as it provides additional validation of the PCA results. While PCA visually displays separation patterns based on principal dimensions, K-means ensures that these patterns are indeed formed into clear statistical groups. In other words, K-means reinforces the evidence that Keller exhibits more consistent agronomic performance in the ratoon system, while B100 shows greater fluctuations. The integration of PCA and K-means clustering thus provides a more comprehensive multivariate overview for understanding the stability of sorghum varieties in the ratoon system. In simple terms, the multivariate analyses consistently showed that ‘Keller’ maintained similar agronomic profiles across main and ratoon crops, while ‘B100’ exhibited greater variability. PCA and clustering analyses confirmed clear separation between varieties and planting phases, indicating that ‘Keller’ possesses higher agronomic stability under ratooning conditions.

3.3. Univariate analysis and relationships between agronomic parameters

Further detailed analysis was also conducted using a univariate approach, because although multivariate analysis was able to show general patterns of separation between varieties and ratoon phases, individual evaluation of each agronomic parameter was still necessary to see the specific contribution of each character. Univariate analysis (Fig. 4 and Fig. 5) shows that agronomic parameters of sorghum varied significantly between varieties and between growth stages, from main crop to ratoon (Main, Ratoon-1, and Ratoon-2). These results indicate clear differences in growth characteristics (such as plant height, stem diameter, leaf length and width) as well as yield components (fresh weight of stems, leaves, roots, and seeds per plant). Overall, the trend shows a decrease in parameter values as the crop transitions from the main crop to the first ratoon and subsequently to the second ratoon, although the extent of this decrease varies among parameters and varieties.

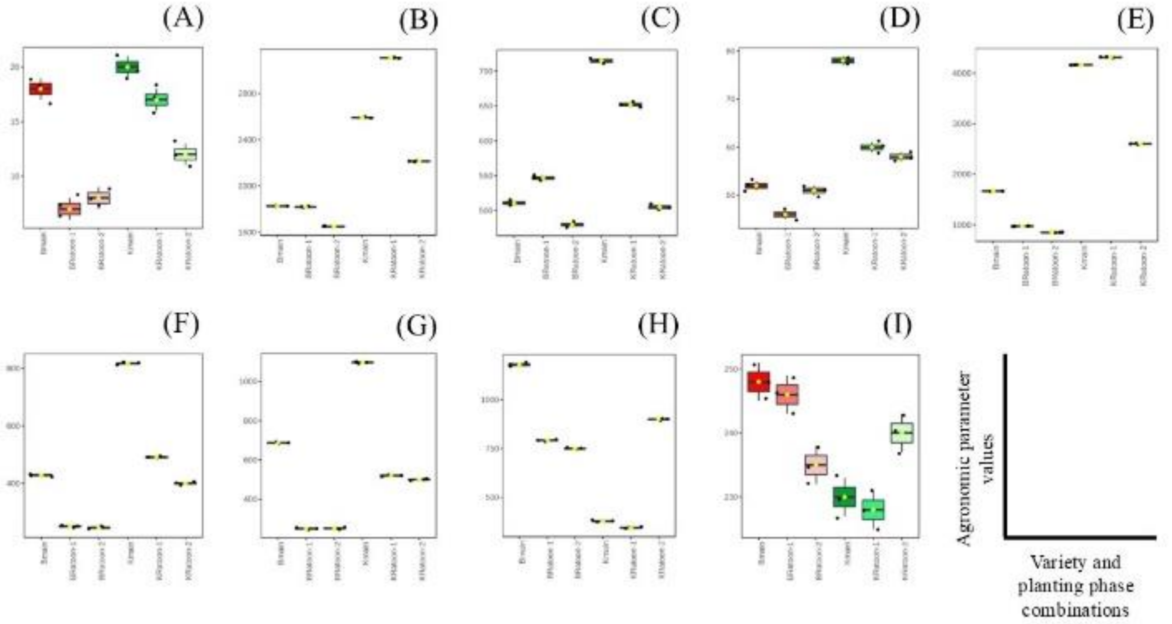

Figure 4: Boxplot of the distribution of agronomic parameter values for sorghum based on variety (B100 and Keller) and planting phase (Main, Ratoon-1, and Ratoon-2). (A) Stem diameter (cm), (B) Plant height (mm), (C) Leaf length (mm), (D) Leaf width (mm), (E) Fresh stem weight (g), (F) Fresh leaf weight (g), (G) Fresh root weight (g), (H) Seed fresh weight per plant (g/plant), and (I) Spikelet length (mm). The figure shows variations between varieties and ratoon phases, with significant differences in most growth and yield parameters

The boxplot Fig. 4 results showed significant variation between varieties and ratoon phases for most growth and yield parameters. The Keller variety consistently exhibited higher values for important traits such as plant height, fresh stem weight, fresh leaf weight, fresh root weight, and seed yield compared to B100, which generally showed lower distributions and tended to fluctuate between planting phases. These differences become more pronounced in the ratoon phase, where Keller maintains growth stability and productivity, while B100 experiences a sharper decline.

The results of the percentage change analysis show differences in adaptation patterns between the Keller (K) and B100 (B) varieties throughout the transition from the main crop to ratoon-1 and ratoon-2. In terms of stem diameter (Fig. 5A), B100 experienced a gradual decline of –15.00% from main to ratoon-1 and –29.41% from ratoon-1 to ratoon-2, with a total decline of –40.00%. Keller experienced a sharp decline in the first phase (–61.11%), but showed recovery in the next phase with an increase of +14.29%, resulting in a total decline from main to ratoon-2 of –55.56%. In terms of plant height (Fig. 5B), B100 increased by +19.91% from main to ratoon-1, but then decreased drastically by –28.80% from ratoon-1 to ratoon-2, resulting in a total decrease of –14.62%. In contrast, Keller was more stable with a very small decrease of –0.38% from main to ratoon-1 and –9.29% from ratoon-1 to ratoon-2, with a total of –9.64%. For leaf length (Fig. 5C), B100 continued to decline both from main to ratoon-1 (–8.81%) and ratoon-1 to ratoon-2 (–22.55%), with a total of –29.37%. Keller, on the other hand, showed an adaptive pattern: after decreasing by –12.25% in the first phase, leaf length increased again by +7.05% in the second phase, resulting in a total decrease of only –6.07%. A similar pattern was seen in leaf width (Fig. 5D). B100 experienced a large decrease (–23.08% in the first transition and –3.33% in the second transition, for a total of –25.64%), while Keller decreased by –11.54% in the first phase but recovered by +10.87% in the second phase, resulting in a total decrease of only –1.92%. In terms of stem wet weight (Fig. 5E), B100 declined sharply from the start (–39.79%), followed by a smaller decline in the next phase (–7.56%), with a total of –41.58%. Keller experienced a milder decline (–12.36% in the first phase and –41.58% in total), although it remained negative in ratoon-2 (–48.80%).

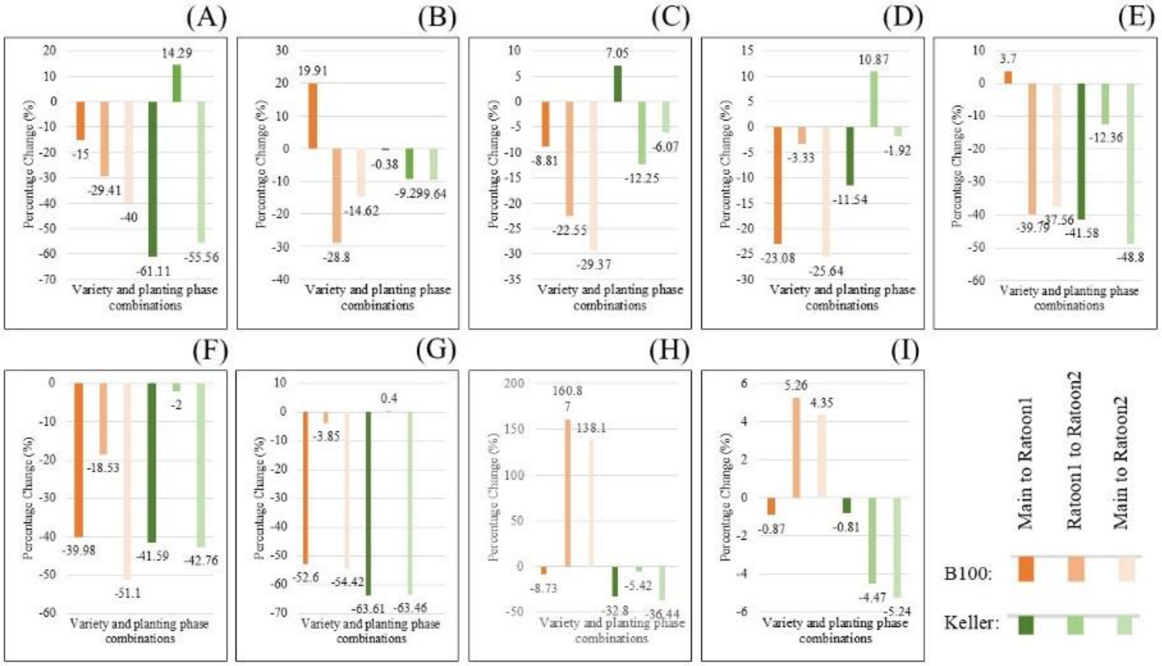

Figure 5: Percentage change (%) of various agronomic parameters of sorghum based on variety (B100 and Keller) and planting phase (Main, Ratoon-1, and Ratoon-2). (A) Stem diameter, (B) Plant height, (C) Leaf length, (D) Leaf width, (E) Stem wet weight, (F) Leaf wet weight, (G) Root wet weight, (H) Seed wet weight, and (I) Spikelet length. Positive values on the Y-axis indicate positive changes (increases), while negative values indicate negative changes (decreases)

For wet leaf weight (Fig. 5F), B100 again showed a large decrease, namely –39.98% from main to ratoon-1 and –18.53% from ratoon-1 to ratoon-2, for a total of –51.10%. Keller was more stable, with a decrease of –41.59% in the first phase and only –2.00% in the second phase, resulting in a total of –42.76%. In terms of wet root weight (Fig. 5G), B100 decreased by –52.60% from main to ratoon-1 and –3.85% from ratoon-1 to ratoon-2, for a total of –54.42%. Keller decreased more significantly by –63.61% in the first phase, recovered slightly by +0.40% in the second phase, with a total remaining high at –63.46%. The most striking difference was seen in wet seed weight (Fig. 5H). B100 increased significantly, +160.80% from main to ratoon-1 and remained high at +138.10% from ratoon-1 to ratoon-2, with a total increase well above 100%. In contrast, Keller experienced a decline, –32.80% in the first phase and –5.42% in the second phase, resulting in a total decline of –36.44%. Finally, spikelet length (Fig. 5I) showed a positive trend in B100 with an increase of +5.26% from main to ratoon-1 and +4.35% from ratoon-1 to ratoon-2, while Keller experienced consecutive decreases of –4.47% and –5.24%.

Keller showed a sharp decline in the ratoon-1 phase, especially in vegetative traits. However, a number of parameters such as stem diameter, leaf length, and leaf width showed recovery in ratoon-2, indicating an adaptive capacity after entering the ratoon system. Nevertheless, reproductive traits such as seed weight and spikelet length continued to decline gradually until ratoon-2.

In contrast, B100 actually showed better performance in reproductive characteristics, with a significant increase in seed weight and spikelet length throughout the ratoon cycle. However, its vegetative performance tended to decline sharply since ratoon-1 and did not show any significant recovery in the ratoon-2 phase.

After analyzing agronomic performance variations using univariate approaches and percentage changes, further steps were taken with a correlation test between parameters (Fig. 6). This analysis is useful because although each parameter can be assessed separately, the relationships between agronomic parameters can provide a deeper understanding of how vegetative growth is related to generative yield. Thus, correlations help identify key parameters that can serve as indicators of productivity and consistency of variety performance in the ratoon system. Figure 6 shows a heat map of the results of Pearson's correlation analysis. Red indicates a strong positive correlation, while blue indicates a negative correlation. The results of the analysis show that stem diameter, plant height, leaf length, leaf width, fresh stem weight, and fresh root weight have a strong positive correlation with each other. This means that an increase in one vegetative component is generally followed by an increase in other vegetative components. Conversely, fresh seed weight shows a negative correlation with most of these vegetative parameters, which likely reflects a trade-off between vegetative growth and seed yield accumulation. The observed negative correlation between vegetative traits and seed weight suggests a potential trade-off in assimilate allocation, particularly under ratoon conditions where carbohydrate reserves and nutrient availability are limited. However, this interpretation is based on correlative evidence. Future studies incorporating physiological indicators such as nutrient partitioning, carbohydrate translocation, and nitrogen use efficiency would provide deeper biological insights into the mechanisms underlying this vegetative–reproductive trade-off.

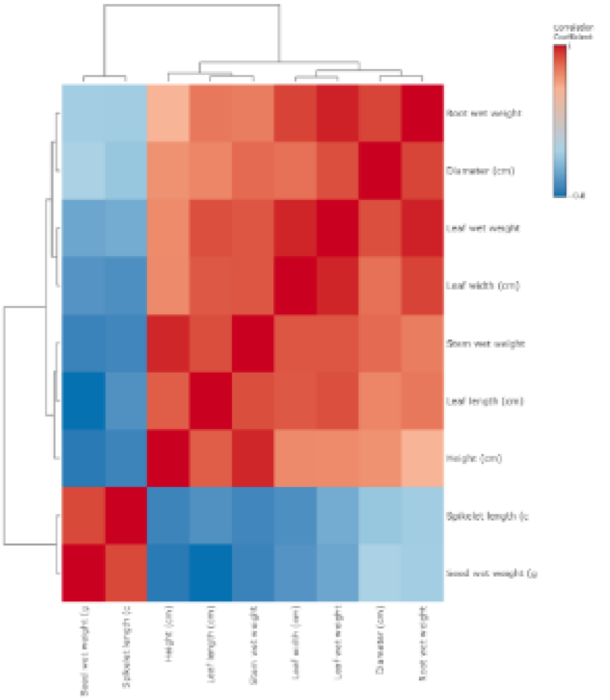

Figure 6: Heatmap of Pearson correlation analysis between sorghum agronomic parameters. Red indicates strong positive correlation, while blue indicates negative correlation. It can be seen that stem diameter, plant height, leaf length, leaf width, and stem and root wet weight are strongly positively correlated with each other, while seed wet weight shows a negative correlation pattern with most vegetative parameters

In this context, trade-off can be understood as a possible compromise in resource allocation, where energy and nutrients used to support vegetative growth may limit their availability for seed formation and filling, and vice versa. These correlation results thus indicate the potential for an inverse relationship between plant investment in the vegetative and reproductive phases, although further interpretation still requires additional analysis to confirm the underlying mechanisms. This negative correlation phenomenon is also likely reinforced by the inclusion of data from ratoon crops, which have different physiological conditions and resource availability compared to the main crop. In ratoons, plants generally face limited energy and nutrient reserves, so the tendency for a trade-off between vegetative growth and seed yield accumulation may be more pronounced than in the main crop.

In the context of varieties, these results are consistent with the univariate analysis and percentage change showing differences in performance between Keller and B100. Keller is able to maintain a better balance: although its vegetative growth is relatively strong, seed yield accumulation remains high and consistent across planting phases. This indicates that the vegetative–generative trade-off in Keller is more moderate. In contrast, B100 shows a more pronounced negative correlation, reflected in a sharp decline in seed yield when vegetative growth increases. This pattern confirms that B100 is less efficient in allocating resources to generative yield formation.

This shows that a decline in growth until the second ratoon is indeed inevitable, but the Keller variety still shows better potential. Maintenance through proper cultivation management is essential to maintain productivity and sustainability of yields. These findings are in line with the statement that enhancing nitrogen levels improved yield and yield components in both main and ratoon crops, with a stronger impact observed on the ratoon crop compared to the main crop (Zhou et al. 2022).

3.4. Stability of sugar levels in the ratoon system

To assess the stability of the Keller variety more comprehensively, sugar content tests were also conducted from the main crop to second ratoon, as shown in Table 1. The results indicate that Keller has high sugar content from the outset, at 18.0% in the main crop, nearly double that of B100, which was only 8.7%. From the main crop to the first ratoon, sugar content in Keller decreased from 18.0% to 15% (a decrease of 16.7%). Furthermore, from the first ratoon to the second ratoon, the sugar content decreased again from 15% to 13% (a decrease of 13.3%). In total, the sugar content of Keller decreased by approximately 27.8% from the main phase to the second ratoon, but remained above 13%. In contrast, B100 exhibited a different pattern: from the main crop to the first ratoon, it increased from 8.7% to 13% (an increase of 49.4%), but in the second ratoon, it decreased again to 8% (a decrease of 38.5%), thus showing overall low stability. These results confirm that although Keller experienced a downward trend, its sugar content remained relatively high and consistent until the second ratoon, while B100 was more fluctuating. Thus, Keller has better potential to support sustainable sorghum sugar production.

Table 1: Sugar content of Keller and B 100 sorghum varieties in main crops and ratoon crops 1 and 2

Variety	Main	Ratoon 1	Ratoon 2
Keller	18.0	15	13
B 100	8.7	13	8

The growth process of ratoon in sorghum up to the second ratoon is shown in Figure 1. After the main plant produces panicles and is harvested, side shoots (*suckers*) grow from the base of the stem and develop into the first ratoon. Subsequently, after the first ratoon is harvested, new shoots grow again from the base of the stem and form the second ratoon. According to Harmini et al. (2021), ratooning involves harvesting the initial crop, allowing the stubble to regenerate, and then managing the regrowth in a manner similar to sorghum established from seed. This mechanism demonstrates that sorghum has regenerative capabilities that allow for repeated harvesting without the need for replanting (Zhou et al. 2022). According to research by Xu et al. (2021), the ratoon ability is influenced by genetic, physiological, and cultivation management factors. The ratoon ability to date remains an important focus for improvement due to its role in cost efficiency, production sustainability, and optimal resource utilization. In the context of sustainability, the ratoon system is highly promising as it can enhance land use efficiency, labor, and input inputs while maintaining productivity, especially in stable varieties like Keller. This is in line with Orr et al. (2020), who assert that the business case for sorghum is stronger than that for millet due to its greater impact on poverty and food security. Although this study did not explicitly assess economic performance, the agronomic advantages observed under the ratooning system have clear implications for farm-level efficiency. Previous field-based studies have demonstrated that ratoon cultivation in sorghum can reduce production costs by minimizing land preparation, seed input, and planting labor, while still maintaining substantial yield levels. Ratoon sorghum systems have been reported to increase cumulative production and farmers' income through multiple harvests within a single planting cycle, primarily due to lower input requirements and improved resource-use efficiency (Nkosi et al., 2024; Syuryawati et al., 2021). In this context, the stable agronomic performance of the 'Keller' variety up to the second ratoon observed in the present study suggests its strong potential to support economically viable ratooning practices, particularly in dryland farming systems where input efficiency is a critical constraint.

Ratooning ability have generally evaluated plant stability using simple phenotypic criteria, such as seed or stem yield on ratoons, number of tillers, biomass, light use efficiency, and resistance to pests, diseases, and drought (Abu-Ellail et al. 2019; Olaoye 2001; Chapman et al. 1992; Rafiq et al. 2006; Qin et al. 2017b). Selection is also often carried out directly based on ratoon yields, or indirectly through main crop yields (plant cane) assuming that varieties that are superior in the main crop will also be superior in ratoons (Chapman 1998). Although these methods are useful, their limitations include long selection cycles, high resource requirements, and limitations in comprehensively describing relationships between agronomic parameters (Chapman et al. 1992). Additionally, ratoon productivity can be improved through the identification and implementation of appropriate cultivation practices (Santos et al., 2003; Petroudi et al., 2011; Rogé et al., 2016). With univariate analysis, patterns of change per parameter can be observed. With multivariate analysis, overall consistency of patterns and interactions between variables can be observed. This study is part of that identification process by showing that the Keller variety has superior ratooning capacity. Integrating the two allows for a more comprehensive assessment of the consistency of Keller's performance from the main crop to ratoon-2. This research is also an important step in assessing the superiority of varieties to support ratoon yield through appropriate cultivation management.

4. CONCLUSION

The integration of univariate and multivariate analyses effectively demonstrated that the ‘Keller’ sorghum variety possesses superior agronomic stability compared to ‘B100’ across the main, first ratoon, and second ratoon crops. While ‘B100’ exhibited high fluctuation and significant vegetative decline, ‘Keller’ showed a consistent clustering pattern and the capacity to recover vegetative traits (stem diameter and leaf dimensions) in the second ratoon. Furthermore, ‘Keller’ maintained a relatively high and stable sugar content (ranging from 13.0% to 18.0%) throughout the cycles, whereas ‘B100’ dropped significantly to 8.0% in the final phase. Based on these findings, it is recommended that farmers and stakeholders in dry land areas utilize the ‘Keller’ variety for sustainable sorghum cultivation using the ratoon system. The stability of ‘Keller’ ensures production efficiency by reducing the need for replanting seeds. Additionally, researchers are advised to adopt the combined univariate–multivariate statistical approach for a more comprehensive evaluation of plant breeding data, as it successfully captures complex biological interactions that single-variable analysis might miss.

This study has limitations, primarily because the experiment was conducted at a single dryland location in Bengkulu, Indonesia. As a result, genotype responses across contrasting environmental conditions (G × E) could not be fully assessed. In addition, although a trade-off between vegetative growth and seed yield was identified through correlation analysis, the physiological mechanisms underlying this relationship in ratoon crops remain unresolved. Validation of the agronomic stability of the ‘Keller’ variety under diverse agro-climatic conditions therefore requires evaluation across multiple locations. Future research should expand ratoon evaluations to include a wider range of sorghum genotypes across multiple environments to strengthen comparative insights and support breeding recommendations for ratoon-adapted varieties. Within this framework, particular emphasis should be placed on optimizing nutrient management strategies, especially nitrogen availability and carbohydrate partitioning, to mitigate the decline in reproductive traits observed in later ratoons. Integrating genotype selection with targeted nutrient optimization is expected to enhance yield stability, physiological efficiency, and the overall sustainability of sorghum ratooning systems.

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