Association Analysis for Different Morphological Traits in Sorghum [*Sorghum bicolor* (L.)Moench] **of the Central Plateau Zone of Rwanda**

Abstract*:* Sorghum has the largest share of cultivated land for cereal crops in Rwanda but the productivity is low due to many constraints including drought stress and the unavailability of adaptable cultivars with high yields. However, direct selection of genotypes for yield might not be successful since yield is a complex trait controlled by many genes and subjected to high interaction between genotype and environment.This study therefore was carried out to estimate the associations among traits and to determine the direct and indirect effects of traits on the grain yield of sorghum genotypes.Thirty six sorghum genotypes were evaluated for 12 quantitative traits in simple lattice design atRubona Research Station of the Rwanda Agricultural and Animal Resources Board in 2019. Grain yield had positive and significant genotypic and phenotypic correlations with the number of kernels per panicle, panicle weight, aboveground biomass, inflorescence width, harvest index, leaf area index, and days to 50% flowering. Moreover, aboveground biomass, harvest index, panicle weight, inflorescence width, and leaf area index had direct positive effects on grain yield both at genotypic and phenotypic levels showing the true associations of the traits with grain yield indicating that the indirect selection of these traits can be applied to improve grain yield. The results of this study revealed the potential of simultaneous improvement of grain yield and other yield components through selection. Thus, it is concluded that the four traits (aboveground biomass, head/panicle weight, inflorescence width, and leaf area) are suggested for the selection of sorghum genotypes for high yield in the study area of Rwanda.

Keywords: Association, direct effect,genotypic correlations, phenotypic correlations,quantitative traits.

1. Introduction

Sorghum was domesticated in central and eastern Africa between 4000 and 6000 years ago, and it was initially used as a food crop in this region of Africa (Ge *et al*., 2022). Sorghum has a high tolerance to many abiotic stresses because it was domesticated and evolved in arid and semiarid ecosystems. Due to these features, sorghum is an ideal genetic resource to meet the demands of modern crop breeding to ensure food security in the face of climate change (Prasad *et al.*, 2021; Ge *et al*., 2022). Sorghum is among the farmers' preferred crops in Rwanda, as it accounted for 57.8% of the total area covered by cereals in the 2022 cultural season (NISR, 2022).This preference is strengthened by the fact that sorghum is more adaptable to drought and tolerant of places with poor soils when compared to maize, which is the most common cereal in Rwanda. Sorghum is a short-day C4 plant (Prasad *et al.*, 2021; Raghavendra *et al.*, 2022), and due to its ease of adaptation to hot and dry agroecologies, it is a crop that complies with climate change.

Sorghum is mainly grown for its grain yield in Rwanda and is used as the primary raw material for porridge preparation and local brewing. Sorghum has a robust local market, making it possible for smallholder farmers to use it as a reliable source of revenue to meet their basic needs (Niyibigira *et al*., 2013). Despite of its importance and having genetic flexibility to withstand environmental challenges sorghum yield is low in Rwanda due to extreme environmental conditions and the pest and diseases (Niyibigira, *et al*., 2024).

Sorghum is also known for its high nutritional contents, with considerable health and dietary benefits (Nemukondeni*et al*., 2022; Chhikara*et al*., 2023). It is a vital source of energy, vitamins, antioxidants, and minerals (Hassan, 2023). Sorghum grains have been suggested to be included in the diet for the prevention and control of chronic diseases due to the presence of abundant tannins, lipids, dietary fiber, and phenolic compounds (Salvati *et al*., 2024). Its high dietary fiber (6%) content facilitates digestion and may help in prevention of cardiovascular diseases and weight loss, while its essential minerals like zinc, iron, magnesium, and phosphorus may intervene in growth, maintenance, and metabolic processes (Chhikara*et al*., 2023).

Many factors contributed to low yield of sorghum including extreme environmental conditions. It is known that sorghum can cope with different types of environmental stress such as heat, drought, salinity and flood stresses (Ejeta and Knoll, 2007). However, the crop is not immune for all level of environmental stress. For instance drought is expected to negatively impact on global food security in the coming years (Godfray and Garnett, 2014). As scientists indicated molecular, physiological, and morphological functioning of the plant are affected by drought stress and resulting in pronounced yield losses (Farooq *et al*., 2009; Sakhi *et al*., 2014). The development of drought tolerant and adapted crop varieties is one of the measures to be taken to enhance production and productivity under drought and other extreme environmental conditions. However, due to the lag in sorghum breeding and poor adoption of improved cultivars by growers, it has not kept pace with the increasing demand for sorghum in Sub-Sahara African countries(Derese *et al*., 2018)which is also true for low yield in Rwanda. The development of varieties for high yield and stress tolerance is possible through selection of sorghum land-races which are preferred by most farmers for their desirable traits. However, direct selection of genotypes for yield and stress such as drought tolerance might not be successful since yield and stress tolerance are complex traits controlled by a large number of genes and subjected to high genotype by environment interaction (Ezeaku *et al*., 1999; Blum, 2011). Therefore, information on the association of traits is vital for genetic gain of yield from selection breeding.

Although the improvement of the sorghum crop is determined by the genetic diversity found in the existing genotypes, the information on how the yield is associated with its components can help in the selection of multiple traits that can lead to increased yield (Amare *et al*., 2015). However, yield is a complex trait that is not easily heritable and is affected by many other traits with varying degrees of heritability. These traits are also interrelated, and it is difficult to determine their true effect on yield by merely examining correlation results (Akatwijuka *et al*., 2019). Path coefficient analysis is viewed as the best solution to overcome this problem, because it quantifies the contribution of each trait by splitting the correlation coefficient into direct and indirect contributions of different traits to the yield (Akatwijuka *et al.*, 2019; Kavya *et al.*, 2020; Tadele *et al*., 2022). Correlation and path coefficients research have been conducted in sorghum genotypes in various parts of Africa (Derese *et al*. 2018; Akatwijuka *et al*., 2019; Bejiga, *et al*. 2021; Andiku *et al*., 2022), but no such studies have been carried out on sorghum genotypes in Rwanda. Therefore, this study was conducted to estimate the associations among traits and to determine the direct and indirect effects of traits on grain yield of sorghum genotypes in Rwanda.

2. Materials and Methods

2.1.Description of Study Area

This research was conducted between January and July 2019 at the Rwanda Agriculture and Animal Resources Development Board (RAB)'s Rubona research station in the central plateau zone, during the 2019 and 2020 sorghum cropping season. The Rubona research station is situated in the Huye district of the Southern Province, with coordinates of 2^{o}48'S latitude, 29^{o}76'E longitude, and an altitude of 1706 m.a.s.l. (Mukamuhirwa*et al.*, 2018). The mean temperature and annual rainfall at this research station are 18.7°C and 1200 mm, respectively (Shumbusha*et al.*, 2017).

2.2.Experimental Materials and Design

A total of 36 sorghum genotypes from the Rwanda National Genebank and Sorghum Research Program (Table 1) was laid out in a simple lattice design, having a plot measuring 3 m x 2 m (6 m^2) consisting of four rows with 10 plants in each row for a total of 40 plants per plot. Rows were spaced 0.75 m apart, and plants within rows were separated 0.20 m apart. Two seeds were placed into a hole of 25 mm, and after germination, one seedling was thinned. The farm manure was applied at planting at a rate of 20 t/ha, and it was supplemented with mineral fertilizers $N_{17}P_{17}K_{17}$ at a rate of 250 kg/ha and urea (46% N) at a rate of 100 kg/ha. In contrast to urea, which was applied six weeks after germination, $N_{17}P_{17}K_{17}$ was applied two weeks after germination. Weeding was done manually when necessary, and fall armyworms were controlled withProfenofos 40% + Cypermethrin 4% EC at a concentration of 2 ml/L of water. These practices followed the crop management recommendations for sorghum.

Table 1. List of sorghum landraces and varieties evaluated at Rubona research station

Number	Landrace/variety name	Collection district	Source
1	Amakoma	Kamonyi	RNGB
2	Amera	Kamonyi	RNGB
3	Bukobwa	Gisagara	RNGB
4	Bukobwa	Huye	RNGB
5	Bukobwa	Gisagara	RNGB
6	Cyamwiha	Kamonyi	RNGB
7	Gatemwa	Huye	RNGB
8	Gihove	Kamonyi	RNGB
9	Igihove	Ruhango	RNGB
10	Ikinyaruka	Nyanza	RNGB
11	Kinyaruka	NA	SRP
12	Indinganire	Nyanza	RNGB
13	IS21219	NA	SRP
14	IS8193	NA	SRP
15	Kat369	NA	SRP
16	Kebo	Ruhango	RNGB
17	Kigosorabaswa	Nyanza	RNGB
18	Kigufi	NA	SRP
19	Kinanira	Nyanza	RNGB
20	Mabereyingoma	NA	SRP
21	Mugabo	Huye	RNGB
22	Munebwe	Huye	RNGB
23	Ndamirabana	Gisagara	RNGB
24	Ntuncurimboga	Nyanza	RNGB
25	Nyakami	Ruhango	RNGB
26	Nyiragahengeri	Ruhango	RNGB
27	Nyiragikori	Gisagara	RNGB
28	Nyiragikoriy'umweru	Huye	RNGB
29	Nyiragitenderi	Gisagara	RNGB
30	Nyirakaganza	Ruhango	RNGB
31	Nyirakanyamunyo	Nyanza	RNGB
32	Nyirakinuma	Huye	RNGB
33	Nyiramugufi	Gisagara	RNGB
34	Rudasakwa	Kamonyi	RNGB
35	Umuceri	NA	SRP
36	Amasaka	Ruhango	RNGB

Note: RNGB: Rwanda National Genebank, SRP: Sorghum Research Program

2.3.Data Collection

Data were gathered on sample plants and plots from the two middle rows. Data on days to 50% flowering (DF) and days to 90% maturity (DM) were recorded by counting the days after sowing when 50% of the plants had their first open flower and 90% of the panicles had reached physiological maturity (grains had black layers at the base). To determine plant height (PLH), the average of five randomly chosen plants was measured in centimetersfrom the base to the tip of the panicle at physiological maturity. The leaf area index (LAI) was recorded during the flowering period as the ratio of unit leaf area per unit ground on the net plot. After harvesting, the inflorescence length (INFL) of the average of five randomly selected plants was measured from the lower panicle branch to the tip of the panicle. Data on inflorescence width (INFW) was recorded in centimeters from the average of five randomly selected plants, measured from the widest portions of the panicle after harvest. Head/Panicle weight (PW) data was estimated in grams from the average of five randomly selected main panicles measured before threshing. After threshing, the average kernels number from five main panicles selected randomly was calculated to determine the number of kernels per panicle (NKPP). Grain yield (GY) was calculated as kg ha^{-1} by weighing the kernels on the entire plot after threshing. The obtained yield was then adjusted to a standard moisture content of 12.5%. Above ground biomass (ABGB) was estimated in kilograms from all the plants of the plot after being dried with the sun to a constant dry weight and finally converted to kg ha^{-1}. The ratio of grain yield to all above-ground biomass for each plot was used to calculate the harvest index (HI). From 250 randomly selected grain duplicates, the thousand kernel weight (TKW) was measured in grams, averaged, and multiplied by four. A standard moisture content of 12.5% was applied to the obtained thousand kernel weight.

2.4.Data Analysis

2.4.1. Genotypic and phenotypic correlation coefficient analysis

The genotypic and phenotypic correlations between pair of traits were estimated as suggested by (Johnson *et al*., 1955; Singh and Chaudhary, 1985):
$r_{g=}\frac{\mathrm{Gcov12}}{\sqrt{\mathrm{V_{g1}.V_{g2}}}}$ and $r_p = \frac{\mathrm{Pcov12}}{\sqrt{\mathrm{V_{p1}.V_{p2}}}}$, Where, r_g= Genotypic correlation coefficient, r_p= Phenotypic correlation coefficient, Gcov12 = Genotypic covariance between traits 1 and 2, Pcov12 = Phenotypic covariance between traits 1 and 2, Vg1 = Genotypic variance of trait 1, Vp1 = Phenotypic variance of trait 1, Vg2 = Genotypic variance of trait 2 and Vp2 = Phenotypic variance of trait 2.

The coefficients of correlations at genotypic level were tested for their significance using the following formula outlined by Robertson: $t=\frac{r_{g12}}{SE_{g12}}$, with $SE_{g12} = \sqrt{\frac{(1-r^2)^2}{2h^2{}_1h^2{}_2}}$

The calculated "t" value was compared with the tabulated "t" value at (n-2) degree of freedom at a 5% level of significance.
Where r_{g12}=genotypic correlation coefficient, $h^2 1$ = heritability of trait 1 and $h^2 2$= Heritability of trait 2.
The coefficients of correlation at a phenotypic level were tested for their significance using t-test: $t=\frac{r_{p12}}{SE_{rp12}}$Where, r_{p12}= Phenotypic correlation; SE (rp) = Standard error of phenotypic correlation obtained using the following formula:$SE_{rp12} = \sqrt{\frac{(1-r^2)^2}{2h^2{}_1h^2{}_2}}$Where: SE_{rp12} = standard error of phenotypic correlation coefficient between trait 1 and 2, h^2_1 = Heritability value of trait 1 and h^2_2 = heritability value of trait 2.

2.4.2. Path Coefficient Analysis

Path coefficient analysis was performed using the method described by (Dewey and Lu, 1959):
rij = Pij + Σrikpkj
Where, rij = mutual association between the independent trait (i) and dependent trait (j) as measured by the genotypic (phenotypic) correlation coefficients.
Pij = direct effects of the independent trait (i) on the dependent trait (j) as measured by the genotypic (phenotypic) path coefficients, and Σrikpkj = Summation of components of indirect effects of a given independent trait (i) on a given dependent trait (j) via all other independent traits (k).
The residual effect enables a precise explanation of the pattern of interaction of other possible components of yield. It is estimated with the help of direct effects and a simple correlation coefficient. It was estimated using the formula;
$1=p^2R + \Sigma$ p ijrij
Where, p^2R is the residual effect.
p ijrij = the product of direct effect of any variable and its correlation coefficient with the dependent trait.
The residual effect (p^2R) was computed using the formula $R=\sqrt{1-\sum P_{iy}r_{iy}}$. Where, P_{iy}= direct effect of the independent variable i on the dependent variable *y*; r_{iy}= the correlation coefficient of the independent trait *i* with the dependent variable *y*.

3.RESULTS AND DISCUSSION

3.1.Genotypic and Phenotypic Correlation Coefficients

3.1.1. Correlation of yield with other traits

The results of genotypic and phenotypic correlations are presented in Table 2. Grain yield had a positive and highly significant ($P < 0.01$) genotypic and phenotypic correlation with the number of kernels per panicle (0.640/0.639) and panicle weight (0.585/590). Also, grain yield recorded a positive and significant ($P <0.05$) genotypic correlation and a positive and significant phenotypic correlation ($P<0.01$) with aboveground biomass (0.415/0.418), days to 50% flowering (0.402/0.394), inflorescence width (0.376/0.379), leaf area index (0.353/0.352), and harvest index (0.338/0.345).

The results of a significant and positive correlation between grain yield and days to 50% flowering suggest that the selection of early flowering sorghum genotypes may result in a high grain yield, which is a fortune for drought-prone regions. The result of the same association between the flowering period and grain yield was reported earlier by Gebrie and Genet (2019) and Kavya *et al.*(2020).

The fact that these traits showed a strong correlation with grain yield at both the genotypic and phenotypic levels suggested that these traits could have crucial importance in the selection process for sorghum genotypes with high grain yield. According to Jain (2010), the genotypic correlation coefficient gives an indication of the genetic relationships between traits and helps in determining which traits should be prioritized in breeding programs. Given that the genotypic correlation coefficients are higher than phenotypic for the number of kernels per panicle and days to 50% flowering, it is an indication of strong inherent relationships between these traits, as reported byJohnson *et al*. (1955). Consistent with the results of this study,Gebreyohannes*et al*. (2018), and Jafar *et al*. (2023)found a strong sorghum grain yield association with the number of seeds per panicle and panicle weight. Similar findings were also reported byGebrie and Genet (2019) for panicle width, by Girma *et al*. (2020) for harvest index, and by Endalamaw *et al*. (2017) for aboveground biomass.

The results also exhibited a non significant positive genotypic correlation with plant height and days to 90% maturity. On the other hand, grain yield recorded a negative non significant negative correlation with thousand kernels weight, indicating the lack of evidence of a meaningful negative relationship between grain yield and thousand kernels weight. Consistent with the results of this study, a negative and non significant correlation between sorghum grain yield and thousand kernels weight was reported by Kavya *et al*. (2020), and a positive and non significant correlation between plant height and grain yield was reported bySeetharam and Ganesamurthy (2013) and Kavya *et al*. (2020).

Table 2. Genotypic (above diagonal) and phenotypic (below-diagonal) correlations of 12 quantitative traits of sorghum genotypes at Rubona, 2019

Trait	PLH	LAI	INFL	INFW	HPW	NKPP	TKW	FD	MD	ABGB	HI	GY
PLH		0.672**	-0.098	0.437**	0.467**	0.402*	0.122	0.731**	0.644**	0.802**	-0.623**	0.289
LAI	0.665**		-0.1412	0.436**	0.447 **	0.426 **	-0.001	0.578**	0.469**	0.502**	-0.352 *	0.353 *
INFL	-0.072	-0.125		-0.470**	-0.08	-0.115	-0.088	0.04	0.04	-0.008	-0.077	-0.312
INFW	0.426**	0.417 **	-0.386**		0.686 **	0.669 **	0.265	0.422 *	0.248	0.157	-0.042	0.376 *
HPW	0.460**	0.442 **	-0.048	0.672**		0.908 **	0.151	0.549	0.286	0.275	0.087	0.585 **
NKPP	0.402**	0.426 **	-0.081	0.652**	0.900 **		-0.182	0.590 **	0.328	0.262	0.138	0.640 **
TKW	0.12	0.009	-0.051	0.259*	0.158	-0.159		-0.144	-0.189	-0.002	-0.108	-0.154
DF	0.714**	0.575**	0.038	0.398**	0.537 **	0.581 **	-0.139		0.892 **	0.769 **	-0.458**	0.402 *
DM	0.628**	0.467 **	0.038	0.231	0.281 *	0.325 **	-0.174	0.890 **		0.754 **	-0.470**	0.289
ABGB	0.794**	0.504 **	0.004	0.157	0.277 *	0.266 *	0.009	0.766 **	0.750 **		-0.639**	0.415 *
HI	-0.603**	-0.347**	-0.061	-0.024	0.097	0.141	-0.091	-0.456**	-0.467**	-0.631**		0.338 *
GY	0.296 *	0.352**	-0.270*	0.379**	0.590 **	0.639 **	-0.117	0.394 **	0.285 *	0.418 **	0.345 **	

*and **: significant at 5% and at 1% level of significant test, respectively. DF= days to 50% flowering; DM= days to 90% maturity; PLH (cm) = plant height; LAI = leaf area index; INFL (cm) = inflorescence length and INFW (cm) = inflorescence width, HPW= panicle weight, NKPP= number of kernels per panicle; TKW= thousand kernels weight; ABGB= aboveground biomass, GY= grain yield; HI= harvest index.

3.1.2. Correlation coefficient among other traits

Plant height exerted a positive and highly significant genotypic and phenotypic correlation with aboveground biomass (0.802/0.794), days to 50% flowering (0.731/0.714), leaf area index (0.672/0.665), days to 90% maturity (0.644/0.628), panicle weight (0.467/0.460), and inflorescence width (0.437/0.426) (Table 2). These results suggest that taller genotypes require a longer period to flower and mature, have wide and heavy panicles, a large leaf area index, and a high yield of above ground biomass. Similar to these findings, Gebreyohannes*et al*. (2018), Thange *et al*.(2021), and Adedugba*et al*. (2023)reported a highly significant positive correlation between plant height and days to flowering and days to maturity in their studies.

Days to 50% flowering and days to 90% maturity showed a positive and highly significant correlation with leaf area index and aboveground biomass at genotypic and phenotypic levels, indicating that the selection of early maturing varieties, with good trait for drought tolerance, will compromise the height, leaf area index, and biomass of the genotypes. On the contrary, early maturing genotype selection will favor the harvest index, as the harvest index showed a negative and highly significant correlation with days to 50% flowering and days to 90% maturity (Table 2). Similar to the results of the studies, Amare *et al*.(2015)reported a positive, highly significant correlation between days to flowering and leaf area index, and they also reported a negative significance between days to flowering and harvest index at the phenotypic level.

Inflorescence width had a positive and highly significant correlation with panicle weight and number of kernels per panicle at both genotypic and phenotypic levels, indicating that the selection of the genotypes based on inflorescence width will positively influence the weight and number of kernels per panicle. Opposed to this, the same selection of genotypes based on panicle width will disfavor the length of the panicle, as inflorescence length showed a negative and highly significant correlation at genotypic and phenotypic levels (-0.470/-0.386). The results of the present studies are in line with those reported byEndalamaw *et al*.(2017); Akatwijuka *et al*.(2019), when they found a positive, highly significant correlation between panicle width and panicle weight.

3.2.Path Coefficient

3.2.1. Genotypic path coefficient analysis of grain yield with other traits

The results of genotypic path coefficient showed positive direct effects of aboveground biomass (1.168), harvest index (0.833), panicle weight (0.394), inflorescence width (0.194), and leaf area index (0.145) on grain yield. Lenka and Misra (1973)categorized indirect and direct effects into negligible (0.00–0.09), low (0.10–0.19), moderate (020–0.29), high (0.30–0.10), and very high (<1.00). Following Lenka's categorization, aboveground biomass had a very high positive effect, harvest index and panicle weight showed high positive effects, while inflorescence width and leaf area index exhibited moderate positive effects (Table 3). This demonstrated that the selection of sorghum genotypes based on aboveground biomass, harvest index, panicle weight, inflorescence width, and leaf area index will be productive in improving grain yield. Consistent with these results, Derese *et al*. (2018), Jafar *et al*. (2023)reported a positive effect of aboveground biomass and harvest index on grain yield, whileAkatwijuka *et al*. (2019)found a positive effect of panicle weight and panicle width on sorghum grain yield in Uganda.

On the other hand, thousand kernels weight, plant height, number of kernels per panicle, days to 90% maturity, inflorescence length, and days to 50% maturing had a negative direct effect on grain yield, suggesting that improving one of these traits at the same time with grain yield is challenging. So, caution should be taken when selecting one of these traits simultaneously with grain yield. The results of this study were also in line with those reported by Deshmukh *et al*. (2018)for days to 50% flowering and the number of seeds per panicle, and byMalaghan and Kajjidoni(2019)for inflorescence length. Even so, these authors reported positive direct effects of plant height, days to maturity and thousand kernels weight on grain yield, which is in contrast to the results of this study.

Furthermore, aboveground biomass had a high positive indirect effect on grain yield through plant height, days to 50% flowering, days to 90% maturity, leaf area index, panicle weight, and number of kernels per panicle (Table 3). The same above ground biomass trait showed a moderate indirect positive effect on grain yield via inflorescence width. Also, in addition to their positive direct effect on grain yield, the harvest index had low and negligible indirect positive effects on grain yield via number of kernels per panicle and panicle weight. Panicle weight also showed low and moderate indirect positive effects on grain yield through, leaf area index, plant height, and inflorescence width (Table 3). These indicated that the selection of the sorghum genotypes based on these traits would be useful in improving grain yield. Similar to the results of the present study, Mamo and Worede (2020)reported a positive and indirect effect of biomass on sorghum grain yield through panicle weight, flowering days, and number of seeds per panicle, whereasGebrie and Genet(2019)found a positive and indirect effect of panicle weight on grain yield through panicle width.

The present genotypic path coefficient's residual effect was 0.070 (Table3), indicating that component variables alone accounted for 93.00% of the variation in grain yield, with other traits not evaluated in this study accounting for the remaining 7%.

Table 3.Genotypic direct (diagonal) and indirect (off diagonal) effects of 11 traits on grain yield of 36 sorghum genotypes evaluated at Rubona in 2019

Trait	PLH	LAI	INFL	INFW	HPW	NKPP	TKW	FD	MD	ABGB	HI	r_gGY
PLH	**-0.219**	0.098	0.014	0.085	0.184	-0.075	-0.029	-0.068	-0.118	0.937	-0.519	0.289
LAI	-0.147	**0.145**	0.021	0.084	0.176	-0.08	0	-0.053	-0.086	0.587	-0.294	0.353*
INFL	0.021	-0.021	**-0.147**	-0.091	-0.032	0.022	0.021	-0.004	-0.007	-0.01	-0.064	-0.312
INFW	-0.096	0.063	0.069	**0.194**	0.270	-0.126	-0.064	-0.039	-0.045	0.183	-0.035	0.376*
HPW	-0.102	0.065	0.012	0.133	**0.394**	-0.171	-0.036	-0.051	-0.052	0.321	0.073	0.585**
NKPP	-0.088	0.062	0.017	0.13	0.358	**-0.188**	0.044	-0.055	-0.06	0.306	0.115	0.640**
TKW	-0.027	0	0.013	0.051	0.059	0.034	**-0.241**	0.013	0.035	-0.002	-0.09	-0.154
FD	-0.16	0.084	-0.006	0.082	0.216	-0.111	0.035	**-0.093**	-0.163	0.899	-0.381	0.402*
MD	-0.141	0.068	-0.006	0.048	0.113	-0.062	0.046	-0.083	**-0.183**	0.88	-0.391	0.289
ABGB	-0.176	0.073	0.001	0.03	0.108	-0.049	0	-0.072	-0.138	**1.168**	-0.533	0.415*
HI	0.136	-0.051	0.011	-0.008	0.034	-0.026	0.026	0.043	0.086	-0.747	**0.833**	0.338*

Residual factor = 0.0702.DF= days to 50% flowering; DM= days to 90% maturity; PLH (cm) = plant height; LAI = leaf area index; INFL (cm) = inflorescence length and INFW (cm) = inflorescence width, HPW= panicle weight, NKPP= number of kernels per panicle; TKW= thousand kernels weight; ABGB= aboveground biomass, GY= grain yield; HI= harvest index

3.2.2. Phenotypic path coefficient analysis of grain yield with other traits

The phenotypic path coefficient results revealed a very high positive direct effect of aboveground biomass (1.120) on grain yield, whereas their indirect effect was through all the remaining traits except the harvest index (Table 4). The harvest index also showed a high positive effect on grain yield (0.828), while its indirect effect was via panicle weight and the number of kernels per panicle. Panicle weight (0.244), leaf area index (0.153), and inflorescence width (0.131) exhibited moderately positive direct effects on grain yield. They also showed indirect positive effects through the number of kernels per panicle, panicle width, plant height, and leaf area index for panicle weight, and through plant height, inflorescence width, inflorescence length and the number of kernels per panicle for leaf area index. A negligible positive direct effect of the number of kernels per panicle on grain yield was also noticed, as were its indirect positive effects via aboveground biomass, harvest index, and thousand kernels weigh. Hence, these traits with positive direct effects should be considered in future selection activities for higher grain yield. In agreement with the study, Thange *et al*. (2021)reported a positive direct effect and a positive indirect effectof panicle weight on sorghum grain yield through the number of kernels per panicle,while Ngidi *et al*. (2024) reported apositive direct effect of harvest index on grain yield. Also,Mulualem *et al*. (2018)reported a positive direct effect of panicle weight on grain yield, but they also found positive direct effects of thousand kernel weight, plant height, and days to maturity on grain yield, which contrasts with the results of the present studies.

On the contrary, plant height, days to 50% flowering, days to 90% maturity, inflorescence length, and thousand kernels weight exerted negative direct effects on grain yield. This indicates that the genotype selection based on these traits may affect negatively the grain yield, except for days to 50% flowering, which is significantly correlated to grain yield through its indirect positive effect of thousand kernels weight. Similar to the results of this study, Kavya *et al*. (2020); Derese *et al*. (2018) and Akatwijuka *et al*. (2019)reported direct negative effects of days to 50% flowering, plant height, days to maturity, and thousand kernels weight on sorghum grain yield.

The phenotypic path coefficient had a residual effect of 0.076, showing that the traits involved in the present study explained 92.4% of the variations in sorghum grain yield, while the rest of the variation is attributed to non-considered traits in the study.

Table 4. Phenotypic direct (diagonal) and indirect (off diagonal) effects of 11 traits on grain yield of 36 sorghum genotypes evaluated at Rubona in 2019

Residual factor = 0.0757

Trait	PLH	LAI	INFL	INFW	HPW	NKPP	TKW	FD	MD	ABGB	HI	r_gGY
PLH	**-0.188**	0.102	0.011	0.056	0.112	0.004	-0.018	-0.090	-0.083	0.890	-0.499	0.296*
LAI	-0.125	**0.153**	0.019	0.054	0.108	0.004	-0.001	-0.073	-0.062	0.565	-0.288	0.355**
INFL	0.014	-0.019	**-0.153**	-0.050	-0.012	-0.001	0.008	-0.005	-0.005	0.004	-0.051	-0.270*
INFW	-0.080	0.064	0.059	**0.131**	0.164	0.007	-0.039	-0.050	-0.030	0.175	-0.020	0.379**
HPW	-0.086	0.068	0.007	0.088	**0.244**	0.009	-0.024	-0.068	-0.037	0.310	0.080	0.590**
NKPP	-0.076	0.065	0.012	0.085	0.219	**0.010**	0.024	-0.073	-0.043	0.298	0.117	0.639**
TKW	-0.023	0.001	0.008	0.034	0.039	-0.002	**-0.151**	0.016	0.023	0.010	-0.075	-0.117
FD	-0.134	0.088	-0.006	0.052	0.131	0.006	0.021	**-0.126**	-0.118	0.858	-0.378	0.394**
MD	-0.118	0.072	-0.006	0.030	0.068	0.003	0.026	-0.112	**-0.132**	0.841	-0.387	0.285*
ABGB	-0.149	0.077	-0.001	0.020	0.067	0.003	-0.001	-0.097	-0.099	**1.121**	-0.523	0.418**
HI	0.113	-0.053	0.009	-0.003	0.024	0.001	0.014	0.058	0.062	-0.708	**0.828**	0.345**

4. CONCLUSION

The results of genotypic and phenotypic correlations between grain yield and other traits showed positive correlations between grain yield and the number of kernels per panicle, panicle weight, aboveground biomass, inflorescence width, harvest index, leaf area index, and days to 50% flowering. Genotypic and phenotypic path coefficient analysis results showed positive direct effects of aboveground biomass, harvest index, panicle weight, inflorescence width, and leaf area index on grain yield. The presence of a positive correlation between grain yield and other traits implies that the selection of these traits may result in grain yield improvement. Moreover, positive direct effects of traits on grain yield showed the presence of a true association between these traits and yield, indicating that the indirect selection of these traits can be applied to improve grain yield. Aboveground biomass, head/panicle weight, inflorescence width, and leaf area showed strong positive correlations and positive direct effects on grain yield, implying that the selection of genotypes based on these traits would undoubtedly increase the sorghum grain yield.

Disclaimer (Artificial intelligence)

I 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.

5. REFERENCES

1. Adedugba, A.A., Adeyemo, O.A., Adetumbi, A.J., Amusa, O.D., Ogunkanmi, L.A. 2023. Evaluation of Genetic Variability for Major Agro-Morphological and Stalk Sugar Traits in African Sorghum Genotypes. 2023. *Heliyon*, 9, e14622.
2. Akatwijuka, R., Rubaihayo, P.R. and Odong, T.L. 2019. Correlations and Path Analysis of Yield Traits in Sorghum Grown in Southwestern Highlands of Uganda. *African Crop Science Journal*, 27 (3): 437.
3. Amare, K., Zeleke, H. and 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): 125–33.
4. Andiku, C., Shimelis, H., Shayanowako, A.I., Gangashetty, P.I. and Manyasa, E. 2022. Genetic Diversity Analysis of East African Sorghum (*Sorghum bicolor* [L.] Moench) Germplasm Collections for Agronomic and Nutritional Quality Traits. *Heliyon*, 8 (6): e09690.
5. Bejiga, T., Berhanu, A. and Temesgen, T. 2021. Genetic Variability and Correlation of

Agronomic and Malt Quality Traits in Ethiopian Sorghum [*Sorghum bicolor* (L .) Moench] Landraces at Sheraro , Northern Ethiopia 15 (July): 193–205.

6. Blum, A. 2011. *Plant Breeding for Water-Limited Environments*. Ney York. Springer.
7. Chhikara, N., Tanwar, R., Panghal, A., Chaudhary, G., and Kumari, A. 2023. Nutritional, Phytochemical and Functional Potential of Sorghum: A Review. Food Chemistry Advances, 3, 100501.
8. Derese, S.A, Shimelis, H., Mwadzingeni, L. and Laing, M. 2018. Agro-morphological Characterisation and Selection of Sorghum Landraces. *Acta Agriculturae Scandinavica, Section B—Soil & Plant Science,* 68 (7): 585-595.
9. Deshmukh, S.B., Bagade, A.B. and Choudhari, A.K. 2018. Correlation and Path Analysis Studies among Rabi Sorghum (*Sorghum bicolor* (L.) Moench) Mutants. *International Journal of Current Microbiology and Applied Sciences*, 6: 1014–20.
10. Dewey, R. and Lu, K.H . 1959. A Correlation and Path-Coefficient Analysis of Components x of Crested Wheatgrass Seed Production. 78: 515–18.
11. Ejeta, G and Knoll, J.E. 2007. Marker-Assisted Selection in Sorghum. *in*: Varshney, R.K., Tuberosa, R. (Eds.). Genomic-Assisted Crop Improvement. *Genomics-Assisted Crop Improvement*. 2,187-205.
12. Endalamaw, C., Adugna, A. and Mohammed, H. 2017. Correlation and Path Coefficient Analysis of Agronomic and Quality Traits in a Bioenergy Crop , Sweet Sorghum [*Sorghum bicolor* (L.) Moench]. *African Journal of Biotechnology*, 16 (47): 2189–2200.
13. Ezeaku, I.E, Gupta, S.C. and Prabhakar, V.R. 1999. Classification of Sorghum Germplasm Accessions Using Multivariete Methods. *African Crop Science Journal* 7 (1): 1–9.
14. Farooq, M., Wahid, A., Kobayashi, N. and D. Basra S.M.A. Fujita. 2009. Plant Drought Stress : Effects , Mechanisms and Management To Cite This Version : Review Article." *Agronomy for Sustainable Developmen* 29 (1): 185–212.
15. Ge, F., Xie, P., Wu, Y. and Xie, Q. 2022. Genetic Architecture and Molecular Regulation of Sorghum Domestication. *aBIOTECH*, 4: 57-71
16. Gebreyohannes, A., Tadesse, T., Seyoum, A., Nida, H., Nega, A., Senbetay, T. and Endalemaw, C. 2018. Genetic Variability in Agronomic Traits and Associations in Sorghum [(*Sorghum bicolor* (L.) Moench)] Genotypes at Intermediate Agro-Ecology Sorghum Growing Areas of Ethiopia. *African Journal of Agricultural Research*, 13 (49): 2780–87.
17. Gebrie, G. and Genet, T. 2019. Morphological Characterization and Evaluation of Sorghum [*Sorghum bicolor* (L.) Moench] Landraces in Benishangul Gumuz, North-Western Ethiopia. *Greener Journal of Agricultural Sciences*, 9 (1): 37–56.
18. Girma, F., Mekbib, F., Tadesse, T., Menamo, T. and Bantte, K. 2020. Phenotyping Sorghum [*Sorghum bicolor* (L.) Moench] for Drought Tolerance with Special Emphasis to Root Angle. *African Journal of Agricultural Research* 16 (8): 1213–22.
19. Godfray, C.H.H. and Garnett, T. 2014. Food Security and Sustainable Intensification. *Philosophical Transactions of the Royal Society B: Biological Sciences* ,369 (1639).
20. Hassan, S.M. 2023. Nutritional, Functional and Bioactive Properties of Sorghum (*Sorghum*

bicolor(L.) Moench) with its Future Outlooks: A Review. *Open Journal of Nutrition and Food Sciences*, 5(1): 1030.

21. Jafar, M., Bulti, T., and Mengistu, G. 2023. Correlation and Path Coefficient Analysis of Quantitative in Sorghum [*Sorghum bicolor* (L.) Moench] Genotypes at Fedis, Eastern Ethiopia. *International Journal of Agricultural Sciences and Technology*, 3(2): 10-19.
22. Jain, S.K. Elangovan, M. and Patel, N.V. 2010. Correlation and Path Coefficient Analysis for Agronomical Traits in Forage Sorghum [*Sorghum bicolor* (L.) Moench]. *Indian Journal Of Plant Genetic Resources* 23 (1): 15–18.
23. Johnson,R.W., Robinson, H.F. and Comstock, R.E. 1955. Genotypic and Phenotypic Correlations in Soybeans and Their Implications in Selection 1. *Agronomy Journal*, 47 (10): 477–83.
24. Kavya, P., Rao, V.S., Vijayalakshmi, B., Sreekanth, B., Radhakrishna, Y. and Umar, S.K.N. 2020. Correlation and Path Coefficient Analysis in Sorghum [*Sorghum bicolor* (L.) Monech] for Ethanol Yield. *Journal of pharmacognosy and Phytochemistry*, 9 (2): 07–10.
25. Lenka, D. and Misra, B. 1973. Path Coefficient Analysis of Yield in Rice Varieties. *Indian Journal of Agricultural Science*, 43: 376–79.
26. Malaghan, S. and Kajjidoni S.T. 2019. Character Association and Path Analysis of Grain Yield in Rabi Sorghum [*Sorghum bicolor* (L .) Moench]. 7 (1): 2309–13.
27. Mamo, M. and Worede, F. 2020. Character Association and Path Analysis of Sorghum (*Sorghum bicolor*(L.) Moench). *Black Sea Journal of Agriculture*, 3 (2): 96–102.
28. Mukamuhirwa, F., Butare, L., Kelly, J., Waweru, B., Niyibigira, T., and Mukamurezi, G. 2018. Evaluation of Introduced Bean Genotypes for Adaptability and Root Rot Resistance in Rwanda. International Journal of Agriculture, Environment and Bioresearch, 3 (05).
29. Mulualem, T., Alamrew, S., Tadesse, T. and Wegary, D. 2018. Genetic Variability, Heritability and Genetic Advance for Agronomical Traits of Ethiopian Sorghum. *Genotypes. Acad. Res. J. Agri. Sci., Res* 6 (4): 251–59.
30. Nemukondeni, N., Mbajiorgu, C.A., Hassan, Z.M., Sebola, N.A., Manyelo, T.G., Bodede, O. and Mabelebele, M. 2022. Physical Characteristics, Nutritional Composition and Phenolic Compounds of some of the Sorghum Landraces obtained in South Africa. *Food Research*, 6 (4): 312 – 328.
31. Ngidi, A., Shimelis, H., Abady, S., Chaplot, V., and Figlan, S. 2024. Genetic Variation and Association of Yield, Yield Components, and Carbon Storage in Sorghum (*Sorghum bicolor* [L.] Moench) Genotypes. *BMC Genomic Data*, 25:74.
32. NISR National Institute of Statistics of Rwanda. 2022. Seasonal Agricultural Survey (SAS). 2022 Annual Report.Kigali, Rwanda.
33. Niyibigira, T., Wassu, M., Tamado, T., Tesfaye, L.T., Rukundo, P. 2024. Sorghum farmers' perceptions of climate change, its effects, temperature and precipitation trends, and determinants of adaptation strategies in the central plateau zone of Rwanda, 10, 1: 2334999.
34. Niyibigira, T., Ngugi, K., de Villiers, S., Kiambi, D., Mutitu, E., Osama, S., Ngugi, A.J., Abdalla, M., Ali, R., Mugoya, C. and Masiga, C. 2013. Introgressing Striga Resistance from

A Mapped Donor Source into a Rwandan Adapted Sorghum Variety. *Journal of Renewable Agriculture,* 1 (1): 6.

35. Raghavendra, V.C., Girish, G., Ashok, M.B., Temburne, B.V., Yogeesh, L.N. and Govindappa, M.R. 2022. The Association Studies Between Yield and Its Attributing Traits in M 4 Generation of Rabi Sorghum [*Sorghum bicolor* (L .) Moench]. *Biological Forum – An International Journal,* 14 (2): 508–11.
36. Prasad, V.B.R., Govindaraj, M., Djanaguiraman, M.,Djalovic, I., Shailani, A., Rawat, N., Singla-Pareek, S.L., Pareek, A. and Prasad, P.V.V. 2021. Drought and High Temperature Stress in Sorghum: Physiological, Genetic, and Molecular Insights and Breeding Approaches. *International Journal of Molecular Sciences,* 22 (18), 9826.
37. Sakhi, S., Rehman, S., Okuno, K., Shahzad, A. and Jamil, M. 2014. Evaluation of Sorghum (*Sorghum bicolor*) Core Collection for Drought Tolerance: Pollen Fertility and Mean Performance of Yield Traits and Its Components at Reproductive Stage. *International Journal of Agriculture and Biology* 16 (2): 251–260.
38. Salvati, D., Paschoalinotto, B.H., Mandim, F., Steinmacher, N.C., Pereira, C., and Dias, M.I. 2024. Exploring the Impacts of Sorghum (*Sorghum bicolor* L. Moench) Germination on the Flour's Nutritional, Chemical, Bioactive, and Technological Properties. Foods, 13, 491.
39. Seetharam, K., and Ganesamurthy, K. 2013. Characterization of Sorghum Genotypes for Yield and Other Agronomic Traits through Genetic Variability and Diversity Analysis. *Electronic Journal of Plant Breeding* 4 (1): 1073–79.
40. Shumbusha, D., Shimelis, H., Laing, M. and Asiimwe, T. Phenotypic Diversity Analysis of Sweetpotato for Breeding Dual-Purpose Varieties. *Acta Agriculturae Scandinavica Section B: Soil and Plant Science*, 67 (4): 340–51.
41. Singh, R.K. and Chaudhary, B.D. 1985. *Line x Tester Analysis. Biometrical Methods in Quantitative Genetic Analysis*. *Contemporary Sociology*. Vol. 22. Kalyani, Ludhiana, India.
42. Tadele, M., Mohammed, W. and Jarso, M. 2022. Correlation and Path Coefficient Analysis of Grain Yield and It's Contributing Traits in Faba Bean (*Vicia faba* L.) Genotypes. *Journal of Plant Biology and Crop Research,* 5 (1): 1059.
43. Thange, V.B., Bagade, A.B. and Deshmukh, J.D. 2021. Correlation and Path Coefficient Analysis Studies in Mutant PVK 801 Genotype of Sorghum (*Sorghum bicolor* (L.) Moench). *International Journal of Chemical Studies,* 9 (1): 1696–98.