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Impact of organo-mineral fertilization, sowing dates and climate variability on yields and water productivity of three improved sorghum cultivars in the Sudanian agroecological zone of Mali

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Sorghum production in Mali faces challenges, including low soil fertility and climate variability. To assess the effects of management practices (fertilizer types, sowing dates) on biomass and grain yields, as well as water use efficiency (WUE) of grain yield, experiments were conducted at the ICRISAT Samanko and IER N'Tarla research stations. A split-split plot design was used as the experimental design during the 2021 and 2022 growing seasons, with four fertilization types as factors: F1 (the control); F2 (the recommended option, 100 kg ha^{-1} DAP + 50 kg ha^{-1} Urea); F3 (the organic amendment, 5000 kg ha^{-1} cow dung); and F4 (the combined option, 50 kg ha^{-1} DAP + 25 kg ha^{-1} Urea + 2500 kg ha^{-1} cow dung). Two sowing dates (SWD1, medium, and SWD2, late sowings) and three sorghum varieties were also included. The results revealed that SWD1 produced higher biomass and grain yields, as well as WUE, compared to SWD2 at Samanko during both seasons. SWD1 outperformed SWD2 for biomass and grain yields, with increases of 65% and 30%, respectively. The organo-mineral fertilization (F4) recorded the highest biomass and grain yields and WUE compared to the other fertilization types (F2, F3, and F1). During both cropping seasons (2021 and 2022), the hybrid Pablo produced the highest biomass (4083 and 6795 kg ha^{-1}) and grain (1765 and 2740 kg ha^{-1}) yields, as well as the highest water WUE (3.83 and 6.15 kg ha^{-1} mm^{-1}) at Samanko, while the Soubatimi variety produced the highest biomass (6171 and 7085 kg ha^{-1}) at N'Tarla. For the study's agroecological zones, Pablo and Soubatimi for SWD1, and Jakunbe for SWD2, all with the organo-mineral fertilization were recommended.

Key words: Sowing dates, fertilization types, sorghum varieties, grain yield, WUE.

INTRODUCTION

Sorghum (*Sorghum bicolor* (L.) Moench) occupies a major niche in many semi-arid subtropical farming systems due to its low cost of production and better response to favorable conditions with high grain yield (Bughdady, 2016). It has the advantage of performing relatively well under stress conditions such as drought and floods (Anil Kumar et al., 2018; Isaacs et al., 2023). Sorghum is one of the most important food crops highly produced and consumed in Mali by more than half of the population, particularly in rural areas and low-income households in urban areas (ZEF et al., 2017). Besides its use as a staple food, sorghum remains also one of the ready sources of income for most of the country's predominantly rural population, as part of their production is traded for financial needs (Smale et al., 2016). National sorghum production for the year 2018 was estimated at 1 4 23 358 tons on an area of 1 5 85 986 ha with an average yield of 0.897 t ha^{-1} (Annuaire Statistique, 2019; Diarisso et al., 2023). As a subsistence crop, sorghum is generally grown in the country's Sahelian zone as well as in its Savannah zone (between 500-1200 mm rainfall isohyets), under farming systems with low productivity less than 1 t ha^{-1} (Weltzien et al., 2018). Among constraints hampering national sorghum production, unsustainable management practices related to soil fertility (characterized by the depletion of major soil nutrients), issues of sowing dates due to climate variability (poor rainfalls with its inadequate distribution, difficulty on rainy season onset and dry spells occurrences), and low adoption rate of improved sorghum cultivars remain the most important ones (Badolo et al., 2022; Isaacs et al., 2024).

In West and Central Africa (WCA), it was generally noted that soils are high weathered with low organic matter content and deficient in nutrients (Breman, 1998; Weltzien et al., 2018; Vanlauwe et al., 2023). These soils continue to be degraded by continuously losing their nitrogen and phosphorus contents under farmers' current cereals production systems. Nitrogen is the most important nutrient for crops, having a dynamic impact on all growth, yield, and grain-quality-determining processes (Dabre et al., 2024). Thus, increase nitrogen use efficiency (NUE) in sorghum would provide opportunities to achieve higher yields and better grain quality (Ostmeyer et al., 2022). Moreover, Leiser et al. (2012) through multi-years and multi-locations trials on P-fertilization in Mali, showed that low soil-P results in more than 50% grain yield losses. Findings of Diancoumba et al. (2021) in Mali emphasized that fertilizers' application can significantly improve sorghum grain yields. Numerous studies have shown the benefits effects of organo-mineral fertilization on sorghum biomass and grain yields as well as yield components and on the improvement of soil water-holding capacity (Mwadalu et al., 2022; Togo et al., 2023; Akinseye et al., 2023). Consequently, combined application of organic and inorganic resources is crucial for sustainable crop production intensification in smallholder farming systems given its positive and synergic interactions (Vanlauwe et al., 2011). In addition to soil fertility issues, high spatial and temporal variability of rainfall across the Sahel influences the rainy season planting period (Hulme et al., 2001; Marteau et al., 2011; Haussmann et al., 2012). In most areas of West Africa, the delay in the rainy season onset has been consistently observed (Graef and Haigis, 2001; Tofa et al., 2020). There is still no consensus answer in the literature about the question of how much rain and over which period defines the onset of the rainy season (Akinseye et al., 2016). Studies showed that planting too early might lead to crop failure, and in turn, planting too late might reduce valuable growing time and crop yields (Traore et al., 2014; Buriro et al., 2015; Dieng et al., 2018; Kumi et al., 2023). Saini et al. (2018) found that sowing in rainfall season onset increase the sorghum grain and biomass yields. Moreover, sowing date has been also observed to indirectly affect grain quality in maize and sorghum (Koca and Canavar, 2014; Mohmed et al., 2015). Kok et al. (2017) noted that early sowing gave better sorghum grain quality than late sowing. Seeds are at the core of food production (Munyi, 2022). In Mali, most of the farmers are still relying on their local varieties which have been exhausted through generations of cultivation (Sissoko et al., 2019). In recent years, ICRISAT and its partners (National Research Institutes) on their breeding programs have released good sorghum materials in terms of open pollinated varieties (OPV) and hybrid sorghums (Smale et al., 2016; Diancoumba et al., 2024) but the rate of adoption these technologies is still low at about 30% (Kelly et al., 2015; Isaacs et al., 2023).

The various challenges that sorghum cultivation faces in Mali, require continuous assessment and adoption of effective management practices. This includes evaluating the impact of improved crop technologies under different conditions such as sowing dates and fertilization through field trials conducted over multiple seasons and locations. In addition, smallholder farmers face financial constraints that limit their capacity to invest in inputs for crops like sorghum and millet. Therefore, it is crucial to explore cost-effective management practices, such as using half doses of organo-mineral fertilization rates. Our study aims to investigate the effects of different fertilizer types and sowing dates (intermediate and late) on the biomass and grain yields, as well as on the water use efficiency (WUE), of three improved sorghum varieties.

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Table 1. Characteristics of cultivars used.

Genotypes	Type	Origin	Cycle	Grain yield (t ha^{-1})	Photoperiod sensitivity
Soubatimi	A short stalk, medium maturity, dual purpose improved variety	Mali (ICRISAT-IER)	100-110	3.5	Slightly photoperiod sensitive
Jakunbe	A tall stalk, early maturity, local-improved variety	Mali (IER)	90-100	2	Slightly photoperiod sensitive
Pablo	A tall stalk, dual-purpose hybrid sorghum	Mali (ICRISAT-IER)	110-120	5	Photoperiod sensitive

Table 2. Different sowing dates for the on-station sites during the 2 cropping years.

Locations	Year 2021		Year 2022	
	SWD1	SWD2	SWD1	SWD2
Samanko	06/21/2021	07/11/2021	06/29/2022	07/20/2022
N'Tarla	06/28/2021	07/18/2021	07/02/2022	07/23/2022

SWD1, sowing date 1; and SWD2, sowing date 2.

MATERIALS AND METHODS

Description of the study locations

The experiments were conducted during the 2021 and 2022 cropping seasons, in two locations, in the Sudanian agroecological zone of Mali. The first location was the ICRISAT research station of Samanko (12°53'N; -8°07'W and 330 m above sea level) considered as the Southern part of the Sudanian zone. The second location was the IER research station of N'Tarla (12°61'N; -5°68'W and 319 m above sea level) representing the Northern part of the Sudanian zone. At Samanko, the rainfall is unimodal between 900 to 1200 mm per annum and the soil is comprised of typical soil of South-Sudanian, a Ferric lixisol clay loam dominated by sandy-clay soil with a pH of 5.6 with low fertility and deficient in organic matter (Kaya et al., 2007). At N'Tarla, the climate is characterized by a high inter-annual variability with an average rainfall of 846 ± 163 mm and the rainy season extends from June to October with a rainfall peak in August (Traore et al., 2013). The largest share of the cultivated land is allocated to cereal production. Soils are mainly Ferric Lixisols with low clay content (<10%) in the topsoil and they are in general moderately acidic with a pH of around 6 (Traore et al., 2015).

Vegetal materials

Three improved sorghum cultivars were used for this study and their characteristics described in Table 1.

Experimental design and crop management

In each location the trial was laid out in a randomized split-split-plot design of 24 treatments in 3 replications for a total of 72 treatments per site. The basic plot area was 30 m^2 (6 m length×5 m width) for each treatment, containing eight ridges along 6 m length with 0.75 m in-between. Fertilizer types were assigned to the main plots, sowing dates to the sub-plots, and varieties to the sub-sub-plots. The fertilization types were comprised of four levels, the control F_1 (zero fertilizer), the sole inorganic option F_2 (100 kg ha^{-1} of DAP + 50 kg ha^{-1} of Urea), the sole organic option F_3 (5 t ha^{-1} of cow dung) and the combined option F_4 (50 kg ha^{-1} of DAP + 25 kg ha^{-1} of Urea + 2.5 t ha^{-1} of cow dung); two sowing dates (SWD1, first sowing date at intermediate sowing time and SWD2, second sowing date at late sowing time). A period of three (3) weeks interval was observed between the first and the second sowings (Table 2). Before sowings, trials' plots were plowed with a tractor to approximately 30 cm depth. Sowing (Table 2) was done at a spacing of 0.75 m between rows and 0.30 m between the hills within the row resulting in a plant density of 4.44 plants m^{-2} or 44,444 hills ha^{-1}. Weeding was done manually three times during the season on each plot using a hand hoe. Two weeks after sowing, thinning was carried out to one plant per hill. Cow dung was applied 2 days before sowing. Concerning DAP and Urea fertilizers, they were applied after weeding around 17 and 40 days after sowing to avoid competition between plants and weeds. All plots were treated with EMACOT 050 WG insecticide (Emamectine benzoate 50 g kg^{-1}) to control legionary caterpillar (*Spodoptera exempta*) attacks. During the 2 cropping seasons, harvest activities were progressively done between mid-October and mid-December.

Data collection

Soil data

Prior to the 2021 cropping season sowings, composite soil samples of each of the two topsoil layers (0-20 and 20-40 cm) were taken from different points of the two experimental fields to determine the soil physical and chemical characteristics. Particle size distribution was determined using the pipette method (Gee and Or, 2002). Soil pH in water was measured potentiometrically in a 1:2.5 soil: distilled water suspension using a glass electrode pH meter (van Reeuwijk, 1993). Total soil organic carbon was measured using a modified Walkley and Black chromic acid wet chemical oxidation and spectrophotometric method (Heanes, 1984). Total nitrogen (total N) was determined using a micro-Kjeldahl digestion method (Houba et al., 1995) and available phosphorus was extracted using the Bray 1 method (Reeuwijk, 1993). Monovalent silver thiourea complex cation

(AgTU) method was used to determine cation exchange capacity (CEC) and exchangeable bases. Ammonium (NH_4^+) and nitrate (NO_3^-) were determined by an automated spectrophotometric method, utilizing the Berthelot reaction (Mehlich, 1984). In addition to the soil samplings, cow dung used as organic manure during the 2 cropping seasons (2021 and 2022) was also sampled to determine its organic carbon, nitrogen, and total phosphorus contents.

Climatic data

Daily rainfall and minimum and maximum air temperature data for the 2 cropping seasons (2021 and 2022) were collected from an agro-meteorological station of experimental sites. Data for daily solar radiation were sourced from the National Aeronautics and Space Administration (NASA) database of Climatology Resource for Agroclimatology at the website http://power.larc.nasa.gov/cgibin/giwrap/solar/agro.cgi?email=agroclim@larc.nasa.gov. These climatic data were used to assess the climate variability across the agroecological zones as well as the crop evapotranspiration or crop water use (ETc), and the crop water use efficiency (WUE) estimation. Furthermore, historical data of 31 years (1990–2020) of the two experiment locations were collected from the two research institutes (ICRISAT and IER) databases.

Agronomic data

A quadrat of 1.80 m^2 delimited in each elementary plot was used for biomass and grain yield evaluation at maturity. After harvesting panicle and straw and sun drying them for one month, biomass yield was determined per m^2 and extrapolate to the hectare. The sun-dried panicles were threshed, and the total grain weight was recorded to evaluate the plot grain yield in kg ha^{-1}. For crop water use efficiency (WUE), the FAO ETo Calculator software (version 3.2), a crop model, was used to compute the daily reference evapotranspiration (ETo [mm day^{-1}]) based on the Penman-Monteith method (Allen et al., 1998; Raes, 2012). The model was provided with the climatic data (solar radiation, minimum and maximum temperatures) from the two experimental sites for the years 2021 and 2022. The model was then run to generate the daily ETo values for both years, which were exported into Excel. Subsequently, the cumulative reference evapotranspiration (ETo) values for the growing season (the period from sowing to the last harvest date) were calculated. Given that there were two sowing dates (SWD1 and SWD2) per year and per site, the cumulative ETo values for the corresponding growing seasons were computed. The exercise was done for the 8 sowing dates which constitute the two years experiment in the two sites. The next stage was to match each treatment in the different experiments with its cumulative reference evapotranspiration (Eto) value at harvest date. After, the cumulative reference Eto was used in Equation 1 to determine the crop evapotranspiration or the crop water use for each treatment. The formula of Allen et al. (1998) was described as follows:

$$ETc = Eto*Kc \quad (1)$$

where ETc = crop evapotranspiration or crop water use in (mm), ETo = reference evapotranspiration in (mm), and Kc = crop coefficient for sorghum, which was 0.71 as specified in the FAO-56 manual (Allen et al., 1998). Subsequently, crop water use efficiency (WUE) was calculated using the following formula (Equation 2):

$$WUE = \text{Crop grain yield} / ETc \quad (2)$$

Data analysis

Data were subjected to analysis of variance (ANOVA) using a split-plot design with the GENSTAT analytical tool (19th edition). Fisher's least significant differences (LSD) test at the 5% level was applied to compare the means of the tested treatments (Gomez and Gomez, 1984). Instat+ software, version 3.36, and Excel were used to analyze the data and create figures of weather parameter patterns for both locations.

RESULTS

Experiment sites soil characterization

The soil of the experimental sites was initially characterized to assess its fertility status before the establishment of the trials. Laboratory analysis results indicated that the topsoil layers (0-20 cm and 20-40 cm) at both Samanko and N'Tarla were sandy loam soils (Table 3). The soil pH was moderately acidic (4.57 and 4.72) at both experimental sites. The soil organic carbon content (% OC) ranged between 0.28 - 0.29% at Samanko and 0.30 - 0.34% at N'Tarla, indicating low organic carbon levels at both sites. The total nitrogen content (%N) was extremely low at Samanko (0.021 - 0.024%) and low at N'Tarla (0.5 - 0.5%). The available phosphorus values were very low at both locations, with Samanko ranging from 1.88 - 1.05 mg kg-1 and N'Tarla from 2.82 - 1.32 mg kg-1. Similar low levels of soil content in CEC, NH4+, and NO3- were observed at both sites. The cow dung manure used in the 2021 cropping season contained 31.2% C, 0.8% N, and 0.67% P, while in the 2022 season, these values were 28.7% C, 0.7% N, and 0.64% P (Table 4).

Rainfall and temperature patterns during the experiments

Figures 1 and 2 display the monthly rainfall distribution and the monthly mean air temperatures (minimum and maximum) recorded at the two experimental sites (Samanko and N'Tarla) during the 2021 and 2022 cropping seasons, as well as the long-term averages for the period from 1990 to 2020. The total annual rainfall at Samanko, in the Southern Sudanian agroecological zone, was 1097 mm in 2021 and 1117 mm in 2022. At N'Tarla, in the Northern Sudanian agroecological zone, rainfall for the 2021 and 2022 cropping seasons were 979 and 1176 mm, respectively. The rainfall recorded during both cropping seasons at the two experimental sites (Samanko and N'Tarla) exceeded their long-term average rainfall (1990-2020), which was 959 mm yr-1 at Samanko and 893 mm yr^{-1} at N'Tarla (Figures 1 and 2). This indicates that both cropping seasons were wetter than average, even though the 2021 cropping season received less rainfall than the 2022 season at both sites. Results also indicated that N'Tarla received less rainfall than Samanko in the 2021 season, while the situation reversed in the 2022 growing season.

Regarding intra-seasonal rainfall variability, results showed high variability between months in both locations

Table 3. Experimental site soil initial conditions during the 2021 cropping season.

Soil layers / Soil properties	Agroecological zone			
	Samanko		N'Tarla	
	0-20 cm	20-40 cm	0-20 cm	20-40 cm
Chemical properties				
pH-water (1:2.5)	4.57	4.75	4.72	4.91
Total Organic carbon (%)	0.28	0.29	0.3	0.34
Total Nitrogen (%)	0.02	0.02	0.05	0.05
Phosphore-Bray1 (mg/kg)	1.88	1.05	2.82	1.32
CEC-Agtu ($cmol^+$/kg)	0.64	1.84	1.76	3.15
Ammonium ($NH_4^{+-}N$) (mg/kg)	10.24	11.99	12.49	8.81
Nitrate (NO^{3-}) (mg/kg)	26.69	4.73	10.14	5.74
Physical characteristics				
% Sand (2000-50µm)	69.46	53.91	83.63	76.02
% Silt (50-2µm)	11.13	27.49	13.29	11.01
% Clay (< 2µm)	19.41	18.6	3.08	12.97
Textural class	Sandy loam		Sandy loam	

Table 4. Chemical composition of cow dung used as organic manure during the two cropping seasons.

Variable	2021 cropping season	2022 cropping season
Organic carbon (%)	31.23	28.68
Nitrogen (%)	0.84	0.66
Total Phosphorus (%)	0.67	0.64

over the two years. At Samanko, the wettest months were August (358 mm) in 2021 and July (354 mm) in 2022. At N'Tarla, the highest rainfall occurred in June (228 mm) in 2021, while in 2022, the wettest month was September, with 314 mm. Additionally, a flooding event was observed at Samanko in early August during the 2021 cropping season, and light dry spells were noted at both sites during the sorghum reproductive stage and grain filling period.

During the growing seasons (from June to October), the mean monthly temperatures (minimum and maximum) ranged from 23.12 to 36.35°C at Samanko, while at N'Tarla, they ranged from 20.67 to 35.99°C. When compared to the long-term averages for both sites, temperatures at Samanko showed an increasing trend (22.72 and 35.32°C), while at N'Tarla, the comparison did not reveal any significant temperature trend (22.32 and 35.67°C).

Effects of fertilizer types, sowing dates, and variety on improved sorghum cultivars biomass and grain yields at Samanko and N'Tarla

Biomass yield

At Samanko, a significant difference was observed among sowing dates and varieties at the 1% significance level, and among fertilizer types at the 5% significance level. Interaction analyses revealed a significant difference between sowing dates and fertilizer types (SWD*FRT) and between sowing dates and variety (SWD*VTY) at the 5% probability level (Table 5). The results for sowing dates showed that, whether in the 2021 cropping season (SWD1: 4091 kg ha^{-1} and SWD2: 2484 kg ha^{-1}) or in the 2022 cropping season (SWD1: 5372 kg ha^{-1} and SWD2: 4179 kg ha^{-1}), biomass yields from the first sowing date (SWD1) were higher than those from the second sowing date (SWD2). In the 2021 cropping season, biomass yield in SWD1 was 65% greater than in SWD2. Similarly, in the 2022 cropping season, the biomass yield from SWD1 was 29% greater than that from SWD2 (Table 5).

For fertilization, biomass yields from all fertilized treatments (F2: inorganic fertilizer, F3: organic fertilizer, and F4: organo-mineral fertilization) were higher than those from the control treatment (F1: unfertilized) in both cropping seasons. In the 2021 cropping season, biomass yields for F4 (4097 kg ha^{-1}), F2 (3996 kg ha^{-1}), and F3 (3152 kg ha^{-1}) were 115, 110, and 66% greater, respectively, than the control treatment (F1: 1904 kg ha^{-1}). In the 2022 season, treatments F4 (5668 kg ha^{-1}), F3 (5268 kg ha^{-1}), and F2 (5176 kg ha^{-1}) recorded biomass yields that were 90, 76,

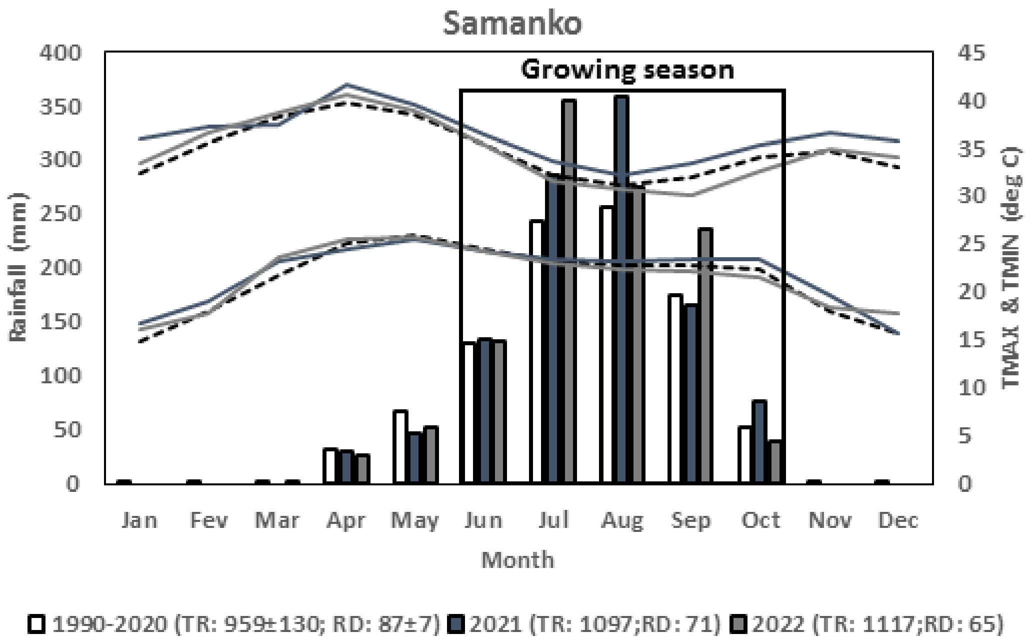

Figure 1. Comparison between long-term (1990–2020) monthly rainfall, mean temperature (minimum and maximum) with those of the 2021 and 2022 cropping seasons at Samanko experiment site.

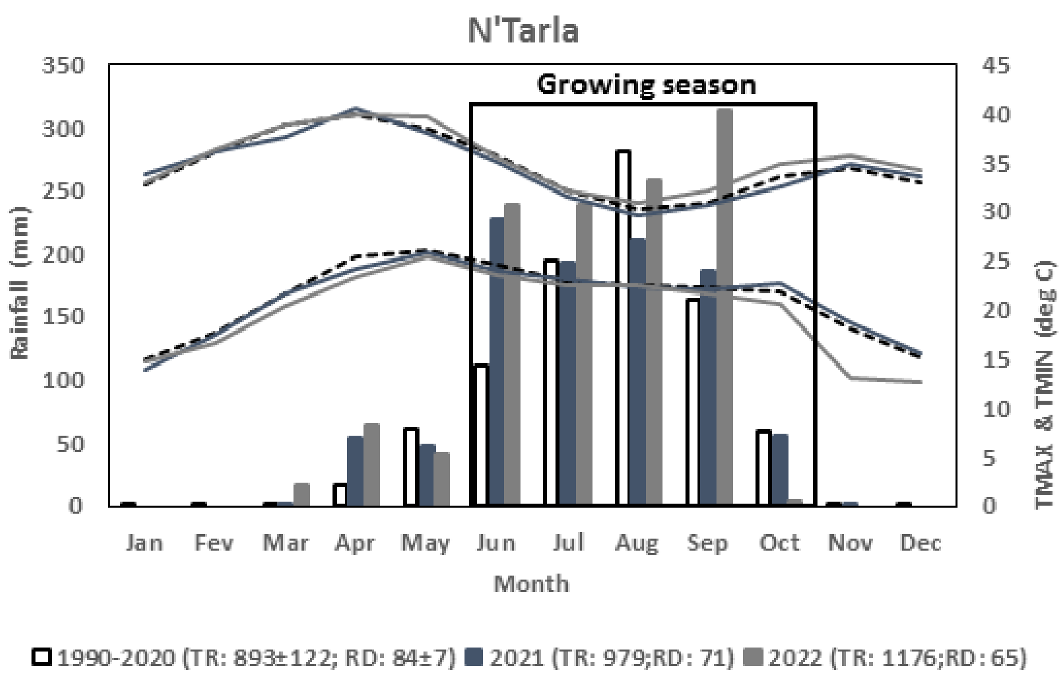

Figure 2. Comparison between long-term (1990–2020) monthly rainfall, mean air temperature (minimum and maximum) with those of the 2021 and 2022 cropping seasons at N'Tarla experiment site.

and 73% greater, respectively, than the biomass yield of F1 (2991 kg ha^{-1}) (Table 5).

Comparisons between varieties in both cropping seasons showed that Pablo produced the highest biomass yield compared to Jakunbe, the lowest biomass variety. In the 2021 cropping season, Pablo (4083 kg ha^{-1}) had a biomass

Table 5. Fertilizer types, sowing dates and variety effects on biomass and grain yields at Samanko and N'Tarla in 2021 and 2022 cropping seasons.

Sources of variation	Samanko				N'Tarla			
	Biomass yield (kg ha^{-1})		Grain yield (kg ha^{-1})		Biomass yield (kg ha^{-1})		Grain yield (kg ha^{-1})	
	2021	2022	2021	2022	2021	2022	2021	2022
Sowing dates (SWD)								
SWD1	4091	5372	1485	2065	6105	5668	2305	2285
SWD2	2484	4179	1362	1384	4257	4256	1696	2081
Pr (>F)	<.001		0.003		NS		NS	
LSD	642.3		325.1		867.2		330.1	
Fertilizer types (FRT)								
F1	1904	2991	661	1061	4236	4297	1624	1858
F2	3996	5176	1685	1797	5513	4690	2180	2156
F3	3152	5268	1366	2023	5267	5418	2127	2421
F4	4097	5668	1779	2219	5709	5442	2072	2298
Pr (>F)	0.010		0.032		NS		NS	
LSD	658.6		334.5		1529.3		368.9	
Varieties (VTY)								
Jakunbe	2618	2787	960	990	2542	3002	726	983
Pablo	4083	6795	1765	2740	4798	6830	2724	2632
Soubatimi	3162	4745	1363	1625	6171	7085	2552	2935
Pr (>F)	<.001		<.001		<.001		NS	
LSD	552.2		328.2		851.8		338.4	
Interactions								
SWD*FRT	0.025		NS		NS		NS	
SWD*VTY	0.029		NS		NS		0.022	
FRT*VTY	NS		NS		NS		NS	
SWD*FRT*VTY	NS		NS		NS		NS	

SWD1 and SWD2: sowing dates 1 and 2; F1: zero fertilizer (control); F2: pure mineral fertilizers made of DAP at 100 kg ha^{-1} + Urea at 50 kg ha^{-1}; F3: pure organic fertilizer made of cow dung at 5000 kg ha^{-1}; F4: organo-mineral fertilizers made of half doses of F2 and F3 [DAP at 50 kg ha^{-1} + Urea at 25 kg ha^{-1} + cow dung at 2500 kg ha^{-1}]; Pr (>F): probability value (p-value) of the F statistic; L.S.D.: Least significant difference of means (5% level); NS: no significant difference.

yield that was 29 and 56% greater than those of Soubatimi (3162 kg ha^{-1}) and Jakunbe (2618 kg ha^{-1}), respectively. In the 2022 cropping season, Pablo (6795 kg ha^{-1}) had a biomass yield that was 43 and 144% greater than those of Soubatimi (4745 kg ha^{-1}) and Jakunbe (2787 kg ha^{-1}), respectively (Table 5).

At N'Tarla, biomass yields during the two growing seasons showed a significant difference among varieties at the 1% level. Interaction analyses revealed a significant difference only for the interaction SWD*FRT*VTY. Results indicated that each of the three varieties produced higher biomass yields in the 2022 cropping season compared to the 2021 season. In the 2021 cropping season, Soubatimi produced the highest biomass yield (6171 kg ha^{-1}), while Jakunbe had the lowest biomass yield (2542 kg ha^{-1}). Soubatimi's biomass yield was 29 and 143% greater than those of Pablo and Jakunbe, respectively. In the 2022 cropping season, Soubatimi again produced the highest biomass yield (7085 kg ha^{-1}), compared to Jakunbe, the lowest biomass variety (3002 kg ha^{-1}). Soubatimi's biomass yield was 4 and 136% greater than those of Pablo and Jakunbe, respectively (Table 5).

Grain yield

At Samanko, grain yields between the two cropping seasons showed a significant difference among sowing dates and fertilizer types at a 5% probability level, and among varieties at a 1% probability level. Results for sowing dates indicated that, whether for the 2021 cropping season (SDW1: 1485 kg ha^{-1} and SDW2: 1362 kg ha^{-1}) or the 2022 cropping season (SDW1: 2065 kg ha^{-1} and SDW2: 1384 kg ha^{-1}), grain yields for SDW1 were greater than those for SDW2. In the 2021 cropping season, the grain yield for SDW1 was 9% greater than that of SDW2. In the 2022 cropping season, the grain

Table 6. Fertilizer types, sowing dates, and variety effects on grain water use efficiency at Samanko and N'Tarla in 2021 and 2022 cropping seasons.

Sources of variation	Samanko WUE-Grain yield (kg ha^{-1} mm^{-1})		N'Tarla WUE-Grain yield (kg ha^{-1} mm^{-1})	
	2021	2022	2021	2022
Sowing dates (SWD)				
SWD1	3.07	4.67	5.17	5.34
SWD2	2.97	3.69	4.26	5.41
Pr (>F)	0.042		NS	
LSD	0.754		0.795	
Fertilizer types (FRT)				
F1	1.39	2.30	3.67	4.43
F2	3.72	4.20	5.10	5.26
F3	3.01	4.88	5.06	6.10
F4	3.96	5.32	5.04	5.73
Pr (>F)	0.021		NS	
LSD	0.797		0.928	
Varieties (VTY)				
Jakunbe	2.41	2.68	1.95	2.72
Pablo	3.83	6.15	6.45	6.33
Soubatimi	3.69	3.83	5.75	7.09
Pr (>F)	<.001		NS	
LSD	0.771		0.843	
Interactions				
SWD*FRT	NS		NS	
SWD*VTY	NS		0.019	
FRT*VTY	NS		NS	
SWD*FRT*VTY	NS		NS	

ETc- Crop: Crop evapotranspiration; WUE-Grain yield: crop water use efficiency to produce grain yield. SWD1 and SWD2: sowing dates 1 and 2 with 21 days in-between; F1: zero fertilizer (control); F2: pure mineral fertilizers made of DAP at 100 kg ha^{-1} + Urea at 50 kg ha^{-1}; F3: pure organic fertilizer made of cow dung at 5000 kg ha^{-1}; F4: organo-mineral fertilizers made of half doses of F2 and F3 [DAP at 50 kg ha^{-1} + Urea at 25 kg ha^{-1} + cow dung at 2500 kg ha^{-1}]; Pr (>F): probability value (p-value) of the F statistic; L.S.D.: Least significant difference of means (5% level); NS: no significant difference.

yield for SDW1 was 29% greater than that of SDW2 (Table 5). A comparison between fertilizer types showed that, whether in the 2021 or 2022 season, the grain yields of all the fertilized treatments (F2, F3, and F4) were greater than those of the unfertilized treatment (F1 control plots). In the 2021 season, F4, with the highest yield (1779 kg ha^{-1}), was 169% greater than F1 (661 kg ha^{-1}). This was followed by the yields of F2 (1685 kg ha^{-1}) and F3 (1366 kg ha^{-1}), which were 155 and 107% greater than F1, respectively. In the 2022 season, the yield for F4 (2219 kg ha-1) was again the highest, 109% greater than that of F1 (1061 kg ha^{-1}). It was followed by F3 (2023 kg ha^{-1}) and F2 (1797 kg ha^{-1}), which were 91 and 69% greater than F1, respectively. For varieties, during both cropping seasons, Pablo produced the highest grain yield, while Jakunbe produced the lowest. In the 2021 cropping season, the yields were as follows: Pablo (1765 kg ha^{-1}), Soubatimi (1363 kg ha^{-1}), and Jakunbe (960 kg ha^{-1}). In the 2022 cropping season, the results were: Pablo (2740 kg ha^{-1}), Soubatimi (1625 kg ha^{-1}), and Jakunbe (990 kg ha^{-1}). At N'Tarla, no significant difference was observed among sowing dates, fertilizer types, and varieties in terms of grain yield (Table 5).

Effects of fertilizer types, sowing dates and varieties on water use efficiency of grain yield (WUE) at Samanko and N'Tarla

At Samanko, the analysis of variance showed significant effects of sowing dates and fertilizer types at a p-value of 0.05, and of varieties at a p-value of 0.0001, on crop water use efficiency (WUE). No significant interactions were observed at the 5% threshold (Table 6). Regarding sowing dates, whether for the 2021 cropping season (SWD1: 3.07

kg ha^{-1} mm^{-1} and SDW2: 2.97 kg ha^{-1} mm^{-1}) or the 2022 cropping season (SWD1: 4.67 kg ha^{-1} mm^{-1} and SDW2: 3.69 kg ha^{-1} mm^{-1}), results indicated that the WUE for SWD1 was higher than that of SWD2. For fertilization, whether in the 2021 or the 2022 season, crop WUE for all fertilized treatments (F2, F3, and F4) was greater than that of the control treatment F1. In the 2021 season, fertilizer type F4 recorded the highest WUE (3.96 kg ha^{-1} mm^{-1}), followed by fertilizer type F2 (3.72 kg ha^{-1} mm^{-1}) and fertilizer type F3 (3.01 kg ha^{-1} mm^{-1}). In the 2022 cropping season, F4 again had the highest WUE (5.32 kg ha-1 mm-1), followed by F3 (4.88 kg ha^{-1} mm^{-1}) and F2 (4.20 kg ha^{-1} mm^{-1}) (Table 6). Regarding varieties, in both cropping seasons, Pablo was the variety that efficiently used water to produce the highest grain yield (3.83 kg ha^{-1} mm^{-1} in 2021 and 6.15 kg ha^{-1} mm^{-1} in 2022), while Jakunbe had the lowest WUE (2.41 kg ha^{-1} mm^{-1} in 2021 and 2.68 kg ha^{-1} mm^{-1} in 2022) (Table 6). At N'Tarla, no significant difference was observed among sowing dates, fertilizer types, and varieties in terms of crop water use efficiency (Table 6).

DISCUSSION

Soil characterization

The pH water at Samanko and N'Tarla varied from 4.57 and 4.72, respectively. According to FAO (2000), the preferable pH ranges for most crops and productive soils have to be between 4 and 8. The organic carbon content was 0.28 at Samanko and 0.3 at N'Tarla (Table 3). According to Pieri (1989), the critical values of the organic carbon content are considered as low when they are below 0.6%. Moreover, total nitrogen content (%N) was very low (0.02%) at Samanko and low (0.5%) at N'Tarla according to the classification of Tekalign (1991) which has classified soil total N content of <0.05% as very low, 0.05-0.12% as poor, 0.12-0.25% as moderate and >0.25% as high. This deficiency may decrease the crop performance during the growth and development stages. In the two sites, available soil P contents varying from 1.05 to 2.82 mg kg^{-1} were well below the critical level of 8 mg kg^{-1} established for millet-sorghum crops in the Sahel (Bationo et al., 1989).

Rainfall and temperatures patterns during the experiments

The rainfall pattern analysis showed both inter- and intra-seasonal rainfall variability during the two cropping seasons at Samanko (Figure 1) and N'Tarla (Figure 2). This climatic situation in the two agroecological zones aligns with Nicholson's (2013) analysis of the Sahel rainfall pattern, in which he described how rainfall variability increases as one moves from south to north. Compared to the long-term 1990–2020 rainfall average (959 mm yr^{-1} and 893 mm yr^{-1}), the rainfall amounts and their distribution during the experimental years were favorable at both locations. The good rainfall recorded at both sites over the two years supports the findings of Traore et al. (2013) and Zagre et al. (2024), who noted a slight increase in precipitation over the past thirty years. Once again, this highlights that the main challenge in the Sahelian zone is not always the total amount of rainfall during the season, but rather the significant spatiotemporal variability that is observed.

Agronomic parameters' responses to different management practices

Biomass yield

At Samanko, during both cropping seasons, the highest biomass yields were observed at the first sowing date (4091 kg ha^{-1} in 2021 and 5372 kg ha^{-1} in 2022 for SWD1) compared to the second sowing date (2484 kg ha^{-1} in 2021 and 4179 kg ha^{-1} in 2022 for SWD2). This difference may be due to the photosensitivity of the tested varieties (Table 5). Generally, early sowing allows for more stover buildup. Research by Saini et al. (2018) on sorghum reported similar results. Additionally, according to Nwajei (2023), early sowing extends the growth period, resulting in greater dry matter accumulation in millet. In contrast, delayed sowing leads to reduced dry matter accumulation.

At Samanko, during both cropping seasons, the F4 treatment (50 kg ha^{-1} of DAP + 25 kg ha^{-1} of urea + 2500 kg ha^{-1} of cow dung) recorded the highest biomass yield (4097 kg ha-1) compared to the F1 treatment (no fertilizer), which produced the lowest biomass yield (1904 kg ha-1) (Table 5). Our results are consistent with those of Bayu et al. (2006), who observed that applying 5 t FYM ha^{-1} in combination with 50% of the recommended inorganic fertilizer rate resulted in a sorghum stover yield comparable to that obtained from applying 100% of the recommended inorganic fertilizer rate.

At Samanko, during both cropping seasons, the Pablo variety recorded the highest biomass yield (4083 kg ha^{-1} in 2021 and 6795 kg ha^{-1} in 2022) (Table 5). However, at N'Tarla, during both cropping seasons, the highest biomass yield was produced by the Soubatimi variety (6171 kg ha^{-1} in 2021 and 7085 kg ha^{-1} in 2022). This difference may be attributed to the genetic characteristics of the varieties, as well as the soil fertility differences between the two sites. Naoura et al. (2023) and Dembele et al. (2021) demonstrated that genetic traits, soil conditions, temperature, and rainfall are key factors influencing dry matter accumulation in cereal crops.

Grain yield

At Samanko, the results showed that grain yields were higher for SWD1 than for SWD2 during the 2021 and 2022 cropping seasons (Table 5). This difference may be explained by the higher accumulation of photosynthates observed in SWD1 plants, due to the photosensitivity of the varieties. Early sowing extends the plant's growth cycle, allowing varieties to engage in more photosynthetic activity and accumulate more dry matter, which promotes better grain filling compared to delayed sowing. These findings are consistent with those of Ekeleme et al. (2011) and Wang et al. (2019), who reported that grain yield in sorghum is significantly reduced with delayed sowing.

At Samanko, during both years of experimentation, the F4 treatment recorded the highest grain yield compared to the F1 treatment (Table 5). These results align with Togo et al. (2023), who highlighted the importance of organo-mineral fertilization in improving sorghum grain yield and its components. They also noted that the application of organic matter enhances soil structure and fertility. Akinseye et al. (2023) similarly demonstrated the essential role of organo-mineral fertilization management strategies in sorghum cultivation in Mali.

During both cropping seasons at Samanko, the hybrid variety Pablo achieved the highest grain yield (1765 kg ha^{-1} in 2021 and 2740 kg ha^{-1} in 2022), while Jakunbe recorded the lowest yields (960 kg ha^{-1} in 2021 and 990 kg ha^{-1} in 2022) (Table 5). This difference can be attributed to the genetic performance of the varieties, along with their efficient response to agronomic practices. These results are consistent with those of Dembele et al. (2020), who reported that hybrid varieties perform well under Mali's growing conditions in terms of both grain and straw yields.

Water use efficiency of grain yield (WUE)

The results obtained at Samanko showed that WUE in SWD1 (3.07 and 4.67 kg ha^{-1} mm^{-1} for the 2021 and 2022 seasons, respectively) was higher than in SWD2 (2.97 and 3.69 kg ha^{-1} mm-1 for the 2021 and 2022 seasons, respectively) (Table 6). These results are consistent with those of Hadebe et al. (2017), who found that biomass and grain yield water use efficiency (WUE) were higher with early planting dates compared to late planting dates.

Among the fertilization treatments at Samanko, the organo-mineral fertilization strategy (F4) recorded the highest WUE (3.96 and 5.32 kg ha^{-1} mm^{-1} for 2021 and 2022, respectively) compared to the control treatment (F1), which had the lowest WUE (1.39 and 2.30 kg ha^{-1} mm^{-1} for 2021 and 2022, respectively) (Table 6). This increase in WUE may be due to improved nitrogen uptake from both inorganic and organic sources in the F4 fertilizer, coupled with an enhancement in the soil's water balance. Similar results were reported by Singh et al. (2023), who found that water use efficiency improved with better soil management practices.

At Samanko, during both cropping seasons, the hybrid variety Pablo produced the highest WUE (3.83 and 6.15 kg ha^{-1} mm^{-1} in the 2021 and 2022 seasons, respectively). It was followed by Soubatimi (3.69 and 3.83 kg ha^{-1} mm^{-1} for 2021 and 2022, respectively), and Jakunbe (2.41 and 2.68 kg ha^{-1} mm^{-1} for 2021 and 2022, respectively) (Table 6). These differences may be attributed to the heterosis effect in Pablo, which enables it to produce more grain per unit of water. Our results are in agreement with those of Ajeigbe et al. (2018), who recorded higher WUE with the hybrid sorghum variety (ICSV400).

Conclusion

The current study concluded that soil nitrogen and phosphorus contents were low at both Samanko and N'Tarla. Rainfall was variable during the growing seasons in both agroecological zones (Southern and Northern Sudanian zones), and these environmental factors had different effects on the growth and development of the tested varieties. The results also revealed that biomass and grain yields, as well as water use efficiency (WUE) of grain yield, were higher at the first sowing date (SWD1) at Samanko during both experimental years. The organo-mineral fertilization treatment (F4: 50 kg ha^{-1} DAP + 25 kg ha^{-1} urea + 2500 kg ha^{-1} cow dung) produced the best biomass and grain yields, as well as the highest WUE, during both cropping seasons at Samanko.

Among the varieties, (i) Pablo was the highest-yielding variety in biomass at Samanko, while Soubatimi was the highest-yielding at N'Tarla; (ii) Pablo also had the highest grain yield, followed by Soubatimi and Jakunbe, during both cropping seasons at Samanko; and (iii) Pablo had the best WUE for grain yield production.

As a recommendation for both agroecological zones, it is suggested to use Pablo and Soubatimi for SWD1, and Jakunbe for SWD2, all with the use of organo-mineral fertilization at half doses.

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CONFLICT OF INTERESTS

The authors have not declared any conflict of interests.

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