Innovations

Agronomic Performance and Multivariate Analysis in Sorghum Genotypes under Climate-Smart Management Practices in the Central Plateau Zone, Rwanda

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Abstract: *This study evaluated 36 genotypes for phenology, yield and components, productivity and drought tolerance indices, and responses to conventional and climate-smart practices (tied ridging, mulching, and zai pits). The genotypes showed significant differences under conventional and under combined climate-smart practices. The average grain yield of the genotypes increased by 23.1% under the combined climate-smart management practices. Genotypes Gihove and Nyirakinuma had higher grain yields under both conventional (3664.5 and 3299.0 kg ha^{-1}) and combined climate-smart practices (3953.0 and 3468.3 kg ha^{-1}). Productivity and tolerance indices showed superior performance for the two genotypes. Correlation analysis showed relative productivity, yield index, and geometric, harmonic, and mean productivity indices as indicators of sorghum genotype yield over combined climate-smart practices. The first and second principal components accounted for 60.83% and 38.57% of the total variability of the genotypes for the 10 productivity indices, respectively. Cluster analysis grouped the 36 genotypes into four clusters, and genotypes Gihove and Nyirakinuma in cluster IV performed well for yield and productivity indices, suggesting that they could be recommended under conventional and climate-smart management practices to achieve high yields with minimal variation after further evaluation. The observed differences indicate the existence of genetic diversity that could be used to develop drought-tolerant and high-yielding varieties in Rwanda.*

Keywords: *Clustering, Sorghum grain yield, Principal component analysis, Productivity and tolerant indices, Water use efficiency, Sorghum in Rwanda*.

1.0 Introduction

Sorghum is native to Sub-Saharan Africa and is a highly appreciated grain crop that has grown there for generations (Yahaya et al., 2023). It is the fifth most significant and extensively grown cereal crop in the world. It is the main food source in the arid regions of Africa, China, and India. In Africa, sorghum is the second most important cereal crop after maize in terms of the area harvested (28,134,341 ha) (FAO, 2021). In Rwanda, sorghum is the second main cereal grown after maize, and it is among the preferred crops by farmers in cultural season B (which ends in drought season *Icyi*), ranking fourth after common bean, banana, and cassava, with an area of 139,793 ha (NISR, 2022). Sorghum is genetically adapted to hot and arid agroecologies with periodic droughts, where it is challenging to cultivate other crops (Khandelwal et al., 2019). The crop uses less water than other cereals, such as wheat and maize (Begna et al., 2022) and withstands both intermittent and permanent water stress. This is mostly attributed to the plant's extensive and thick root system, capacity to maintain comparatively high levels of stomatal conductance, and ability of the crop to regulate the internal tissue water potential through osmotic adjustment and phenological plasticity (Verma et al., 2018). This might help the crop survive challenging circumstances and grow in a wide range of environments; however, it is not always considered resilient in an absolute sense, although it is generally thought to be more durable in harsh conditions when compared to other crops (Tack et al., 2017).

Drought is a major factor influencing agricultural productivity worldwide. For instance, sorghum is a crop that is constrained by drought because it is grown mainly in arid to semi-arid tropics in regions where drought is severe (Nadew et al., 2021). In Sub-Saharan Africa, severe drought can cause up to 90% sorghum yield reduction. More than 40% of grain production losses can be attributed to pre-flowering drought stress, whereas losses of 50–90% can be attributed to post-flowering drought stress. Drought stress also affects different components of sorghum grain yield such as the number of grains per panicle and seed size (Yahaya et al., 2023). Rwandan agriculture is extremely susceptible to risks associated with the climate and weather, such as extended droughts (mainly in the eastern and southeastern regions) (WB et al., 2015). Sorghum yield is also constrained by droughts related to climate change, and the central plateau zone is one of the regions affected in Rwanda (Niyibigira et al., 2024). However, it is difficult to predict the precise effects of climate change on the distribution and severity of drought stress, which will likely affect the food security and livelihoods of people who depend on the production of sorghum. One option is the use of crops that have the biological capacity to adapt, which depends on the availability of greater genetic diversity that is likely to increase the resilience of crop production systems in the face of new climatic changes (FAO, 2015).

The assessment and presence of genetic diversity determines the selection of genotypes with desirable trait combinations, such as drought, which can help improve sorghum yield (Yusuf et al., 2020). The presence of a wide diversity of African sorghum genetic resources for multiple breeding utilities, including drought tolerance, has been reported by several authors (Tesfaye et al., 2008; Mofokeng et al., 2017). However, it is difficult to identify the genotypes for tolerance in sorghum because drought tolerance is a complex trait controlled by many genes coding for various traits contributing to tolerance with its own inheritance pattern (Nazari et al., 2021). One option for researchers is to use various drought tolerance indices to identify drought-tolerant genotypes (Anwaar et al., 2020). Additionally, achieving sustainability and productivity of the crop requires not only the diversity of varieties and species, but also the diversification of management strategies (Galluzzi et al., 2011).

The sustainability and productivity of varieties developed for drought-prone areas are achieved by evaluating the response of those genotypes to different climate-smart practices. Tied ridging, mulching, and zai pits are among the climate-smart practices utilized to conserve soil and water. Tied ridging is a climate-smart practice utilized to conserve soil and water. Ridges are small earthen ridges with an upslope furrow that accommodates a runoff catchment strip between the ridges (Germer et al., 2015). Tied ridging has been reported to increase water use efficiency, maize and common bean grain yield, soil water content, and stomatal conductance compared to conventional practices (Bagula et al., 2022; Amankwaa-Yeboah et al., 2022). Mulching is a climate-smart practice that covers the surface of the soil around plants with organic or inorganic materials for better growth and development (Mohammad et al., 2022). Mulching has been reported to address climate change through the conservation of soil moisture, regulation of soil temperature, water intake in the soil, increased crop yield, improved soil microbiological activity, and improved soil fertility (Lalljee, 2013; Shrestha et al., 2014; Subedi et al., 2019; Mohammad et al., 2022). A Zai pit is a climate-smart practice that consists of small planting pits measuring 20-30 cm in width and 10-20 cm in depth (Danjuma and Mohammed, 2015). Various authors reported zai pits as one of the smallholder climate change adaptation strategies through increasing crop yield and improving soil water preservation and infiltration in dry regions, while in heavy rain regions, zai pits limit erosion and rainwater runoff (Kebenei et al., 2023; Bowers et al., 2024).

According to Sandeep et al. (2018), sorghum grain yield is highly determined by crop management practices and other factors, such as soil water content at planting, rainfall amount and its distribution during the growing season, plant available water, and other climatic conditions. The assessment of diversity among sorghum genotypes and identification and availability of new high-yielding varieties in Rwanda are the major activities of the Rwanda Agriculture and Animal Resources Development Board. However, if the selected genotypes are not accompanied by appropriate cultural practices, they cannot show their real yield potential. Therefore, in the case of climate change-induced drought, considering climate smart practices is the right option to sustain sorghum productivity. In this respect, this study was conducted to assess the genetic diversity of sorghum genotypes for phenological traits, water use efficiency, yield components, grain yield, and productivity indices under both conventional and climate-smart practices.

2. 0 Materials and Methods

2.1 Description of Study Area

This study was conducted during the 2019 sorghum cropping season (January 2019 to July 2019) at the Rubona Research Station of the Rwanda Agriculture and Animal Resources Development Board (RAB), located in the central plateau zone of Rwanda. The research station is at an altitude of 1706 m.a.s.l., and is located in the Huye district of the Southern Province, at 2°48' S latitude and 29°76' E longitude (Mukamuhirwa et al., 2018). The station has an annual average precipitation and temperature of 1200 mm and 18.7°C, respectively (Shumbusha et al., 2017), with frequent drought spells.

2.2 Experimental Materials, Treatments and Design

Thirty sorghum landraces obtained from the Rwanda National Genebank and six varieties obtained from the Sorghum Research Program were evaluated in this study. Thirty landraces were collected from five districts in the central plateau zone of Rwanda. The National Genebank collected six landraces (per district) from Gisagara, Huye, and Ruhango districts, whereas seven and five sorghum landraces were collected from Nyanza and Kamonyi districts, respectively. The list of landraces according to their local names is presented in Tables 3–5. Six varieties (SDL880-160, Kinyaruka, IS8193, IS21219, Kat369, and Mabereyingoma) were selected based on their adaptability to the central plateau zone of Rwanda. These 36 sorghum genotypes were evaluated for their response to three climate-smart management practices: tied ridging, mulching, zai pits, and conventional practice (bare soil) at four adjacent experimental fields.

A simple lattice design consisting of 36 plots was used for each of the four environments (conventional and three climate-smart practices). The plot was 3 m × 2 m (6 m^2) in size, consisting of four rows with 10 plants in each row and a total of 40 plants per plot. The spacing within rows and between rows was 0.20 m and 0.75 m, respectively. Two seeds were planted in a 25 mm hole, and one seedling was thinned after germination. Cattle manure (20,000 kg ha^{-1}) was applied at planting and supplemented with mineral fertilizers $N_{17}P_{17}K_{17}$ at a rate of 250 kg ha^{-1} (two weeks after germination) and urea (46% N) at a rate of 100 kg ha^{-1} (six weeks after germination). Sorghum management practices were carried out uniformly on all the plots, as per the recommendation for the site. Fall armyworms were managed using Profenofos 40% + cypermethrin 4% EC at a concentration of 2 ml L^{-1} of water.

2.3 Data Collection

A sorghum descriptor (IBPGRI/ICRISAT, 1993) was used to collect data on days to 50% flowering (DF), days to 90% maturity (DM), head/panicle weight (HPW), number of kernels per panicle (NKPP), thousand kernel weight (TKW), grain yield (GY), and aboveground biomass (ABGB). The harvest index (HI) was calculated as the percentage of the ratio of grain yield to the total aboveground biomass for each plot. Days to 50% flowering (DF) and days to 90% maturity (DM) were converted into thermal time (growing degree days GDD), as described by McMaster and Wilhelm (1997): GDD = [(Tmax+ Tmin) / 2] – Tbase, where Tmax= maximum daily temperature, Tmin= minimum daily temperature, and Tbase = base temperature below which sorghum growth ceases at 7 °C (Duplessis, 2008). In addition, the water use efficiency for grain yield and water use efficiency for aboveground biomass was estimated as the ratio of grain yield or aboveground biomass to the total amount of rainfall from sowing to harvesting, as suggested by Stanhill (1986).

Productivity and drought tolerance indices were estimated using the equations presented in Table 1.

Table 1: Productivity and drought tolerance/susceptibility indices used to evaluate 36 sorghum genotypes

Index	Description	Formula	Reference
Mean productivity (MP)	High values are more desirable	(Yp + Ys) /2	(Rosielle and Hamblin, 1981)
Geometric mean productivity (GMP)	High values are more desirable	$\sqrt{(Yp)(Ys)}$	(Schneider et al., 1997)
Harmonic mean (HM)	High values are more desirable	$\frac{2(Ys)(Yp)}{(Ys)+(Yp)}$	(Jafari et al., 2009)
Yield reduction Index (YRI)	Low values indicate more suitable for conventional management	1-(Ys/Yp)	(Golestani Araghi and Assad, 1998)
Grain yield stability index (GYSI)	High values indicate more stability under bare and CSPs	$\frac{Ys}{Yp}$	(Bouslama and Schapaugh, 1984)
Response sensitivity index for CSPs (RSI)	Values < 1 are more insensitive or tolerant	$\frac{1-(Ys/Yp)}{1-(\mu Ys/\mu Yp)}$	Modified stress susceptibility index

			(Fischer and Maurer, 1978)
Yield index (YI)	High values indicate more tolerant to conventional management	Ys/μYs	(Gavuzzi et al., 1997)

Note: CSPs= climate-smart practices, YS and YP represent yield under conventional management/bare soil and yield under combined climate-smart practice, μYs= mean grain yield of conventional management plots, μYp= mean grain yield of climate-smart practice plots.

2.4 Data Analysis

The collected data for phenological parameters, water use efficiency, yield components, and grain yield for each management practice were subjected to analysis of variance (ANOVA) for simple lattice design using R software. The combined ANOVA over the three climate-smart practices computed after the homogeneity of error variances was evident using the F-ratio test, as suggested by Gomez and Gomez (1987). Duncan's multiple range test (DMRT) at 5% probability was used to compare the means of traits in which the genotypes exhibited significant mean squares. The relative productivity of the three climate-smart practices in relation to conventional management practices was also estimated as a percentage of the difference in mean yield between the combined climate-smart practices and conventional management practices. Pearson's correlation, principal component analysis (PCA), and clustering were performed using JMP Pro16 to assess the association between yield under climate-smart practices, drought tolerance indices, and the diversity of genotypes. The Euclidean distance matrix (Sneath and Sokal, 1973) estimated from 10 yield, productivity, and sensitivity indices was used for clustering of genotypes using dendrograms constructed by Unweighted Pair Group Methods with Arithmetic Means (UPGMA).

3.0 Results and Discussion

3.1 Phenology and Water Use Efficiency of Genotypes

The analysis of variance indicated significant ($p < 0.01$) differences among the genotypes in phenology and water use efficiency under conventional and combined climate-smart management practices (Table 2). The observed significant differences among the 36 sorghum genotypes agreed with the results of various phenotypic and genetic analyses that have revealed diverse sorghum genetic resources in Africa (Amelework et al., 2016; Olatoye et al., 2018). Sorghum originates in Africa, and high crop diversity is normally found in its area of origin (Venkateswaran et al., 2019). Significant differences between sorghum genotypes for growing degree days in India have been reported (Ventakesha et al., 2023).

The genotypes performed differently across the conventional and the combined three climate-smart management practices (CSMPs) (Table 3). The overall mean of the sorghum genotypes for growing degree days to attain 50% flowering (GDDF) was higher under conventional management, whereas it was nearly equal in both management practices for growing degree days to attain 90% maturity (GDDM). The genotype Kinyaruka had the lowest GDDF (1112.7) and GDDM (1810.7) under conventional management practices and the lowest GDDF and GDDM of 1118.9 and 1837.4, respectively, under the combined climate-smart practices. The highest GDDF of 1576.9 and 1556.8 were estimated for genotype Kinanira under conventional and combined climate-smart management practices, respectively, whereas genotype Umuceri had the highest GDDM of 2322.7 and 2324.1, respectively, under conventional and combined climate-smart management practices.

Table 2: Mean squares of analysis of variance for growing degree days, water use efficiency, yield and yield components of 36 sorghum genotypes under conventional and combined climate-smart practices

Conventional management						Combined climate-smart management practices						
Trait	Rep (1)	Block (Rep) (10)	G (35)	Error (25)	CV (%)	Rep (1)	Block (Rep) (10)	G (35)	CSMP (2)	G x CSMP (70)	Error (133)	CV (%)
GDDF	142	14.2	33066.00**	32	0.42	3	28	95321**	19774**	796**	35	0.44
GDDM	53	45.9	19541.30**	47.4	0.34	11	33	52633**	18242**	746**	34	0.29
WUEY	0.046	0.018	1.47 **	0.023	4.47	0.25	0.05	4.94**	9.30**	0.43**	0.02	3.39
WUEB	0.359	0.167	32.13**	0.16	2.77	2.58	0.45	108.67**	95.44**	4.86**	0.51	4.17
HPW	2.84	1603.95	1737.18**	41.47	5.52	231.9	23.2	7448.9**	33.4*	62.2**	18	3.51
NKPP	18643.8	1843959	2245059.72**	37942.6	4.69	180838	27132	10648296**	5227759**	247267**	14900	2.57
TKW	0.2	16.26	14.45**	1.23	4.98	1.13	0.87	55.45**	2.86*	2.57**	0.69	3.64
ABGB	131154	61109	11738996**	58409	2.77	942693	164367	39712585**	34874904**	1775294**	186341	4.17
GY	16836.1	323930	448318.54**	8561.05	4.52	89711	17177	1805429**	3396990**	156828**	8376	3.63
HI	0.27	0.4	77.901**	0.606	3.17	0.9	0.8	249.99**	19.67**	3.96**	0.67	3.23

Note: *and **refer to statistical significance at p<0.05 and p <0.01, respectively; numbers in parenthesis represent degrees of freedom; Rep: replication, G = genotypes; CSMP = climate-smart management practices; CV (%) = percent coefficient of variation; GDDF = growing degree days for 50% days of flowering; GDDM = growing degree days for 90% maturity; WUEY ($kgha^{-1}$ mm^{-1})= water use efficiency for grain yield; WUEB (kg ha^{-1} mm^{-1})= water use efficiency for biomass; HPW (g) = head/panicle weight; NKPP= number of kernels per panicle; TKW (g) = thousand kernels weight; ABGB (kg ha^{-1}) = aboveground biomass; GY (kg ha^{-1})= grain yield; HI (%) = harvest index.

All genotypes except some showed variation in GDDF and GDDM within and over management practices (Table 3). This might be due to the limited water availability under conventional management, which delayed the initiation of flowers and increased GDDF. The observed lower GDDM (over the combined climate-smart management practices) might be due to the availability of water, which helps recover and enhance the maturity of sorghum genotypes. This might also be due to the different mechanisms of pre-and post-flowering drought tolerance, and the sorghum genotype usually showed tolerance against only one of them (Rosenow et al., 1983; Gebisa et al., 2000). Water or drought stress can significantly delay floral initiation and affect panicle development and the appearance of new leaves (Ndlovu et al., 2021). It was also reported the recovering of sorghum plants performance for photosynthesis rate and the appearance of leaves by the availability of water or re-watering after water or drought stress recovering of the plants performance for photosynthesis rate and appearance of leaves (Gano et al., 2021).

The overall water use efficiency (WUE) of sorghum genotypes was higher over the combined climate-smart practices than conventional management practice by 2.69 $kgha^{-1}mm^{-1}$ (18.62%) and 0.78 $kgha^{-1}$ mm^{-1} (23.01%) for biomass and grain yield, respectively. Genotype Kinanira had the highest WUE of 25.81 and 31.06 $kgha^{-1}mm^{-1}$ for biomass under conventional and over the combined climate-smart management practices, respectively, while genotype Gihove had the highest WUE of 6.06 and 6.54 $kgha^{-1}mm^{-1}$ for yield under conventional and over the combined climate-smart management practices, respectively. Genotype Ikinyaruka recorded the lowest WUE of 6.04 and 2.22 $kgha^{-1}mm^{-1}$ for aboveground biomass and grain yield, respectively, under conventional management and 8.53 $kgha^{-1}mm^{-1}$ for aboveground biomass over the combined climate-smart practices while genotype Umuceri had the lowest WUE of 2.07 $kgha^{-1}mm^{-1}$ for grain yield over the combined climate-smart management practices. The genotypes with higher WUE for yield showed lower WUE for biomass yield and vice versa, whereas, except for some, most of the genotypes that registered lower WUE for yield had higher WUE for aboveground biomass yield (Table 3).

The observed significant variations among sorghum genotypes for water use efficiency over management practices suggest a higher chance of identifying genotypes for WUE that can produce higher biomass and grain yield under water scarcity, which might be worsened by climate change. The higher percentage of WUE increase in terms of biomass and grain yield production of sorghum genotypes over the combined climate-smart practices compared to conventional management indicates the importance of considering agronomic practices along with the selection of genotypes for tolerance to water stress. Although overlooked, it is suggested that the synergy between breeding and agronomy is important because improvements in grain yield and crop water productivity arise from breeding for superior varieties and from better agronomic and water management practices. It has been argued that

genetic and agronomic solutions are not mutually exclusive to narrow the gap between attainable and actual yields per unit water use. This is more effective for smallholder farmers who face financial resource scarcity for investment (Sadras et al., 2012).
Consistent with the results of this study, Habede et al. (2017) reported significant differences in water use efficiency among sorghum genotypes. Similarly, Garofalo and Rinaldi (2013) reported significant differences in water use efficiency under four irrigation regimes over three years and biomass yield for sorghum. Climate-smart practice (mulching) increased the water use efficiency of the sorghum variety compared to when it was not practiced in Brazilian semiarid regions (Carvalho et al., 2021).

Table 3: Mean performances of 36 sorghum genotypes for growing degree days and water use efficiency of under conventional and climate-smart management practices

	Conventional management				Climate-smart management practices			
Genotype	GDDF	GDDM	WUEY	WUEB	GDDF	GDDM	WUEY	WUEB
Amakoma	1267.6^{no}	2009.2^{k}	2.99^{l-o}	12.55^{lm}	1230.8^{t}	1957.8^{q}	3.89^{k}	15.31^{mno}
Amera	1478.8^{e}	2110.6^{ef}	2.63^{p-s}	12.52^{lm}	1425.4^{i}	2073.6^{g}	3.61^{lm}	16.49^{jkl}
Bukobwa 1	1325.1^{l}	1964.5^{lm}	3.02^{lmn}	14.29^{ij}	1333.5^{n}	1975.0^{o}	3.61^{lm}	16.53^{jkl}
Bukobwa 2	1267.6^{no}	1939.3^{no}	3.34^{jkl}	13.35^{kl}	1239.7^{s}	1919.7^{tu}	3.70^{l}	14.42^{op}
Bukobwa 3	1261.5^{o}	1932.7^{op}	2.58^{p-s}	12.74^{lm}	1257.2^{r}	1951.9^{qr}	3.60^{lmn}	17.25^{hij}
Cyamwiha	1387.1^{i}	2021.8^{jk}	2.45^{rst}	12.52^{lm}	1381.3^{k}	2017.6^{l}	3.69^{l}	17.48^{ghi}
Gatemwa	1312.9^{l}	1951.9^{mn}	3.50^{h-k}	15.45^{fgh}	1350.3^{m}	1966.5^{p}	3.24^{qr}	15.14^{no}
Gihove	1522.2^{c}	2116.2^{de}	6.06^{a}	21.90^{c}	1513.8^{d}	2104.7^{f}	6.54^{a}	22.62^{d}
Igihove	1255.5^{o}	1951.9^{mn}	3.60^{hij}	12.25^{m}	1278.4^{p}	1973.0^{op}	3.99^{jk}	14.43^{op}
Ikinyaruka	1138.3^{r}	1906.5^{q}	2.22^{t}	6.04^{p}	1140.7^{w}	1901.0^{v}	3.11^{rs}	8.53^{t}
Indinganire	1380.8^{i}	2015.9^{k}	2.90^{m-q}	15.71^{fg}	1384.4^{k}	2060.4^{h}	3.94^{jk}	18.71^{f}
Kebo	1497.5^{d}	2092.1^{gh}	4.73^{c}	16.81^{de}	1491.2^{e}	2114.8^{d}	5.29^{d}	18.07^{fgh}
Kigosorabaswa	1431.9^{g}	2009.2^{k}	2.82^{n-q}	12.72^{lm}	1426.1^{i}	1994.2^{n}	4.44^{hi}	21.41^{e}
Kinanira	1576.9^{a}	2153.9^{c}	3.23^{klm}	25.81^{a}	1556.8^{a}	2145.6^{b}	4.68^{g}	31.06^{a}
Mugabo	1294.9^{m}	2021.8^{jk}	3.49^{ijk}	13.22^{kl}	1228.6^{t}	1991.9^{n}	4.68^{g}	16.94^{ijk}
Munebwe	1539.8^{b}	2172.2^{b}	3.70^{ghi}	21.36^{c}	1482.9^{f}	2127.2^{c}	4.69^{g}	23.73^{c}
Ndamirabana	1312.9^{l}	1945.6^{no}	3.45^{ijk}	15.82^{fg}	1336.0^{n}	1954.0^{q}	3.92^{jk}	16.91^{ijk}
Ntuncurimboga	1287.9^{m}	1970.6^{l}	3.53^{h-k}	13.81^{jk}	1226.0^{t}	1969.0^{op}	4.28^{i}	16.15^{klm}
Nyakami	1418.9^{h}	2079.8^{h}	3.09^{lmn}	16.17^{ef}	1404.1^{j}	2065.2^{h}	3.56^{l-o}	18.32^{fg}
Nyiragahengeri	1189.2^{p}	1945.6^{no}	3.99^{efg}	13.81^{jk}	1202.1^{u}	1945.4^{r}	4.96^{f}	14.95^{no}
Nyiragikori	1418.9^{h}	2047.9^{i}	3.47^{ijk}	14.29^{ij}	1421.1^{i}	2049.8^{i}	3.40^{opq}	14.62^{o}
Nyiragikoriy'umweru	1455.8^{f}	2034.5^{ij}	3.01^{l-o}	14.72^{hij}	1469.4^{g}	2067.0^{h}	4.49^{h}	21.31^{e}
Nyiragitenderi	1461.5^{f}	2098.5^{fg}	4.25^{de}	14.33^{ij}	1457.9^{h}	2112.5^{de}	5.51^{c}	18.06^{fgh}

Nyirakaganza	1274.3^{n}	2021.8^{jk}	2.94^{m-p}	13.96^{jk}	1266.0^{q}	2002.7^{m}	4.11^{j}	18.75^{f}
Nyirakanyamunyo	1319.1^{l}	2047.9^{i}	2.76^{n-r}	12.48^{lm}	1306.5^{o}	2037.3^{j}	3.62^{lm}	15.71^{lmn}
Nyirakinuma	1522.2^{c}	2129.3^{d}	5.46^{b}	17.14^{d}	1521.9^{c}	2128.8^{c}	5.74^{b}	17.56^{ghi}
Nyiramugufi	1351.0^{k}	2009.2^{k}	3.03^{lmn}	15.47^{fgh}	1360.9^{l}	2024.3^{k}	3.41^{n-q}	17.11^{ij}
Rudasakwa	1539.8^{b}	2129.3^{d}	3.85^{fgh}	14.91^{ghi}	1543.5^{b}	2123.2^{c}	5.10^{ef}	18.52^{f}
Umuceri	1528.3^{bc}	2322.7^{a}	2.33^{st}	23.15^{b}	1543.4^{b}	2324.1^{a}	2.07^{t}	25.01^{b}
Unkown/amasaka	1497.5^{d}	2110.6^{ef}	4.42^{cd}	16.71^{de}	1477.0^{f}	2106.6^{ef}	5.16^{de}	18.62^{f}
SDL880-160	1261.5^{o}	1932.7^{op}	2.91^{m-q}	7.54^{o}	1204.4^{u}	1917.5^{u}	4.08^{jk}	10.32^{s}
Kinyaruka	1112.7^{s}	1810.7^{s}	2.57^{q-t}	11.29^{n}	1118.9^{x}	1837.4^{w}	3.30^{pq}	13.66^{pq}
IS8193	1152.3^{q}	1875.5^{r}	4.12^{def}	11.32^{n}	1170.6^{v}	1932.6^{s}	5.13^{def}	13.48^{qr}
IS21219	1368.6^{j}	2098.5^{fg}	4.33d^{e}	15.29^{fgh}	1401.9^{j}	2110.6^{def}	5.13^{def}	17.30^{hij}
Kat 369	1152.3^{q}	1919.5^{pq}	2.56^{q-t}	7.60^{o}	1202.8^{u}	1926.2^{st}	3.46^{m-p}	9.79^{s}
Mabereyingoma	1294.9^{m}	1976.8^{l}	2.65^{o-s}	11.01^{n}	1284.7^{p}	1989.8^{n}	3.05^{s}	12.76^{r}
Mean	1357.1	2024.3	3.39	14.45	1351.1	2025	4.17	17.14

Note: Means within columns followed by the same letter/s are not significantly different according to Duncan's multiple range test. GDDF= growing degree days for 50% days of flowering; GDDM= growing degree days for 90% maturity; WUEY (kg ha^{-1} mm^{-1}) = water use efficiency for yield; WUEB (kg ha^{-1} mm^{-1}) = water use efficiency for biomass.

3.2 Yield Components, Yield of Genotypes

The sorghum genotypes showed significant ($p< 0.01$) differences in panicle weight, number of kernels per panicle, and thousand kernel weight when evaluated under conventional and combined climate-smart management practices (Table 2). The average panicle weight, and number of kernels per panicle were higher in combined climate-smart practices than in conventional management practice by 4.21 g (3.61%), and 603.15 kernels (14.52%), respectively (Tables 4 and 5). The genotype Nyirakinuma recorded the highest panicle weight of 212.8 and 219.1 g and the largest number of kernels per panicle of 7595.2 and 7985.4 kernels under conventional management and combined climate-smart practices, respectively. On the other hand, the Umuceri genotype had the lightest panicle weight (42.0 and 32.7 g) and a small number of kernels per panicle (1531.1 and 1365.2 kernels) under conventional and combined climate-smart management practices (Tables 4 and 5). For thousand kernels weight, the Ndamirabana and Bukobwa 1 genotypes registered the heaviest grain over combined climate-smart and conventional management practices, respectively, having the same weight of 27.8 g. On the contrary, the Ntuncurimboga genotype had the lightest grains under both conventional (15.1 g) and climate-smart management practices (15.0 g). The existence of significant differences among the 36 genotypes across management practices for these traits showed the presence of genetic variability and the possibility of using these genotypes in the improvement of sorghum in the future. Similar to the results of the present study, Derese et al. (2018) reported highly significant differences in panicle weight and thousand seed weights among sorghum genotypes.

The sorghum genotypes also showed highly significant ($p < 0.01$) differences in grain yield, aboveground biomass, and harvest index under both conventional and combined climate-smart management practices (Table 2). The average of grain yield, aboveground biomass, and harvest index were higher in the combined climate-smart practices than in conventional management practices by 473.24 kg (23.10%), 1628.62 kg (18.65%), and 0.85 (3.47%), respectively (Tables 4 and 5). The Gihove genotype had the highest grain yield of 3664.5 kg ha^{-1} and 3953.0 kg ha^{-1} under conventional and combined climate-smart management practices, respectively, whereas the genotypes Ikinyaruka (1343.0kg ha^{-1}) and Umuceri (1251.2 kg ha^{-1}) showed the lowest grain yield under conventional and combined climate-smart management practices, respectively (Tables 4 and 5). For aboveground biomass, the Kinanira genotype registered the highest values of 15601.1 and 18775.6 kg ha^{-1}, while SDL880-160 genotype recorded the highest harvest index of 38.68 and 39.53 under conventional and combined climate-smart management practices, respectively. In contrast, genotypes Ikinyaruka and Umuceri showed the lowest aboveground biomass and harvest index under both conventional and combined climate-smart management practices.

The significant differences found among sorghum genotypes for grain yield, aboveground biomass, and harvest index over management practices suggested a greater chance of finding genotypes that can produce high grain yield and aboveground biomass under conditions of water scarcity. The good performance of climate-smart management practices in comparison with conventional management may be attributed to the capacity of these practices to retain soil water, reduce soil nutrient losses, and improve soil productivity, as reported by Bekele and Chemeda (2022). Similarly, Abi et al. (2024) reported a higher sorghum grain yield due to the effect of tied ridging management practices.

Table 4: Mean performances of 36 sorghum genotypes of yield components and yield evaluated under conventional management practice

	Conventional management					
Genotype	HPW	NKPP	TKW	ABGB	GY	HI
Amakoma	105.9^{h-l}	3906.9^{j-m}	19.8^{l-p}	7587.4^{lm}	1813.0^{l-o}	23.89^{jkl}
Amera	165.8^{c}	5071.7^{e}	20.1^{l-p}	7568.5^{lm}	1589.5^{p-s}	21.00^{m-p}
Bukobwa 1	119.2^{e-h}	3646.5^{k-n}	27.8^{a}	8635.6^{ij}	1824.5^{lmn}	21.13^{m-p}
Bukobwa 2	115^{e-i}	3678.9^{k-n}	25.5^{a-e}	8070.7^{kl}	2018.0^{jkl}	24.99^{hij}
Bukobwa 3	105.7^{h-l}	3722.2^{k-n}	24.6^{b-h}	7699.3^{lm}	1560.5^{p-s}	20.27^{opq}
Cyamwiha	110.7^{f-j}	3983.9^{ijk}	23.4^{d-j}	7569.4^{lm}	1481.5^{rst}	19.59^{pqr}
Gatemwa	110.3^{f-j}	3510.8^{l-p}	25.8^{a-e}	9337.2^{fgh}	2118.5^{h-k}	22.70^{klm}
Gihove	183.1^{b}	6121.8^{c}	22.8^{f-k}	13240.6^{c}	3664.5^{a}	27.68^{fg}
Igihove	123.1^{efg}	4448.6^{gh}	23.8^{c-i}	7404.5^{m}	2176.0^{hij}	29.39^{ef}
Ikinyaruka	85.0^{m}	3049.1^{pq}	20.5^{k-o}	3648.9^{p}	1343.0^{t}	36.80^{b}
Indinganire	114.0^{e-i}	3574.4^{k-n}	25.1^{b-f}	9496.7^{fg}	1750.5^{m-q}	18.44^{rs}
Kebo	173.0^{bc}	6825.9^{b}	19.1^{n-q}	10163.3^{de}	2859.5^{c}	28.12^{efg}
Kigosorabaswa	120.1^{e-h}	4511.2^{fgh}	20.1^{l-p}	7690.5^{lm}	1706.0^{n-q}	22.18^{lmn}
Kinanira	139.3^{d}	4399.0^{ghi}	24.6^{b-h}	15601.1^{a}	1951.5^{klm}	12.51^{t}
Mugabo	128.3^{de}	3648.2^{k-n}	26.4^{abc}	7991.5^{kl}	2111.5^{h-k}	26.43^{gh}
Munebwe	114.7^{e-i}	4569.8^{fgh}	19.5^{m-p}	12912.2^{c}	2239.5^{ghi}	17.34^{s}
Ndamirabana	125.1^{def}	3974.9^{i-l}	26.5^{ab}	9561.4^{fg}	2088.0^{ijk}	21.85^{mno}
Ntuncurimboga	69.4^{n}	3560.5^{k-o}	15.1^{r}	8345.6^{jk}	2134.5^{h-k}	25.60^{hij}
Nyakami	114.1^{e-i}	4585.1^{fgh}	20.2^{k-p}	9773.9^{ef}	1867.5^{lmn}	19.10^{qr}
Nyiragahengeri	60.7^{n}	2855.6^{q}	16.8^{qr}	8347.3^{jk}	2412.0^{efg}	28.90^{ef}
Nyiragikori	106.8^{h-l}	3368.1^{nop}	23.2^{e-j}	8637.8^{ij}	2096.5^{ijk}	24.26^{ijk}
Nyiragikoriy'umweru	123.0^{efg}	4912.2^{ef}	21.7^{i-n}	8897.3^{hij}	1817.0^{l-o}	20.42^{n-q}
Nyiragitenderi	138.9^{d}	4728.7^{efg}	24.9^{b-g}	8660.2^{ij}	2570.0^{de}	29.66^{e}
Nyirakaganza	106.3^{h-l}	3358.8^{nop}	25.2^{a-f}	8440.6^{jk}	1774.5^{m-p}	21.03^{m-p}
Nyirakanyamunyo	108.9^{g-k}	4199.8^{hij}	22.2^{h-l}	7543.1^{lm}	1667.5^{n-r}	22.11^{mn}
Nyirakinuma	212.8^{a}	7595.2^{a}	21.1^{j-o}	10363.9^{d}	3299.0^{b}	31.84^{d}
Nyiramugufi	129.2^{de}	4252.6^{hij}	23.4^{d-j}	9348.9^{fgh}	1834.5^{lmn}	19.60^{pqr}
Rudasakwa	161.7^{c}	6131.4^{c}	21.8^{i-m}	9013.7^{ghi}	2325.5^{fgh}	25.80^{hi}
Umuceri	42.0^{o}	1531.1^{r}	22.4^{g-l}	13997.1^{b}	1407.0st	10.05^{u}
Unkown/amasaka	117.9^{e-i}	5604.9^{d}	17.8^{pq}	10101.4^{de}	2672.5^{cd}	26.45^{gh}
SDL880-160	95.9^{j-m}	3449.7^{m-p}	20.5^{k-o}	4557.1^{o}	1761.5^{m-q}	38.68^{a}
Kinyaruka	94.5^{klm}	3305.3^{nop}	20.1^{l-p}	6823.3^{n}	1551.0^{q-t}	22.74^{klm}
IS8193	102.7^{i-l}	3333.1^{nop}	26.5^{ab}	6840.3^{n}	2491.5^{def}	36.42^{b}
IS21219	92.1^{lm}	3106.4^{opq}	18.8^{opq}	9244.9^{fgh}	2614.5^{de}	28.28^{ef}
Kat 369	94.5^{klm}	3424.8^{nop}	26.0^{a-d}	4592.1^{o}	1544.5^{q-t}	33.65^{c}
Mabereyingoma	87.5^{m}	3591.6^{k-n}	20.0^{l-p}	6658.4^{n}	1601.0^{o-s}	24.03^{ijk}

Mean	116.59	4153.85	22.31	8732.38	2048.26	24.52

Note: Means within columns followed by the same letter/s are not significantly different according to Duncan's multiple range test. HPW (g) = head/panicle weight; NKPP= number of kernels per panicle; TKW (g) = thousand kernel weight; ABGB (kg ha^{-1}) = aboveground biomass; GY (kg ha^{-1}) = grain yield; HI (%) = harvest index.

Table 5: Mean performances of 36 sorghum genotypes of yield components and yield evaluated under combined climate-smart management practice

	Combined climate-smart management practices					
Genotype	HPW	NKPP	TKW	ABGB	GY	HI
Amakoma	117.5^{hi}	4539.9^{k}	19.7^{n}	9255.9^{mno}	2354.5^{k}	25.38^{k}
Amera	125.8^{fg}	5968.0^{fg}	19.8^{mn}	9970.4^{jkl}	2180.0^{lm}	21.87^{n}
Bukobwa 1	111.6^{jkl}	4061.9^{opq}	26.6^{bc}	9994.4^{jkl}	2182.5^{lm}	21.80^{nop}
Bukobwa 2	117.6^{hi}	3928.9^{qr}	25.8^{cd}	8715.7^{op}	2235.8^{l}	25.68^{jk}
Bukobwa 3	116.0^{hij}	4887.4^{j}	25.7^{cd}	10425.5^{hij}	2174.3^{lmn}	20.78^{opq}
Cyamwiha	120.7^{gh}	5403.1^{h}	25.0^{de}	10568.5^{ghi}	2233.2^{l}	21.29^{nop}
Gatemwa	100.1^{klm}	3242.4^{t}	24.5^{ef}	9153.3^{no}	1956.5^{qr}	21.20^{nop}
Gihove	186.8^{b}	6603.8^{d}	25.3^{de}	13675.0^{d}	3953.0^{a}	28.89^{gh}
Igihove	140.8^{d}	4863.3^{j}	24.6^{ef}	8723.9^{op}	2411.0^{jk}	27.99^{hi}
Ikinyaruka	97.4^{pq}	3510.2^{s}	20.5^{k-n}	5154.2^{t}	1878.7^{s}	36.51^{c}
Indinganire	124.2^{fg}	4272.9^{mn}	24.5^{ef}	11310.0^{f}	2383.5^{jk}	21.11^{l-p}
Kebo	215.6^{a}	7556.5^{b}	20.9^{i-}	10923.^{fgh}	3198.7^{d}	29.25^{g}
Kigosorabaswa	112.0^{jkl}	5876.8^{g}	20.83^{i--n}	12943.0^{e}	2683.8^{hi}	20.73^{pq}
Kinanira	143.4^{d}	5094.8^{i}	25.9^{cd}	18775.6^{a}	2830.7^{g}	15.01^{s}
Mugabo	129.5^{ef}	3920.5^{qr}	27.4^{ab}	10242.4^{ijk}	2830.6^{g}	27.67^{i}
Munebwe	125.3^{fg}	5306.6^{h}	20.8^{j-n}	14343.9^{c}	2835.3^{g}	19.77^{qr}
Ndamirabana	131.4^{e}	4477.4^{kl}	27.8^{a}	10219.2^{ijk}	2368.2^{jk}	23.17^{lm}
Ntuncurimboga	65.4^{s}	4048.6^{o-r}	15.0^{p}	9763.9^{klm}	2589.2^{i}	26.58^{j}
Nyakami	118.0^{hi}	4773.9^{j}	21.0^{i-l}	11072.1^{fg}	2149.0^{l-o}	19.40^{r}
Nyiragahengeri	72.1^{r}	3278.3^{t}	17.4^{o}	9038.4^{no}	2995.5^{f}	33.05^{e}
Nyiragikori	106.9^{lmn}	3301.2^{t}	21.3^{h-l}	8836.1^{o}	2054.2^{opq}	22.96^{m}
Nyiragikoriy' umweru	121.5^{gh}	6228.7^{e}	21.5^{h-k}	12884.0^{e}	2716.8^{h}	21.07^{nop}
Nyiragitenderi	133.0^{e}	5425.9^{h}	24.2^{efg}	10915.7^{fgh}	3328.5^{c}	30.53^{f}
Nyirakaganza	113.7^{ijk}	4381.7^{lm}	25.8^{cd}	11331.5^{f}	2481.7^{j}	21.85^{no}
Nyirakanyamunyo	121.7^{gh}	4754.6^{j}	23.4^{g}	9495.8^{lmn}	2189.3^{lm}	23.02^{m}
Nyirakinuma	219.1^{a}	7985.4^{a}	21.8^{hij}	10614.6^{ghi}	3468.3^{b}	32.67^{e}
Nyiramugufi	124.6^{fg}	4840.8^{j}	23.9^{fg}	10340.o^{ij}	2060.5^{n-q}	19.91^{qr}

Rudasakwa	170.3^{c}	7241.9^{b}	23.6^{fg}	11198.0^{f}	3218.0^{c}	27.53^{i}
Umuceri	32.7^{t}	1365.2^{u}	21.9^{hi}	15119.4^{b}	1251.2^{t}	8.33^{t}
Unkown/amasaka	116.6^{hij}	6079.8^{f}	17.0^{o}	11257.2^{f}	3120.0^{de}	27.65^{i}
SDL880-160	105.3^{mno}	4331.3^{lmn}	22.2^{h}	6239.4^{s}	2466.3^{jk}	39.53^{a}
Kinyaruka	97.0^{pq}	3999.4^{pqr}	21.4$^{h\text{-}k}$	8259.9^{pq}	1997.0^{pq}	24.13^{l}
IS8193	108.7^{klm}	4087.0^{op}	25.0^{de}	8148.9^{qr}	3099.2^{def}	38.02^{b}
IS21219	101.0^{op}	3518.8^{s}	20.2^{lmn}	10458.6^{hij}	3102.5^{def}	29.59^{g}
Kat 369	102.9^{no}	4192.8^{no}	27.1^{ab}	5915.8^{s}	2093.0$^{m\text{-}p}$	35.39^{d}
Mabereyingoma	95.0^{q}	3901.8^{r}	21.2$^{h\text{-}l}$	7715.1^{r}	1842.5^{s}	23.88^{lm}
Mean	120.8	4757	22.8	10361	2521.5	25.37

Note: Means within columns followed by the same letter/s are not significantly different according to Duncan's multiple range test. HPW (g) = head/panicle weight; NKPP= number of kernels per panicle; TKW (g) = thousand kernel weight; ABGB (kg ha^{-1}) = aboveground biomass; GY (kg ha^{-1}) = grain yield; HI (%) = harvest index.

3.3 Productivity of Climate-smart Management Practices

The sorghum genotypes had a relative productivity of combined climate-smart practices (RPCSP in %) ranging from -11.08 to 57.32% compared to conventional management. A total of 15 and 18 genotypes had RPCSP (%) between 5.13 and 24.39 and 26.61 and 57.32%, respectively (Table 6). Mean productivity (MP), geometric mean productivity (GMP), and harmonic mean (HM) of genotypes ranged from 1329.08 to 3808.75, 1326.8 to 3806.02, and 1324.52 to 3803.29, respectively. Moreover, 14 genotypes had RPCSP (%) in the range of 5.13 and 45.05% with higher MP, GMP, and HM than the overall mean of the genotypes (Table 6). This indicated that near to 39% of the genotypes produced higher grain yield over combined climate-smart management practices than conventional management with higher productivity indices (MP, GMP, and HM) than the overall mean productivity indices of genotypes. Higher yields above the average and high values for MP, GMP, and HM indicate desirable performance in environments where the genotypes were evaluated (Rosielle and Hamblin, 1981; Schneider et al., 1997; Jafari et al., 2009). The observed wide range of response variations and productivity under conventional and over combined climate-smart management practices also suggests the opportunity to identify productive genotypes for different management practices. Yield in low- and high-yielding environments can be considered separate traits that are not necessarily maximized by identical sets of alleles (Khayatnezhad et al., 2010).

Yield reduction index (YRI) for genotypes ranged from -0.12 to 0.36, whereas grain yield stability index (GYSI), response sensitivity index (RSI), and yield index (YI) ranged from 0.64 to 1.12, -1.1 to 2.13, and 0.66 to 1.79, respectively. A total of 19 genotypes had high YRI and RSI values (than the overall mean) of 0.20 to 0.36 and 1.07 to 2.13 for YRI and RSI, respectively, indicating that these genotypes were more productive and responsive to combined climate-smart practices than the other genotypes. In addition, 15 genotypes had higher (than the overall mean) GYSI and YI of 0.84 to 1.12 and 1.02 to 1.79, respectively, indicating that these genotypes were more stable at both management practices and more tolerant to conventional management practices. Exceptionally, three genotypes (Nyiragikori, Gatemwa, and Umuceri) had a higher mean grain yield under conventional management than under combined climate-smart practices. These three genotypes also had lower MP, GMP, and HM than the overall mean of the genotypes with negative YRI and RSI and >1 for GYSI and YI, except for one genotype with a YI of 0.69 (Table 6).

This suggests that these genotypes were more productive, stable, and tolerant under conventional management and insensitive to combined climate-smart practices. Consistent with the results of this study, it has been reported that tolerant genotypes also have low yields (Sory, 2015; Abebe et al., 2020). Significant differences in yield and productivity in sorghum genotypes have been reported under different water regimes and conservation practices (Garofalo and Rinaldi, 2013; Habede et al., 2017; Carvalho et al., 2021).

Sadras et al. (2012) highlighted the importance of synergy between breeding for high-yielding varieties and better agronomic and water management practices for smallholder farmers facing unprecedented climate conditions. Many researchers have used indices, but different authors have concluded that the effectiveness of selection indices depends on stress severity, although none of the indicators could clearly identify cultivars with high yields under stress and non-stress conditions (Khayatnezhad et al., 2010). Fernandez (1992) proposed effective selection criteria for genotypes that have high yields in stress and non-stress environments, genotypes that have high yields only in non-stress or stress environments, and genotypes that have low yields in stress and non-stress environments.

Table 6: Mean productivity and response sensitivity indices of combined climate-smart practices as compared to conventional management in sorghum genotypes

Genotype	GY3CSP	GYBS	MP	GMP	HM	RPCSP	YRI	GYSI	RSI	YI
Amakoma	2354.5	1813.0	2083.75	2066.09	2048.57	29.87	0.23	0.77	1.13	0.89
Amera	2180.0	1589.5	1884.75	1861.48	1838.5	37.15	0.27	0.73	1.58	0.78
Bukobwa 1	2182.5	1824.5	2003.5	1995.49	1987.51	19.62	0.16	0.84	0.69	0.89
Bukobwa 2	2235.83	2018.0	2126.92	2124.13	2121.34	10.79	0.10	0.90	0.53	0.99
Bukobwa 3	2174.33	1560.5	1867.42	1842.02	1816.97	39.34	0.28	0.72	1.44	0.76
Cyamwiha	2233.17	1481.5	1857.33	1818.91	1781.28	50.74	0.34	0.66	1.76	0.72
Gatemwa	1956.5	2118.5	2037.5	2035.89	2034.28	-7.65	-0.08	1.08	-1.10	1.03
Gihove	3953.0	3664.5	3808.75	3806.02	3803.29	7.87	0.07	0.93	0.33	1.79
Igihove	2411.0	2176	2293.5	2290.49	2287.48	10.80	0.1	0.9	0.55	1.06
Ikinyaruka	1878.67	1343	1610.83	1588.41	1566.3	39.89	0.29	0.71	1.38	0.66
Indinganire	2383.5	1750.5	2067	2042.62	2018.54	36.16	0.27	0.73	1.56	0.85
Kebo	3198.67	2859.5	3029.08	3024.33	3019.59	11.86	0.11	0.89	0.49	1.4
Kigosorabaswa	2683.83	1706	2194.92	2139.77	2086.01	57.32	0.36	0.64	2.13	0.83
Kinanira	2830.67	1951.5	2391.08	2350.33	2310.27	45.05	0.31	0.69	1.72	0.95
Mugabo	2830.67	2111.5	2471.08	2444.78	2418.76	34.06	0.25	0.75	1.45	1.03
Munebwe	2835.33	2239.5	2537.42	2519.87	2502.44	26.61	0.21	0.79	1.15	1.09
Ndamirabana	2368.17	2088	2228.08	2223.68	2219.28	13.42	0.12	0.88	0.72	1.02
Ntuncurimboga	2589.17	2134.5	2361.83	2350.87	2339.95	21.30	0.18	0.82	1.07	1.04
Nyakami	2149.5	1867.5	2008.5	2003.54	1998.6	15.10	0.13	0.87	0.59	0.91
Nyiragahengeri	2995.5	2412	2703.75	2687.96	2672.27	24.19	0.19	0.81	1.15	1.18
Nyiragikori	2054.17	2096.5	2075.33	2075.23	2075.12	-2.02	-0.02	1.02	-0.78	1.02
Nyiragikoriy'umweru	2716.83	1817	2266.92	2221.82	2177.62	49.52	0.33	0.67	1.9	0.89
Nyiragitenderi	3328.5	2570	2949.25	2924.76	2900.48	29.51	0.23	0.77	1.2	1.25
Nyirakaganza	2481.67	1774.5	2128.08	2098.5	2069.34	39.85	0.28	0.72	1.42	0.87
Nyirakanyamunyo	2189.33	1667.5	1928.42	1910.68	1893.11	31.29	0.24	0.76	1.16	0.81
Nyirakinuma	3468.33	3299	3383.67	3382.61	3381.55	5.13	0.05	0.95	0.26	1.61
Nyiramugufi	2060.5	1834.5	1947.5	1944.22	1940.94	12.32	0.11	0.89	0.63	0.9
Rudasakwa	3081.5	2325.5	2703.5	2676.94	2650.65	32.51	0.25	0.75	1.42	1.14
Umuceri	1251.17	1407	1329.08	1326.8	1324.52	-11.08	-0.12	1.12	-0.75	0.69
Unkown/amasaka	3120	2672.5	2896.25	2887.59	2878.96	16.74	0.14	0.86	0.61	1.3
SDL880-160	2466.33	1761.5	2113.92	2084.33	2055.16	40.01	0.29	0.71	1.5	0.86
Kinyaruka	1997	1551	1774	1759.93	1745.97	28.76	0.22	0.78	0.87	0.76
IS8193	3099.17	2491.5	2795.33	2778.77	2762.31	24.39	0.2	0.8	0.93	1.22
IS21219	3102.5	2614.5	2858.5	2848.07	2837.67	18.67	0.16	0.84	0.71	1.28

Kat 369	2093	1544.5	1818.75	1797.95	1777.4	35.51	0.26	0.74	1.39	0.75
Mabereyingoma	1842.5	1601	1721.75	1717.51	1713.28	15.08	0.13	0.87	0.53	0.78
Mean	2521.58	2048.3	2277.13	2263.91	2243.34	24.71	0.18	0.82	0.93	1

Note: CSP = climate-smart practice, GY3CSP = grain yield under three climate-smart management practices. GYBS= grain yield under conventional management/bare soil. MP= mean productivity. GMP= geometric mean productivity. HM= harmonic mean. RPCSP (%) = relative productivity of the three climate-smart practices (CSPs). YRI= yield reduction index. GYSI= grain yield stability index. RSI= response sensitivity index for CSPs and YI= yield index.

Accordingly, 15 sorghum genotypes had grain yields above the overall mean yield of genotypes under conventional management and combined climate-smart practices, whereas 20 genotypes had lower grain yields under both management practices. Among the 15 sorghum genotypes, Gihove and Nyirakinuma had higher grain yields under both management practices and lower relative productivity under the combined climate-smart management practices of 7.87 and 5.13%, respectively. These two genotypes also showed higher values of YI (1.79 and 1.61) and <1 values of YRI, GYSI, and RSI. This suggests that the two genotypes could be recommended for sorghum production under conventional and climate-smart management practices more than the other genotypes that performed better under both management practices, after further evaluation.

3.4 Associations of Yield and Productivity Indices

The mean grain yield of genotypes under combined climate-smart practices and conventional management had a positive and significant correlation, and the mean yields of genotypes under both management practices had a positive and significant correlation with MP, GMP, HM, and YI (Table 7). In addition, the yield of genotypes under conventional management had a negative (r = - 0.35) and a positive significant correlation (r = 0.35) with YRI and GYSI, respectively, and the mean grain yield of genotypes under combined climate-smart practices had a positive and non-significant correlation with RPCSP (r = 0.09). The mean productivity (MP) and geometric mean (GMP) indices had a perfect positive significant correlation (r=1), and the two indices also had a perfect or near-perfect positive and significant correlation with HM and YI. Relative productivity over combined climate-smart practices (RPCSP) had a positive and significant correlation with YRI and RSI, but on the other hand it had a negative and significant correlation with GYSI. Yield reduction (YRI) and stability (GYSI) indices had a significant negative correlation, while YRI and GYSI had a significant correlation, but in opposite directions to RSI (r = 0.98 and r= -0.98). In addition, the yield index (YI) was significantly positively and negatively correlated with the GYSI and YRI, respectively (Table 7).

Table 7: Correlation coefficients of grain yield, productivity and stress indices of 36 sorghum genotypes under combined climate-smart management practices

	GYBS	MP	GMP	HM	RPCSP	YRI	GYSI	RSI	YI
GY3CSP	0.87**	0.97**	0.96**	0.95**	0.09	0.15	-0.15	0.21	0.87**
GYBS		0.96**	0.97**	0.98**	-0.40*	-0.35*	0.35*	-0.28	1.00**
MP			1.00**	1.00**	-0.15	-0.09	0.09	-0.03	0.96**
GMP				1.00**	-0.18	-0.12	0.12	-0.05	0.97**
HM					-0.20	-0.14	0.14	-0.08	0.98**
RPCSP						0.99**	-0.99**	0.96**	-0.40*
YRI							-1.00**	0.98**	-0.35*
GYSI								-0.98**	0.35*
RSI									-0.28

Note: * and ** refer to statistical significance at $p < 0.05$ and $p < 0.01$, respectively. GY3CSP = grain yield under combined climate-smart management practices; GYBS= grain yield under conventional management/bare soil; MP= mean productivity; GMP= geometric mean productivity; HM= harmonic mean; RPCSP (%) = relative productivity over three climate-smart practices (CSPs) index, YRI= yield reduction index, GYSI= grain yield stability index, RSI= response sensitivity index for CSPs, YI= yield index.

The results of correlation analysis revealed that the mean (MP), geometric (GMP), and harmonic (HM) mean productivity indices, yield index, and relative productivity over combined climate-smart practices could be used as indicators of sorghum genotype yield. The observed positive and highly significant correlation between the mean grain yield of genotypes over combined climate-smart and conventional management practices suggested that the grain yield of genotypes under one of the practices could be used as an indicator of the yield performance of the other management practices. Similarly, Sory (2015) reported strong correlations between yield under stress and non-stress environments and had positive correlations with mean productivity and geometric mean productivity indices. Abebe et al. (2020) also reported a negative and non-significant correlation between grain yield in a good environment and grain yield stability index.

3.5 Principal Component Analysis

The principal component analysis for grain yield, productivity, and sensitivity indices of the 36 sorghum genotypes over combined climate-smart management practices are presented in Table 8. The two principal components (PCs) with eigenvalues > 1 explained 99.40% of the total variation. The first PC contributed 60.83% of the total variation and the second PC explained 38.57% of the variability. The high percentage (99.40%) of total variation obtained in this study could be related to the strong relationship among the evaluated productivity indices. The first PC contribution to the total variability was mainly due to grain yield under conventional management, yield index, harmonic, geometric, and mean productivity indices, whereas response sensitivity for climate-smart practices, grain yield reduction index, and relative productivity indices contributed significantly to the second PC. In agreement with these results, Abebe et al. (2020) and Nazari et al. (2021) also reported two PCs contributing to more than 98% of the total variation in sorghum genotypes studied in Ethiopia and Iran, respectively. Similarly, Abebe et al. (2020) reported high contributions of the mean productivity, geometric mean, harmonic mean, and yield indices to the first principal component.

Table 8: Eigenvalue and contribution of principal component axis for grain yield, productivity and stress indices of 36 sorghum genotypes over combined climate-smart management practices

Character	PC1	PC2
Mean grain yield over three climate-smart practices	0.831	0.552
Grain yield under conventional management	0.996	0.077
Mean productivity	0.943	0.332
Geometric mean productivity	0.951	0.310
Harmonic mean	0.957	0.288
Relative productivity over three CSPs	-0.470	0.873
Yield reduction index	-0.418	0.906
Grain yield stability index	0.418	-0.906
Response sensitivity index for CSPs	-0.357	0.920
Yield index	0.996	0.077
Eigenvalue	6.083	3.857
Variability explained (%)	60.83	38.57
Cumulative explained (%)	60.83	99.40

Note: CSPs = climate-smart practices

According to Chahal and Gosal (2002), in the first principal component, characters with the highest absolute values near unity have a greater impact on clustering than those with lower absolute values near zero. Therefore, in the present study, the differentiation of the genotypes into different clusters was due to the high positive weights (0.943–0.996) of grain yield under conventional management, yield index, harmonic mean, geometric mean, and mean productivity indices.

3.6 Cluster and Mean Cluster Analysis

Dendrograms constructed by Unweighted Pair Group Methods with Arithmetic Means (UPGMA) grouped the 36 sorghum genotypes into four distinct clusters. Clustering was based on the Euclidean distance matrix estimated from 10 yield, productivity, and sensitivity indices (i.e. grain yield under combined climate-smart management practices, grain yield under conventional management/bare soil, mean productivity, geometric mean productivity, harmonic mean, relative productivity over combined climate-smart practices, yield reduction index, grain yield stability index, response sensitivity index for CSPs, and yield index). Clusters I, II, and III consisted of 21 (58.33%), 10 (27.78%), and 3 (8.33%) genotypes, respectively, whereas Cluster IV consisted of 2 (5.56%) genotypes (Figure 1).

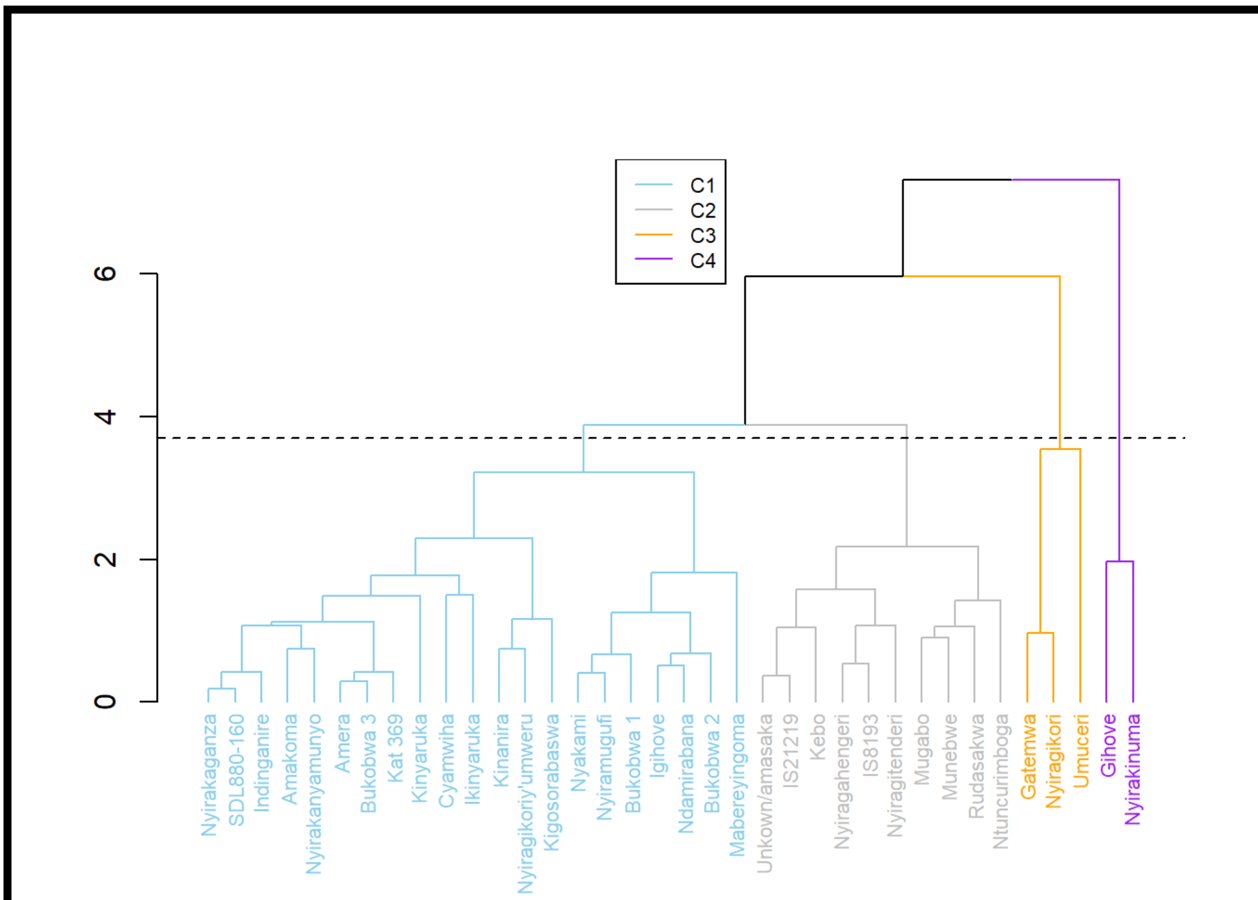

Figure 1: Dendrogram depicting dissimilarity of 36 sorghum genotypes by Unweighted Pair Group Method with Arithmetic Means (UPGMA) clustering method from Euclidean distances matrix estimated from 10 yield, productivity and sensitivity indices evaluated under conventional and combined climate-smart management practices.

The observed clustering of genotypes into different groups indicated the existence of a good opportunity to develop high-yielding sorghum varieties with tolerance to low water availability based on the differential response of genotypes to different management practices. Diversification of management strategies is important because the achievement of sustainability and productivity of the crop relies not only on the diversity of varieties and species (Galluzzi et al., 2011). According to Sadras et al. (2012), agronomic and genetic interventions must be combined to reduce the difference between achievable and actual yields per unit water usage. The presence of genetic diversity can help in the improvement of sorghum yield since it enables the selection of genotypes with desirable trait combinations, such as drought (Yusuf et al., 2020). However, identifying genotypes for tolerance in sorghum is difficult because of the complex nature of drought tolerance traits controlled by many genes and their inheritance patterns (Nazari et al., 2021), and it is suggested to use various tolerance indices as one of the options (Anwaar et al., 2020).

All 12 genotypes under Clusters II and IV had higher grain yields under both management practices than the overall mean yield of the genotypes. Except for relative productivity over the three CSPs, grain yield reduction index, and response sensitivity index for CSPs, the genotypes Gihove and Nyirakinuma under Cluster IV had higher mean values than the overall mean of the genotypes for the remaining yield and productivity indices (Table 9). The two genotypes in this cluster could be recommended for sorghum production under conventional and combined climate-smart management practices to obtain high yields without much variation after further evaluation. The ten genotypes under Cluster II had higher mean values than the overall mean of genotypes for all yield, productivity, and sensitivity indices, except for relative productivity over the three CSPs, response sensitivity index for CSPs, and grain yield stability index. However, the genotypes under this cluster had relative productivity over combined climate-smart management practices in the range between 11.86 and 34.06% (Table 6), with a cluster mean of 23.98%, which was lower by only 0.73% than the overall mean of the genotypes (24.71%) (Table 9). This suggests that the genotypes in this cluster could be responsive to combined climate-smart management practices and should be recommended for the evaluated management practices after further evaluation. In addition, the same genotypes can be used as parental lines to produce hybrids or lines that produce high yields under varying management practices and are more responsive to combined climate-smart management practices.

The clustering of genotypes using grain yields of genotypes under conventional and combined climate-smart management practices, productivity, and sensitivity indices, and the results of mean cluster analysis indicated a wide variation among genotypes for the response to varying management practices. These results also demonstrate the importance of combining improved agronomic and water management techniques with breeding for greater yield varieties (Sadras et al., 2012). The matching of clustering and mean cluster analysis results and grouping of genotypes by effective selection criteria proposed by Fernandez (1992) suggest the importance of both methods to overcome the shortcomings of selection-based indices in identifying cultivars with high yield under stress and non-stress conditions (Khayatnezhad et al., 2010). The results of this study are in line with the findings of Nazari et al. (2021) and Abebe et al. (2020), who grouped drought-tolerant and drought-sensitive sorghum genotypes based on grain yield under well-watered and water-limited conditions, productivity, and drought indices. The authors also suggested the importance of identifying genotypes based on mean yields under varying water regimes, along with low values for tolerance, yield reduction, and stress susceptibility indices.

Table 9: Mean values of four clusters of 36 sorghum genotypes for grain yield, productivity and sensitivity indices over combined climate-smart management practices

	Cluster			
Trait	I (21)	II (10)	III (3)	IV (2)
Mean grain yield over combined three climate-smart practices (kg ha^{-1})	2281.56	3018.10	1753.95	3710.67
Grain yield under conventional management (kg ha^{-1})	1748.62	2443.10	1874.00	3481.75
Mean productivity	2015.09	2730.60	1813.97	3596.21
Geometric mean productivity	1994.38	2714.39	1812.64	3594.32
Harmonic mean	1973.97	2698.31	1811.31	3592.42
Relative productivity over combined CSPs (%)	31.31	23.98	-6.92	6.50
Yield reduction index	0.23	0.19	-0.07	0.06
Grain yield stability index	0.77	0.81	1.07	0.94
Response sensitivity index for combined CSPs	1.20	1.02	-0.88	0.30
Yield index	0.85	1.19	0.91	1.70

Note: CSPs = climate-smart practices. Numbers in parentheses represent the number of genotypes in each cluster.

4.0 Conclusion

The study found significant differences in sorghum genotypes for the evaluated parameters under conventional and under combined climate-smart management practices. This indicated the existence of genetic variations among genotypes and differential responses of genotypes for combined climate-smart management practices that could be used in the development of new drought-tolerant and high-yielding sorghum varieties in Rwanda. The results of principal component analysis showed two components accounting for 99.40% of the total variation, whereas the results of clustering and mean cluster analysis showed four groups of genotypes with distinguishing mean performances for yield, productivity, and tolerance indices. The Gihove and Nyirakinuma genotypes registered higher yields than all genotypes under conventional and over combined climate-smart management practices. These two genotypes also had higher mean values for all yield, productivity, and sensitivity indices except for relative productivity, yield reduction, and response sensitivity indices. Thus, the two genotypes could be recommended for sorghum production under conventional and climate-smart management practices to obtain high yields without much variation after further evaluation under locations. The results provide insight into the importance of assessing genetic diversity under various management practices to develop sorghum varieties adaptable to varying levels of water availability and management practices.

Acknowledgements: the authors thank the Africa Center of Excellence for Climate-Smart Agriculture and Biodiversity Conservation (SABC), Haramaya University in Ethiopia, for funding this research. The authors also appreciate the Rwanda Agriculture and Animal Resources Development Board for providing the area in which the research was conducted, different materials, and technical support.

Disclosure of Interest: The authors report there are no competing interests to declare.

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