Journal of Agricultural Science and Practice
Volume 10(5), pages 102-109, October 2025
Article Number: 1E5E40EB2
ISSN: 2536-7072
https://doi.org/10.31248/JASP2025.542
https://integrityresjournals.org/journal/JASP

Full Length Research

Genetic variability for tolerance to low soil nitrogen in sorghum (*Sorghum bicolor* [L.] Moench) genotypes

Rukaiya Aliyu Sami*, Louis Aaron Obonyilo, and Daniel Afang Aba

Department of Plant Science. Institute for Agricultural Research, Ahmadu Bello University, Zaria.

*Corresponding author. Email: rukkysami@gmail.com

Received 12th August 2025; Accepted 12th September 2025

ABSTRACT: Sorghum is a significant cereal crop in sub-Saharan Africa, but its production is hindered by challenges stemming from poor soil fertility, particularly low nitrogen levels. Low soil nitrogen (N) availability is a major constraint to sorghum (Sorghum bicolor [L.] Moench) productivity, particularly in sub-Saharan Africa. Eighty-one sorghum genotypes were screened across two locations: Samaru and Minjibir in 2022. A 9 x 9 lattice design with two replications was used for the experiment. Data collected on yield and agronomic traits were subjected to analysis of variance and analysed using R and SAS software. The results revealed substantial variations among the genotypes for traits such as plant height, leaf death, panicle weight, days to 50% flowering, days to maturity, lodging rating, desirability rating, and yield, both under optimal soil nitrogen levels and low soil nitrogen levels. Notably, there were significant genetic variances in all the traits except 100 seed weight. Yield had a phenotypic coefficient of variation (PCV) of 96.20% and a genotypic coefficient of variation (GCV) of 44.86% at Samaru under low soil nitrogen. While at Minjibir yield had a PCV value of 92% and a GCV value of 53% under low soil nitrogen. The study reveals substantial genetic variation among sorghum genotypes under low soil nitrogen, with grain yield exhibiting high GCV and heritability values, indicating its reliability for selecting tolerant genotypes.

Keywords: Genotypic coefficient of variation (GCV), heritability, high soil nitrogen, low soil nitrogen, phenotypic coefficient of variation (PCV), Sub-Saharan Africa.

INTRODUCTION

Sorghum (*Sorghum bicolor* [L.] Moench) ranks fifth among the world cereals, following wheat, maize, rice and barley in production area and total production (Bakari *et al.,* 2023). The crop is important in many regions of the world where drought stress is common. Sorghum is a tropical cereal crop that grows in a wide range of environments, and it plays an important role as a staple food for many people. All of the species occurred in this region between 5,000 and 7,000 years ago (Hossain *et al.,* 2022). Sorghum is now widely cultivated in the drier areas of Africa, Asia, Australia, North, Central and South America (Dalton and Hodjo 2021).

It is primarily a crop grown in hot, semi-arid tropical environments with an average rainfall of between 400–600 mm, and it's not tolerant to cool temperatures (Serba *et al*., 2020). Sorghum can be successfully grown on a wide range of soil types. It is well-suited to heavy vertisols found commonly in the tropics, as well as light sandy soils. Ciampitti (2021). It is tolerant to salinity as compared to maize and does well in a range of soil pH of 5.0 – 8.5. Worldwide annual sorghum production ranges from 40 to 45 million tons from approximately 40 million hectares (Rooney *et al*., 2007).

The largest producers of sorghum are the United States of America, with an annual production of 17 million tons, and the largest sorghum-producing nation in Africa is Nigeria (FAOSTAT, 2017). In Nigeria, sorghum is mostly cultivated in the northern part of the country, covering the Sudan savannah, the Guinea savannah and the Sahel savannah. Production is done on a small scale in states located in the

Derived savannah. In Africa, sorghum is mostly cultivated and used as food by several households, and also as livestock feed, for industrial production of drinks, alcohol, sugar, and syrup (Bakari *et al*., 2023).

Sorghum cultivation in Nigeria is faced with the problem of declining soil fertility, most importantly, low soil nitrogen being the most serious of them, because of its instability in the soil and the vital role it plays in plant growth and yield (Hossain *et al.,* 2022).

Nitrogen (N) is vital for the proper growth and development of many crops. Nitrogen is a crucial constituent of chlorophyll, protoplasm and enzymes (Yeshiwas, 2017). Nitrogen functions in several places, like playing a key role in plants' metabolism. It also participates in protein synthesis Kaur *et al.,* 2020). It is a structural part of Adenosine triphosphate (ATP), Nicotinamide adenine dinucleotide (NAD) + hydrogen (H) (NADH), Nicotinamide adenine dinucleotide phosphate (NADP) + hydrogen (H) NADPH, storage proteins, nucleic acids and enzymes (Omar *et al*., 2023). Higher nitrogen levels have been reported to increase plant height, stem thickness, leaf area, leaf area index, dry matter accumulation, net assimilates ratio and as well as yield per hectare (Cheema *et al.,* 2010). As such, nitrogen being the most limiting nutrient, its supply along with other nutrients becomes a matter of paramount importance in the maintenance of soil fertility for sustained high crop production.

Low soil nitrogen (low N) is a common occurrence in farmers' fields in sub-Saharan Africa (SSA). During seasons with sufficient rainfall, soil nitrogen can be leached below the root zones (Pasley *et al.,* 2021), thereby leaving the crop nitrogen deficient. Soil nitrogen deficiency is further worsened by the widespread removal of crop residues for use as animal feed and fuel (Chen *et al*., 2014). Furthermore, the high cost of nitrogen fertiliser and poor weed control increase the incidence of nitrogen stress in many instances (Darko and Mensah, 2024). The heavy reliance on fertiliser has resulted in a greater need for environmental protection measures. This study aims to investigate the variation existing among sorghum genotypes under low and high soil nitrogen conditions.

Hypothesis

Null: There is no significant genetic variability among sorghum genotypes for tolerance to low soil nitrogen conditions.
Alternate: There is significant genetic variability among sorghum genotypes for tolerance to low soil nitrogen conditions.

MATERIALS AND METHODS

The study was conducted at the Research Farm of the Institute for Agricultural Research/Ahmadu Bello University (IAR/ABU), Samaru (11°11'N, 07°38' E and 686 m above sea level) in the northern Guinea savannah ecological zone of Nigeria. The second site was at the Agricultural Research Station (ARS) in Minjibir (12° 10'42''N, 08°39'33''E and 620 m above sea level) in the Sudan savannah ecological zone of Nigeria. Eighty-one sorghum genotypes sourced from the Sorghum Improvement Unit of the Institute for Agricultural Research, ABU Zaria and ICRISAT Kano were used for the study.

Soil sample collection/analysis

At the field in each location, composite soil samples were taken twice before sowing, from a depth of 0-30 cm. Sampling was done using a hand probe, and samples were analysed at the Department of Soil Science Lab, Ahmadu Bello University, Zaria, for Nitrogen, Potassium and Phosphorus content of the soil. Soil nitrogen content analysis was determined by Kjeldahl digestion and colourimetric determination on Technicon AA11 Autoanalyser (Bremner and Mulvaney, 1982). The fields were initially depleted of nitrogen in previous seasons by sowing of maize, and no fertiliser or manure was added to deplete the soil of nitrogen.

Field evaluation

The 81 sorghum genotypes were sown in IAR low-N fields in Samaru Zaria and ARS Minjibir station, Kano, during the 2022 rainy season. The experimental fields were divided into low-N and high-N blocks separated far enough from each other to prevent the effect of nitrogen mobility from one field to another. The low-N field was located at the top of the gradient, while the high-N field was located down the gradient. The experiment was laid out using a 9 x 9 lattice design with 2 replications. Five seeds were manually sown per hole at a depth of 2 cm, which were later thinned to 2 plants per hole at 2 weeks after sowing. Each plot consisted of four rows of 3 m long with an inter-row and intra-row spacing of 75 cm and 30 cm. Data was collected only from the two inner rows of each plot to avoid edge effect. Nitrogen and other macro nutrients such as potassium and phosphorus were applied to the plants using urea to supply N (90 kg/ha), single super phosphate to supply P_2O_5 (60kg/ha) and muriate of potash to supply K_2O (60 kg/ha). The low-N block received 30 kg/ha quantity of nitrogen, 60 kg/ha of both Potassium and Phosphorus at both locations (Bollam *et al.,* 2021). The nitrogen was applied in 2 splits, 15 kg /ha of nitrogen was applied as the first dose, together with 60 kg/ha of P_2O_5 and K_2O, two weeks after sowing, using urea.

The second dose of 15 kg/ha of nitrogen was applied as top dressing four weeks after the first dose application using urea. Meanwhile, the high-N blocks received 90 kg/ha of nitrogen, 60 kg/ha of potassium (P_2O_5) and 60 kg/ha of phosphorus (K_2O) at the two locations (Buah and Mwinkaara, 2009; Bollam *et al.,* 2021). The 90 kg/ha of nitrogen that was applied to the high-N blocks was applied in 2 splits. 45 kg/ha of N was applied as the first dose together with 60 kg/ha of P_2O_5 and K_2O two weeks after sowing (using urea, single super phosphate and muriate of potash to supply N, P_2O_5 and K_2O), while the second dose 45 kg/ha of nitrogen was applied as top dressing four weeks after the first dose application using urea. Weed control was done manually by hoe weeding at two, six and ten weeks after sowing. The weeds were carefully packed outside (neatly swept) only from the low-N blocks to avoid decay and addition of nitrogen to the plots in the blocks. Insect pest control was also carried out according to standard agronomic practice.

Data collection

Plant Height was estimated as the average height in centimetres of six randomly selected plants, measured from the ground to the point of the flag leaf, which was taken 2 weeks after heading. Days to 50% flowering was measured as the duration in days from sowing until the majority of the panicles reached 50%. Days to maturity is the time in days from sowing until the majority of the plants in the plots have matured. Panicle weight was estimated as the average weight of six randomly selected plant panicles from each plot, which was taken after harvest.

Leaf death, in each plot, was assessed and assigned scores at both 10 and 15 weeks after sowing, utilising a scale ranging from 1 to 5. A score of 1 corresponds to more than 80 % of chlorotic/dead leaves among the plants in the plot, 2 indicates 60 % of chlorotic/dead leaves, 3 signifies 40% of chlorotic/dead leaves among the plants in the plot, 4 denotes 20 % of chlorotic/dead leaves among the plants in the plot, and 5 represents less than 5 % of chlorotic/dead leaf area below the panicle of the plants in the plot. The overall ratings for desirability, adaptation, or breeding potential were assessed near or at maturity using a scale ranging from 1 to 5. A rating of 5 represented the highest level of desirability, adaptation, or breeding potential (considered "Best"), followed by 4 for "Good," 3 for "Fair," 2 for "Poor," and 1 for Very Poor. The lodging of plants, which includes weak neck, stalk breakage, or damage from high winds, was assessed visually as a percentage estimate near maturity.

The lodging was rated on a scale from 1 to 5, where 1 indicated more than 80 % of plants in the plot have lodged, 2 indicated 60 % of the plants in the plot have lodged, 3 indicated 40 % of the plants in the plot have lodged, 4 indicated 20 % of plants in plot have lodged, and 5 indicated less than 10 % of plants in the plot have lodged. 100 seeds were selected randomly from the threshed seeds of each plot, and the weight was taken. Grain yield was recorded as the weight of harvested grain expressed in t/ha with a moisture content of 13%.

Statistical analysis

Analysis of variance (ANOVA) for individual location was done. Random model was used for the analysis, and the ANOVA was done using Statistical Analysis System (SAS) version 9.13 (SAS Institute, 2011). Fisher's least significant difference (LSD) test (α = 0.05) was used to separate the means. To test for homogeneity of variances for both locations, the Hartley test (Hartley 1950) of homogeneity was employed. The location was found not to be homogeneous, so the data were not pooled. The following random model was used for ANOVA. Genetic components were estimated to determine the source of the observed variations, as used by Sivasubramaniam and Madhava Menon (1973).

Formular used for calculating variance components

Genotypic Coefficient of Variation (GCV): The genotypic coefficient of variation was estimated using the formula described by Singh and Chaudhary (1985) as:

$$GCV = \frac{\sqrt{\sigma_g^2}}{\bar{x}} \times 100$$

Where: GCV = Genotypic Coefficient of Variation, $\sigma_g^2 =$ Estimate of genetic variance, $\bar{X} =$ Grand mean of the respective character

Phenotypic Coefficient of Variation: The phenotypic coefficient of variation was estimated using the formula described by Sivasubramaniam and Madhava Menon (1973) as:

$$PCV = \frac{\sqrt{\sigma_p^2}}{\bar{x}} \times 100$$

Where: PCV = Phenotypic coefficient of variation, σ_p^2 = estimate of phenotypic variance, $\bar{X}$ = grand mean of the respective character.

RESULTS AND DISCUSSION

Soil nitrogen content before the experiment

Soil nitrogen content analyses, conducted using the Kjeldahl digestion and colourimetric method on a Technicon AA11 Autoanalyser, revealed that both locations exhibited very low nitrogen content (Table 1). The soil from Minjibir recorded a nitrogen concentration of 0.0553%, while that from Samaru had a slightly higher value of 0.0744%. Despite this marginal difference, both values fall within the range categorised as very low nitrogen content, indicating that the soils in both experimental fields were nitrogen-deficient prior to treatment.

Table 1. Soil test result for nitrogen content for Samaru and Minjibir.

Location	Nitrogen content	Remark
Minjibir	0.0553%	Very low on nitrogen content
Samaru	0.0744%	Very low on nitrogen content

Table 2. Mean Squares from ANOVA for agronomic traits of 81 sorghum genotypes screened under low soil nitrogen environment at Samaru and Minjibir in 2022.

Source of Variation	Df	Plant Height	Leaf Death	Days to Flowering	Lodging Rating	Desirability Rating	Days to Maturity	Panicle Weight	100 Seed weight	Grain Yield
Samaru										
Rep	1	2325.62	6.70	2.72	5.93	9.39	193.39	840.50	0.01	200399.21
Genotype	80	1629.39*	6.70*	123.20*	2.23*	2.19*	201.20*	861.50*	0.01	164787.85*
Block (Rep)	16	148.43	0.83	15.21	2.23	0.75	24.31	416.58	0.01	54724.70
Error	64	335.24	0.51	13.66	1.06	0.60	120.46	389.93	0.01	22564.40
Minjibir										
Rep	1	14792	7.56	8.00	2.23	2.23	140.75	595.12	0.01	341484.80
Genotype	80	4591.77*	2.01*	55.26*	2.37*	2.90*	190.42*	3035.70*	0.01	410546.42*
Block (Rep)	16	2867.90	1.60	7.42	1.60	0.79	31.76	1643.88	0.01	159588
Error	64	1361.89	0.80	7.86	1.07	0.62	106.57	1993.72	0.20	88350.83

Analysis of variance (ANOVA) for agronomic traits of sorghum genotypes screened under low and high soil nitrogen environments at Samaru and Minjibir in 2022

Tables 2 and 3 present the results of the analysis of variance (ANOVA) from the experiments conducted under low soil nitrogen and high soil nitrogen environments at Samaru and Minjibir in 2022. The results revealed significant mean squares among the genotypes under both low soil nitrogen and high soil nitrogen environments. The findings revealed significant variations ($p \leq 0.05$) in grain yield and other measured traits, excluding 100-seed weight, which exhibited non-significance under low soil nitrogen in both environments. The findings also revealed significant variation ($p \leq 0.05$) in grain yield and other measured traits, excluding 100-seed weight (100 SW), which exhibited non-significant differences under high soil nitrogen in both environments (Table 3).

The observed genetic variability is a critical foundation for selection in breeding programs targeting nitrogen-use efficiency. The identification of genotypes that maintained superior grain yield under low nitrogen conditions highlights their potential as donor lines in low-input agricultural systems. These findings are in line with Dembele *et al*. (2020), who reported significant genotypic variation for nitrogen-efficiency-related traits in sorghum. Similarly, Kimani *et al*. (2009) emphasised that such diversity is essential for meaningful crop improvement. The variations are likely driven by both inherent genetic differences and genotype-by-environment interactions, as noted by Buah and Mwinkara (2009). Therefore, the alternate hypothesis is accepted while the null hypothesis is rejected. Overall, this study underscores the feasibility of selecting nitrogen-efficient sorghum genotypes for sustainable production under varying nitrogen regimes.

Selection of best-performing genotypes among the eighty-one sorghum genotypes

Final selection of best-performing genotypes under low soil nitrogen was based on a linear base index.

Table 3. Mean squares from ANOVA for agronomic traits of 81 sorghum genotypes screened under high soil nitrogen environment at Samaru and Minjibir in 2022.

Source of Variation	Df	Plant Height	Leaf Death	Days to Flowering	Lodging Rating	Desirability Rating	Days to Maturity	Panicle Weight	100 Seed Weight	Grain Yield
Samaru										
Rep	1	5100.50	0.30	277.43	0.02	10.89	2473.39	388.90	0.01	1273292.70
Genotype	80	918.62*	1.21*	110.69*	1.49*	1.68*	628.46*	178.26*	0.01	179855.80*
Block (Rep)	16	345.44	1.23	54.83	1.05	0.72	256.16	117.00	0.01	85718.56
Error	64	345.00	0.54	32.66	0.83	0.76	261.13	91.84	0.01	67551.12
Minjibir										
Rep	1	5315.95	1.58	28.54	4.17	7.14	140.75	674.67	0.01	766505.42
Genotype	80	751.97*	3.03*	23.07*	2.32*	2.93*	190.42*	4731.90*	0.01	922696.59*
Block (Rep)	16	239.38	1.65	17.66	1.92	1.27	31.76	2698.19	0.01	358628.70
Error	64	360.06	0.95	10.61	1.00	0.81	106.57	2931.90	0.01	198928.42

Table 4. Best performing genotypes among the eighty-one genotypes screened under low soil-N at Samaru 2022.

Genotypes	Base index	Ranking	GYD (kg/ha)	PHT (cm)	LDT (score)	PWT (g)	DRT (score)	LRT (score)	DTF	DTM
Icsg_1980736	9.64	1	817.78	133.00	4.00	70.00	5.00	4.50	71.00	118.00
Samsorg_44	9.39	2	2191.11	117.00	3.00	76.50	5.00	5.00	89.00	138.00
Germplasm2021-2	7.94	3	743.33	169.50	4.00	78.00	5.00	5.00	84.00	138.00
ICSG_1980308	5.54	4	857.78	222.00	2.00	69.00	4.50	4.00	89.00	138.00
Samsorg_49	5.51	5	805.56	87.50	2.50	46.00	4.50	5.00	76.00	130.00
ICSG_1981294	5.42	6	795.56	76.50	4.50	62.50	4.50	5.00	77.00	134.00
ICSG_1980223	4.91	7	612.22	101.50	4.50	38.00	4.00	5.00	82.00	118.00

PHT=Plant height, GYD= Grain yield, LDT= Leaf death, PWT=Panicle weight, DRT= Desirability rating, LRT=lodging rating, DTF= Days to flowering, DTM= Days to maturity.

The base index (BI) was adopted from the modification of that described by Badu-Apraku *et al.* (2011b) that combined standardised trait values with breeder-defined weights reflecting the low-N breeding objective. The formular used from calculating BI is given as:

$$BI = YD_{LwN}+PHT+LDT+PWT+DRT+LRT-DTF-DTM$$

Where: YD_{LwN} = grain yield under low soil nitrogen, PHT=plant height, LDT = leaf death, PWT=panicle weight, DRT = desirability rating, LRT = lodging rating, DTF = days to flowering, DTM = days to maturity. Each parameter of the BI was standardised (with mean = 0 and standard deviation = 1) to minimise the effects of different scales of measurement.

A positive BI, therefore, indicated that a genotype possessed tolerance to low soil nitrogen, while genotypes with negative BI values were non-tolerant to low soil nitrogen. A genotype by trait biplot (GT biplot) was used to visualise multi-trait profiles and corroborate index-based rankings. Tables 4 and 5 present the best-performing genotypes at Samaru and Minjibri.

Variance components and heritability estimates for agronomic traits of 81 sorghum genotypes screened under low soil nitrogen environments at Samaru and Minjibir

The phenotypic (PCV) and genotypic (GCV) coefficients of variation shown on Tables 6 and 7 demonstrated substantial variability among traits, underscoring considerable potential for selection.

Table 5. Best performing genotypes among the eighty-one genotypes screened under low soil-N at Minjibir in 2022.

Genotypes	Base index	Ranking	GYD (kg/ha)	PHT (cm)	LDT (score)	PWT (g)	DRT (score)	LRT (score)	DTF	DTM
ICSG_1980305	14.51	1	1766.67	204.00	4.50	79.50	5.00	4.50	82.00	124.00
ICSG_1980287	14.26	2	2387.78	109.00	4.50	193.50	4.50	4.50	86.00	138.00
Soumba	13.28	3	1961.11	144.50	4.50	101.50	5.00	4.50	82.00	134.00
KSV15	12.91	4	1194.44	246.50	3.00	202.50	4.00	4.50	85.00	138.00
ICSV400	11.53	5	947.78	171.00	4.50	103.50	4.50	4.50	77.00	139.50
ICSG_1980315	11.17	6	1100.00	110.00	4.50	100.00	4.50	4.00	73.00	122.50
ICSG_1980736	9.10	7	744.44	123.50	4.00	103.50	4.50	4.00	89.00	118.00
ICSG_1981294	9.04	8	1207.78	114.00	4.50	86.50	4.50	4.50	88.00	134.00
ICSG_1980296	6.10	9	1058.89	148.00	3.00	101	3.00	4.50	81.00	150.00

PHT=Plant height, GYD= Grain yield, LDT= Leaf death, PWT=Panicle weight, DRT= Desirability rating, LRT=lodging rating, DTF= Days to flowering, DTM= Days to maturity.

Table 6. Variance components for agronomic traits of 81 sorghum genotypes screened under low soil nitrogen environment at Samaru in 2022.

TRAITS	Mean	PCV (%)	GCV (%)	σ_g^2	σ_p^2	σ_e^2	h_b^2 (%)
Days to flowering	78.75	10.91	7.71	36.82	73.86	37.04	49.85
Days to maturity	133.46	8.79	4.78	40.69	137.56	96.87	29.58
Panicle weight	33.1	4.64	3.31	1.20	2.36	1.16	50.87
Lodging rating	3.90	25.69	13.23	0.31	1.17	0.86	26.50
100 seed weight	0.69	96.03	30.93	1.08	10.41	9.33	10.37
Desirability rating	2.77	39.71	24.48	0.46	1.21	0.75	38.02
Leaf death	3.92	24.73	13.26	0.27	0.94	0.67	28.72
Plant height	104.96	0.53	0.25	0.07	0.31	0.24	22.58
Grain yield	338.16	11.45	10.24	1200	1500	1.76	80.00

The consistently higher PCV relative to GCV across environments indicates that environmental factors substantially influence trait expression (Amare *et al.,* 2015, Fasahat *et al*., 2016; Ngidi *et al*., 2024). For instance, 100-seed weight at Samaru exhibited very high PCV (96.03 %) but much lower GCV (30.93 %), reflecting wide phenotypic variation with limited genetic control. Such traits are unreliable for direct selection unless evaluated across multiple environments or under controlled stress conditions to reduce environmental effect (Ndukauba *et al*., 2018). Furthermore, grain yield displayed moderate PCV and GCV values (PCV: 11.45–12.03 %; GCV: 10.24–11.05 %) with a narrow PCV–GCV gap, suggesting a strong genetic component. Its consistently high heritability (80–84 %) confirms that yield is reliable to direct selection, even in early breeding generations, making it an efficient target for genetic gain (Badu-Apraku *et al.,* 2011a; Adu *et al*., 2021).

Heritability (Broad sense) estimates (Tables 6 and 7) varied considerably across traits and locations, reflecting differences in genetic control and environmental sensitivity. Traits such as panicle weight and days to flowering (50–61 %) exhibited moderate to high heritability, indicating balanced genetic and environmental influence, thus suitable for targeted selection under defined conditions (Leiser *et al.*, 2012). Traits like lodging

Table 7. Variance components for agronomic traits of 81 sorghum genotypes screened under low soil nitrogen environment at Minjibir in 2022.

Traits	Mean	PCV (%)	GCV (%)	σ_g^2	σ_p^2	σ_e^2	h_b^2 (%)
Days to flowering	85.35	4.91	2.76	5.53	17.55	12.02	31.51
Days to maturity	133.35	8.90	5.27	49.40	141.01	91.61	35.03
Panicle weight	38.16	4.23	3.31	1.60	2.60	1.00	61.54
Lodging rating	2.70	49.14	27.96	0.57	1.76	1.19	32.39
100 seed weight	0.72	48.11	39.28	0.08	0.12	0.04	66.67
Desirability rating	2.12	65.36	47.64	1.02	1.92	0.90	53.13
Leaf death	2.41	59.55	40.87	0.97	2.06	1.09	47.09
Plant height	80.47	1.05	0.53	0.18	0.72	0.54	25.00
Grainl	319.88	12.03	11.05	1250	1480	0.49	84.46

rating and plant height showed low GCV and heritability, implying that environmental variation masks genetic potential. These traits are unlikely to respond effectively to direct selection and may be better addressed through indirect selection or rigorous multi-environment evaluation (Chauhan *et al*., 2020).

Remarkably, the relatively high heritability value of desirability rating (53 %) and 100-seed weight (67%) at Minjibir suggests greater genetic stability in specific environments, highlighting the potential for location-specific breeding programs. However, the variability in heritability across sites reinforces the necessity of G × E interaction studies and emphasises the importance of breeding strategies tailored to particular agro-ecological zones (Teressa *et al*., 2021; Des Marais *et al*., 2013).

Implications for selection and breeding

High heritability + high GCV (e.g., grain yield) priority traits are reliable for direct selection, which is expected to deliver rapid genetic progress. The presence of significant GCV for key traits such as grain yield and panicle weight, coupled with high heritability values, indicates promising potential for genetic gain under selection. These findings corroborate earlier reports by Bello *et al*. (2021), who highlighted wide genetic diversity in sorghum traits associated with nitrogen use efficiency.

High PCV but low GCV, which was recorded for the trait (e.g., 100-seed weight at Samaru), strongly suggest environmental influence. And multi-environment trials to ensure reliable selection are recommended. Also, low heritability + low GCV (e.g., plant height) indicated limited genetic gain potential, which can be improved through indirect selection or enhanced agronomic management. Meanwhile, traits with variable heritability (e.g., desirability rating) can be improved through location-specific or multi-location breeding strategies.

Conclusion

In summary, traits with high heritability and strong genetic determination, particularly grain yield, represent the most promising targets for direct selection to accelerate genetic improvement. Traits heavily influenced by the environment necessitate multi-environment testing to identify stable genotypes, while low-heritability traits may be more effectively improved indirectly or through optimised crop management. Collectively, these findings provide a robust framework for designing environment-tailored breeding strategies that enhance both genetic gain and yield stability.

CONFLICT OF INTEREST

The authors have no competing interests to declare that are relevant to the content of this article.

REFERENCES

Adu, G. B., Badu-Apraku, B., & Akromah, R. (2021). Strategies for selecting early maturing maize inbred lines for hybrid production under low soil nitrogen and striga infestation. *Agronomy*, *11*(7), 1309.

Amare, K., Zeleke, H., & Bultosa, G. (2015). Variability for yield, yield related traits and association among traits of sorghum (Sorghum Bicolor (L.) Moench) varieties in Wollo, Ethiopia. *Journal of Plant Breeding and Crop Science*, *7*(5), 125-133.

Badu-Apraku, B., Oyekunle, M., Akinwale, R. O., & Lum, A. F. (2011a). Combining ability of early-maturing white maize inbreds under stress and nonstress environments. *Agronomy journal*, *103*(2), 544-557.

Badu-Apraku, B., Akinwale, R. O., Ajala, S. O., Menkir, A., Fakorede, M. A. B., & Oyekunle, M. (2011b). Relationships among traits of tropical early maize cultivars in contrasting environments. *Agronomy journal*, *103*(3), 717-729.

Bakari, H., Djomdi, Ruben, Z. F., Roger, D. D., Cedric, D., Guillaume, P., & Gwendoline, C. (2023). Sorghum (Sorghum bicolor L. Moench) and its main parts (by-products) as promising sustainable sources of value-added ingredients. *Waste and Biomass Valorization*, *14*(4), 1023-1044.

Bello, D., Kadams, A. M., Simon, S. Y., & Mashi, D. S. (2007). Studies on genetic variability in cultivated sorghum (*Sorghum* *bicolor* L. Moench) cultivars of Adamawa State Nigeria. *American-Eurasian Journal of Agricultural and Environmental Science*, 2(3), 297-302.

Bollam, S., Romana, K. K., Rayaprolu, L., Vemula, A., Das, R. R., Rathore, A., Gandham, P., Chander, G., Deshpande, S. P., & Gupta, R. (2021). Nitrogen use efficiency in Sorghum: exploring native variability for traits under variable N-Regimes. *Frontiers in Plant Science*, *12*, 643192.

Bremner, R. J. M. and Mulvaney, C. S. (1982). Nitrogen—Total. In Page, A. L. (ed.). *Methods of soil analysis, Part 2: Chemical and microbiological properties,* 2nd edition (pp. 595-624). American Society of Agronomy & Soil Science Society of America.

Buah, S. S. J., & Mwinkaara, S. (2009). Response of sorghum to nitrogen fertilizer and plant density in the Guinea savanna zone. *Journal of Agronomy*, *8*(4), 124-130.

Chauhan, S., Mishra, U., & Singh, A. K. (2020). Genetic variability, heritability and genetic advance studies for yield and yield related traits in pearl millet [Pennisetum glaucum (L.) R. Br.]. *Journal of Pharmacognosy and Phytochemistry*, *9*(3), 1199-1202.

Cheema, M. A., Farhad, W., Saleem, M. F., Khan, H. Z., Munir, A., Wahid, M. A., Rasul, F., Hammad, H. M., Cheema, M., & Farhad, W. (2010). Nitrogen management strategies for sustainable maize production. *Crop and Environment*, *1*(1), 49-52.

Chen, B., Liu, E., Tian, Q., Yan, C., & Zhang, Y. (2014). Soil nitrogen dynamics and crop residues. A review. *Agronomy for Sustainable Development*, *34*(2), 429-442.

Ciampitti, I. A., Prasad, P. V., Kumar, S. R., Kubsad, V. S., Adam, M., Eyre, J. X., ... & Gambin, B. (2021). Sorghum management systems and production technology around the globe. In *Sorghum in the 21st century: Food–fodder–feed–fuel for a rapidly changing world* (pp. 251-293). Singapore: Springer Singapore.

Dalton, T. J., & Hodjo, M. (2021). Trends in global production, consumption, and utilization of Sorghum. In *Sorghum in the 21st Century: Food–Fodder–Feed–Fuel for a Rapidly Changing World* (pp. 3-15). Singapore: Springer Singapore.

Darko, Y. A., & Mensah, A. O. T. (2024). Community health concerns: assessing nitrogen in Ghanaian drinking water sources. *Ayden International Journal of Environmental Sciences and Allied Research*, *1*(1), 47-54.

Dembele, J. S. B., Gano, B., Vaksmann, M., Kouressy, M., Dembele, L. L., Doumbia, M., Teme, N., Diouf, D., & Audebert, A. (2020). Response of eight sorghum varieties to plant density and nitrogen fertilization in the Sudano-Sahelian zone in Mali. *African Journal of Agricultural Research*, *16*(10), 1401-1410.

Des Marais, D. L., Hernandez, K. M., & Juenger, T. E. (2013). Genotype-by-environment interaction and plasticity: exploring genomic responses of plants to the abiotic environment. *Annual Review of Ecology, Evolution, and Systematics*, *44*(1), 5-29.

FAO (2017): Food and Agriculture Organization of the United Nations, Land Resources. FAOSTATS-Crops. http://faostat.fao.org/site/567/default.aspx#ancor.

Fasahat, P., Rajabi, A., Rad, J. M., & Derera, J. (2016). Principles and utilization of combining ability in plant breeding. *Biometrics & Biostatistics International Journal*, *4*(1), 00085.

Hartley, H. O. (1950). The maximum F-ratio as a short-cut test for heterogeneity of variance. *Biometrika*, *37*(3/4), 308-312.

Hossain, M. S., Islam, M. N., Rahman, M. M., Mostofa, M. G., & Khan, M. A. R. (2022). Sorghum: A prospective crop for climatic vulnerability, food and nutritional security. *Journal of Agriculture and Food Research*, *8*, 100300.

Kaur, P., Singh, S. K., Kaur, R., & Sidhu, M. K. (2020). Response of different levels of nitrogen and spacing on growth and yield of cauliflower grown under central region of Punjab. *International Journal of Bio-resource and Stress Management*, *11*(4), 320-326.

Kimani, J. M., Tongoona, P., Derera, J., & Nyende, A. B. (2011). Upland rice varieties development through participatory plant breeding. *ARPN Journal of Agricultural and Biological Science*, *6*(9), 39-49.

Leiser, W. L., Rattunde, H. F. W., Piepho, H. P., Weltzien, E., Diallo, A., Melchinger, A. E., & Haussmann, B. I. (2012). Selection strategy for sorghum targeting phosphorus-limited environments in West Africa: Analysis of multi-environment experiments. *Crop Science*, *52*(6), 2517-2527.

Ngidi, A., Shimelis, H., Abady, S., Chaplot, V., & Figlan, S. (2024). Genetic variation and association of yield, yield components, and carbon storage in sorghum (Sorghum bicolor [L.] Moench) genotypes. *BMC Genomic Data*, *25*(1), 74.

Pasley, H., Nichols, V., Castellano, M., Baum, M., Kladivko, E., Helmers, M., & Archontoulis, S. (2021). Rotating maize reduces the risk and rate of nitrate leaching. *Environmental Research Letters*, *16*(6), 064063.

Rooney, W. L., Blumenthal, J., Bean, B., & Mullet, J. E. (2007). Designing sorghum as a dedicated bioenergy feedstock. *Biofuels, Bioproducts and Biorefining*, *1*(2), 147-157.

Serba, D. D., Yadav, R. S., Varshney, R. K., Gupta, S. K., Mahalingam, G., Srivastava, R. K., Gupta, R., Perumal, R., & Tesso, T. T. (2020). Genomic designing of pearl millet: A resilient crop for arid and semi-arid environments. In *Genomic designing of climate-smart cereal crops* (pp. 221-286). Cham: Springer International Publishing.

Singh, R. K., & Chaudhary, B. D. (1985). Biometrical methods in quantitative genetic analysis. New Delhi: Kalyani Publishers.

Sivasubramaniam, S., & Madhava Menon, P. (1973). Genotypic and phenotypic variability in rice. *Madras Agricultural Journal,* 60(9/12), 1093-1096.

Teressa, T., Semahegn, Z., & Bejiga, T. (2021). Multi environments and genetic-environmental interaction (GxE) in plant breeding and its challenges: a review article. *International Journal of Research Studies in Agricultural Sciences*, *7*(4), 11-18.

Yeshiwas, Y. (2017). Effect of different rate of nitrogen fertilizer on the growth and yield of cabbage (*Brassica oleraceae*) at Debre Markos, North West Ethiopia. *African Journal of Plant Science*, *11*(7), 276-281.