International Journal of Plant Production (2025) 19:927–935
https://doi.org/10.1007/s42106-025-00380-0

RESEARCH

Yield and Agronomic Performance of CIMMYT Improved Wheat Nurseries in South Western Uganda

Ivan Kabiita Arinaitwe[1] · Rogers Akatwijuka[1] · Dianah Natukwasa[1] · Jonasi Mucunguzi[1] · Lawrence Aula[1,2] · Emmanuel Ibukunoluwa Moyin-Jesu[1] · Wilson Mwetonde Bamwerinde[1]

Received: 31 July 2025 / Accepted: 22 September 2025 / Published online: 8 October 2025

Abstract
Wheat (*Triticum aestivum* L.) production levels in Uganda are very low and do not meet the huge national demands. This is partly attributed to the lack of improved and end user acceptable varieties. To meet the demand, most of the wheat is imported, costing Uganda valuable foreign exchange. This import burden could potentially be addressed by increasing access to improved varieties among farmers. This study evaluated the performance of three CIMMYT improved wheat nurseries (18TH STEMRRSN, 15TH HZAN, 41ST SAWSN) alongside two locally grown varieties (Kyehure Mixed and Kacumu) at Kabale University in Southwestern Uganda for three growing seasons between 2024 and 2025. Apart from spike circumference, nurseries had a significant effect on yield and other agronomic traits evaluated ($P \leq 0.05$). The nursery 18TH STEMRRSN had the highest yield of 7.9 t/ha. This yield was 64.8% hgiher than the yield of local varieties, but there was no difference among improved nurseries.The nursery 18TH STEMRRSN had the highest 1,000-grain weight, was stable in terms of yield across the three seasons, was resistant to lodging because of their short height, and had moderate field resistance to wheat stem rust. Therefore, 18TH STEMRRSN has the potential to improve wheat production in Uganda. More studies on improved wheat genotypes across seasons and in different locations in Uganda are necessary before recommendations for widespread adoption are made.

Keywords Wheat · CIMMYT improved nurseries · Varieties · Yield · Genotype · Season · Southwestern Uganda

Introduction

Wheat (*Triticum aestivum* L.) is a major staple crop for millions of people in Sub-Saharan Africa (SSA) and much of it is imported from countries outside the African continent. Wheat consumption in SSA is increasing rapidly, faster than any other major food grain (Mason et al., 2012). In all African countries, wheat consumption has steadily increased over the past 20 years, resulting from a growing population, transitioning food preferences, and socioeconomic changes associated with urbanization (Macauley & Ramadjita, 2015). Per capita wheat consumption in SSA has also increased at the rate of 0.35 kg/year, outpacing maize and rice (Mason et al., 2012). Wheat is considered a good source of protein, minerals, B-group vitamins, and dietary fiber. It is an excellent health-building food that helps in the prevention and treatment of some digestive disorders (Iqbal et al., 2022). Wheat flour is used to prepare bread, produce biscuits, confectionery products, noodles, and vital wheat gluten or seitan. It is also used as animal feed, for ethanol production, brewing of wheat beer, wheat-based raw material for cosmetics (Iqbal et al., 2022). Meanwhile, wheat production in SSA is failing to keep pace with growing demand (Mason et al., 2012). Wheat consumption in SSA is generally higher in urban areas than in rural areas (Mason et al., 2012). According to FAO, Africa produced 26.3 million tonnes of wheat on 9.2 million hectares of land and imported 41.7 million tonnes in 2023 (FAOSTAT, 2023). As a result, Africa spent USD 15.4 billion on wheat imports alone (FAOSTAT, 2023), making it the world's biggest

✉ Ivan Kabiita Arinaitwe
ivankabiita@gmail.com; info@kab.ac.ug

1 Department of Crop Science and Production, Faculty of Agriculture and Environmental Sciences, Kabale University, P. O. Box 317, Kabale, Uganda

2 Panhandle Research, Extension, and Education Center, Department of Agronomy and Horticulture, University of Nebraska-Lincoln, Lincoln, USA

wheat importer. Wheat imports account for 60% of Africa's wheat consumption and 80% for SSA countries (Macauley & Ramadjita, 2015).

The domestic consumption of wheat products in Uganda is steadily rising. In Uganda today, annual wheat consumption stands at about 800,000 metric tonnes (FAOSTAT, 2023). Wheat has increasingly become an important crop not only at the domestic level but also in the industrial sector. Yet, the country remains a net importer of wheat in order to meet its domestic demand. Uganda is among the low wheat producing countries, producing 25,000 metric tonnes, which is far less than the world's leading producers such as China, India, and Russia, which produced 137.7, 107.7, and 104.2 million metric tonnes respectively (FAOSTAT, 2023). In 2023, wheat became the eighth most imported product in Uganda with ~790,000 metric tonnes imported into the country at a cost of about USD 256 million (FAOSTAT, 2023). The reliance on imported wheat is becoming a serious challenge, considering that recent human-caused and natural crises (such as Ukraine-Russia war, COVID-19 pandemic, and the increasing climate change) are affecting production and trade systems worldwide. Short- and medium-term strategies are needed to amleiorate over reliance on wheat imports, which could jeopardize food and national security (Bentley et al., 2022). Uganda has the capacity to grow wheat for its domestic demand and, thus, substitute for wheat imports. Wheat has been grown in the highlands of Uganda for many decades, although it has not become a major contributor to food consumption in rural areas. In the 1970s, cereals such as wheat and rice dominated the food and income baskets of the highland regions of Kigezi (Desanker & Magadza, 2001; FAO, 2004; Twagiramaria & Tolo, 2016). The main wheat growing areas in Uganda are: the Southwest (Kabale, Kisoro and Rukungiri); the west (Kabarole, Kasese, Bushenyi and Mbarara); the east (Mbale and Kapchorwa) and the West Nile (Nebbi) region in northwestern Uganda (grown in small quantities) (Kagorora et al., 2021). Wheat production in Uganda, however, faced so many challenges that led to low production and productivity in the region. Some of the reasons that have led many wheat farmers to abandon the traditionally grown wheat are low value varieties, that led to poor yields which do not meet market standards; poor quality seeds; emergency of new pests and diseases; and climate change (Desanker & Magadza, 2001; FAO, 2004). The major diseases of wheat are notably yellow rust (*Puccinia striiformis*), leaf rust (*Puccinia recondita*), stem rust (*Puccinia graminis f. sp. tritici*), Race Ug99 of the fungus *Puccinia graminis tritici* that causes stem or black rust disease (*Septoria tritici*), and Fusarium head scab (Turyamureeba & Bungutsiki, 1991; Pretorius et al., 2000; Singh et al., 2007, 2011). Introducing improved wheat and or improving local wheat varieties that meet the farmer and end user's preferred traits such as yield, grain quality, resistance to pests, and other culinary traits is key in revamping wheat production in Uganda. The objective for this study was, therefore, to determine the yield and agronomic performance of introduced CIMMYT improved wheat lines (18TH STEMRRSN, 41ST SAWSN, and 15TH HZAN) and local varieties of Kacumu and Kyehure Mixed.

Materials and Methods

Study Site

The study was conducted at Kabale University farm (1°16'15.9"S, 29°59'02.0"). Kabale University is located in the highlands of Kigezi subregion, in the Southwestern agro-ecological zone (SW-AEZ) of Uganda.

The farm is located 2,000 m above sea level. The experiment was set up on the foot slope of the hills at an elevation of 11.5% with well-drained dark-red and brownish loamy soils (Ferrasols).

Experimental Materials

The plant materials used in the study included three CIMMYT improved wheat nurseries that were procured from International Maize and Wheat Improvement Center (CIMMYT) of Carretera México and two locally grown varieties obtained from local farmers. The main features of these genotypes and the origins are shown in Table 1.

Experimental Design and Crop Management

The experimental design was a randomized complete block design (RCBD) established with four blocks. The treatments assigned to the experimental units were five experimental genotypes shown in Table 1. Each genotype was replicated four times. The genotypes were evaluated across

Table 1 Wheat genotypes used in the study

SN	GENOTYPES	ORIGIN	TYPE	KEY TRAITS
1	18TH STEMRRSN	CIMMYT	Spring bread wheat *(Triticum durum* L.*)*	Stem Rust Resistance Screening Nursery (STEMRRSN)
2	15TH HZAN	CIMMYT	Spring bread wheat *(Triticum aestivum* L.*)*	Elite Zinc Advanced Nursery (HZAN)
3	41ST SAWSN	CIMMYT	Spring bread wheat *(Triticum aestivum* L.*)*	Semi-arid Wheat Screening Nursery (SAWSN)
4	Kyehure Mixed	Farmers	Not known	Not known
5	Kacumu	Farmers	Not known	Not known

Table 2 Seasons in Uganda during which the experiment was carried out

Seasons	Classification	Months	Planting date	Harvest date	Total precipitation (mm)	Minimum temperature °C	Maximum temperature °C
Season one 2024	First rainy season	March to July 2024	10th March 2024	1st-2nd July 2024	325.2	13.3	22.9
Season two 2024	Second rainy season	August to December 2024	28th August 2024	27th December 2024	496.9	12.8	22.5
Season three 2025	First rainy season	March to July 2025	15th March 2025	2nd July 2025	393.7	12.9	22.0

Table 3 Scale for field scoring of wheat steam rust on wheat genotypes

Percentage score on stem, leaf or spike	Translation of percentage onto the scale	Translation of the scale	Description of action
0–10%	1	Resistant	Very little or no pustules or uredia are present, often with a hypersensitive reaction
11–20%	2	Moderately Resistant	Some pustules or small uredia are present, often surrounded by either chlorotic or necrotic areas.
21–40%	3	Intermediate	Variable sized uredia are present; some with chlorosis, necrosis, or both.
41–60%	4	Moderately Susceptible	Medium sized uredia are present and possibly surrounded by chlorotic areas.
61–100%	5	Susceptible	Large uredia are present, generally with little or no chlorosis and no necrosis.

three seasons in 2024 and 2025 (Table 2). Although there are two growing seasons per year (first and second rainy seasons), we treated each season as unique since in 2025, wheat was not grown in the second rainy season due to logistical reasons, making the study to have three distinct growing seasons. Each experimental unit measured 6 m × 8 m, and blocks were separated by a separation strip of 1 m.

Wheat was planted in March of each first rainy season and in August of the second rainy season at a spacing of 30 cm × 3 cm. A single seed was planted per hill at a depth of 3 cm deep and no organic or inorganic fertilisers were applied. Manual weeding was performed twice, that is, 20 and 40 days after sowing the wheat. No irrigation was applied to crops during the growing season.

Agronomic and Yield Data Collection

Data were collected on the following agronomic yield and yield related parameters: Plant height (cm) from the ground to the tip of the spike, internode length (cm), spike length (cm) was taken from top to the bottom of the spike, using a calibrated clear plastic ruler, spike circumference (cm) taken from the middle of the spike and stem circumference (cm) were measured using a vernier caliper vernier and Number of tillers was determined by counts. Internodal length and stem circumference were recorded for the last internode just below the spike. These parameters were collected every 30 days after planting (DAP) throughout the growing season and averaged. At harvest, the wheat was threshed, and the weight (g) of 1000 randomly sampled wheat grains was recorded for each genotype. From each experimental unit, the weight of wheat grains per genotype was measured in kilograms (kg) and later used to compute yield in t/ha with the weight adjusted to 12.5% moisture content.

Disease Data Collection

Wheat genotypes were evaluated based on the stem rust severity on stem, leaves and spikes under natural infection and field conditions. Disease scoring was noted as percentage of the rust infection on the plant area and later translated on scale as shown below (Table 3).

Data Analysis

The data analysis was done in R (Core Team, 2025) using RStudio (Posit team, 2025) as an integrated development environment. The fixed effects were season, genotypes, and season × genotypes interaction, while, replications were nested within season and formed the error term for estimating the effect of seasons on dependent variables under consideration. Treatment means of the different dependent variables, were separated using honestly significant difference (HSD) at 5% significance level. The GGE scatter and ranking biplots across seasons were generated for only the yield using GenStat (Payne et al., 2011).

Table 4 Table of mean squares from ANOVA for wheat yield and growth parameters at Kabale university farm and Butanda in Uganda

Source of variation	d.f.	Mean squared error							
		Plant height	stem circumference	Internode length	Number of tillers	Spike length	Spike circumference	1,000-grain weight	Yield
Season	2	614.6^{ns}	7.97^{ns}	1508**	19.6^{ns}	12.9^{ns}	8.5^{ns}	295**	76.1*
Replications within season	9	670.1	6.43	133.4	11.1	3.37	2.6	27.4	19.2
Genotype	4	2325.7***	0.816^{ns}	602.3***	38.3**	9.88***	0.87*	75.7*	20.2**
Genotype × Season	8	237.8^{ns}	0.416^{ns}	30.9^{ns}	11.7^{ns}	5.17***	0.75*	11.3^{ns}	9.1^{ns}
Residual/Error	36	148.5	0.385	28.5	9.81	0.551	0.25	20.8	3.8

*** Significant at ≤0.001 probability level, ** Significant at ≤0.01 probability level, * Significant at ≤0.05 probability level, ns = non-significant at 0.05 probability level, d.f = degrees of freedom

Table 5 Mean performance of yield and agronomic wheat parameters among three wheat growing seasons

Season	Plant height	Stem circumference	Internode length	Number of tillers	Spike length	Spike circumference	1,000 grains weight	Yield
			cm				g	t/ha
Season one 2024	79.5	3.2	31.2a	8.7	11.9	2.8	37.0a	4.5a
Season two 2024	73.6	2.1	14.4b	8.2	11.1	4.1	44.6b	8.1ab
Season three 2025	68.4	2.2	26.6a	6.8	10.3	3.1	39.4a	5.1a
Mean	73.8	2.5	24.1	7.9	11.1	3.3	40.3	5.9
$HSD_{0.05}$	22.9	2.2	10.2	2.9	1.62	1.4	4.62	3.4
P-value	0.43	0.34	<0.001	0.23	0.06	0.09	<0.01	0.05

HSD, honestly significant difference

Results

Analysis of Variance for the Effect of Wheat Genotypes on Yield and Agronomic Traits

Genotypes had a significant effect on wheat yield and agronomic parameters including plant height, internode length, number of tillers, spike circumference, and 1,000 grains weight and yield ($P<0.05$; Table 4). However, there were no significant effect of genotypes on stem circumference ($P>0.05$; Table 4). The effect of seasons was significant on internode length and 1,000-grain weight. Genotype × season interaction had a significant effect on spike length and spike circumference ($P<0.05$).

Effect of Seasons on Average Yield and Agronomic Traits

The plant height, stem circumference, number of tillers, spike length, spike circumference, and yield did not differ among the three seasons and had an average value of 73.8 cm, 2.5 cm, 7.9, 11.1 cm, 3.3 cm, and 3.7 t/ha, respectively (Table 5). Internodal length of wheat averaged across genotypes was significantly higher in season one and three than in season two. Seasons one and three had similar internodal length with an average of 28.9 cm compared to 14.4 cm in season two (Table 5). The yield and the 1000-grain weight also statistically signifciant among seasons. The seasons one and three having similar weights, with a mean of 4.8 t/ha and 38.2 g for 1,000 grains wieght, these values were substantially lower than that of season two by 68.8 and 16.8% for yield and the 1000-grain weight respectively.

Effect of Genotypes on Yield and Agronomic Traits

The heights of introduced CIMMYT improved wheat genotypes were not statistically different, but their heights were substantially lower than those of the two locally grown varieties. On average, CIMMYT improved nurseries had a height of 64.5 cm, which was 36.3% less than the height of local varieties (Kyehure and Kacumu) (Table 6). Heights were not statistically different among the two local varieties (Table 6). Conversely, stem circumference did not differ among the five genotypes and they had an average circumference of 2.5 cm (Table 6). Internode lengths did not vary substantially among CIMMYT improved nurseries and were on average less than those of locally grown variety by at least 29.4% (Table 6). There were also differences in internode lengths of local varieties with Kyehure Mixed having 1.41 times more length than Kacumu, with 25.5 cm internode length. Kyehure mixed had a statistically higher number of tillers than CIMMYT but no difference with the Kacumu cultivar (Table 6). On average, CIMMYT

Table 6 Mean agronomic and yield performance of wheat genotypes

Genotype	Plant height	Stem circumference	Internode length	Number of tillers	Spike length	Spike circumference	1,000 grains weight	Yield
			cm				g	t/ha
18TH STEMRRSN	59.3a	2.4	19.0a	6.5a	10.6a	3.4	43.4b	7.9b
15TH HZAN	67.2a	2.6	19.5a	6.7a	10.5a	3.2	39.7ab	5.7ab
41ST SAWSN	66.9a	2.9	20.6a	7.2a	10.5a	3.7	40.5b	6.3ab
Kyehure Mixed	94.2c	2.2	35.9c	10.9b	11.1a	3.3	41.5b	5.0a
Kacumu	81.5b	2.5	25.5b	8.1ab	12.6b	3.0	36.6a	4.7a
Mean	73.8	2.5	24.1	7.9	11.1	3.3	40.3	5.8
$HSD_{0.05}$	12.2	0.79	5.3	3.1	0.74	0.5	4.55	1.95
P-value	<0.001	0.10	<0.001	0.01	<0.001	0.17	0.014	<0.01

HSD, honestly significant difference

Table 7 Mean stem rust disease score for wheat genotypes evaluated in 2024

Genotype	Stem score	Leaf score	Spike score
41ST SAWSN	1.6^{a}	1.3^{a}	1.1
Kyehure Mixed	1.9^{ab}	1.9^{b}	1.2
18TH STEMRRSN	2.5^{bc}	2.0^{b}	1.2
15TH HZAN	2.9^{c}	2.9^{c}	1.2
Kacumu	3.6^{d}	3.5^{d}	2.4^{b}
Mean	2.5	2.3	1.4
LSD 0.05	0.6	0.5	0.6
P-value	<0.001	<0.001	<0.001

Different letters within a column show significant differences between the treatment means at $P<0.05$

improved nurseries had 60.7% fewer tillers than Kyehure mixed with 10.9 tillers.

The yield (7.9 t/ha) of introduced CIMMYT improved nursery (18TH STEMRRSN) was statistically higher than the two local genotypes (Kacumu and Kyehure Mixed). This nursery (18TH STEMRRSN) had a yield at least 1.57 times higher than the yield of local varieties (Table 5). The locally grown varieties, Kacumu, Kyehure Mixed and the CIMMYT nurseries 15TH HZAN and 41ST SAWSN had yields that did not differ significantly. For the 1,000-grain weight, the introduced improved CIMMYT nurseries: 18TH STEMRRSN, 41ST SAWSN, and the locally grown Kyehure Mixed variety had a statistically higher weight compared to the locally grown Kacumu variety. The introduced CIMMYT improved genotype, 15TH HZAN, had an intermediate 1,000-grain weight and did not statistically differ from Kacumu and the rest of the CIMMYT improved nurseries (Table 6).

Kacumu, a local variety, had the highest spike length of 12.6 cm and was substantially larger than the rest of the genotypes by at least 5.7% (Table 6). The spike lengths of 15TH HZAN, 18TH STEMRRSN, 41ST SAWSN, and Kyehure mixed were not significantly different and had an average spike length of 10.7 cm. Spike circumference differed between Kacumu and 41ST SAWSN, 41ST SAWSN having the largest circumference of 3.7 cm, which was 1.24 times larger than the one for Kacumu (Table 6). There was no difference in the circumference of the genotypes 18TH STEMRRSN, 15TH HZAN, 41ST SAWSN, and Kyehure mixed, with an average of 3.4 cm.

Mean Stem Rust Disease Score

The rust disease scores on stem, leaf, and spike were significant different among genotypes ($P<0.001$; Table 7). Locally grown variety Kacumu had significanty higher scores than the other wheat genotypes for the stem (3.6) and leaf (3.5) (Table 7). The introduced CIMMYT improved genotype, 41ST SAWSN had the lowest score for the stem (1.6), leaf (1.3), and spike (1.1) among all the evaluated genotypes and these scores were substantially smaller than the largest scores registered with Kacumu. The locally grown genotype, Kyehure Mixed and the introduced CIMMYT improved nursery 18TH STEMRRSN had moderate scores that were statistically similar, whereas 15TH HZAN had relatively high scores for the stem, leaf, and spike, with leaf score being significantly different from 41ST SAWSN, 18TH STEMRRSN, and Kyehure Mixed (Table 7).

Season Scatter and Ranking Biplot for Yield

The scatter biplot for yield between the three seasons shows an acute angle between vectors connecting season one of 2024, season two of 2024, and season three of 2025. The scatter biplot also grouped season one of 2024, season two of 2024 in one mega season, and season three of 2025 in its own independent season. The genotype 18TH STEMRRSN appears in the same biplot sector as the two seasons of season one of 2024, season two of 2024, which were grouped as one mega season, and 41ST SAWSN appears in the same biplot sector as season three of 2025 (Fig. 1). From the current study, partitioning genotype and genotype by season interaction through bi-plot analysis showed that interaction

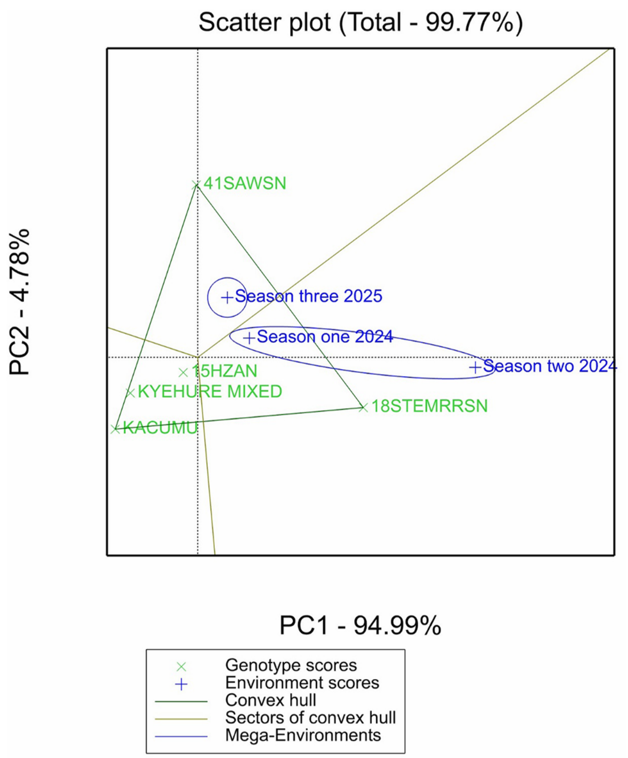

Fig. 1 A scatter biplot of the performance of genotypes in the mega seasons encompassing the three seasons where wheat genotypes were evaluated

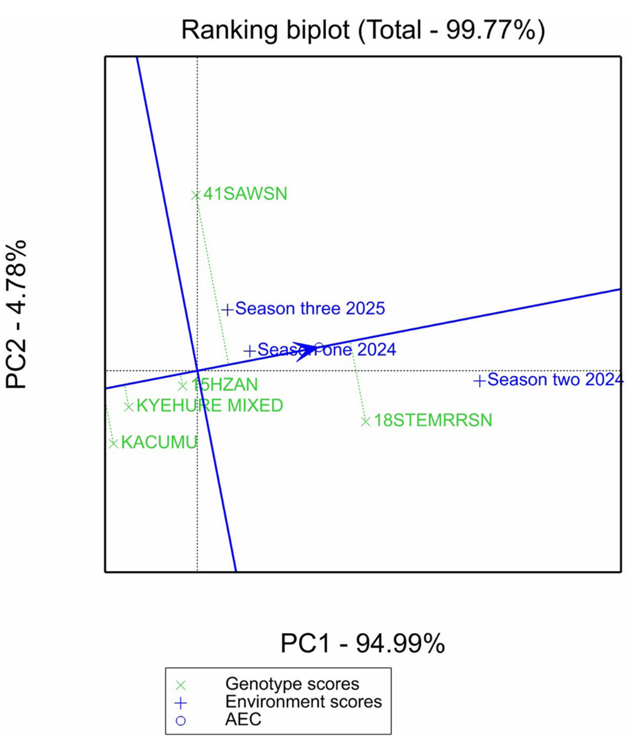

Fig. 2 The Ranking biplots for wheat genotype performance under season one of 2024

principal components axes (IPCA) for IPCA1 and IPCA2 explained 99.77% (PCA1 contributing 94.99% and PCA2 contributing 4.7%) of the total variation for yield in t/ha.

The ranking biplots showed that nursery 18TH STEMRRSN was ranked first, followed by 41ST SAWSN under season one 2024 (Fig. 2) and season two 2024. Under both seasons, nursery 18TH STEMRRSN projected short lines orthogonal to the biplot axis.

Discussion

Variation of Wheat Genotypes from ANOVA

There were differences in performance between genotypes being evaluated for both agronomic, yield, and yield-related parameters. This means that agronomic, yield, and yield-related parameters evaluated responded differently depending on the genotypes under consideration. The presence of genetic variation in the evaluated wheat genotypes is critical for selecting good genotypes for advancement and also for further improvement of the genotypes for yield and resistance to abiotic and biotic stresses (Faysal et al., 2022). The lack of significant differences for genotype by season interaction for most of the parameters indicated that the performance of different wheat genotypes did not vary depending on the season.

Mean Performance of the Wheat Genotypes

The introduced CIMMYT improved nursery 18TH STEMRRSN outperformed the rest of the evaluated genotypes for yield and weight of 1,000 grains. The weight of 1000 grains in wheat is an indicator of grain size and can be used to estimate the milling performance and is also related to test weight (Sissons et al., 2020). Test weight is a measure of grain density and good grain packing into a given volume, with values of 76 kg/hL or higher desirable (Sissons et al., 2020). However, two CIMMYT improved nurseries (15TH HZAN 41ST SAWSN) did not yield better than the two local varieties.

The CIMMYT improved nurserie performed better than the local varieties (Kyehure Mixed and Kacumu) for plant height and internode length. The local varieties were taller than the CIMMYT improved wheat nurseries. This attribute renders the local varieties susceptible to lodging, which in turn affects wheat production. In wheat, traits such as plant height, diameter and thickness stem, strength of upper and lower internodes are correlated to lodging (Wang et al., 2011; Mondal, 2020). Tall cereals such as wheat and rice genotypes are highly prone to lodging, whereas their shorter counterparts can withstand lodging pressure (Todaka et al., 2015; Shah et al., 2019). According to Niu et al. (2022), the use of semi-dwarf genes in cereal crops significantly improved yield stability through increased lodging resistance.

Mean Stem Rust Disease Score

The introduced CIMMYT improved nursery 41ST SAWSN had significantly low scores for stem, leaf, and spike for the stem rust disease. This nursery can be categorised as resistant to wheat stem rust from natural infestation under field conditions. The CIMMYT nursery 18TH STEMRRSN and the locally grown Kyehure Mixed can be categorised as moderately resistant under field natural infestation, while the locally grown Kacumu and CIMMYT nursery 15TH HZAN can be categorised as moderately susceptible. Wheat production in Uganda has been heavily affected by fungal rust diseases, mostly the stem rust caused by the Ug99 race of *Puccinia graminis tritici* (Singh et al., 2011). Most of the locally grown wheat varieties in Uganda are susceptible to wheat stem rust. Wheat production in Uganda can be boosted by promoting growing new wheat germplasm with resistance to stem rust developed through breeding (Singh et al., 2011; Kayim et al., 2022).

Seasons and Stability Performance

Season two 2024 which is the second season in Uganda, running from August to December had statistically high yields, 1,000 grain weight and short internode length for the wheat genotypes. The increase in wheat yields for season two 2024 could be attributed to increase in precipitation that was recieved. Increase in precipitation significantly increases wheat productivity (Lai et al., 2025). (Ousayd et al., 2024) reported that rainfall is strongly and positively correlated to wheat yields, most particulary in the months of December to March in Morocco. Temperature fluctuations negatively impact wheat yield (Ousayd et al., 2024). According to You et al. (2009), authors reported that that a 1 °C increase in wheat growing season temperature reduced wheat yields by about 3–10% wheat yields in China.

Stability studies are useful for selecting genotypes that reliably perform well across different environments as well as those adapted to specific locations (González-Barrios et al., 2019). The CIMMYT improved nursery 18TH STEMRRSN appears in the same biplot sector grouping the two seasons of season one of 2024, season two of 2024. This result means that the CIMMYT improved nursery 18TH STEMRRSN was the best performer in terms of yield in the two seasons. CIMMYT improved nursery 41ST SAWSN appeared in the same biplot sector as season three of 2025, meaning that it was the best performer during that season in terms of yield. The CIMMYT improved nursery 18TH STEMRRSN had the shortest line projected on the axis for two seasons (season one of 2024 and season two of 2024), followed by 41ST SAWSN. This result means that nurseries 18TH STEMRRSN and 41ST SAWSN were the most stable compared to other genotypes evaluated. The length of the lines between genotypes and their orthogonal projection onto the biplot axis is a measure genotype stability. Short lines indicate high stability while long lines indicate low stability (Mullualem et al., 2024).

Conclusion

The introduced CIMMYT improved nursery 18TH STEMRRSN had the highest yield in t/ha of 7.9 t/ha, had high 1,000-grain weight, were stable in terms of yield across the threes seasons, are resistant to lodging beacuse of their short plant height and had moderate field resistance to wheat stem rust. This work demonstrated that the introduced CIMMYT improved nursery 18TH STEMRRSN is a viable candidate for further evaluation and release. The CIMMYT improved nursery 18TH STEMRRSN has so far gone through the Early evaluation trials (EET) and is recommended to go through following steps are required for introdction, development and release of new varieties in Uganda as laid out by the Ministry of Agriculture, Animal Industry and Fisheries (MAAIF). The steps include: Preliminary yield trials (PYT), Advanced yeild trials (AYT), National performance trials (NPT) and onfarm trials (OF) while screening for pests and disease resistance. The CIMMYT improved nursery 18TH STEMRRSN could then be recommended for release to the farming communities to improve wheat production in Uganda. There is a potential to reduce reliance on wheat import by adapting improved genotypes such as 18TH STEMRRSN. The locally grown wheat varieties in Uganda need to be profiled and characterised to ascertain their type.

Acknowledgements We acknowledge the International Maize and Wheat Improvement Center (CIMMYT) of Carretera México for providing the improved wheat genotypes that were used in the study.

Author Contributions I.K.A., W.M.B. and R.A. conceived and designed the work. JM., D.N. and I.K.A. collected data. I.K.A., L.A. and EIM. produced the primary content and analysed the data presented. I.K.A. and L.A. wrote the main manuscript text. All authors wrote and reviewed the paper.

Funding No funding was received for conducting this study.

Data Availability No datasets were generated or analysed during the current study.

Declarations

Competing Interests The authors declare no competing interests.

References

Bentley, A. R., Donovan, J., Sonder, K., Baudron, F., Lewis, J. M., Voss, R., Rutsaert, P., Poole, N., Kamoun, S., Saunders, D. G. O., Hodson, D., Hughes, D. P., Negra, C., Ibba, M. I., Snapp, S., Sida, T. S., Jaleta, M., Tesfaye, K., Becker-Reshef, I., & Govaerts, B. (2022). Near- to long-term measures to stabilize global wheat supplies and food security. *Nature Food*, *3*(7), 483–486. https://doi.org/10.1038/s43016-022-00559-y

Desanker, P. V., & Magadza, C. (2001). Africa. In McCarthy J.J., Canziani O.F., Leary N.A., Doken D.J. & White K.S., (Eds.), *Climate change (2001): Impacts, adaptation and vulnerability*. IPCC Working Group II, Third Assessment Report. Cambridge University Press.

FAO. (2004). Monitoring progress towards the world food summit and millennium development goals. In A. Marx (Ed.), *The state of food insecurity Report. food and agriculture organization of the united nations*. Vialedelle Terme di Caracalla, Rome.

FAOSTAT (2023). https://www.fao.org/faostat/en/#data. Accessed on 18-02-2025.

Faysal, A. S. M., Ali, L., Azam, M. G., Sarker, U., Ercisli, S., Golokhvast, K. S., & Marc, R. A. (2022). Genetic variability, character association, and path coefficient analysis in transplant Aman rice genotypes. *Plants*, *11*(21), 2952. https://doi.org/10.3390/plants11212952

González-Barrios, P., Díaz-García, L., & Gutiérrez, L. (2019). Mega-environmental design: Using genotype× environment interaction to optimize resources for cultivar testing. *Crop Science*, *59*(5), 1899–1915. https://doi.org/10.2135/cropsci2018.11.0692

Iqbal, M. J., Shams, N., & Fatima, K. (2022). Nutritional quality of wheat. In *Wheat-Recent Advances*. IntechOpen. https://doi.org/10.5772/intechopen.104659

Kagorora, J. P. K., Kansiime, M. K., Owuor, C., & Tumwine, J. (2021). A review of some aspects of Uganda's crop agriculture: Challenges and opportunities for diversified sector output and food security.

Kayim, M., Nawaz, H., & Alsalmo, A. (2022). Fungal diseases of wheat. In *Wheat-Recent Advances*. IntechOpen. https://doi.org/10.5772/intechopen.102661

Lai, X., An, D., & Shen, Y. (2025). Effects of rainfall variability on productivity and profitability in the intensified annual forage–winter wheat cropping systems on the loess plateau of China. *Crop Science*, *65*(2), e70006. https://doi.org/10.1002/csc2.70006

Macauley, H., & Ramadjita, T. (2015). Cereal crops: Rice, maize, millet, sorghum, wheat. http://hdl.handle.net/123456789/4510

Mason, N. M., Jayne, T. S., & Shiferaw, B. A. (2012). Wheat consumption in Sub-Saharan Africa: Trends, drivers, and policy implications. https://doi.org/10.22004/ag.econ.14693

Mondal, T. (2020). Lodging in wheat: Its causes, ill effects and management for higher productivity and profitability. *Indian Farmer*, *7*(09), 832–837.

Mullualem, D., Tsega, A., Mengie, T., Fentie, D., Kassa, Z., Fassil, A., Wondaferew, D., Gelaw, T. A., & Astatkie, T. (2024). Genotype-by-environment interaction and stability analysis of grain yield of bread wheat (*Triticum aestivum* L.) genotypes using AMMI and GGE biplot analyses. *Heliyon*, *10*(12). https://doi.org/10.1016/j.heliyon.2024.e32918

Niu, Y., Chen, T., Zhao, C., & Zhou, M. (2022). Lodging prevention in cereals: Morphological, biochemical, anatomical traits and their molecular mechanisms, management and breeding strategies. *Field Crops Research*, *289*, 108733. https://doi.org/10.1016/j.fcr.2022.108733

Ousayd, L., Epule, T. E., Belaqziz, S., Ongoma, V., Amazirh, A., & Chehbouni, A. (2024). The impact of precipitation, temperature, and soil moisture on wheat yield gap quantification: Evidence from Morocco. *Agriculture & Food Security*, *13*(1), 55. https://doi.org/10.1186/s40066-024-00509-w

Payne, R. W., Harding, S. A., Murray, D. A., Soutar, D. M., Baird, D. B., Glaser, A. I., Welham, S. J., Gilmour, A. R., Thompson, R., & Webster, R. (2011). *The guide to Genstat Release 14. Part 2: Statistics*. VSN International.

Posit team (2025). RStudio: Integrated development environment for R. Posit Software, PBC, Boston, MA. http://www.posit.co/

Pretorius, Z. A., Singh, R. P., Wagoire, W. W., & Payne, T. S. (2000). Detection of virulence to wheat stem rust resistance gene Sr31 in *Puccinia graminis. f. sp. tritici* in Uganda. *Plant Disease*, *84*(2), 203–203. https://doi.org/10.1094/PDIS.2000.84.2.203B

R Core Team. (2025). R: A language and environment for statistical computing. R Foundation for Statistical Computing, Vienna, Austria. https://www.R-project.org/

Shah, L., Yahya, M., Shah, S. M. A., Nadeem, M., Ali, A., Ali, A., Wang, J., Riaz, M. W., Rehman, S., Wu, W., & Khan, R. M. (2019). Improving lodging resistance: Using wheat and rice as classical examples. *International Journal of Molecular Sciences*, *20*(17), 4211. https://doi.org/10.3390/ijms20174211

Singh, R. P., Hodson, D. P., Jin, Y., Huerta-Espino, J., Kinyua, M. G., Wanyera, R., Njau, P., & Ward, R. W. (2007). Current status, likely migration and strategies to mitigate the threat to wheat production from rzace Ug99 (TTKS) of stem rust pathogen. *CABI Reviews*, (2006), 13. https://doi.org/10.1079/PAVSNNR20061054

Singh, R. P., Hodson, D. P., Huerta-Espino, J., Jin, Y., Bhavani, S., Njau, P., Herrera-Foessel, S., Singh, P. K., Singh, S., & Govindan, V. (2011). The emergence of Ug99 races of the stem rust fungus is a threat to world wheat production. *Annual Review of Phytopathology*, *49*(1), 465–481. https://doi.org/10.1146/annurev-phyto-072910-095423

Sissons, M., Kadkol, G., & Taylor, J. (2020). Genotype by environment effects on durum wheat quality and yield-implications for breeding. *Crop Breeding Genetics and Genomics*, *4*(3). https://doi.org/10.20900/cbgg2020001

Todaka, D., Shinozaki, K., & Yamaguchi-Shinozaki, K. (2015). Recent advances in the dissection of drought-stress regulatory networks and strategies for development of drought-tolerant Transgenic rice plants. *Frontiers in Plant Science*, *6*, 84. https://doi.org/10.3389/fpls.2015.00084

Turyamureeba, G., & Bungutsiki, B. (1991). Recent advances in the development of high yielding wheat varieties for the cool, moist environments of Uganda. *In The Seventh Regional Wheat Workshop for Eastern, Central and Southern Africa* (19–86). Nakuru, Kenya, September 16.

Twagiramaria, F., & Tolo, C. U. (2016). Climate variability and soil nutrients status along altitudinal gradient in Kigezi Highlands, Southwestern Uganda. *Natural Resources*, *7*(01), 1. https://doi.org/10.4236/nr.2016.71001

Wang, Y., Wang, X., Yang, L., Li, P., Zhu, J., Kazuhiko, K., & Wang, Y. (2011). Ozone stress increases lodging risk of rice cultivar liangyoupeijiu: A FACE study. *Acta Ecologia Sinica*, *31*, 6098–6107.

You, L., Rosegrant, M. W., Wood, S., & Sun, D. (2009). Impact of growing season temperature on wheat productivity in China. *Agricultural and Forest Meteorology*, *149*(6–7), 1009–1014. https://doi.org/10.1016/j.agrformet.2008.12.004