Agro-Morphological Characterization and Diversity Analysis of Selected Sorghum Genotypes in Kenyan Agro-Ecologies

ABSTRACT

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| --- |
| Sorghum *(Sorghum bicolor)* is a very important cereal crop cultivated globally, primarily in arid and semi-arid regions. It ranks fifth among the most important cereal crops globally, after wheat, rice, maize, and barley. Despite its crucial role in food security and climate resilience in arid and semi-arid regions, sorghum production remains suboptimal, with yields consistently falling below the crop’s genetic potential. Understanding its morphological diversity is essential for effective breeding programs and genetic resource conservation. This study aimed to determine valuable morphological variation among selected sorghum genotypes against released varieties using a diverse set of traits and their correlations. The experiment was laid out using a Randomised Complete Block Design with three replications using 13 genotypes sourced from the University of Eldoret, and 03 checks from the Kenya Seed Company in Kenya. The genotypes were grown in Endebess and Sigor for one season and evaluated based on morphological traits. Using GenStat statistical software 14th Edition, data on qualitative and quantitative traits were analysed at 5% level of significance. The significant differences among the sorghum genotypes were tested using analysis of variance (ANOVA). Correlation Matrices, first, second and third principal component (PCA) were performed. Principal component analysis revealed the three most important PCs that contributed 81.78%, 15.33% and 1.5% of the total variation, respectively. At the Endebess site, grain yield exhibited the highest genotypic variation among the evaluated sorghum genotypes. E1291 recorded the longest leaves (67.87 cm), whereas Kalatur exhibited the shortest (36.13 cm). Moreover, mean comparisons between the two environments showed that Sigor recorded a higher mean grain yield (2.01 t ha⁻¹) compared to Elgon Downs (1.73 t ha⁻¹). Plant height (0.889) was the trait that contributed most to the variation in the first PC. Number of days to harst (0.814) contributed most to the variation in the second PC, whereas leaf length (0.842) was the largest contributor to the variation observed in the third PC. Correlation analysis showed significant positive relationships between 50% days to emergence to 50% days to flowering and days to maturity (r=0.7 and r=0.9), respectively, suggesting that these traits can be used as selection criteria in breeding programs. The frequency distribution analysis indicated a high occurrence of pigmented leaves (93.75%) and brown grain colour (68.75%), reflecting the natural variability within the studied population. The phenotypic evaluation of sixteen sorghum genotypes revealed significant agro-morphological diversity, confirming the genetic variability. These findings support informed selection and genetic improvement to boost yield and stress resilience in sorghum breeding for Kenya and similar regions. |

*Keywords: Genetic, diversity, Agro-morphological traits, Principal component analysis, Spearman correlation analysis, frequency distribution.*

# 1. INTRODUCTION

Sorghum (*Sorghum bicolor* (L.) Moench) is a cereal crop of immense global importance, particularly in arid and semi-arid regions (Kazungu et al., 2023). It is believed to have been domesticated more than 5,000 years ago in the north -East of Africa and has since spread to most parts globally (Burgarella et al., 2021). Sorghum (*Sorghum bicolor*) is currently ranked fifth in world cereal crop production after maize, wheat, rice, and barley (Ngidi et al., 2024). Its genetic versatility has enabled sorghum to support millions of livelihoods, from smallholder farmers in Africa and Asia to commercial producers in the United States and Australia (Pereira & Hawkes, 2022).

Sorghum is vital for food security in many developing countries, particularly where rainfall is low and soils are poor. It is a smart food, feed, and bioenergy crop, adapted worldwide to temperate and tropical climates. It is a genomic resources rich crop (Upadhyaya et al., 2019; Kazungu et al., 2023). It serves as a staple food grain for more than 500 million people, providing essential calories and nutrients (Khalifa & Eltahir, 2023). In addition to its role as a food crop, sorghum is an important source of fodder for livestock (Julian et al., 2025), especially in mixed farming systems. Its adaptability also makes it suitable for industrial purposes, including ethanol production, biodegradable packaging materials, and brewing industries (Xiao et al., 2021).

Industrially, sorghum is predominantly used by companies producing beverages, breakfast cereals, and confectionery and a small percentage of the grain is also used as animal feed. The crop’s economic potential has not been fully realised in sub-Saharan African (SSA) countries due to a number of production and productivity constraints (Ahmad Yahaya et al., 2022). Despite its crucial role in food security and climate resilience in arid and semi-arid regions, sorghum production remains suboptimal, with yields consistently falling below the crop’s genetic potential (Mwamahonje et al., 2024). This persistent yield stagnation is largely attributed to a lack of Identification of higher yielding varieties and a lack of improved research in the cultivated varieties, making them highly vulnerable to emerging pests, diseases, and increasing environmental stresses exacerbated by climate change (Allan et al., 2020). Knowledge of the genetic diversity of crop species helps the breeder in choosing desirable parents for breeding and in gene introgression from distantly related germplasm (Sejake et al., 2020). To develop superior cultivars that are high-yielding, drought-tolerant, and nutritionally enhanced, there is a critical need to harness the full spectrum of genetic diversity available within cultivated sorghum (Akinola et al., 2020). Understanding of the genetic architecture and variation among breeding lines and commercial varieties will not only support breeding for resilience and productivity but also ensure long-term sustainability of sorghum improvement efforts.

This study is therefore justified by the need to identify and quantify genetic diversity among selected sorghum breeding lines and varieties, strengthen variety protection through characterisation and enhance the overall efficiency and impact of sorghum breeding programs through informed, data-driven selection. The outputs will ultimately support food and income security for smallholder farmers in Kenya and similar dryland ecosystems.

# 2. MATERIAL AND METHODS

## 2.1 Experimental/Plant Materials

The study comprised 16 sorghum genotypes, which were selected for their differences in grain colour and different sources including research institutions and Universities in Kenya. These materials were selected to ensure a comprehensive assessment of genetic diversity, agronomic performance, and adaptability across environments. Released varieties provided a benchmark for evaluating the performance of advanced lines, while the elite lines represented potential candidates for release or use as parental materials in breeding.

## 2.2 Experimental sites

The field screening of the selected sorghum genotypes was conducted in West Pokot County (Sigor) and Trans Nzoia County (Endebess) agro-ecological zones in Kenya. These sites were chosen to capture a broad spectrum of environmental conditions that could influence the performance of sorghum genotypes, particularly in terms of morphological traits. West Pokot (Sigor) is situated at an altitude of 1200–1600 meters above sea level (ASL), with geographical coordinates 35°28'10" E longitude and 1°29'17" N latitude. The area receives a relatively low annual average rainfall of 450 mm, characteristic of arid and semi-arid lands (ASALs). The soils are predominantly sandy loam with a reddish-brown colouration, and the mean annual temperature is approximately 25.02°C. Trans Nzoia (Endebess) is located at a higher altitude range of 1600–1800 m ASL, at 34°51'24" E longitude and 1°4'26" N latitude. The region receives a higher annual average rainfall of about 1000 mm and is characterised by black cotton soils, which are generally fertile and have good moisture retention capacity. The mean annual temperature in Endebess is lower, at approximately 20.47°C. (NEMA, 2013).

## 2.3 Experimental design and field management

The experiment was laid out in a Randomised Complete Block Design (RCBD) replicated three times. Each experimental plot area consisted of 4 rows of 2.5 m length with 0.6 m spacing between rows and 0.20 m between plants. The total area of each plot having a size of 6m2. There was a 1m2 distance between each plot pair. Fertiliser was administered at a rate of 50 kg/acre (Ayako et al., 2021).To avoid direct contact with the seed, fertiliser was spread at the time of seed sowing and thoroughly mixed with the soil. Urea was applied as a side dressing after 35 to 40 days of seedling emergence (knee height stage). To maintain plant spacing and balance plant density, thinning was done three weeks following planting.

##  2.4 Data collection

Data was collected on morphological characters used to characterise sorghum genotypes according to descriptors for sorghum (*Sorghum bicolar* (L.) Moench)(IBPGR & ICRISAT, 1993). These characters included leaf midrib colour, panicle compactness, glume colour, grain colour, leaf orientation, glume covering, awns, threshability, plant height, 100-seed weight, number of days to emergence, flowering and harvest, number of leaves, seed size, plant dry weight, panicle length and width, grain yield and plant dry weight.

**2.5. Data analysis**

Using GenStat statistical software 14th Edition, data on qualitative and quantitative traits were analysed at 5% level of significance. The significant differences among the sorghum genotypes were tested using analysis of variance (ANOVA). The average variations between the experimental genotypes as well as the relationships between these two variables, were tested using Fisher’s test to ascertain whether the observed differences were significant. Correlation Matrices, first, second and third principal component (PCA) were performed. The frequency distribution of the traits on each genotype was also performed and ranked (Gebre et al., 2025)

**3. RESULTS**

**3.1 Mean response of sorghum genotypes in two locations**

Data of the quantitative traits was analysed using Analysis of Variance (ANOVA), and results are indicated in Tables 1,2 & 3. The findings demonstrate the presence of significant genetic variability among the genotypes, as well as environmental influence on trait performance. Highly significant differences (*p*≤0.001) were noted among the sorghum genotypes in seed weight, 50% days to flowering, days to harvest, grain yield, leaf length, leaf width, number of leaves, panicle length, panicle width, plant dry weight and plant height.

The Endebess site demonstrated the greatest genotypic variation in grain yield among the assessed sorghum genotypes. N57 exhibited the highest grain yield at (3.10 t/ha), whereas Kalatur demonstrated the lowest grain yield at (0.35 t/ha). Additionally, the analysis showed that the genotypes differed significantly in plant height (p < 0.001), with T30B being the tallest (158.4 cm) and E1 being the shortest (85.4 cm).

Significant differences between the genotypes were also seen in foliage characteristics such as leaf length, leaf width, and number of leaves per plant. E1291 recorded the longest leaves (67.87 cm), whereas Kalatur exhibited the shortest (36.13 cm). Leaf width was greatest in E1 (8.33 cm) and narrowest in Kalatur (3.29 cm). The number of leaves per plant varied greatly, with E95A producing the most (10.6 leaves) and Kalatur having the fewest (5.33 leaves).

Panicle traits among the evaluated genotypes varied significantly. The longest panicles were observed in E5 (25.93 cm), while N57 had the shortest (18.93 cm). Significant differences (p < 0.001) were also noted in Plant dry weight, where E1291 recorded the highest weight (1.93 kg), and Foehn the lowest (0.73 kg). Stem thickness varied significantly across genotypes, with T30B exhibiting the thickest stems (7.28 cm) and N68 the thinnest (5.06 cm).

Phenological parameters like days to emergence, flowering, and maturity showed substantial variation (p < 0.001). E1291 and C26 emerged earliest (21 days after sowing), while E117B emerged latest (28 days). The shortest duration to flowering was recorded in Foehn, whereas the longest was noted in both E118B and E117B (97.67 days). Maturity duration was longest in T30B, MUK 60, and Gadam (174.3 days), and shortest in E118B (168.3 days). Additionally, 100-seed weight showed highly significant differences, with Foehn recording the highest weight (1.5 g) and E117B the lowest (0.65 g).

At Sigor, highly significant differences (p ≤ 0.001) were observed among sorghum genotypes in grain yield, leaf width, plant height, and plant dry weight. Genotype E118B achieved the highest grain yield (3.31 t/ha), while Kalatur again recorded the lowest yield (1.017 t/ha), demonstrating poor performance across both sites. Plant height varied significantly among genotypes, with N57 attaining the greatest height (246.4 cm), whereas Foehn was the shortest (139.9 cm). Plant dry weight also differed significantly, with Kalatur recording the highest weight (1.7 kg), while MUK 60 had the lowest (0.77 kg). For leaf width, E95A recorded the broadest leaves (13.22 cm), whereas Kalatur had the narrowest (5.27 cm), consistent with its generally poor vegetative performance.

Mean comparisons between the two environments showed that Sigor recorded higher mean grain yield (2.01 t ha⁻¹) compared to Elgon Downs (1.73 t ha⁻¹). Similarly, plants at Sigor were taller (190.3 cm) than those at Elgon Downs (120.7 cm), with larger leaf dimensions (LL: 69.27 cm vs. 55.22 cm; LW: 9.28 cm vs. 6.04 cm). Moreover, sorghum genotypes matured earlier at Sigor (105.96 days) compared to Elgon Downs (173.25 days). Sigor recorded the earliest emergence (DE: 8.85 vs. 23.75) respectively. Sigor site recorded the highest plant dry weight (1.28 vs 1.15) respectively. These findings point to both great genetic variability and pronounced environmental influence on sorghum trait.

**Table 1: Mean of thirteen quantitative traits of the sixteen selected sorghum genotypes evaluated at Endebess**

|  |  |  |  |  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
| **Genotype** | **100-SDW** | **DE** | **DF** | **DH** | **GYLD** | **LL** | **LW** | **NL** | **PAL** | **PAW** | **PDW** | **PH** | **STK** |
| E117B | 0.65a | 28fg | 97.67h | 169ab | 1.17cd | 56.4cde | 7.3gh | 9.2efg | 24.6def | 7.67bcd | 1.43ef | 101.1b | 6.43de |
| N68 | 0.67a | 24.33cd | 96.67fgh | 172.7de | 1.82efg | 58.87cde | 6.47fg | 8.93efg | 19.13ab | 5.47a | 0.97abcd | 144.8d | 5.06a |
| T30B | 0.7ab | 22.67abc | 93.33defg | 174.3efg | 2.17gh | 62.13ef | 5.33bc | 8.67def | 19.4abc | 8.27cde | 1.2cdef | 158.4ef | 7.28f |
| E95A | 0.733abc | 23bc | 92.67def | 174ef | 1.94fgh | 61.87def | 6.87fgh | 10.6h | 25.33ef | 8.4de | 1.37ef | 118.5c | 6.44de |
| N57 | 0.733abc | 23bc | 92de | 174.7fg | 3.10jk | 55.27cde | 6.4efg | 9.07efg | 18.93a | 7.07bcd | 0.87abc | 146.9de | 5.78abcd |
| T53B | 0.77abc | 22.67abc | 92de | 174.3efg | 1.41de | 57.07cde | 5.33bc | 7.8cd | 20.47abc | 9.27e | 1.17bcdef | 137.3d | 5.66abc |
| E5 | 0.8abc | 22.67abc | 91.67cde | 174.3efg | 3.57k | 54.8cd | 6.27cdef | 8.53de | 25.93ef | 7.6bcd | 1.53f | 108.2bc | 5.98bcde |
| E1291(check) | 0.83abc | 21a | 85b | 176g | 2.36hi | 67.87f | 7.47hi | 9.93gh | 26.27f | 7.73bcd | 1.93g | 171.3f | 6.06bcde |
| C26 | 0.9bc | 21a | 92de | 176g | 2.40hi | 66.78f | 5.47bcde | 9.13efg | 22.53bcde | 8.13cde | 1.27def | 117.4c | 6.4cde |
| E1 | 0.9bc | 26.67ef | 95efgh | 170.3bc | 1.55def | 61.2def | 8.33i | 9.67fgh | 24.93def | 8.2cde | 0.93abcd | 85.4a | 6.6ef |
| E118B | 0.9bc | 28.67g | 97.67h | 168.3a | 0.22a | 55.04cde | 6.53fgh | 8.93efg | 22.88cdef | 6.87abc | 0.8ab | 110.8bc | 5.56ab |
| MUK-60 | 0.93c | 22.67abc | 92de | 174.3efg | 2.67ij | 56.27cde | 6.33def | 9.33efg | 21.8abcd | 6.53ab | 1.37ef | 105.2bc | 6.39cde |
| Kari Mtama 1(check) | 1.33d | 23.33bc | 90cd | 173.7ef | 0.6ab | 53.47c | 5.31b | 7.27bc | 25.4ef | 7.6bcd | 1.13bcde | 116.1c | 5.89bcde |
| Kalatur | 1.43d | 25.33de | 87.67bc | 171.7cd | 0.35ab | 36.13a | 3.29a | 5.33a | 24.53def | 7.33bcd | 0.73a | 110.8bc | 5.94bcde |
| Gadam(check) | 1.47d | 22.67abc | 80.33a | 174.3efg | 0.75bc | 43.57b | 3.34a | 6.33ab | 19.4abc | 6.6ab | 0.99abcd | 112.1bc | 5.78abcd |
| Foehn | 1.5d | 23bc | 77a | 174ef | 1.54def | 36.87ab | 5.42bcd | 5.67a | 24.73def | 7.87bcde | 0.73a | 112.1bc | 6.5de |
| **Means** | **0.95** | **23.75** | **90.77** | **173.25** | **1.73** | **55.22** | **6.04** | **8.40** | **22.89** | **7.54** | **1.15** | **120.70** | **6.11** |
| **F pr.** | \*\* | \*\* | \*\* | \*\* | \*\* | \*\* | \*\* | \*\* | \*\* | \*\* | \*\* | \*\* | \*\* |
| **L.S.D 5%** | 0.23 | 1.83 | 4.05 | 1.83 | 0.48 | 7.17 | 0.95 | 1.01 | 3.50 | 1.48 | 0.38 | 13.37 | 0.76 |
| **S.E** | 0.14 | 1.10 | 2.43 | 1.10 | 0.29 | 4.30 | 0.57 | 0.61 | 2.10 | 0.89 | 0.23 | 8.02 | 0.46 |
| **CV%** | 14.40 | 4.60 | 2.70 | 0.60 | 16.70 | 7.80 | 9.40 | 7.20 | 9.20 | 11.80 | 19.50 | 6.60 | 7.50 |

*\* Significant at 5% level (p ≤ 0.05), \*\* = Highly significant (p ≤ 0.01), NS = Not significant (p ≥**0.05 where; SDW- 100-seed weight (g), DEM- 50% days to emergence, DF- 50% days to flowering, GYLD-Grain yield (tha-1), LL- Leaf length (cm), LW-Leaf width (cm), NLVS- Number of leaves, PAL- Panicle length (cm), PAW- Panicle width (cm), PDW- Plant dry weight (tha-1), PHT- Plant height (cm), STM-T- Stem thickness (cm), LSD- Least Significant Difference, Fpr- F Probabilities, CV%- percentage of coefficient of variation. \*Means with the same letter are not significantly different*

**Table 2:** **Mean of thirteen quantitative traits of the sixteen selected sorghum genotypes evaluated at Sigor**

|  |  |  |  |  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
| **Genotype**  | **SDW** | **DE** | **DF** | **DH** | **GYLD** | **LL** | **LW** | **NLVS** | **PAL** | **PAW** | **PDW** | **PH** | **STK** |
| N68 | 0.70ᵃ | 8.33ab | 74ᵃᵇ | 111ᵃᵇ | 1.77ᵇᶜᵈ | 65ᵃᵇᶜ | 9.34ᵇᶜ | 10.67ᵃ | 23.67ᵃᵇ | 8.6ᵇᶜ | 1.4ᵇᶜ | 206.2ᵈᵉ | 5.6ᵃᵇ |
| E117B | 0.73ᵃᵇ | 8.00ab | 85ᵇ | 108ᵃᵇ | 2.72ᶠᵍ | 70.75ᵃᵇᶜᵈ | 9.78ᵇᶜᵈ | 12.44ᵃ | 23.08ᵃᵇ | 8.3ᵇᶜ | 1.47ᵇᶜ | 243.8ᶠᵍ | 6.61ᵃᵇᶜ |
| T53B | 0.83ᵃᵇᶜ | 9.00ab | 69.33ᵃᵇ | 98ᵃ | 1.02ᵃ | 65.67ᵃᵇᶜ | 11.41ᵈ | 11.17ᵃ | 28.42ᵇ | 6.6ᵃᵇ | 1.67ᶜ | 184.1ᵇᶜ | 8.14ᶜ |
| E1 | 0.83ᵃᵇᶜ | 9.00ab | 72.33ᵃᵇ | 108.7ᵃᵇ | 1.34ᵃᵇ | 73.58ᶜᵈ | 9.28ᵇᶜ | 10.25ᵃ | 22.42ᵃᵇ | 6.53ᵃᵇ | 1.45ᵇᶜ | 195.6ᶜᵈ | 5.24ᵃ |
| E95A | 0.87abc | 10ab | 77ab | 101ab | 1.5abc | 73.5cd | 9.56bc | 13.22a | 19.42a | 7.73bc | 0.87a | 224.6ef | 6.46abc |
| N57 | 0.87abc | 8.67ab | 80.67ab | 105ab | 2.592ef | 68.47abcd | 10.25bcd | 11.92a | 24.25ab | 8.13bc | 1.5bc | 246.4g | 6.73abc |
| C26 | 0.97abcd | 8.67ab | 77.33ab | 98.3a | 2.323def | 73.78cd | 10.56cd | 11.94a | 19.42a | 8.23bc | 1.53c | 170.9b | 6ab |
| E118B | 0.97abcd | 7.67a | 75.33ab | 134.7c | 3.312g | 67.08abcd | 10.56cd | 11.75a | 19.92a | 7.47abc | 1.2b | 173.6b | 6.67abc |
| GADAM(check) | 0.97abcd | 7.67a | 69.33ab | 112.7ab | 2.108cdef | 67.58abcd | 5.73a | 11.89a | 23.87ab | 8.4bc | 1.4bc | 174.3b | 7.47bc |
| E5 | 1bcd | 9.33ab | 69.33ab | 101ab | 2.383def | 71.75bcd | 9.17bc | 11.33a | 23.67ab | 6.53ab | 0.8a | 179.3bc | 6.4abc |
| Kari Mtama 1(check) | 1bcd | 7.67a | 77.67ab | 102ab | 2.032cde | 72.33bcd | 9.97bcg | 10.92a | 22.93ab | 7.7bc | 1.47bc | 182.4bc | 5.98ab |
| Kalatur | 1.07cd | 10.33ab | 75.67ab | 99a | 1.017a | 71.58abcd | 5.27a | 12.17a | 25.92ab | 7.2abc | 1.7c | 183.6bc | 6.5abc |
| Foehn | 1.17d | 9.67ab | 60.33a | 93a | 1.873bcd | 65.64abc | 8.6b | 10.75a | 23.53ab | 5.53a | 0.87a | 139.9a | 5.42a |
| T30B | 1.17d | 10.67ab | 70ab | 106.7ab | 2.087cde | 63.75ab | 9.41bc | 11a | 24.17ab | 9c | 0.87a | 197.7cd | 5.52a |
| E1291(check) | 1.2d | 10.67ab | 69.67ab | 121.7bc | 1.507abc | 62.75a | 9.53bc | 10.56a | 27.13b | 6.87ab | 1.6c | 195.1cd | 6.27abc |
| MUK-60 | 1.2d | 8.33ab | 70.33ab | 94.7a | 2.303def | 75.17d | 10bcd | 12.22a | 24.15ab | 7.13abc | 0.77a | 147a | 7.03abc |
| **Means** | **0.97** | **8.85** | **73.3** | **106** | **1.993** | **69.27** | **9.28** | **11.51** | **23.5** | **7.5** | **1.284** | **190.3** | **6.38** |
| **F pr.** | \* | NS | NS | NS | \*\* | NS | \*\* | NS | NS | NS | \*\* | \*\* | NS |
| **L.S.D 5%** | 0.28 | 2.69 | 19.08 | 21.98 | 0.61 | 8.98 | 1.81 | 3.29 | 6.86 | 2.07 | 0.31 | 19.87 | 1.92 |
| **S.E** | 0.17 | 1.62 | 11.44 | 13.18 | 0.37 | 5.38 | 1.08 | 1.98 | 4.12 | 1.24 | 0.19 | 11.92 | 1.15 |
| **CV%** | 17.30 | 18.20 | 15.60 | 12.40 | 18.40 | 7.80 | 11.70 | 17.20 | 17.50 | 16.60 | 14.40 | 6.30 | 18.10 |

*\* Significant at 5% level (p ≤ 0.05), \*\* = Highly significant (p ≤ 0.01), NS = Not significant (p > 0.05) Where; SDW- 100-seed weight (g), DEM- 50% days to emergence, DF- 50% days to flowering, GYLD-Grain yield (tha-1), LL- Leaf length (cm), LW-Leaf width (cm), NLVS- Number of leaves, PAL- Panicle length (cm), PAW- Panicle width (cm), PDW- Plant dry weight (tha-1), PHT- Plant height (cm), STM-T- Stem thickness (cm), LSD- Least Significant Difference, Fpr- F Probabilities, CV%- percentage of coefficient of variation.* *\*Means with the same letter are not significantly different*

**Table 3: Mean response of the selected sorghum genotypes at the two sites**

|  |  |  |  |  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
| **Genotype** | **100- SDW** | **DE** | **DF** | **DH** | **GYLD** | **LL** | **LW** | **NL** | **PAL** | **PAW** | **PDW** | **PH** | **STK** |
| Foehn | 1.33a | 16.33abc | 68.67d | 133.50c | 1.71ef | 51.25e | 7.01b | 8.21d | 24.13ab | 6.70b | 0.80e | 113.60g | 5.96ab |
| Kalatur | 1.25ab | 17.83ab | 81.67abc | 135.30c | 0.69h | 53.86e | 4.28c | 8.75cd | 25.23ab | 7.27ab | 1.21bcd | 147.20e | 6.22ab |
| GADAM(check) | 1.22ab | 15.17c | 74.83cd | 143.5abc | 1.42efg | 55.58de | 4.54c | 9.11bcd | 21.63b | 7.50ab | 1.19bcd | 143.20e | 6.62ab |
| Kari Mtama 1(check) | 1.167abc | 15.50bc | 83.83abc | 137.8bc | 1.35fg | 62.90bc | 7.64ab | 9.09bcd | 24.17ab | 7.65ab | 1.30bc | 149.20de | 5.93ab |
| MUK-60 | 1.07bcd | 15.50bc | 81.17abc | 134.50c | 2.49b | 65.72abc | 8.17ab | 10.78abc | 22.98ab | 6.83b | 1.07cd | 126.10f | 6.71a |
| E1291(check) | 1.02cd | 14.83c | 77.33bcd | 148.80ab | 1.93cd | 65.31abc | 8.50a | 10.25abc | 26.70a | 7.30ab | 1.77a | 183.20b | 6.16ab |
| C26 | 0.93de | 14.83c | 84.67abc | 137.20bc | 2.36b | 70.28a | 8.01ab | 10.54abc | 20.98b | 8.18ab | 1.40b | 144.20e | 6.20ab |
| E118B | 0.93de | 18.17a | 86.33ab | 151.50a | 1.79cde | 61.06bcd | 8.55a | 10.34abc | 21.40b | 7.17ab | 1.00de | 142.20e | 6.11ab |
| T30B | 0.93de | 16.67abc | 81.67abc | 140.50abc | 2.16bc | 62.94bc | 7.99ab | 9.83bcd | 21.78b | 8.63a | 1.03cde | 178.10b | 6.40ab |
| E5 | 0.90de | 16abc | 80.50abc | 137.70bc | 2.98a | 64.41abc | 7.72ab | 9.93abcd | 24.80ab | 7.07b | 1.17bcd | 143.80e | 6.19ab |
| E1 | 0.87def | 17.83ab | 83.67abc | 139.50abc | 1.47efg | 67.39ab | 8.81a | 9.96abcd | 23.68ab | 7.37ab | 1.18bcd | 140.50e | 5.92ab |
| E95A | 0.80ef | 16.50abc | 84.83abc | 137.50bc | 1.72cdef | 67.68ab | 8.21ab | 11.91a | 22.38ab | 8.07ab | 1.12cd | 171.50bc | 6.45ab |
| N57 | 0.80ef | 15.50bc | 86.33ab | 139.80abc | 2.89a | 61.87bcd | 8.33a | 10.49abc | 21.59b | 7.60ab | 1.18bcd | 196.70a | 6.26ab |
| T53B | 0.80ef | 15.83abc | 80.67abc | 136.20bc | 1.21g | 60.23cd | 8.38a | 9.48bcd | 24.44ab | 7.93ab | 1.42b | 160.70cd | 6.90a |
| E117B | 0.69f | 18a | 91.33a | 138.50bc | 1.94cd | 63.58abc | 8.53a | 10.82ab | 23.84ab | 7.98ab | 1.45b | 172.40bc | 6.52ab |
| N68 | 0.68f | 16.33abc | 85.33abc | 141.80abc | 1.79cde | 61.93bcd | 7.91ab | 9.80bcd | 21.40b | 7.03b | 1.18bcd | 175.50b | 5.33b |
| **Mean** | **0.96** | **16.30** | **82.05** | **139.60** | **1.87** | **62.25** | **7.66** | **9.96** | **23.19** | **7.52** | **1.22** | **155.50** | **6.24** |
| Fpr | \*\* | \*\* | NS | \*\* | \*\* | \*\* | \*\* | \* | \* | \*\* | \*\* | \*\* | \* |
| L.S.D | 0.25 | 2.85 | 13.28 | 15.04 | 0.55 | 8.31 | 1.48 | 2.4 | 5.34 | 1.83 | 0.34 | 16.54 | 1.60 |
| S.E | 0.15 | 1.75 | 8.14 | 9.21 | 0.34 | 5.09 | 0.91 | 1.47 | 3.27 | 1.12 | 0.21 | 10.13 | 0.98 |
| CV% | 15.8 | 10.7 | 9.9 | 6.6 | 18 | 8.2 | 11.9 | 14.8 | 14.1 | 14.9 | 17.2 | 6.5 | 15.7 |

*\*\* Highly significant (p ≤ 0.01), \* = Significant (0.01 < p ≤ 0.05), NS = Not significant (p > 0.05) Where;**SDW- 100-seed weight (g), DEM- 50% days to emergence, DF- 50% days to flowering, GYLD-Grain yield (tha-1), LL- Leaf length (cm), LW-Leaf width (cm), NLVS- Number of leaves, PAL- Panicle length (cm), PAW- Panicle width (cm), PDW- Plant dry weight (tha-1), PHT- Plant height (cm), STM-T- Stem thickness (cm), LSD- Least Significant Difference, Fpr- F Probabilities, CV%- percentage of coefficient of variation. \*Means with the same letter are not significantly different.*

## 3.2 Principal component analysis

The quantitative data were subjected to principal component analysis (PCA), which revealed that the three most important PCs contributed PC1 (81.78%), PC2 (15.33%) and PC3 (1.5%) of the total variation. Plant height (0.889) was the trait that contributed most to the variation in the first PC. Number of days to harvest (0.814) contributed most to the variation in the second PC, whereas leaf length (0.842) was the largest contributor to the variation observed in the third PC.

**Table 4: A factor loading of the quantitative morphological traits in sixteen sorghum genotypes evaluated across two locations, showing the most important PCs**

| **Factor loadings** |
| --- |
| **Traits** | **PC1** | **PC2** | **PC3** |
| %100\_SDW\_g | -0.001  | -0.005  | -0.015  |
| DE | -0.103  | 0.119  | 0.055  |
| DF | -0.064  | 0.346  | 0.491  |
| DH | -0.426  | 0.814  | -0.069  |
| GYLD\_t | 0.005  | 0.002  | 0.031  |
| LL | 0.109  | -0.090  | 0.842  |
| LW | 0.028  | -0.027  | 0.106  |
| NL | 0.027  | -0.005  | 0.116  |
| PAL | -0.006  | -0.044  | -0.070  |
| PAW | 0.004  | 0.020  | 0.017  |
| PDW | 0.003  | 0.005  | 0.013  |
| PH | 0.889  | 0.440  | -0.102  |
| STK | 0.002  | -0.002  | 0.006  |
| % variation | 81.780  | 15.330  | 1.500  |
| Latent roots | 388506.000  | 72840.000  | 7114.000  |

*\*SDW-seed weight, DE- 50% days to emergence, DF- 50% days to flowering, GYLD- Grain yield, LL- leaf length, LW- Leaf width, NL- Number of leaves, PAL- Panicle length, PAW- Panicle width, PDW- Plant dry weight, PH- Plant height*.

## 3.3 Combined Spearman’s rank correlation analysis of qualitative and quantitative traits

Thirteen important qualitative traits and fourteen quantitative traits were analysed using Spearman’s rank correlation coefficients (Table 5). The qualitative traits were grain and midrib colors, inflorescence shape and compactness, glume covering, glume color and either presence or absence of awns, leaf orientation, leaf pigmentation, seedling vigour, seed size, threshability, pest (Sucking bugs, fall armyworm, stem borer), disease (Anthracnose, smut, bacterial stripe and blight), and drought resistance.

Number of days to 50% flowering was strongly negatively correlated to 1000-seed weight (r=-0.5) at P˂0.01. Days to emergence was significantly positively correlated to 50% days to flowering and days to maturity (r=0.7 and r=0.9) respectively, while it is strongly negatively correlated to leaf length (r=-0.6), leaf width (r=-0.7), number of leaves in a plant (r=-0.6) and plant height (r=-0.7) at P˂0.01. Number of days to 50% flowering is strongly positively correlated to number of days to the harvest of the crop (r=0.7) at P˂0.01.

The number of days to harvest is strongly negatively correlated to leaf length (r=-0.6), leaf width (r=-0.8), number of plant leaves (r=-0.6) and height of the plant (r=-0.6) at P˂0.01. Disease resistance is strongly positively correlated to pest resistance (r=0.5) and strongly negatively correlated to seedling colour (r=-0.5) at *p*˂0.01. Drought resistance is strongly negatively correlated to ear head shape and compactness (r=-0.6) at P˂0.01. Ear head shape and compactness of the sorghum genotypes are strongly negatively correlated to the orientation of the leaves (r=-0.6) and colour of the seeds (r=-0.6), while it is strongly positively correlated to the ability to thresh (r=0.6) at *p*˂0.01.

Colour of glumes was strongly negatively correlated to seedling vigour (r=-0.5) at *p*˂0.01. The length of leaves was strongly positively correlated to the width of leaves (r=0.8), the number of leaves (r=0.8) and the height of plants (r=0.6) at *p*˂0.01. Orientation of leaves showed a strong negative correlation to threshability (r=-0.6) at *p*˂0.01. The colour of the midrib exhibited a strong positive correlation to the size of the seed (r=0.5) at P˂0.01.

The number of leaves also exhibited a significantly positive correlation to plant dry weight (r=0.5) and height of the plant (r=0.7) at P˂0.01. Seedling vigour was strongly negatively correlated with seed size (r=-0.5) at P˂0.01

**Table 5 Spearman’s rank correlation analysis of qualitative and quantitative traits**

| **t** | **\_SDW** | **DE** | **DF** | **DH** | **DR** | **DRR** | **EHSC** | **GCL** | **GCV** | **GY** | **LL** | **LOR** | **LP** | **LW** | **MDC** | **NL** | **PAL** | **PAW** | **PDW** | **PH** | **PR** | **SC** | **SS** | **STK** | **SV** | **TSH** |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
| **SW** |  **-** |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |
| **DE** | **0.0**  |  **-** |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |
| **DF** | **-0.5\*\*\***  | **0.7\*\*\*** |  **-** |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |
| **DH** | **-0.1**  | **0.9\*\*\***  | **0.7\*\*\***  |  **-** |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |
| **DR** | **0.2**  | **0.0**  | **-0.1**  | **0.0**  |  **-** |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |
| **DRR** | **-0.4**  | **0.0**  | **0.1**  | **0.0**  | **-0.1**  |  **-** |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |
| **EHSC** | **0.3**  | **0.0**  | **-0.1**  | **0.0**  | **0.0**  | **-0.6\*\*\***  |  **-** |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |
| **GCL** | **-0.1**  | **0.1**  | **0.1**  | **0.0**  | **0.2**  | **0.3**  | **-0.1**  |  **-** |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |
| **GCV** | **-0.3**  | **0.0**  | **0.1**  | **0.0**  | **-0.1**  | **0.4**  | **-0.1**  | **0.2**  |  **-** |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |
| **GY** | **-0.2**  | **-0.3**  | **0.0**  | **-0.1**  | **0.0**  | **0.0**  | **0.0**  | **-0.1**  | **0.1**  |  **-** |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |
| **LL** | **-0.3**  | **-0.6\*\*\***  | **-0.3**  | **-0.6\*\*\*** | **-0.2**  | **0.0**  | **0.0**  | **-0.1**  | **0.0**  | **0.3**  |  **-** |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |
| **LOR** | **-0.1**  | **0.0**  | **0.1**  | **0.0**  | **-0.2**  | **0.3**  | **-0.5\*\*\***  | **0.1**  | **-0.2**  | **-0.1**  | **0.0**  |  **-** |  |  |  |  |  |  |  |  |  |  |  |  |  |  |
| **LP** | **0.0**  | **0.0**  | **0.1**  | **0.0**  | **-0.4**  | **0.1**  | **0.3**  | **-0.3**  | **-0.2**  | **0.0**  | **0.1**  | **0.2**  |  **-** |  |  |  |  |  |  |  |  |  |  |  |  |  |
| **LW** | **-0.3**  | **-0.7\*\*\***  | **-0.4**  | **-0.8\*\*\***  | **-0.1**  | **0.0**  | **0.0**  | **0.0**  | **0.1**  | **0.3**  | **0.8\*\*\***  | **0.0**  | **0.0**  |  **-** |  |  |  |  |  |  |  |  |  |  |  |  |
| **MDC** | **0.3**  | **0.0**  | **-0.1**  | **0.0**  | **0.1**  | **0.0**  | **-0.2**  | **0.2**  | **-0.3**  | **-0.2**  | **-0.2**  | **0.4**  | **-0.1**  | **-0.1**  |  **-** |  |  |  |  |  |  |  |  |  |  |  |
| **NL** | **-0.4**  | **-0.6\*\*\***  | **-0.1**  | **-0.6\*\*\***  | **-0.1**  | **0.1**  | **0.0**  | **0.1**  | **0.1**  | **0.3**  | **0.8\*\*\***  | **0.0**  | **0.1**  | **0.8\*\*\***  | **-0.3**  |  **-** |  |  |  |  |  |  |  |  |  |  |
| **PAL** | **0.2**  | **0.0**  | **-0.3**  | **-0.1**  | **0.0**  | **-0.1**  | **0.2**  | **-0.1**  | **0.0**  | **-0.3**  | **-0.1**  | **-0.3**  | **0.0**  | **0.0**  | **-0.1**  | **-0.1**  |  **-** |  |  |  |  |  |  |  |  |  |
| **PAW** | **-0.3**  | **0.0**  | **0.4**  | **0.1**  | **-0.1**  | **0.1**  | **0.0**  | **0.1**  | **0.0**  | **0.2**  | **0.0**  | **0.1**  | **0.1**  | **0.1**  | **0.0**  | **0.3**  | **-0.1**  |  **-** |  |  |  |  |  |  |  |  |
| **PDW** | **-0.4**  | **-0.2**  | **0.2**  | **-0.1**  | **0.0**  | **0.1**  | **0.0**  | **-0.1**  | **0.1**  | **0.2**  | **0.4**  | **-0.1**  | **0.1**  | **0.4**  | **-0.2**  | **0.5\*\*\***  | **0.1**  | **0.4**  |  **-** |  |  |  |  |  |  |  |
| **PH** | **-0.3**  | **-0.7\*\*\***  | **-0.2**  | **-0.6\*\*\***  | **0.0**  | **0.2**  | **-0.1**  | **0.0**  | **0.0**  | **0.2**  | **0.6\*\*\***  | **0.1**  | **0.0**  | **0.6\*\*\***  | **-0.1**  | **0.7\*\*\***  | **-0.2**  | **0.3**  | **0.5\*\*\***  |  **-** |  |  |  |  |  |  |
| **PR** | **0.0**  | **0.0**  | **0.0**  | **0.1**  | **0.5\*\*\***  | **0.1**  | **0.1**  | **0.3**  | **0.2**  | **0.0**  | **-0.1**  | **0.3**  | **-0.2**  | **0.0**  | **0.1**  | **0.0**  | **-0.1**  | **0.0**  | **0.0**  | **0.0**  |  **-** |  |  |  |  |  |
| **SC** | **-0.4**  | **0.0**  | **0.1**  | **0.0**  | **-0.5\*\*\***  | **0.3**  | **-0.6\*\*\***  | **0.1**  | **0.2**  | **0.0**  | **0.2**  | **0.3**  | **-0.2**  | **0.1**  | **-0.2**  | **0.2**  | **-0.1**  | **0.0**  | **-0.1**  | **0.0**  | **-0.4**  |  **-** |  |  |  |  |
| **SS** | **0.3**  | **0.1**  | **0.0**  | **-0.1**  | **0.2**  | **0.0**  | **-0.1**  | **0.3**  | **-0.2**  | **-0.1**  | **-0.3**  | **0.3**  | **0.0**  | **-0.2**  | **0.5\*\*\*** | **-0.1**  | **-0.1**  | **0.0**  | **-0.2**  | **-0.1**  | **0.0**  | **-0.1**  |  **-** |  |  |  |
| **STK** | **-0.1**  | **-0.2**  | **-0.1**  | **-0.1**  | **0.0**  | **0.1**  | **0.1**  | **0.1**  | **0.1**  | **0.1**  | **0.1**  | **0.0**  | **0.0**  | **0.3**  | **-0.1**  | **0.1**  | **0.1**  | **0.3**  | **0.1**  | **0.1**  | **0.1**  | **0.0**  | **0.0**  |  **-** |  |  |
| **SV** | **0.0**  | **-0.1**  | **-0.1**  | **0.0**  | **-0.2**  | **-0.3**  | **0.0**  | **-0.5\*\*\***  | **-0.2**  | **0.2**  | **0.2**  | **-0.3**  | **-0.1**  | **0.0**  | **-0.2**  | **0.1**  | **0.0**  | **-0.1**  | **0.0**  | **0.0**  | **-0.4**  | **0.1**  | **-0.5\*\*\***  | **-0.1**  |  **-** |  |
| **TSH** | **0.1**  | **0.0**  | **-0.1**  | **-0.1**  | **-0.1**  | **-0.4**  | **0.6\*\*\***  | **-0.2**  | **0.2**  | **0.2**  | **0.0**  | **-0.6\*\*\***  | **0.1**  | **0.0**  | **-0.4**  | **0.0**  | **0.3**  | **-0.1**  | **0.1**  | **-0.1**  | **-0.1**  | **-0.3**  | **-0.1**  | **0.1**  | **0.3**  |  **-** |
|  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |

*\*SDW-seed weight, DE- 50% days to emergence, DF- 50% days to flowering, DR- disease resistance, DRR- Drought resistance, EHSC- Ear head shape and compactness, GCL- Glume colour, GCV-Glume covering, GYLD- Grain yield, LL- leaf length, LOR- Leaf orientation, LP- Leaf pigmentation, LW- Leaf width, MDC- Midrib colour, NL- Number of leaves, PAL- Panicle length, PAW- Panicle width, PDW- Plant dry weight, PH- Plant height, PR- Pest resistance, SC- Seed colour, SS- Seed size, STK- Stem thickness, SV- Seedling vigour, TSH- Threshability.*

## 3.4 Frequency distribution of qualitative traits

The frequency distributions of the sorghum accessions for the qualitative traits are presented in Table 6. Fifteen (93.75%) selected sorghum genotypes were pigmented, while one (6.25%) was tan. Six (37.5%) had erect leaves while ten (62.5%) had horizontal leaf orientation. Ear head compactness and shape (EHCS) showed variation with five (31.25%) accessions being compact elliptic, two (12.5%) compact erect, three (18.75%) semi-compact elliptic, five (31.25%) semi-compact erect and one (6.25%) being semi-compact drooping. None of the genotypes had awns at maturity. There was also variation in the midrib colour among the accessions, in that five (31.25%) accessions had dull green midribs, followed by eleven (68.75) accessions with white midribs. In terms of the glume colour, two (12.5%) genotypes had black glumes, one (6,25%) brown, one (6.25%) grey, six (37.5%) purple, four (25%) red, and two (12.5%) siena. eight (50%) of the genotypes had 25% glume covering, and the rest eight (50%) had 50% glume covering. There was also variation in the seed sizes, with one (6.25%) large, seven (43.75%) medium and eight (50%) small. With seed colour, eleven (68.75%) had brown colour, one (6.25%) chalky white, one (6.25%) cream, two (12.5%) red and one (6.25%) speckled white. The genotypes were also tested for threshability, and one (6.25%) had very good threshability, nine (56.25%) good, four (25%) medium and two (12.5%) with poor threshability.

**Table 6: Frequency distribution of the qualitative traits of the sorghum genotypes observed at Elgon downs farm and Sigor**

|  |  |  |  |
| --- | --- | --- | --- |
| **Trait** | **Descriptor** | **Genotypes out of 16 selected** | **Frequency %** |
| Leaf pigmentation | Tan | 1 | 6.25 |
|   | Pigmented | 15 | 93.75 |
| Leaf orientation | Erect | 6 | 37.5 |
|   | Horizontal | 10 | 62.5 |
| Midrib colour | Dull green | 5 | 31.25 |
|   | white | 11 | 68.75 |
| Glume colour | Black | 2 | 12.5 |
|   | Brown | 1 | 6.25 |
|   | Grey | 1 | 6.25 |
|   | Purple | 6 | 37.5 |
|   | Red | 4 | 25 |
|   | Siena | 2 | 12.5 |
| Glume covering | 25 | 8 | 50 |
|   | 50 | 8 | 50 |
| awns | absent | 16 | 100 |
| seed size | large | 1 | 6.25 |
|   | Medium | 7 | 43.75 |
|   | small | 8 | 50 |
| seed colour | Brown | 11 | 68.75 |
|   | Chalky white | 1 | 6.25 |
|   | Cream  | 1 | 6.25 |
|   | Red | 2 | 12.5 |
|   | Speckled white | 1 | 6.25 |
| Threshability | Good | 9 | 56.25 |
|   | Very good | 1 | 6.25 |
|   | Medium | 4 | 25 |
|   | Poor | 2 | 12.5 |
| EHCS | Compact erect | 2 | 12.5 |
|   | Compact elliptic | 5 | 31.25 |
|   | Semi -compact elliptic | 3 | 18.75 |
|   | Semi -compact erect | 5 | 31.25 |
|   | Semi -compact drooping | 1 | 6.25 |

## 3.5 Morphological Variability Based on Qualitative Traits

Field evaluation of the 16 sorghum genotypes revealed notable phenotypic diversity in traits related to grain and panicle morphology. Clear differences were observed in seed colour, ranging from white and cream to reddish-brown. Seed sizes also varied among the genotypes, with some producing large, bold grains and others yielding smaller, compact seeds. In terms of panicle shape, the genotypes displayed a spectrum ranging from compact and semi-compact to loose and open panicles. Compact panicles, as observed in genotypes *E5* and *E1 (Fig.1)*, are generally associated with higher grain density and reduced susceptibility to grain mould in humid areas.

|  |
| --- |
|    Foehn Gadam E95A  **E1 E5 MUK-60**   E1 E5 E95A |

Figure 1. Sorghum genotypes indicating variability in seed size, colour and panicle shapes, i.e Foehn(Large, brown ), Gadam (Medium, chalky white), E95A (Medium, speckled Brown, semi-compact elliptic), E1(Small, brown compact panicle), E5 (small, brown seeded and compact elliptic panicle),

# 4. DISCUSSION

The use of morphological markers is effective and only reliable if they give a wide range of variation between accessions (Karugu, 2009). Morphological markers positively correlated to yield or other important traits that contribute to yield would be very useful to aid in early generation selection. Sixteen sorghum accessions were described and assessed for agro-morphological traits, where qualitative and quantitative features showed a wide range of variation. Crop germplasm has been subjected to phenotypic study using both qualitative and quantitative parameters, (Kisilu & Ngugi, 2021) reported using phenotypic data to assess diversity in 148 sorghum accessions, (Apunyo et al., 2022), also reported phenotypic diversity of sorghum accessions on farmers’ fields in Northern and Eastern Uganda.

Quantitative traits such as seed mass, yield, plant height and earliness are mostly used by farmers and breeders to determine desirable traits for future cropping and improved varieties (Porcuna-Ferrer et al., 2025). Understanding the significant correlation among the characters is crucial for many breeding programs since it allows for the simultaneous selection of desired genotypes and desirable phenotypes (Mofokeng, 2015) .

**4.1 Yield and associated traits**

For certain sorghum varieties, greater grain yield aligns with longer panicles and increased plant dry mass. Yield is determined by a suite of interacting factors, where panicle architecture and total biomass both play critical roles. Recent research has documented robust positive relationships between grain yield and traits such as panicle length and total dry weight (Santhiya et al., 2021; Vinoth et al., 2021), reinforcing the value of selecting genotypes that combine elevated yield with beneficial morpho-physiological characteristics.

**4.2 Phenoloical traits and adaptation**

Early flowering and days to harvest, observed in some genotypes, are beneficial in regions with short rainfall durations or terminal drought. Early maturing genotypes are better suited to drought-prone environments as they can complete their life cycle before the onset of stress (El Mannai et al., 2011). This trait also enables double cropping in some regions. The delayed flowering observed in some genotypes may confer a significant adaptive advantage in environments with extended growing periods. In such regions, prolonged vegetative growth enables these genotypes to utilise the available resources throughout the season fully. This extended duration before the onset of reproductive development enables greater biomass accumulation, enhanced root development, and improved nutrient uptake, all of which contribute to better grain filling and potentially higher yields (Carillo, 2025. Moreover, delayed flowering may help these genotypes avoid early-season environmental stresses, such as transient droughts or pest pressures, by aligning critical reproductive stages with more favourable climatic conditions later in the season (Kazan & Lyons, 2015). Therefore, the late-flowering trait may be particularly valuable in breeding programs targeting highland or tropical agroecologies where the growing season is long and uninterrupted, and where early-maturing varieties might fail to exploit the full productive potential of the environment (Ceccarelli, 2015).

Leaf size and number directly impact the plant’s photosynthetic capacity. Genotypes with longer and wider leaves are expected to accumulate more biomass due to a larger photosynthetic surface area (Santhiya et al., 2021). Similarly, genotypes with more leaves may support sustained growth and assimilate production, contributing indirectly to higher yields.

Panicle length and width influence the number of grains per panicle and overall yield. Genotypes with longer and wider panicles exemplify desirable architecture for improving yield. Wider panicles may accommodate more florets, increasing reproductive success (Parida et al., 2022). Selection for improved panicle traits remains a vital component of yield enhancement strategies.

Plant height and stem thickness are important traits for biomass production and lodging resistance. Tallest genotypes could be suited for fodder production or biomass-related breeding programs. However, taller plants are generally more prone to lodging. The thicker stems may offer structural integrity, reducing the risk of lodging (Ren et al., 2024). Combining moderate height with stem robustness should be a target in breeding programs.

**Genotype × Environment Interaction**

The difference in performance of genotypes across the two environments indicates a strong genotype × environment (G × E) interaction. This interaction has been observed in traits such as grain yield, plant height, and days to harvest, where genotypes responded differently depending on site conditions. The better performance at Sigor suggests that this environment provided more favorable conditions for sorghum growth, which could be attributed to factors such as soil fertility and temperature. These findings align with the work of (Demelash, 2024) who reported significant G × E interactions in multi-environment trials of sorghum, necessitating careful consideration of environment-specific selection. The presence of significant G × E interaction highlights the importance of evaluating genotypes across diverse environments to identify stable and widely adaptable lines. This is particularly crucial in breeding programs targeting marginal and variable agroecologies, where environmental stresses are common (Yuru et al., 2024).

Additionally, site effects on yield and maturity highlight the potential for tailoring genotype recommendations to specific production environments. As observed, genotypes that matured earlier and produced higher yields at Sigor may be better suited for drier or short-season environments, whereas genotypes adapted to Endebess could be exploited for longer growing periods or higher altitude conditions.

**4.3 Principal Component Analysis**

Principal Component Analysis (PCA) is a common technique for reducing data dimensionality, but it involves subjective decisions at various stages. These include choosing which variables to analyse, how to standardise the data, and how many components to retain. Such decisions can influence both the interpretation and the outcome of the analysis, making transparency essential (Gebre et al., 2024).

 Plant height is a major contributor to genetic diversity. Plant height is the most significant trait influencing diversity, playing a crucial role in genotype differentiation. Similarly, Mofokeng et al., (2017) reported that plant height, panicle weight and grain yield significantly influence sorghum diversity. Days to harvest (DH) and days to flowering (DF) contribute to variability in reproductive timing, which is vital for adaptation and breeding.

Principal Component Analysis (PCA) has been extensively utilised to evaluate genetic diversity in sorghum through agro-morphological traits. Various studies have identified key traits contributing to variability. (Kavithamani et al., 2019) conducted PCA on 100 sorghum germplasm accessions and found that 100-seed weight, plant height, leaf blade length, and leaf blade width were significant contributors to genetic diversity. Similarly, Sejake et al. (2020) assessed 100 sorghum accessions and reported that traits such as plant height, panicle length, and grain weight per panicle played crucial roles in genetic variation. In another study, Ngugi & Maswili (2011) evaluated 148 Kenyan sorghum landraces and observed that panicle branches, panicle length, and grain weight were significant in determining phenotypic diversity. A study on Moroccan sorghum ecotypes revealed that plant height, leaf length, and panicle length were among the primary traits contributing to agro-morphological variation (Bouargalne et al., 2022). These studies collectively affirm that PCA is an effective tool for identifying key traits that influence genetic variation in sorghum, aiding in the selection of superior genotypes for breeding and conservation programs.

**4.4 Pearson’s Correlation Analysis**

The Pearson correlation analysis revealed several statistically significant relationships among key plant traits, which provide valuable insights for plant breeding strategies. These correlations can help breeders identify traits that can be simultaneously improved or indicate potential trade-offs.

In order to enhance plant structure or crop output, selection needs to be based on the association of relevant characteristics, which measures the associations or correlations between various plant attributes and identifies key traits that may be used as the basis for breeding to increase crop seed yield (Tilahun et al., 2024). To select ecotypes that are promising, which combine different agronomically important characters, correlation analysis has been used as an important indicator (Bouargalne et al., 2022).

A strong positive correlation between days to flowering and days to harvest suggests that plants that flower later also mature later. Similar results were exhibited in wheat, grain yield per plant showed a significant positive correlation with biological yield per plant, plant height, and thousand-grain weight, indicating that traits influencing plant development stages are interrelated (Devesh, 2021). These results are also similar to those of (Mallu, 2015) who evaluated chick pea genotypes for yield and selection of agronomic traits in Kenya.

Negative correlation showed that the late-flowering plants had better seed weight as compared to the early-flowering genotypes. Similar to our results, (Ouma & Akuja, 2013) showed that the number of days to flowering was significantly and positively correlated with height and yield, but not 100-seed weight. The earlier maturing genotypes had lower seed number and yield than medium and late-maturing genotypes, but greater seed size.

Significant negative correlations between leaf dimensions and days to flowering and harvest suggest that plants with larger leaves tend to mature earlier. In *Populus deltoides*, collar diameter exhibited a significant positive correlation with plant height, highlighting the association between vegetative growth traits (Singh et al., 2016). A negative correlation between the number of leaves and days to flowering/harvest indicates that plants with more leaves mature earlier. Similar results by (Dhurai., 2014) indicated that in rice, grain yield was significantly associated with harvest index and number of grains per panicle, suggesting that traits contributing to yield are interconnected.

A positive correlation between pest and drought resistance suggests that plants tolerant to drought may also exhibit pest resilience. Diseases like anthracnose, smut, blight, and ergot are more likely to strike plants with pest infestations. Plants that have been harmed by pests are more vulnerable to infection by pathogens. Aphids, caterpillars, fall armyworm, stem borer and other pests can harm leaves, increasing the likelihood that disease-causing organisms will infect them. Aphids cover leaves with honeydew, a sugary fluid that draws insects and dangerous fungi (Nazarov et al., 2020)

A significant correlation between seed size and panicle length indicates that larger seeds are associated with longer panicles. Similarly, in maize, plant height, ear length, and number of kernels per row recorded significantly positive genetic correlations with grain yield per plant, emphasising the relationship between structural traits and yield components (Mahesh et al., 2022). A positive correlation between plant dry weight and panicle width suggests that plants with greater biomass tend to have wider panicles. In wheat, grain yield per plant showed significant positive correlations with biological yield per plant and plant height, indicating that biomass-related traits are crucial for yield improvement (Devesh et al., 2021).

**4.5 Qualitative trait distribution**

The diversity of accessions for grain colour observed in this study aligns with the findings of (Sejake et al., 2020), who reported that 46% of 100 landraces exhibited brown grain sorghum, and (Alade & Obilana, 2022), who found that only 2% of 98 accessions had brown grain. In the present study, 68.25% of the genotypes displayed a brown grain colour. Brown grain sorghum is typically associated with a relatively high tannin content, which makes it less attractive to birds (Sejake et al., 2020). In Kenya, brown sorghum serves as a staple food and is consumed in various forms, including porridge and ugali (a cooked dough). It is also widely used as animal feed, particularly for livestock, due to its ability to thrive in semi-arid regions. Additionally, brown sorghum is a key ingredient in the production of traditional alcoholic beverages such as sorghum beer (Kazungu et al., 2023)

White grain sorghum, on the other hand, has a lower tannin content, making it more suitable for milling into flour for baking. However, its lack of tannins makes it more susceptible to bird predation (Sejake et al., 2020). Notably, all sorghum accessions in this study lacked awns at maturity. The absence of awns in sorghum is often associated with reduced evapotranspiration, which is beneficial in dry lowland areas Verma et al., 2017). Awnless sorghum genotypes are preferred due to the reduced effort required for cleaning. This preference is further supported by the fact that a significant proportion of the genotypes examined in this study exhibited good (56.25%) or very good (6.25%) threshability.

Threshability is also influenced by glume coverage, as increased glume coverage tends to reduce threshability (Alade & Obilana, 2022). In this study, 50% of the assessed sorghum genotypes had 25% glume coverage, while the remaining 50% had 50% coverage. Typically, grain sorghums exhibit less glume coverage than fodder sorghums. Furthermore, darker glumes have been associated with resistance to grain mould (Alade & Obilana, 2022). In this study, the distribution of glume colours among the genotypes was as follows: black (12.5%), brown (6.25%), gray (6.25%), purple (37.5%), red (25%), and sienna (12.5%). The variation in glume colour could serve as a useful trait for screening sorghum genotypes for grain mould resistance. Variations in panicle shape have also been documented by (Raj et al., 2018)

The present study found that accessions with compact panicles tended to have higher grain yields compared to other panicle types. This finding aligns with previous research, which suggests that compact panicles contain more seeds than open panicles, contributing to their higher yield potential. Additionally, genotypes with loosely branched panicles may be better suited for humid regions with high rainfall, as they are less susceptible to diseases such as ergot and grain mould (Ringo et al., 2014)

Leaf midrib colour is an important characteristic that farmers use to differentiate between sweet sorghum and grain sorghum (Sejake et al., 2020). The colour of the leaf midrib serves as an indicator of the stem's internal properties. Green midribs are typically associated with more succulent stems containing higher moisture content, indicating juiciness. In contrast, white midribs are associated with drier, pithier stems that contain more air pockets and less moisture (Boukrouh et al., 2023). The pithy nature of white-midrib stems affects their palatability and digestibility, making them less suitable as livestock feed. Given its significance in distinguishing sorghum varieties, leaf midrib colour remains a crucial visual characteristic for farmers in sorghum selection

# 5. CONCLUSION

This phenotypic analysis of sixteen sorghum lines showed a lot of agro-morphological diversity. This confirms that there is genetic diversity that can be exploited for breeding. Yield potential, maturity period, and dual-purpose use exhibited significant variation among genotypes, with E1, E5, MUK-60, and T30B demonstrating superior performance. Correlation and principal component analyses revealed significant trait relationships, including positive associations among plant height, leaf traits, and maturity time. These findings can inform direct selection strategies aimed at enhancing early maturity and yield. The observed diversity supports the objective of classifying genotypes and identifying breeding candidates for specific ecological zones. Integrating phenotypic with molecular data is recommended to enhance selection precision in future breeding programs.

**Disclaimer (Artificial intelligence)**

Author(s) hereby declare that NO generative AI technologies such as Large Language Models (ChatGPT, COPILOT, etc.) and text-to-image generators have been used during the writing or editing of this manuscript.

**REFERENCES**

Abreha, K. B., Enyew, M., Carlsson, A. S., Vetukuri, R. R., Feyissa, T., Motlhaodi, T., Ng’uni, D., & Geleta, M. (2021). Sorghum in dryland: morphological, physiological, and molecular responses of sorghum under drought stress. *Planta*, *255*(1), 20. https://doi.org/10.1007/s00425-021-03799-7

Agele, S. O., I. A., A., E. O., A., & and Olabomi, A. (2008). Responses of growth, yield and N use efficiency of selected tomato cultivars to variations in hydrothermal regimes of the cropping seasons in a tropical rainforest zone of Nigeria. *Journal of Plant Interactions*, *3*(4), 273–285. https://doi.org/10.1080/17429140802112863

Akinola, R., Pereira, L. M., Mabhaudhi, T., de Bruin, F.-M., & Rusch, L. (2020). A Review of Indigenous Food Crops in Africa and the Implications for more Sustainable and Healthy Food Systems. *Sustainability*, *12*(8), 3493. https://doi.org/10.3390/su12083493

Aklilu, E., Bidir, A., Yasin, H., Wubie, A., Tsehay, A., Tahir, Z., Fentie, B., Gelaye, M., Adem, A., Desalign, M., Wubie, G., & Ali, Y. (2020). Stability analysis of seed yield of Ethiopian caraway ( *Trachyspermum ammi* L. Sprague ex Turrill) genotypes in multienvironment trials. *Cogent Food & Agriculture*, *6*(1), 1786312. https://doi.org/10.1080/23311932.2020.1786312

Alade, O. D., & Obilana, L. S. (2022). Morphological Characterization of Sorghum (Sorghum bicolor) Local Accessions Collected from Southern Nigeria using Qualitative and Quantitative Traits. In *Nigerian Agricultural Journal* (Vol. 53, Issue 2). http://www.ajol.info/index.php/najhttps://www.naj.asn.org.ng

Allan, V., Geetha, S., Vetriventhan, M., & Azevedo, V. (2020). Genetic diversity analysis of geographically diverse landraces and wild accessions in Sorghum. *Electronic Journal of Plant Breeding*, *11*, 760–764. https://doi.org/10.37992/2020.1103.125

Apunyo P, Otim M, & Odong T. (2022). Phenotypic characterization of sorghum accessions on farmers’ fields in northern and eastern Uganda. *International Journal of Biodiversity and Conservation*, *14*(4), 181–189. https://doi.org/10.5897/IJBC2022.1564

Ayako, W., Nguru, J., Mathai, N., Chelimo, E., & Mbugua, D. (2021). *Sorghum (Sorghum bicolor) (Variety: E1291) Seed Production Manual*.

Ayana, A., & Bekele, E. (2004). Geographical Patterns of Morphological Variation in Sorghum (Sorghum Bicolor (L.) Moench) Germplasm from Ethiopia and Eritrea: Qualitative Characters. *Hereditas*, *129*, 195–205. https://doi.org/10.1111/j.1601-5223.1998.t01-1-00195.x

Bouargalne, Y., Ben Mrid, R., Bouchmaa, N., Zouaoui, Z., Benmrid, B., Kchikich, A., El Omari, R., Kabach, I., & Mohamed, N. (2022a). Genetic diversity for agromorphological traits, phytochemical profile, and antioxidant activity in Moroccan sorghum ecotypes. *Scientific Reports*, *12*(1), 5895. https://doi.org/10.1038/s41598-022-09810-9

Bouargalne, Y., Ben Mrid, R., Bouchmaa, N., Zouaoui, Z., Benmrid, B., Kchikich, A., El Omari, R., Kabach, I., & Mohamed, N. (2022b). Genetic diversity for agromorphological traits, phytochemical profile, and antioxidant activity in Moroccan sorghum ecotypes. *Scientific Reports*, *12*(1), 5895. https://doi.org/10.1038/s41598-022-09810-9

Boukrouh, S., Noutfia, A., Moula, N., Avril, C., Louvieaux, J., Hornick, J. L., Cabaraux, J. F., & Chentouf, M. (2023). Ecological, morpho-agronomical, and bromatological assessment of sorghum ecotypes in Northern Morocco. *Scientific Reports*, *13*(1), 15548. https://doi.org/10.1038/s41598-023-41565-9

Burgarella, C., Berger, A., Glémin, S., David, J., Terrier, N., Deu, M., & Pot, D. (2021). The Road to Sorghum Domestication: Evidence From Nucleotide Diversity and Gene Expression Patterns. *Frontiers in Plant Science*, *Volume 12-2021*. https://www.frontiersin.org/journals/plant-science/articles/10.3389/fpls.2021.666075

Carillo, P. (2025). Can biostimulants enhance plant resilience to heat and water stress in the Mediterranean hotspot? *Plant Stress*, *16*, 100802. https://doi.org/https://doi.org/10.1016/j.stress.2025.100802

Ceccarelli, S. (2015). Efficiency of Plant Breeding. *Crop Science*, *55*(1), 87–97. https://doi.org/10.2135/cropsci2014.02.0158

Craufurd, P. Q., & Wheeler, T. R. (2009). Climate change and the flowering time of annual crops. *Journal of Experimental Botany*, *60*(9), 2529–2539. https://doi.org/10.1093/jxb/erp196

Demelash, H. (2024). Genotype by environment interaction, AMMI, GGE biplot, and mega environment analysis of elite Sorghum bicolor (L.) Moench genotypes in humid lowland areas of Ethiopia. *Heliyon*, *10*, e26528. https://doi.org/10.1016/j.heliyon.2024.e26528

Devesh, P., Moitra, P. K., & Shukla, R. S. (2021). Correlation and path coefficient analysis for yield, yield components and quality traits in wheat. *Electronic Journal of Plant Breeding*, *12*(2), 388–395. https://doi.org/10.37992/2021.1202.057

Dhurai S. Y., D. M. R. A. P. K. B. (2014). Correlation and path coefficient analysis for yield and quality traits under organic fertilizer management in rice (Oryza sativa L.). *&lt;I&gt;Electronic Journal of Plant Breeding&lt;/I&gt;*, *5*(3). https://www.ejplantbreeding.org/index.php/EJPB/article/view/57

El Mannai, Y., Shehzad, T., & Okuno, K. (2011). Variation in flowering time in sorghum core collection and mapping of QTLs controlling flowering time by association analysis. *Genetic Resources and Crop Evolution*, *58*(7), 983–989. https://doi.org/10.1007/s10722-011-9737-y

Gebre, W., Mekbib, F., Tirfessa, A., & Bekele, A. (2024). Genetic variability among lowland sorghum accessions collected from southern Ethiopia for grain quality traits. *Heliyon*, *10*(4). https://doi.org/10.1016/j.heliyon.2024.e25323

Gebre, W., Mekbib, F., Tirfessa, A., & Bekele, A. (2025). Phenotypic diversity of sorghum [Sorghum bicolor (L.) Moench] genotypes based on qualitative and quantitative traits. *Heliyon*, *11*(3), e42378. https://doi.org/https://doi.org/10.1016/j.heliyon.2025.e42378

IBPGR, & ICRISAT. (1993). *Descriptors for sorghum [Sorghum bicolar (L.) Moench]. International Board for Plant Genetic Resources, Rome, Italy; International Crops Research Institute for the Semi-Arid Tropics, Patancheru, India*.

Julian, J., Tramberend, S., Kabi, F., Fischer, G., & Kahil, T. (2025). Sustainable intensification of fodder crop production can mitigate feed shortage and seasonality in East Africa. *Environmental Development*, *54*, 101158. https://doi.org/10.1016/j.envdev.2025.101158

Kagwiria, D., Koech, O. K., Kinama, J. M., Chemining’wa, G. N., & Ojulong, H. F. (2019). Sorghum Production Practices In An Integrated Crop-Livestock Production System In Makueni County, Eastern Kenya. *Tropical and Subtropical Agroecosystems*, *22*(1), 13–23. https://doi.org/10.56369/tsaes.2508

Karugu, M. A. (2009). *Phenotypic assessment and molecular diversity evaluation using Simple Sequence Repeats of Kenyan Sorghum germ-plasm under drought stress conditions*.

Kavithamani, D., Arumugam, Y., & Selvi, B. (2019). Principal component analysis and grouping of sorghum ( Sorghum bicolor L. Moench) gene pool for genetic diversity. *Electronic Journal of Plant Breeding*, *10*, 1426. https://doi.org/10.5958/0975-928X.2019.00182.0

Kazan, K., & Lyons, R. (2015). The link between flowering time and stress tolerance. *Journal of Experimental Botany*, *67*, erv441. https://doi.org/10.1093/jxb/erv441

Kazungu, F., Muindi, E., & Mulinge, J. (2023). Overview of Sorghum (Sorghum bicolor. L), its Economic Importance, Ecological Requirements and Production Constraints in Kenya. *International Journal of Plant & Soil Science*, *35*, 62–71. https://doi.org/10.9734/IJPSS/2023/v35i12744

Khalifa, M., & Eltahir, E. A. B. (2023). Assessment of global sorghum production, tolerance, and climate risk. *Frontiers in Sustainable Food Systems*, *7*. https://doi.org/10.3389/fsufs.2023.1184373

Kisilu, R. K., & Ngugi, K. (2021). Sorghum Landraces Phenotypic Diversity in Kenya. In *Cutting-edge Research in Agricultural Sciences Vol. 10* (pp. 77–84). Book Publisher International (a part of SCIENCEDOMAIN International). https://doi.org/10.9734/bpi/cras/v10/8858D

Kudadjie, C. Y. (2006). *Integrating science with farmer knowledge: Sorghum diversity management in north-east Ghana Tropical Resource Management Papers Documents sur la Gestion des Ressources Tropicales*.

Mahesh, G., Lal, G., Thupakula, V. K., Aⱷ, K., Subba Reddy, Y. V., & Nalla, S. (2022). Correlation and Path Coefficient Analysis for Grain Yield Components in Maize (Zea mays L.). *International Journal of Plant & Soil Science*. https://doi.org/10.9734/IJPSS/2022/v34i2331558

Mallu, T. S. (2015). *Evaluation of Chickpea Genotypes for Yield and Selected Agronomic Traits in Kenya*.

Mofokeng, A. M., Hussein A, S., & and Laing, M. D. (2017). Agromorphological diversity of South African sorghum genotypes assessed through quantitative and qualitative phenotypic traits. *South African Journal of Plant and Soil*, *34*(5), 361–370. https://doi.org/10.1080/02571862.2017.1319504

Mofokeng, M. (2015). *Diversity Analysis of South African Sorghum Genotypes Using Agronomic Traits, SSR Markers and Protein Content and Amino Acid Composition*.

Mwamahonje, A., Mdindikasi, Z., Mchau, D., Mwenda, E., Sanga, D., Garcia-Oliveira, A. L., & Ojiewo, C. O. (2024). Advances in Sorghum Improvement for Climate Resilience in the Global Arid and Semi-Arid Tropics: A Review. *Agronomy*, *14*(12). https://doi.org/10.3390/agronomy14123025

Nazarov, P. A., Baleev, D. N., Ivanova, M. I., Sokolova, L. M., & Karakozova, M. V. (2020). Infectious plant diseases: etiology, current status, problems and prospects in plant protection. *Acta Naturae*, *12*(3), 46–59. https://doi.org/10.32607/actanaturae.11026

NEMA. (2013). *Trans-Nzoia District Environment action plan- Republic of Kenya, Ministry of Environment and Mineral Resources*.

Ngidi, A., Shimelis, H., Abady, S., Figlan, S., & Chaplot, V. (2024). Response of Sorghum bicolor genotypes for yield and yield components and organic carbon storage in the shoot and root systems. *Scientific Reports*, *14*(1), 9499. https://doi.org/10.1038/s41598-024-59956-x

Ngugi, K., & Maswili, R. (2010). Phenotypic Diversity in Sorghum landraces from Kenya. In *African Crop Science Journal* (Vol. 18, Issue 4).

Ngugi, K., & Maswili, R. (2011). Phenotypic diversity in sorghum landraces from Kenya. *African Crop Science Journal*, *18*(4). https://doi.org/10.4314/acsj.v18i4.68644

Ouma, J., & Akuja, T. (2013). Agronomic and morphological performance of sorghum ( Sorghum bicolour l.) for the dry highlands of Kenya. *Journal of Applied Biosciences*, *63*, 4720. https://doi.org/10.4314/jab.v63i1.87246

Parida, A. K., Sekhar, S., Panda, B. B., Sahu, G., & Shaw, B. P. (2022). Effect of Panicle Morphology on Grain Filling and Rice Yield: Genetic Control and Molecular Regulation. *Frontiers in Genetics*, *Volume 13-2022*. https://doi.org/10.3389/fgene.2022.876198

Pavan Devesh, P. K. M. and R. S. S. (2021). Correlation and path coefficient analysis for yield, yield components and quality traits in wheat. *&lt;I&gt;Electronic Journal of Plant Breeding&lt;/I&gt;*, *12*(2). https://www.ejplantbreeding.org/index.php/EJPB/article/view/3742

Pereira, L., & Hawkes, C. (2022). Leveraging the Potential of Sorghum as a Healthy Food and Resilient Crop in the South African Food System. *Frontiers in Sustainable Food Systems*, *6*, 786151. https://doi.org/10.3389/fsufs.2022.786151

Porcuna-Ferrer, A., Guillerminet, T., Renard, D., Labeyrie, V., Leclerc, C., & Reyes-García, V. (2025). Crop biocultural traits and diversity dynamics among Bassari farmers. *Agriculture and Human Values*. https://doi.org/10.1007/s10460-025-10725-0

Qi, G., Li, N., Sun, S., & Wang, D. (2019). *Overview of Sorghum Industrial Utilization* (pp. 463–476). https://doi.org/10.2134/agronmonogr58.c21

Rahman, M., Khan, M., Sarker, R., Hossain, M., Islam, M., & Akhter, N. (2023). Response of Ajowan (Trachyspermum ammi L.) to different seed rates. *International Journal of Applied Research*, *9*, 97–102.

Raj, P., Pahuja, S. K., Verma, N. K., & Chaudhary, S. (2018). Morphological Characterization of Sorghum [Sorghum bicolor (L.) Moench] Germplasm for DUS Traits. *International Journal of Current Microbiology and Applied Sciences*, *7*(2), 2058–2071. https://doi.org/10.20546/ijcmas.2018.702.246

Ren, A., Jiang, Z., Dai, J., Sun, M., Anwar, S., Tang, P., Wang, R., Ding, P., Li, L., Wu, X., & Gao, Z. (2024). Phenotypic Characterization and Yield Screening of Quinoa Germplasms in Diverse Low-Altitude Regions: A Preliminary Study. *Agronomy*, *14*(7). https://doi.org/10.3390/agronomy14071354

Ringo, J. H., Mneney, E., Onkware, A., O, O. J., Were, B. A., Too, E. J., & Gudu, S. (2014). *Diversity of Sorghum (Sorghum bicolor L. Moench) Germplasm from Tanzania*. *4*(24). www.iiste.org

Salih, Herslman, Labuschange, & Mohammed. (2016). ASSESSMENT OF GENETIC DIVERSITY OF SORGHUM [SORGHUM BICOLOR (L.) MOENCH] GERMPLASM IN EAST AND CENTRAL AFRICA. *WORLD JOURNAL OF BIOTECHNOLOGY*, *01*(03), 1.

Santhiya, V., Selvi, B., Kavithamani, D., & Senthil, A. (2021). Genetic variability and character association among grain yield and their component traits in sorghum [Sorghum bicolor (L.) Moench]. *Electronic Journal of Plant Breeding*, *12*(3), 788–793. https://doi.org/10.37992/2021.1203.109

Sejake, T., Shargie, N., Christian, R., & Tsilo, T. (2020). Assessment of genetic diversity in sorghum germplasm using agro-morphological traits. *South African Journal of Plant and Soil*, *37*(5), 376–388. https://doi.org/10.1080/02571862.2020.1807628

Singh, N. B., Singh, K., & Choudhary, P. (2016). Correlation coefficients and path analysis of quantitative characters in full-sib progenies of Populus deltoides Bartr. *The Indian Journal of Genetics and Plant Breeding*, *75*(1). https://ebook.icar.gov.in/index.php/IJGPB/article/view/63671

ten Berge, H. F. M., Hijbeek, R., van Loon, M. P., Rurinda, J., Tesfaye, K., Zingore, S., Craufurd, P., van Heerwaarden, J., Brentrup, F., Schröder, J. J., Boogaard, H. L., de Groot, H. L. E., & van Ittersum, M. K. (2019). Maize crop nutrient input requirements for food security in sub-Saharan Africa. *Global Food Security*, *23*, 9–21. https://doi.org/https://doi.org/10.1016/j.gfs.2019.02.001

Tilahun, G. W., Jaleto, K., Ali, A., Fufa, N., Tsagaye, D., Fikre, D., & Gebretensay, F. (2024). Evaluation of Ethiopian White Cumin ( *Trachyspermum ammi* L.) accessions for agronomic and quality traits in the Central Highlands of Ethiopia. *Cogent Food & Agriculture*, *10*(1). https://doi.org/10.1080/23311932.2024.2322603

Tuberosa, R. (2012). Phenotyping for drought tolerance of crops in the genomics era. *Frontiers in Physiology*, *3*. https://doi.org/10.3389/fphys.2012.00347

Upadhyaya, H. D., & Vetriventhan, M. (2018). *Ensuring the genetic diversity of sorghum* (pp. 83–110). https://doi.org/10.19103/as.2017.0015.06

Verma, R., Ranwah, B. R., Bharti, B., Kumar, R., Kunwar, R., Diwaker, A., & Meena, M. (2017). Characterization of Sorghum germplasm for various qualitative traits. *Journal of Applied and Natural Science*, *9*(2), 1002–1007. https://doi.org/10.31018/jans.v9i2.1311

Vinoth, P., Selvi, B., Natesan, S., Iyanar, K., Jeyarani, S., & Santhiya, V. (2021). Relationship between Yield and Yield Contributing Traits in Sorghum [Sorghum bicolor (L) Moench]. *International Journal of Plant & Soil Science*, 283–288. https://doi.org/10.9734/ijpss/2021/v33i2430779

Xiao, M.-Z., Sun, Q., Hong, S., Chen, W.-J., Pang, B., Du, Z.-Y., Yang, W.-B., Sun, Z., & Yuan, T.-Q. (2021). Sweet sorghum for phytoremediation and bioethanol production. *Journal of Leather Science and Engineering*, *3*(1), 32. https://doi.org/10.1186/s42825-021-00074-z

Yuru, L., Yun, L., Jia, M., & Jia, X. (2024). GGE biplot analysis for genotype × environment interactions affecting the seed shattering of Psathyrostachys juncea. *Heliyon*, *10*(20), e39105. [https://doi.org/https://doi.org/10.1016/j.heliyon.2024.e39105](https://doi.org/https%3A//doi.org/10.1016/j.heliyon.2024.e39105)

Upadhyaya, H. D., Dwivedi, S. L., Wang, Y. H., & Vetriventhan, M. (2019). Sorghum genetic resources. *Sorghum: A State of the Art and Future Perspetives*, *58*, 47-72.

Sejake, T., Shargie, N., Christian, R., & Tsilo, T. (2020). Assessment of genetic diversity in sorghum germplasm using agro-morphological traits. *South African Journal of Plant and Soil*, *37*(5), 376-388.

Ahmad Yahaya, M., Shimelis, H., Nebie, B., Ojiewo, C. O., & Danso-Abbeam, G. (2022). Sorghum production in Nigeria: opportunities, constraints, and recommendations. *Acta Agriculturae Scandinavica, Section B—Soil & Plant Science*, *72*(1), 660-672.

Kazungu , F. K., Muindi , E. M., Mulinge , J. M., Wamukota , A. W., Muchomba , M. K., Okello , N., Wekesa , G., & Ahmed , H. (2023). Sorghum Growth and Yield as Influenced by Farmyard Manure and Inorganic Fertilizer in Post Mined Soils. *International Journal of Plant & Soil Science*, *35*(16), 331–341.