

Correlations among Agronomic Traits Obtained from Sorghum Accessions Planted in a Field Infected with Three Important Fungal Diseases

Louis K. Prom^{1*}, Hugo E. Cuevas², Ezekiel J. S. Ahn³, Thomas S. Isakeit⁴ & Clint W. Magill⁴

¹ USDA-ARS Southern Plains Agricultural Research Center, College Station, TX, 77845, USA

² USDA-ARS, Tropical Agriculture Research Station, 2200 Pedro Albizu Campos Avenue, Mayaguez, PR, USA

³ USDA-ARS Plant Science Research Unit, St. Paul, MN 55108, USA

⁴ Department of Plant Pathology & Microbiology, Texas A&M University, College Station, TX, 77843, USA

Correspondence: Louis K. Prom, USDA-ARS Southern Plains Agricultural Research Center, College Station, TX, 77845, USA. E-mail: louis.prom@usda.gov

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Abstract

A total of 179 sorghum cultivars planted in replicated plots in Isabela, Puerto Rico, were evaluated for five agronomically important traits grain yield, seed weight, plant height, panicle length, and flowering time. This study identified the top cultivars in each trait through statistical analysis. In a previous study, the reaction of the same cultivars to anthracnose, rust, grain mold, and germination rates was determined. Combining the five traits in this study and the previous four measured traits, a correlation analysis among the nine traits was conducted. The results revealed that there are significant correlations between a few paired traits. Correlations such as plant height and rust infection (Spearman's $\rho = 0.36$), plant height and grain mold infection (Spearman's $\rho = -0.30$), germination rate and plant height (Pearson's $r = 0.31$), germination rate and panicle length (Pearson's $r = 0.27$), panicle length and plant height (Pearson's $r = 0.52$), flowering time and plant height (Pearson's $r = 0.65$), and flowering time and panicle length (Pearson's $r = 0.50$) were found.

Keywords: sorghum, fungal pathogens, grain yield, seed weight, plant height, panicle length, flowering time

1. Introduction

Sorghum [*Sorghum bicolor* (L.) Moench] is a subject of plant genomics research based on its importance as one of the world's leading cereal crops, a biofuels crop of high and growing importance, a progenitor of one of the world's most noxious weeds, and a botanical model for many tropical grasses with complex genomes (Paterson, 2008). It plays a critical role in resilient farming and is projected as a smart crop to overcome food and nutritional insecurity in the developing world (Ruperao et al., 2021). Grain composition varies within and among cereal crops, but generally, grain contains 79–83% starch, 7–14% protein, and 1–7% fat (Rhodes et al., 2017). Crop yields in the arid and semi-arid regions of the world are challenged by low precipitation, leaving populations in these regions particularly vulnerable to chronic hunger and malnutrition (Rhodes et al., 2017). Sorghum is consistently exposed to abiotic and biotic stresses, and among biotic stresses of which anthracnose, rust, and grain mold are major constraints of sorghum productivity (Prom et al., 2022b). Recently, plant architecture traits, including panicle height, panicle length, and flowering time, have been surveyed in sorghum populations (Girma et al., 2019; Morris et al., 2013; Rhodes et al., 2017; Tao et al., 2020; Zhou et al., 2019). Prom et al. (2022b) noted that the germination rate was associated with the resistance response to anthracnose, rust, and grain mold. A significant positive correlation between germination rate and seed weight was noted when the sorghum association panel was evaluated (Prom et al., 2022a). A recent study suggested a potential correlation between sorghum seed morphology related traits and defense response against head smut caused by *Sporisorium reilianum* (Kühn) Langdon & Fullerton (Ahn et al., 2023).

Thus, the grain yield, seed weight, plant height, panicle length, flowering date, of 76 cultivars were measured and combined with the data for response of the same cultivars to anthracnose (caused by *Colletotrichum sublineola* Henn. ex Sacc. & Trotter 1913), rust [caused by *Puccinia purpurea* Cooke (1876)] and grain mold [caused by 40

genera including *Alternaria alternata* (Fr.) Keissl. (1912)] and germination rates (Prom et al., 2022b) to identify possible correlations between the diseases and the nine traits.

2. Materials and Methods

Field trial: A total of 179 accessions from Ethiopia, Gambia, and Senegal maintained by the USDA-ARS, Plant Genetic Resources Conservation Unit, Griffin, Georgia, were evaluated for five priority traits, some of which are used to evaluate the National Plant Germplasm System sorghum collection. Accessions were evaluated during the 2017 and 2018 growing seasons in a randomized complete block design at the USDA Research Station, Isabela, Puerto Rico. Isabela is situated at 128 meters above sea level and lies at 67.3° longitude and 18.3° latitude (Porch et al., 2014). Seeds were planted in 1.8 m rows with 0.9 row spacing and each accession was replicated three times. Prior to planting, fertilizer was applied on the field at a rate of 560 kg/ha (15-5-10 NPK) and sprayed with DiPel (Valent Bioscience Corporation, IL) to control insects. Weeds were controlled with mechanical tillage and hand hoeing.

The flowering date was based on Julian days. At maturity, plant height was measured from the soil to the top of the plant in centimeters, and panicle length was measured from the first branch with racemes to the top of the panicle. Grain yield in grams was based on three harvested panicles per accession, and each panicle was threshed and weighed in grams. Seed weight was based on the grams of 100 randomly selected seeds from each replication.

2.1 Statistical Analysis

For statistical analysis, a parametric two-tailed pooled t-test was conducted with JMP Pro 15 to compare the five traits' scores (Ahn et al. 2019b). For correlation analysis, since all five traits are parametric, Pearson's correlation coefficient (r) was used among the five traits. Data from a previous study for the response of the same accessions to anthracnose, rust, and grain mold and their germination rate were used (Prom et al., 2022b). The combination of the five traits in this study with the scores for the three diseases and germination rate were measured nonparametrically, so Spearman's rank correlation coefficient (r) was used with JMP Pro 15 (SAS Institute, Cary, NC, USA).

3. Results

3.1 Grain Yield

Seventy-six cultivars were measured for grain yield (g). PI665166 showed the most significant grain yield (63.57 grams), which was followed by PI665169 (38.94 grams) and PI669704 (37.25 grams) [mean \pm standard error of the mean (SEM) = 16.63 \pm 1.14 grams among the population] (Figure 1). Table 1 listed the top 10 cultivars with the highest and lowest grain yield without listing the positive and negative control cultivars.

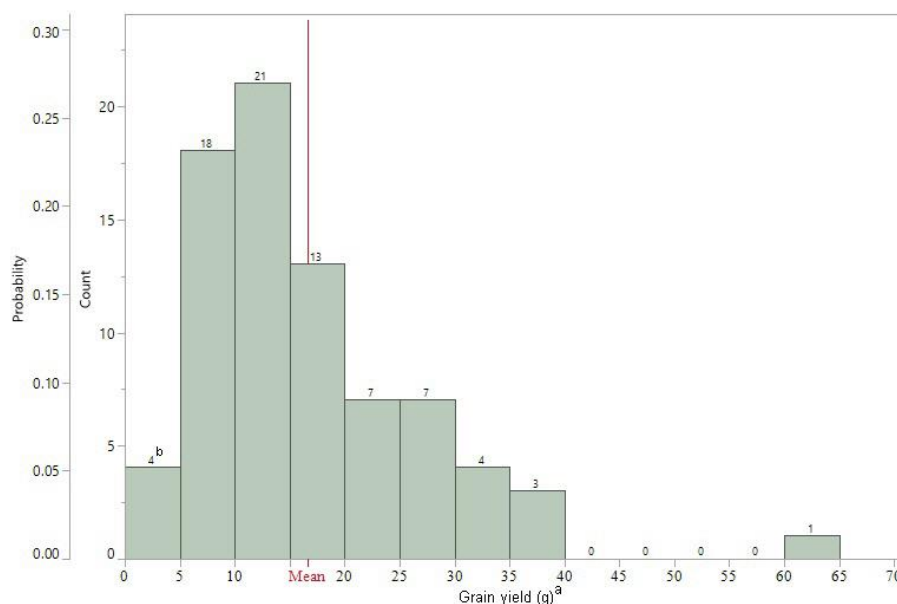


Figure 1. The phenotype distribution of grain yield (grams)

The x-axis indicates the average grain yield, and the y-axis is the number of sorghum lines and probability.

Table 1. Ten cultivars with the highest (left) and lowest (right) grain yield in grams

Cultivar	Average SEM	±	Cultivar	Average SEM	±	Cultivar	Average SEM	±	Cultivar	Average SEM	±
PI665166	63.57	± 18.37	PI514609	32.53	± 6.08	PI330230	7.95	± 2.89	PI533920	5.68	± 1.18
PI665169	38.94	± 1.51	PI514393	31.97	± 4.99	PI534152	7.76	± 1.89	PI576377	4.94	± 1.39
PI669704	37.25	± 11.56	PI665165	30.54	± 14.20	PI563482	7.71	± 0.61	PI194355	4.06	± 0.79
PI514521	35.13	± 16.27	PI267618	29.40	± 9.60	PI576375	6.76	± 1.49	PI267557	3.88	± 0.81
PI533799	34.66	± 4.38	PI514399	27.18	± 4.00	PI570841	5.78	± 1.44	PI534131	3.56	± 1.57

3.2 Seed Weight

Overall, 106 cultivars (excluding positive and negative controls) were weighed for seed weight. Seed weight in the population was scattered from above 1.00 to 3.5 grams (Figure 2). The mean weight was 2.13 ± 0.06 grams across the population. Ten cultivars' seed weights were heavier than 3 grams, while 17 cultivars were less than 1.5 grams. Table 2 lists the top ten cultivars with the heaviest and lightest seed weight as examples.

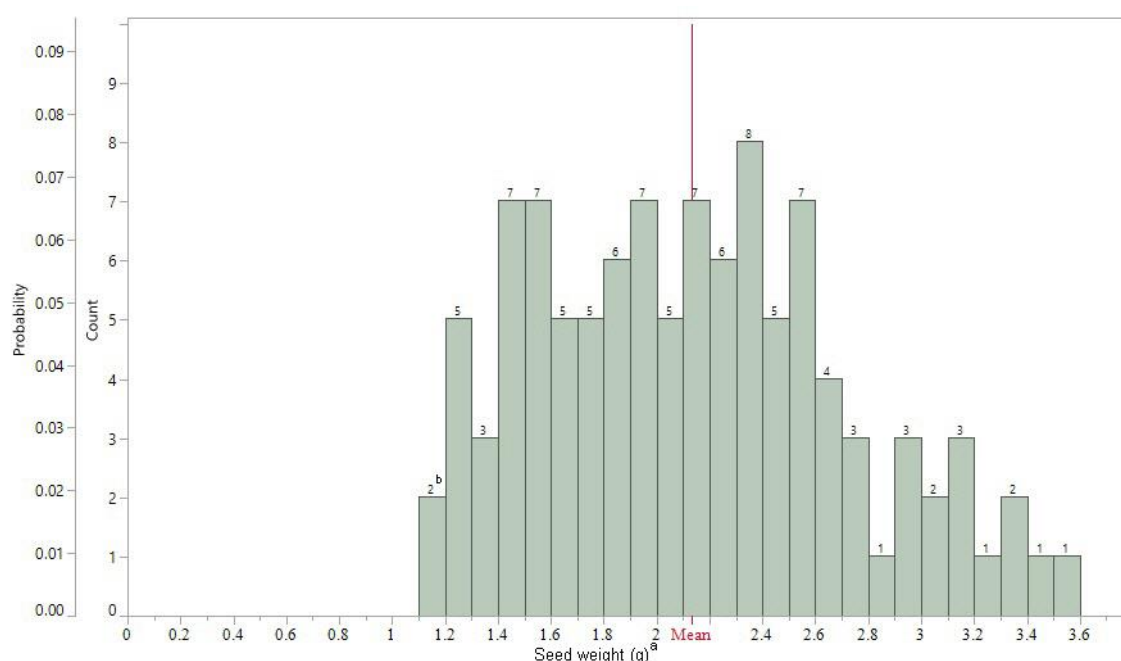


Figure 2. The phenotype distribution of seed weight in grams

The x-axis indicates the average seed weight (g), and the y-axis is the number of sorghum lines and probability.

Table 2. Ten cultivars with the heaviest (left side) and lightest (right side) seed weight in grams

Cultivar	Average SEM	±	Cultivar	Average SEM	±	Cultivar	Average SEM	±	Cultivar	Average SEM	±
PI660638	3.5	± 0.36	PI576380	3.18	± 0.14	PI533920	1.37	± 0.11	PI514310	1.25	± 0.07
PI665169	3.50	± 0.26	PI665165	3.14	± 0.53	PI267557	1.32	± 0.17	PI514506	1.23	± 0.09
PI514286	3.34	± 0.27	PI665166	3.10	± 0.38	PI148101	1.31	± 0.04	PI514308	1.23	± 0.05
PI267606	3.33	± 0.21	PI514288	3.09	± 0.21	PI514394	1.30	± 0.01	PI514534	1.17	± 0.23
PI665167	3.20	± 0.15	PI533923	3.04	± 0.18	PI514437	1.27	± 0.09	PI534131	1.16	± 0.19

3.3 Plant Height

Across 131 tested cultivars (excluding sorghum cultivars for control), plant height was evenly distributed from 73.33 to 310 cm [mean \pm SEM = 189.69 ± 5.32 cm in the population]. Average panicle lengths were evenly scattered and not skewed (Figure 3). The top 10 cultivars with the highest and lowest plant height are listed in Table 3.

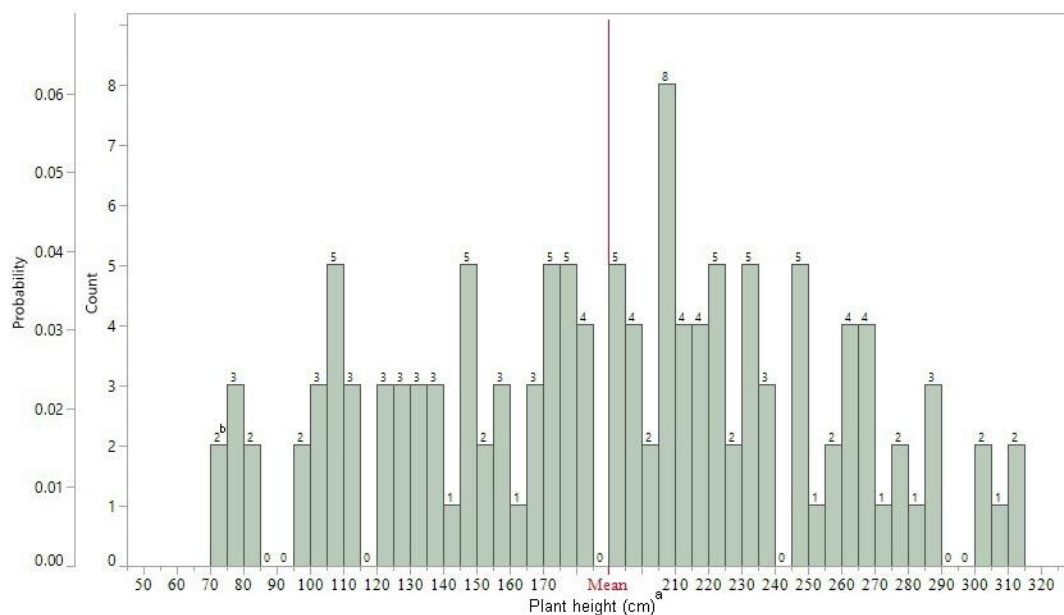


Figure 3. The phenotype distribution of plant height (cm)

The x-axis indicates average plant height based, and the y-axis is several sorghum lines and probability.

Table 3. Ten cultivars with the highest (left side) and lowest (right side) plant height (cm)

Cultivar	Average SEM	±	Cultivar	Average SEM	±	Cultivar	Average SEM	±	Cultivar	Average SEM	±
PI330000	310	± 13.9	PI514347	287.78	± 8.94	PI534131	100	± 5.19	PI533861	76.67	± 1.67
PI514609	310	± 5.77	PI514597	286.67	± 6.67	PI534001	98.33	± 2.84	PI330255	76.67	± 4.41
PI514338	306.67	± 12.02	PI514285	286.67	± 6.67	PI534151	97.75	± 3.85	PI576376	75.83	± 2.67
PI564780	304	± 13.27	PI514348	283.33	± 24.59	PI533920	83.75	± 3.90	PI576381	74.17	± 3.88
PI514457	302.5	± 29.55	PI514440	276.43	± 10.39	PI533799	81.25	± 1.64	PI669639	73.33	± 3.33

3.4 Panicle Length

Among 131 tested cultivars (excluding sorghum cultivars for control), panicle length was distributed from 10 to 53.75 cm [mean ± SEM= 26.55 ± 0.89 cm among the population]. As Figure 4 described, average panicle lengths were evenly distributed. Table 4 shows the top 10 cultivars with the longest and shortest panicle length within 131 lines measured.

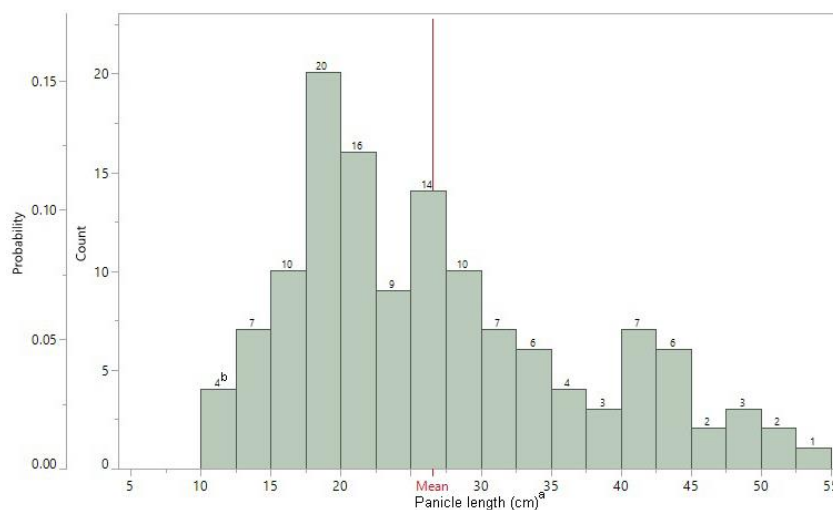


Figure 4. The phenotype distribution of panicle length (cm)

The x-axis indicates the average panicle length, and the y-axis is the number of sorghum lines and probability.

Table 4. Ten cultivars with the longest (left side) and shortest (right side) panicle length (cm)

Cultivar	Average SEM	±	Cultivar	Average SEM	±	Cultivar	Average SEM	±	Cultivar	Average SEM	±
PI514612	53.75	± 4.60	PI514611	47.5	± 3.66	PI533800	14.58	± 1.30	PI251637	13.33	± 0.94
PI514347	52.22	± 3.34	PI514429	45.71	± 5.50	PI267624	14.58	± 1.30	PI330230	12.14	± 1.49
PI514338	51.67	± 1.67	PI514456	45	± 10.41	PI533828	14.17	± 1.20	PI194355	12.08	± 1.30
PI329313	49.29	± 5.28	PI514519	44.17	± 3.27	PI534121	13.75	± 1.09	PI330255	11.67	± 1.67
PI514551	47.78	± 1.88	PI514606	43.75	± 3.15	PI570726	13.33	± 1.67	PI669639	10	± 0

3.5 Flowering Time

Excluding cultivars used as controls, 99 cultivars were tested for flowering time (day); 8 cultivars took more than 140 days to flower, and 12 cultivars took greater than 130 days to bloom. In contrast, 18 cultivars had less than 110 days of flowering time. The average flowering time was 118.20 days ± 1.12 (SEM) within the tested collection (Figure 5). Table 5 lists the top 10 cultivars with the earliest and latest flowering times.

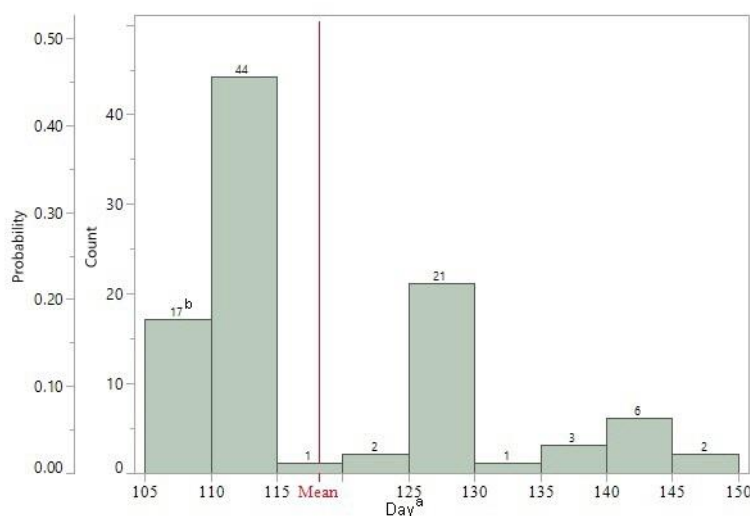


Figure 5. The phenotype distribution of flowering time (days)

The x-axis indicates the average day to flower, and the y-axis shows the number of sorghum lines and probability.

Table 5. Ten cultivars with the earliest and latest flowering time (days)

Cultivar	Average SEM	±	Cultivar	Average SEM	±	Cultivar	Average SEM	±	Cultivar	Average SEM	±
PI514280	148	± 0	PI148101	142	± 0	PI669703	109	± 0	PI533799	109	± 0
PI267655	148	± 0	PI564780	142	± 0	PI669704	109	± 0	PI514288	109	± 0
PI330288	142	± 0	PI514285	142	± 0	PI533800	109	± 0	PI514440	109	± 0
PI570841	142	± 0	PI514287	137	± 0	PI514286	109	± 0	PI669702	109	± 0
PI514609	142	± 0	PI564776	135	± 3.13	PI533828	109	± 0	PI669699	109	± 0

3.6 Correlation Analysis

Correlation analysis revealed that seed weight, plant height, length, and grain yield are associated with sorghum defense response to fungal pathogens. Table 6 shows seed weight was slightly correlated with sorghum responses to anthracnose (Spearman $\rho=0.10$ & $p\text{-value}=0.01$) and grain mold (Spearman $\rho=-0.14$ & $p\text{-value}=0.0005$). Plant height showed a weak negative correlation for response to anthracnose (Spearman $\rho=-0.11$ & $p\text{-value}=0.0045$) and a negative correlation for response to grain mold (Spearman $\rho=-0.30$ & $p\text{-value}<0.0001$). In contrast, it showed a moderately strong positive correlation for response to rust (Spearman $\rho=0.36$ & $p\text{-value}<0.0001$). A similar correlation pattern was observed for panicle length, which recorded weak negative correlations with

anthracnose (Spearman $\rho = -0.19$ & p -value < 0.0001) and grain mold (Spearman $\rho = -0.15$ & p -value = 0.0003) scores and a positive correlation with the score for rust (Spearman $\rho = 0.14$ & p -value = 0.0003). Lastly, grain yield was negatively correlated with grain mold susceptibility (Spearman $\rho = -0.17$ & p -value = 0.0033), but no significance was found for the other two diseases.

Table 6. Correlations between two traits (Spearman's ρ & Pearson's r) and p -value

Pair	Spearman's ρ	Probability	Pair	Pearson's r	Probability
Seed weight-Anthrachnose	0.10	0.01	Germination rate-Seed weight	0.19	<0.0001
Seed weight-Grain mold	-0.14	0.0005	Germination rate- Plant height	0.31	<0.0001
Plant height-Rust	0.36	<0.0001	Germination rate- Panicle length	0.27	<0.0001
Plant height-Anthrachnose	-0.11	0.0045	Panicle length-Seed weight	-0.16	<0.0001
Plant height-Grain mold	-0.30	<0.0001	Panicle length-Plant height	0.52	<0.0001
Plant length-Anthrachnose	-0.19	<0.0001	Grain yield-Seed weight	0.29	<0.0001
Panicle length-Rust	0.14	0.0003	Grain yield- Plant height	0.13	0.0094
Panicle length-Grain mold	-0.15	0.0003	Flowering time-Plant height	0.65	<0.0001
Grain yield-Grain mold	-0.17	0.0033	Flowering time -Panicle length	0.50	<0.0001
			Flowering time -Seed weight	-0.12	0.01
			Flowering time -Germination rate	0.12	0.01

Germination rate was positively correlated with seed weight (Pearson's $r = 0.19$ & p -value < 0.0001), plant height (Pearson's $r = 0.31$ & p -value < 0.0001), and panicle length (Pearson's $r = 0.27$ & p -value < 0.0001). Pearson's r was -0.16 with a p -value < 0.0001 for panicle length and seed weight; it was 0.52 with a p -value < 0.0001 between panicle length and plant height. Grain yield and seed weight positively correlated (Pearson's $r = 0.29$ & p -value < 0.0001). At the same time, grain yield and plant height showed a weak correlation (Pearson's $r = 0.13$ & p -value = 0.0094). Flowering time was positively correlated with plant height (Pearson's $r = 0.65$ p -value < 0.0001) and panicle length (Pearson's $r = 0.50$ & p -value < 0.0001). However, it was negatively correlated with seed weight (Pearson's $r = -0.12$ with p -value = 0.01).

4. Discussion

The projected increase in global population by 2050 to around 9.1 billion will require increases in crop production, including sorghum for food, feed and other uses (FAO, 2009). In sorghum breeding, improvement of certain agronomic characteristics, including uniformity in flowering time and maturity, percent germination, plant height, plant density, tillering ability, and fertilizer responsiveness will be desirable traits (Rakshit et al., 2019). In addition, future increases in cereal production will likely increase diseases that will impact both yield and quality (Prom et al., 2020).

The results in this study indicate that architecture traits in sorghum can also be associated with defense responses to fungal pathogens; panicle height and rust infection was positively correlated (Spearman's $\rho = 0.36$), while it was negatively correlated with grain mold infection (Spearman's $\rho = -0.30$). Panicle length was also associated with anthracnose (Spearman's $\rho = -0.19$) and grain mold (Spearman's $\rho = -0.15$).

Moreover, grain yield, seed weight, and germination rate were associated with architectural traits; germination rate and plant height were moderately correlated (Pearson's $r = 0.31$). Germination rate and panicle length showed a similar level of correlation (Pearson's $r = 0.27$). Also, panicle length and plant height (Pearson's $r = 0.52$), flowering time and plant height (Pearson's $r = 0.65$), and flowering time and panicle length (Pearson's $r = 0.50$) were found to be associated.

In a recent study, it was found that there is a possible negative correlation between anthracnose resistance of sorghum & Johnson grass (*Sorghum halepense*), a wild relative of sorghum, and midrib thickness (Ahn et al., 2020). This study also found a weak positive correlation between anthracnose resistance in Johnson grass and leaf angle (Ahn et al., 2020). Prom et al. (2022a) reported a significant negative correlation between grain mold severity with seed weight and germination rate, while the association between seed weight and germination rate was positive. A negative significant correlation between germination rate and responses to anthracnose and grain mold infection, but a positive correlation was noted between germination rate and rust response (Prom et al., 2022b). Garud et al (2000) noted significant reduction in germination when seeds were infected with *Fusarium* spp. Also, when sorghum and foxtail were inoculated separately with individual fungi *F. solani*, *C. lunata*, *F. moniliforme*, and *A. altanata*, seedling emergence rate was markedly reduced (Yago et al., 2011). The study also shows a positive association between seed weight and germination, indicating the larger/heavier the seeds, the higher the

germination rate. Hou and Romo (1998) noted a positive association between germination rate and seed weight but up to a certain level. Large seeds with higher 1000-seed weight were shown to contain more soluble sugar, higher germination index, vigor index, and seedling biomass than small seeds (Mao et al., 2019). Santi et al (2008) suggested that the higher germination rate of larger seeds is due to larger food reserve as opposed to smaller seeds. Improved plant establishment on field planted bird's-foot trefoil was noted when larger seed sizes were used (McKersie et al., 1981). However, a soybean variety M-351 with medium 100-seed weight (11.7 g) exhibited higher germination rate than two other varieties with heavier 100-seed weight (Adebisi et al., 2013). Similar to the flowering time and panicle length pair in this study, a recent study reported that plant height is correlated with flowering time (Pearson's $r=0.14$) in a nested association mapping (NAM) (Olatoye et al., 2020). Jaiswal et al (2019) noted 22 pairs with significant correlations among tens foxtail millet agronomic traits, including days to flowering, plant height, tiller number, panicle length, and grain yield.

A recent study analyzed plant architecture traits through Genome-wide Association Studies (GWAS) (Girma et al., 2019; Morris et al., 2013; Rhodes et al., 2017; Tao et al., 2020; Zhou et al., 2019). For example, panicle length is associated with the single nucleotide polymorphisms (SNPs) locus S3_788281, and flowering time is related to the SNP locus S10_54425412 (Zhao et al., 2016). Panicle length is also associated with the SNP loci S1_8065027, S2_63553713, and S3_58920501, which are all related to homeobox and SQUAMOSA promoter binding protein (SBP) box (Zhou et al., 2019). The highest probability for an SNP associated with resistance/susceptibility to anthracnose in a sorghum mini core collection is related to a Zinc-finger-homeodomain (ZF-HD) protein encoded by a gene on chromosome 8 (Ahn et al., 2019a) and panicle length was weakly associated with anthracnose (Spearman $\rho=-0.19$) in this study. Sorghum grain mold was associated with homeodomain leucine zipper protein 14 in a sorghum association panel (Prom et al., 2021). Contreras-Soto et al. (2017) identifies 11, 17, and 50 SNP-based haplotypes in a soybean association mapping panel with significant association with 100-seed weight, plant height, and seed yield. A total of 28 correlations was noted among plant height, main spike length, seed weight, 1000-seed weight, and take-all disease response in bread wheat, 17 were positively correlated while six were negatively correlated (Riseh et al., 2022). Also, Riseh et al (2022) noted a negative correlation between take-all disease level and grain yield on wheat. Jamil et al (2019) reported that temperature above 30°C during flowering of wheat plants negatively affect the grain yield. A weak negative correlation was found between panicle length and grain mold (Spearman's $\rho=-0.15$). Genotyping information for the accessions evaluated in this study is unavailable for most lines. However, the phenotypic data analyzed in this study for the traits are expected to be useful for future studies in sorghum architecture traits, grain quality, and quantity.

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Competing interests

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Obtained.

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The Publication Ethics Committee of the Canadian Center of Science and Education.

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The data that support the findings of this study are available on request from the corresponding author. The data are not publicly available due to privacy or ethical restrictions.

Data sharing statement

No additional data are available.

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