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***Research Article***

# Calibration and Evaluation of Ceres-Sorghum Model for Use in Sorghum (*Sorghum bicolor* L. Moench) Production in Sudan Savanna of Nigeria

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## ABSTRACT

A study was conducted at Bayero University Teaching and Research Farm (BUK), Kano, and the International Institute of Tropical Agriculture (IITA) Research Farm, Minjibir. The experiment employed a Randomized Complete Block Design (RCBD) with four replications, using eight sorghum varieties. Data from both locations were used to calibrate and evaluate the CERES-Sorghum model within the DSSAT framework. Calibrated genetic coefficients for all eight cultivars were incorporated into the DSSAT cultivar file. Model performance was assessed using model efficiency (EF), index of agreement (D-index), and root mean square error (RMSE). Calibration results showed strong agreement between observed and simulated values for days to flowering, physiological maturity, leaf number per plant, grain yield, and biomass (D-index: 0.97–0.95; EF: 0.87–0.80; RMSE: 125.68–1.37). Similar accuracy was observed during evaluation. CSR-01, SAMSORG-44, and 2192-2N had the highest panicle partitioning coefficients (G2), while SAMSORG-14, SAMSORG-17, and 12KN ICSV-188 recorded the lowest. CSR-02 and ICSV-400 had intermediate values. For the juvenile phase thermal time (P1), SAMSORG-14, 12KN ICSV-188, and CSR-02 had the highest values, while SAMSORG-17 and SAMSORG-44 had the lowest. ICSV-400 and CSR-01 were intermediate. Photoperiod sensitivity coefficients (P2R) ranged from 1 to 300 GDD, with SAMSORG-17 highest and ICSV-400 lowest. Overall, the model demonstrated satisfactory performance and proved reliable in simulating sorghum growth and yield across the Sudan Savanna agro-ecological zone of Nigeria.

**Keywords:** Calibration; CERES-Sorghum; Evaluation; Sorghum; Savanna

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## INTRODUCTION

Sorghum (*Sorghum bicolor L. Moench*), has long been, an important staple diet for millions of poor rural people in the semiarid tropics of Africa, Asia and Central America (Andrews, 1972; Ahmad *et al*., 2022, Chiambiro *et al*., 2022). Sorghum is the fifth most important grain crop grown in the world, accounting for about 5% of the total cereal production with a total of 65.5 million tons in 2016 (FAOSTAT, 2016). Sorghum, like millet, has its origin from Africa, where both wild and cultivated species originate. It was said to be first domesticated in Ethiopia, Eastern Chad and parts of the Congo between 500 and 700 B.C., (Bennett *et al*.,1990; Fuller and Stevens 2018). Soon after the initial domestication, Sorghum spread to West and East Africa (Romain, 2012).

In Nigeria, sorghum ranks third in importance among cereals, after maize and rice and accounts for 25% of total grain production, with more than 4.5 million tons harvested in 2010 (FAOSTAT, 2016; Ahmad *et al*., 2022). Sorghum is adapted to a broad range of environmental conditions but grows well in hot, arid or semiarid areas (USAID, 2015; Chiambiro *et al*., 2022). It is genetically suited to hot and dry agro-ecologies which are frequently drought-prone and characterized by erratic and scanty rainfall. In Nigeria, these area lies within the Northern Guinea and Sudan Savannah (Ogbonna, 2011). Sorghum can be grown successfully on wide range of soils. It tolerates a pH range of 5.5 to 8.5, and also some degree of alkalinity and poor drainage. It will grow on heavy, deep cracking vertisols and light sand (Hayward and Bernstein, 1958; Butchee *et al*., 2012). In the tropics, Sorghum tends to be grown on the heavier lands and pearl millet on the sand and light soils (Doggett, 1988).

Crop growth models are now increasingly becoming important in recent years as a key component of agriculture-related decision-support systems (Zhai *et al*., 2020; Jones *et al*., 2017; Jame and Cutforth, 1996; Stephens and Middleton, 2002). The models (simulation) have been developed as tools to support strategic decision-making in areas such as research, production, land use, and policy (Jones *et al*., 2017; Penning de Vries *et al*., 1993). The simulation models are also useful tools in evaluating the dangers or risks associated with climate variability in agricultural production; assessing regional yield potential under diverse environmental conditions, and determining optimal fertilizer applications, planting dates, and other management practices to enhance crop yield. Additionally, crop models serve as essential research tools for optimizing cultural practices, fertilizer use, and water management (Zhai *et al*., 2020; Egli and Bruening, 1992; Kaur and Handal, 2000).

Crop simulation models utilize in-built algorithms that express the relationship between plant growth processes (photosynthesis, transpiration, phenological developments, plant water uptake and biomass growth and partitioning) and environmental driving forces (e.g., soil water availability, daily temperature and photoperiod). Also peculiar to these models is the integration of factors that are cultivar-specific “genetic coefficients” to estimate daily growth and response of plants to environmental factors such as weather, soil and management practices (Boote *et al*., 1998). Current innovations couple with the use of decision support systems such as DSSAT (Decision Support Systems for Agro-technology Transfer) (Zhai *et al*., 2020; Jones *et al*., 2003), CROPGRO (Hoogenboom *et al*., 2012), APSIM (McCown *et al*., 1996) and DST LEGUMES (Breman *et al*. 1998) for simulation of crop performance have increasingly helped to boost crop production. Several different models are currently available for many crops that are adapted to the semi-arid tropics including Sorghum.

Sorghum production has been limited by a number of factors that have translated into low yields over decades, even with the development and release of improved high-yielding varieties that are early maturing which are suitable for semi-arid regions (Stoorvogel *et al*., 1993; Wopereis *et al*., 2006; Sanchez *et al*., 1997). Various factors are responsible for the inconsistency and low yields of sorghum in Nigeria Poor agronomic practices, soil characteristic and climatic condition have made sorghum yields unimpressive (Berg *et al*., 2013). Another, very important reasons relate to the variable responses with the use of fertilizer due to varied soil fertility conditions, degrading soil fertility, agricultural system characterized by low input subsistent farming, increasing pressure on agricultural land due to increase in human population and sorghum losing production area to other cereal crops regarded by farmers as high value crops such as maize rice and cowpea. These and other factors have made the attainment of maximum sorghum production in Nigeria low when compared to countries like the U.S.A and India.

The purpose of the study was to determine and ascertain the cultivar specific coefficient of sorghum, calibrate CERES-Sorghum model for use in the Sudan Savanna of Nigeria and the evaluation of its performance in simulating growth and development of different varieties of Sorghum in the study area.

## MATERIALS AND METHODS

The research was conducted simultaneously at Bayero University Kano Teaching and Research Farm (lat 11.58$^0$N and long 8$^0$33’E) and International Institute of Tropical Agriculture (IITA) Research Farm, Minjibir (lat. 12$^0$ 08'N, long. 8$^0$ 32'E,) in both Kano state, Nigeria during the 2014/2015 rainy season.

**Treatments and Experimental Designs**

The treatment consisted of eight (8) sorghum varieties; CSR01, CSR02, SAMSORG 14, SAMSORG 17, SAMSORG 40 (ICSV-400), SAMSORG 44, 12KN (ICSV-188) and 2192-2N randomly allocated to the plots. The experiments were executed in a Randomized Complete Block Design (RCBD) with four (4) replications. Seeds were obtained from ICRISAT-Kano station. The plot size used was 5x4.5m each with a space of 1m between two adjacent plots. The varieties used are described in the Table 1.

**Table 1. Description of the Sorghum Varieties in this Study**

| S/N | Varietal Name | Maturity Group | Potential Yield (t/ha) | Tolerance to Biotic stress |
|---|---|---|---|---|
| 1. | CSR01 | Medium | 3-3.5 | - |
| 2. | CSR02 | Medium | 3-3.5 | - |
| 3. | SAMSORG 14 | Medium | 3-3.5 | - |
| 4. | SAMSORG 17 | Late | 2.5-3 | - |
| 5. | SAMSORG 44 | Medium | 2.5 | - |
| 6. | SAMSORG 40 (ICSV-400) | Early | 2.5 | Striga |
| 7. | 12KN (ICSV-188) | Early | 2.5 | Striga |
| 8. | 2192-2N | Early | 2.5 | - |

**Cultural Practices**

The experimental fields were prepared by clearing, harrowing, and ridging, followed by the application of a herbicide; Primextra (Atrazine + Metolachlor), at a rate of 4 L $ha^{-1}$ prior to planting. Five seeds were sown per stand and later thinned to two seedlings per stand two weeks after sowing. All plots received a uniform application of 30 kg $K_2O$ $ha^{-1}$ as Muriate of Potash (MOP) and 32 kg $P_2O_5$ $ha^{-1}$ as Single Superphosphate. Nitrogen was supplied in the form of urea and applied in three splits: phosphorus (P) and potassium (K) fertilizers were applied entirely at sowing, while the first split of nitrogen was applied at sowing, and the remaining splits were applied at 4 and 6 weeks after sowing.

**Soil Sampling and Analysis**

Two soil profiles were dug, one in each site. Soil sample were collected at various depth from the experimental sites to parameterize the model. Detailed soil data for both locations were available from BUK and ICRISAT. Input data related to soil characteristics collected includes; soil texture, number of layers in soil profile, soil layer depth, pH of soil for each depth, clay, silt and sand contents, organic matter, cation exchange capacity, organic carbon, total N, exchangeable K, available P, etc.

In addition, descriptive information was used, which include: slope, drainage class, soil albedo, runoff potential and root restriction. The soil was classified after analysis using the USDA classification system (Soil Survey Staff, 2010).

The Soil Data Tool (SBuild) in DSSAT v4.6 was utilized to create the soil database used for general simulation purposes. This utility required input data such as the country name, experimental site name, site code, site coordinates, soil series, and soil classification.

**Meteorological Data**

Meteorological data is needed for running the simulation models. Weather Data records for 2014 and 2015 on: Daily minimum and maximum temperature, daily rainfall, daily sunshine hours and daily records of solar radiation were obtained from ICRISAT-Kano station. While historical weather records for preceding years were obtained from Kano weather station of the Institute of Agricultural Research (IAR), Ahmadu Bello University, Zaria.

The Weatherman utility in DSSAT was employed to generate the weather file for the DSSAT CERES-Sorghum model. The data used to create the weather file included station information (weather station name, latitude, longitude, and altitude), daily maximum and minimum temperatures, daily solar radiation, daily rainfall, and daily sunshine hours. These measurements were converted into the DSSAT format, after which the data was edited and exported into the DSSAT suite.

**Agronomic Data**

Agronomic and other related management data were collected and used to create the experimental files (File X). Data on Sowing date, days to emergence and harvest were recorded. Records were also made on plant establishment, growth, and yield in a controlled experiment. plant height, leaf area index, chlorophyll content, days to flowering and maturity, panicle characteristics (number, weight, and length), grain and stalk weights, and threshing percentage were recorded. Data was recorded at key growth stages, and yields are extrapolated to a per-hectare basis for analysis.

**Model Calibration**

The calibration process of the CERES-Sorghum model involves making initial estimates of the genetic coefficients and iteratively running the model to ensure the simulated values closely align with the observed data. Data from an experiment conducted at the International Institute of Tropical Agriculture Research Farm in Minjibir was used for calibration. The data utilized for model calibration included days to anthesis and physiological maturity, harvest index at maturity, maximum leaf area index (LAI), biomass at harvest (kg $ha^{-1}$), stalk weight (kg $ha^{-1}$), and final grain yield (kg ha$^{-1}$). The calibration was carried out using the GENCALC and sensitivity analysis tools in DSSAT (Hunt and Pararajasingham, 1994).

**Model Evaluation nd Statistical Analysis**

Agronomic data were analyzed using analysis of variance (ANOVA) with GENSTAT Discovery Edition version 4.0 (Souter, 2007), and significant means were separated using Tukey's Honestly Significant Difference (HSD) test (Tukey, 1953). Data from the second experiment conducted at the Bayero University Teaching and Research Farm were used to evaluate the model. This evaluation tested the optimized parameters obtained during the calibration process.

Model performance was assessed using four statistical metrics: Root Mean Square Error (RMSE), model forecasting efficiency (EF), mean error (E), and the index of agreement (D statistic), based on methodologies from previous model evaluation studies (Yang and Huffman, 2004; Liu *et al*., 2011). The D statistic, recommended by Willmott (1982), is particularly useful for cross-comparisons, as its values are both relative and bounded.

The lower the RMSE values relative to the mean, the better the model fit. The*D-index* and *EF* are ranges of

$$RMSE = \sqrt{\frac{1}{N}\sum\left(\hat{Yi}-Yi\right)^2}$$

And Index of agreement or d-statistics as;

$$d = 1 - \left[\frac{\sum_{i=1}^{n}\left(\hat{Yi}-Yi\right)\left(\hat{Yi}-Yi\right)}{\sum_{i=1}^{n}\left(\left|\hat{Yi}-\bar{Yi}\right|+\left|Yi-\bar{Yi}\right|\right)}\right]$$

values between 0 and 1, the closer the value to 1, the better the fit.

RMSE is given by the equation; (4)

(5)

Where $\hat{Y}$, $Y$ and $\bar{Y}$ are respectively, the simulated, observed and mean of the observed values and n are the number of observations. For good agreement between model simulations and observations, *d*-statistic should approach unity. RMSE is measure of the deviation of the simulated from the measured values, and is always positive. A zero value

$$EF = \frac{\sum_{i=1}^{n}(m_i-\bar{m})^2-\sum_{i=1}^{n} s_i - m_i}{\sum_{i=1}^{n} m_i - \bar{m})^2}$$

$$E = \frac{\sum_{i=1}^{n}(m_i - S_i)}{n}$$

is ideal, the lower the value of RMSE the higher the accuracy of the model prediction.

The model forecasting efficiency (*EF*) and mean error (*E*) are given as;

Where *n* is the number of meaured dataset, $S_i$is the simulated data, $m_i$ is the measured data, and *m* is the mean of the measured data.

The Easy Grapher program was used to plot graphs of the simulated model outputs, compare the model outputs with observed data, and calculate model performance statistics (Yang and Huffman, 2004; Yang *et al*., 2010). Evaluation statistics were calculated separately for the calibration and evaluation datasets using the equations mentioned earlier.

## RESULT AND DISCUSSION

**Description of the Experimental Soils**

The soil analysis at both experimental sites is presented in Table 2. The table shows the physical and chemical attributes of the various horizons from soil profiles dug at the experimental sites and other input data related to soil properties.

The results clearly showed that, the Minjibir trial site which was used for calibration purpose had a loamy sand surface soil (Ap horizon) with neutral pH and low Organic carbon content. The Cation Exchange Capacity (CEC) and Total Nitrogen level were in the low fertility class, so also the Available Phosphorus. The Bayero University Kano (B.U.K), trial site which was used for evaluation purpose had surface soil (Ap horizon) with a sandy loam texture, slightly acidic pH and low organic carbon content. The available phosphorus and total nitrogen levels were also low, while cation exchange capacity was medium which is in agreement with findings of Dawaki *et al. (*2019) and Abdulkadir *et al. (*2025).

The results from the soil analysis of this study provide a basis to distinguish clearly the soil nature between the two experimental sites. The soil in both trial sites were classified according to the USDA Soil Taxonomy, (Soil survey Staff, 2010). The soil for the Calibration site was classified as *Typic Plinthustalfs,* while that of the evaluation site was classified as *Typic Kanhaplustalf.*

The soils have been described as inherently poor in nutrient and soil organic carbon stocks (Adnan, 2011; Abdulkadir *et al*., 2020, Bala *et al.,* 2024). This is consistent with the results of the present study where values of important nutrient such as total soil N, available P, CEC and soil organic carbon (Ap horizon) were 0.12%, 8.7ppm, 6.7 cmol/kg, 0.66%, for Minjibir and 0.11%, 2.6ppm, 6.98 cmol/kg, 0.10% for B.U.K respectively. The low organic carbon content could be as a result of the high temperatures resulting in rapid organic matter decomposition in combination with a generally low input of organic material (Bagamsah, 2005; Abdulkadir *et al*., 2022; Sani *et al.,* 2024).

The soils in both locations are on average sandy loam with a mean sand content of 79.3 and 76.30 % in the top and subsoil's, respectively. The high sand content of the soils can be attributed to the granite parent material over which they are formed (Sani *et al.,* 2022, 2023). Due to the sandy nature of the soils and their low organic carbon content, water infiltration is high and water holding capacity is low which is not very conducive to crop production, particularly in light of the low and erratic rainfall and the unforeseen dry spells in the region. The soils are on average slightly acidic pH in B.U.K site and neutral pH at Minjibir.

In spite of the substantial differences observed in soil nutrients between the two experimental sites, the values reported here are somewhat below those reported by other studies. Analogous scenario with slight improvement in total soil N, available P, CEC and soil organic carbon values was reported by Abdulkadir *et al. (*2024), Bassam (2014) and Dawaki *et al*. (2019) in their work on Maize in Kano.

**Weather Characteristics of the Experimental Sites**

Mean monthly, minimum and maximum temperatures, solar radiation and rainfall amount are presented in Table 3. Both locations have similar rainfall pattern, amount and distribution. A total rainfall of about 565 – 663 mm was recorded during the rainy season, with a relative humidity range of between 10-37% and 35-97% during the dry and rainy seasons respectively. Temperature averages between 11 - 35$^0$C during dry season and 24- 41$^0$C during the rainy season (ICRISAT, 2015).

Daily minimum and maximum temperatures and solar radiation are depicted in the line graphs while the bars show rainfall. The B.U.K experimental site received more rainfall (663mm) in total and the lowest received in March (0.8mm). The rains also established earlier in B.U.K. At Minjibir, rains started in June and stopped in October. August was the wettest month with about 325mm of rainfall recorded while only 34mm was recorded in September. Rains end at the same period (October) in both locations.

Plant Height, Leaf Area Index (LAI) and Leaf Chlorophyll Content of eight (8) Sorghum Varieties at Minjibir and B.U.K in 2015. The growth and yield component of some observed parameter of the 8 sorghum varieties used in the experiment is presented in Table 4.

**Plant height:** The influence of 8 sorghum varieties grown at Minjibir and BUK on plant height as displayed in Table 5. At Minjibir, CSR-01 variety significantly possessed the highest mean value of plant height (329.5cm) compared to Sorghum variety 2192-2N that possessed the lowest mean value of plant height (96.2cm). At B.U.K, CSR-01 significantly exhibited the highest mean value of plant height (358.5cm) compared to variety 2192-2N that exhibited the lowest mean value of plant height (98.0cm).

**Leaf area index:** The leaf area index observed among the 8 sorghum varieties grown at Minjibir and B.U.K is presented in Table 5. There were no significant differences in the leaf area index among the 8 sorghum varieties at both Minjibir and BUK.

**Leaf chlorophyll content:** The leaf chlorophyll content of the 8 sorghum varieties used in this trial at both locations is presented in Table 5. At Minjibir, there were no significant differences on the leaf chlorophyll content among the 8 sorghum varieties. However, at BUK, 12KN ICSV-188 variety produced significantly higher chlorophyll contents (55.68) than all other varieties except the chlorophyll content produced by SAMSORG 17 (55.25), which was statistically at par. SAMSORG 44, produced the lowest chlorophyll content (49.05).

**Table 2. Soil Physical and Chemical properties at Calibration (Minjibir) and Evaluation (B.U.K) Sites for CERE-Sorghum modelling trial during 2015, rainy season**

| Horizon | Depth (cm) | pH ($H_2O$) | pH ($CaCl_2$) | EC (dS/m) | O.C (%) | Av. P ppm | Ca | Mg | K | Na | CEC | SAND | CLAY | SILT | BS | T.N |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | ---------- cmol/kg ---------- | | | | | ---------- %---------- | | | | |
| **Calibration Site (Minjibir)** | | | | | | | | | | | | | | | | |
| Ap | 0-17 | 6.71 | 6.25 | 0.177 | 0.66 | 8.731 | 2.883 | 1.685 | 0.368 | 0.194 | 6.731 | 84.68 | 7.28 | 8.24 | 82.33 | 0.12 |
| AB | 17-38 | 6.21 | 5.50 | 0.084 | 0.42 | 7.651 | 2.061 | 1.003 | 0.532 | 0.251 | 4.807 | 79.68 | 11.28 | 9.04 | 80.13 | 0.07 |
| Bt | 38-68 | 6.50 | 5.80 | 0.104 | 0.37 | 6.382 | 2.001 | 1.021 | 0.379 | 0.173 | 4.570 | 75.68 | 11.28 | 13.04 | 78.21 | 0.07 |
| Btg | 68-97 | 6.00 | 5.30 | 0.073 | 0.28 | 6.603 | 2.924 | 1.244 | 0.268 | 0.121 | 5.507 | 77.68 | 9.28 | 13.04 | 82.73 | 0.035 |
| **Evaluation Site (B.U.K)** | | | | | | | | | | | | | | | | |
| Ap | 0-15 | 6.58 | 6.09 | 0.063 | 0.100 | 2.61 | 2.072 | 0.206 | 0.38 | 0.087 | 6.98 | 76.64 | 16.08 | 7.28 | 68.72 | 0.105 |
| B | 15-35 | 5.73 | 4.65 | 0.066 | 0.80 | 2.13 | 2.94 | 1.11 | 0.34 | 0.20 | 8.30 | 74.64 | 12.08 | 13.28 | 85.77 | 0.99 |
| Cv | 35-57+ | 6.38 | 4.9 | 0.054 | 0.80 | 2.69 | 2.88 | 1.32 | 0.23 | 0.20 | 5.71 | 77.64 | 12.08 | 10.28 | 66.22 | 0.138 |

**Table 3. Mean Monthly Weather data from January - December 2015 at Calibration (Minjibir) and Evaluation (BUK) Sites for CERE-Sorghum trial during 2015 rainy season**

| Months | Average Monthly Weather Parameters | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | **Calibration Site (Minjibir)** | | | | **Evaluation Site (B.U.K)** | | | |
| | **TMAX ($^0$C)** | **TMIN ($^0$C)** | **SRAD (MJ/m2.d)** | **Rainfall (mm)** | **TMAX ($^0$C)** | **TMIN ($^0$C)** | **SRAD (MJ/m2.d)** | **Rainfall (mm)** |
| January | 29 | 13 | 20 | 0.00 | 28 | 11 | 14 | 0.00 |
| February | 36 | 16 | 15 | 0.00 | 32 | 14 | 16 | 0.00 |
| March | 37 | 21 | 16 | 0.00 | 36 | 21 | 17 | 0.80 |
| April | 38 | 22 | 17 | 0.00 | 37 | 22 | 20 | 0.00 |
| May | 41 | 26 | 18 | 0.00 | 40 | 25 | 19 | 0.00 |
| June | 37 | 25 | 19 | 25.5 | 36 | 24 | 19 | 7.52 |
| July | 33 | 23 | 18 | 19.21 | 33 | 21 | 18 | 13.33 |
| August | 32 | 22 | 16 | 46.40 | 31 | 21 | 17 | 17.22 |
| September | 32 | 22 | 18 | 11.40 | 32 | 23 | 18 | 8.61 |
| October | 36 | 22 | 17 | 10.00 | 36 | 20 | 19 | 16.61 |
| November | 36 | 16 | 17 | 0.00 | 33 | 14 | 17 | 0.00 |
| December | 25 | 14 | 15 | 0.00 | 26 | 12 | 13 | 0.00 |

TMAX = daily maximum temperature ($^0$C), TMIN = Daily minimum temperature ($^0$C), SRAD = Total daily solar radiation (MJ/M$^2$/day), Rainfall = Total daily rainfall precipitation (mm/day)

Source: ICRISAT Meteorological Unit (2017)

**Table 4. Plant Height, Leaf Area Index (LAI) and Leaf Chlorophyll Content of eight (8) Sorghum Varieties at Minjibir and B.U.K In 2015**

| Treatment/Varieties | Plant height (cm) | | Maximum leaf area index | | Leaf chlorophyll content | |
|---|---|---|---|---|---|---|
| | Minjibir | B.U.K | Minjibir | B.U.K | Minjibir | B.U.K |
| CSR-01 | 323.0a | 358.5a | 2.00a | 1.96a | 44.38a | 50.27abc |
| CSR-02 | 329.5a | 354.5a | 1.69a | 2.47a | 46.45a | 51.25abc |
| SAMSORG 44 | 215.0b | 256.0b | 2.01a | 2.20a | 48.58a | 49.05c |
| SAMSORG 14 | 267.8ab | 331.0a | 1.71a | 2.01a | 48.70a | 49.33bc |
| 2192-2N | 96.2c | 98.0d | 1.42a | 1.88a | 50.09a | 52.50abc |
| ICSV-400 | 223.0b | 200.2c | 1.82a | 1.51a | 45.38a | 51.90abc |
| 12KN ICSV-188 | 263.2ab | 231.0bc | 1.64a | 1.88a | 44.38a | 55.68a |
| SAMSORG 17 | 228.2b | 258.0b | 1.87a | 2.38a | 47.55a | 55.25ab |
| Grand mean | 243.2 | 260.9 | 1.77 | 2.03 | 46.94 | 51.90 |
| SED | 21.52 | 14.26 | 0.209 | 0.373 | 3.249 | 1.814 |

Means within a column having similar letter(s) are not significantly different at 5% level of probability using Tukey HSD

**Table 5. Plant Height, Leaf Area Index (LAI) and Leaf Chlorophyll Content of eight (8) Sorghum Varieties at Minjibir and B.U.K In 2015**

| Treatment/Varieties | Plant height (cm) | | Maximum leaf area index | | Leaf chlorophyll content | |
|---|---|---|---|---|---|---|
| | Minjibir | B.U.K | Minjibir | B.U.K | MINJIBIR | B.U.K |
| CSR-01 | 323.0a | 358.5a | 2.00a | 1.96a | 44.38a | 50.27abc |
| CSR-02 | 329.5a | 354.5a | 1.69a | 2.47a | 46.45a | 51.25abc |
| SAMSORG 44 | 215.0b | 256.0b | 2.01a | 2.20a | 48.58a | 49.05c |
| SAMSORG 14 | 267.8ab | 331.0a | 1.71a | 2.01a | 48.70a | 49.33bc |
| 2192-2N | 96.2c | 98.0d | 1.42a | 1.88a | 50.09a | 52.50abc |
| ICSV-400 | 223.0b | 200.2c | 1.82a | 1.51a | 45.38a | 51.90abc |
| 12KN ICSV-188 | 263.2ab | 231.0bc | 1.64a | 1.88a | 44.38a | 55.68a |
| SAMSORG 17 | 228.2b | 258.0b | 1.87a | 2.38a | 47.55a | 55.25ab |
| Grand mean | 243.2 | 260.9 | 1.77 | 2.03 | 46.94 | 51.90 |
| SED | 21.52 | 14.26 | 0.209 | 0.373 | 3.249 | 1.814 |

Means within a column having similar letter(s) are not significantly different at 5% level of probability using Tukey HSD

**Table 6. Phenology of eight (8) Sorghum on days to Panicle Initiation, Anthesis and Physiological Maturity at Minjibir and B.U.K In 2015**

| Treatment/Varieties | Days to 50% Heading | | Days to 50% Flowering | | Days to Physiological maturity | |
|---|---|---|---|---|---|---|
| | Minjibir | B.U.K | Minjibir | B.U.K | MINJIBIR | B.U.K |
| CSR-01 | 103.50b | 87.50ab | 105.00b | 89.50ab | 128.0b | 122.2b |
| CSR-02 | 105.25ab | 86.75b | 106.25b | 88.25bc | 129.7b | 121.2b |
| SAMSORG 44 | 95.00c | 82.75c | 96.75c | 84.75d | 120.5c | 117.2c |
| SAMSORG 14 | 99.25bc | 83.75c | 100.50bc | 85.75cd | 125.7b | 118.8c |
| 2192-2N | 64.17e | 64.75e | 65.77e | 66.50f | 91.5f | 88.5f |
| ICSV-400 | 70.00e | 70.50d | 70.75e | 72.00e | 100.0e | 93.0e |
| 12KN ICSV-188 | 79.50d | 68.75d | 81.00d | 70.75e | 112.0d | 107.0d |
| SAMSORG 17 | 111.50a | 89.50a | 113.00a | 91.50a | 137.2a | 126.0a |
| Grand mean | 91.02 | 79.28 | 92.38 | 81.12 | 118.09 | 111.75 |
| SED | 1.976 | 0.625 | 1.826 | 0.798 | 1.458 | 0.607 |

Means within a column having similar letter(s) are not significantly different at 5% level of probability using Tukey HSD.

**Phenology of eight (8) Sorghum on Days Panicle Initiation, Anthesis and Physiological Maturity at Minjibir and B.U.K in 2015**

The phenology of the eight (8) sorghum varieties used in the trial is presented in Table 6. The table clearly shows the biological phenomena interacting with time from the date of planting to panicle initiation (heading), anthesis (flowering) and physiological maturity days. There were significant different among the Sorghum varieties with regard to number of days to panicle initiation (heading), anthesis (flowering) and physiological maturity days as shown in Table 6.

The highest mean number of days to panicle initiation, anthesis and physiological maturity at Minjibir was observed with Samsorg-17 (112, 113 and 137days), while the lowest was noted with 2192-2N (64, 66, and 96 days). CSR-01 and CSR-02 were similar statistically in all three parameters while SAMSORG-44 and SAMSORG-14 were also statistically at par. ICSV-400 gave (70, 71 and 100days) and 12KN ICSV-188 gave (80, 81 and 112 days) for days to panicle initiation, anthesis and physiological maturity respectively.

At B.U.K, variety 2192-2N significantly possessed the lowest mean number of days to panicle initiation (heading), anthesis (flowering) and days to physiological maturity (65, 67, and 89 days) compared to Samsorg-17 that possessed the highest mean number of days to panicle initiation (heading), anthesis (flowering) and days to physiological maturity (90, 92 and 126days). Analogous scenario was recorded at both experimental sites, with a slight decline in the number of days to panicle initiation, anthesis and physiological maturity at B.U.K. This is a true reflection that environmental factors influence the variation in the development of the plants at every stage. One Thousand Seed Weight (g), Threshing (%) and Grain Yield (kg/ha) of eight (8) Sorghum Varieties at Minjibir and B.U.K in 2015. The characteristics of the Sorghum varieties on 1000-seed weight, threshing percentage Grain yield at Minjibir and B.U.K are shown in Table 7.

**One thousand seed weight (g):** There were significant difference among the eight (8) sorghum varieties relative to 1000-seed weight observed at both Minjibir and B.U.K (Table 7).

At Minjibir, Samsorg-44 and Samsorg-14 significantly expressed highest mean values of 1000-seed weight (76.5g and 69.2g) compared to Samsorg-17 that significantly possessed lower mean value of 1000-seed weight (24.0g). At B.U.K, 12KN ICSV-188 significantly possessed a high mean value of 1000-seed weight (79.6g) than 2192-2N that statistically possessed the lowest mean value of 1000-seed weight (67.7g).

There was slight difference in 1000-seed weight between the two locations. Slightly higher grand mean value (72.5g) was obtained at B.U.K than mean value (61.5g) obtained at Minjibir.

**Threshing percentage (%):** There were significant differences among the varieties considered with respect to threshing percentage at both locations as indicated in Table 7. At Minjibir, the variety that had statistically manifested the highest mean value of threshing percentage (74%) is ICSV-400, compared to Samsorg-17 that statistically produced the lowest mean (11 %). At B.U.K, Sorghum variety ICSV-400 equally, gave the highest mean value of threshing percentage (73 %) compared to variety Samsorg-17 which statistically recorded the lowest mean value of threshing percentage (29 %).

**Grain yield (kg/ha):** It was found that there were significant differences in the grain yield among varieties in both locations (Table 7). The highest yield (2800kg/ha) was obtained from SAMSORG-44 in both locations compared to variety Samsorg-17 that had significantly recorded lowest mean value of yield per kilogram per hectare (1778 and 770kg/ha) in both locations. Slightly higher grand mean value (2284kg/ha) was obtained at Minjibir than (1950kg/ha) mean grain yield of 1950kg $ha^{-1}$ obtained at B.U.K.

MODEL CALIBRATION

The results of the model calibration and the derived parameters are presented in Table 8. Field data collected from Minjibir during the 2015 rainy season, including days to anthesis, days to physiological maturity, maximum leaf area index (LAI), number of leaves per stem, harvest index at maturity, stalk weight after harvest (kg $ha^{-1}$), above-ground biomass at maturity (kg $ha^{-1}$), and final grain yield (kg $ha^{-1}$), were used to calibrate the model. This data was employed to estimate the eco-physiological coefficients required for running the CERES-Sorghum model.

The genetic coefficients were determined by iteratively adjusting parameters to achieve close agreement and a suitable goodness-of-fit between the observed and simulated values, following the procedure described by Hoogenboom *et al*. (2010). The results revealed the optimal combination of values for the genetic coefficients, defined as follows:

- P1: Thermal time from seedling emergence to the end of the juvenile phase
- P2: Thermal time from the end of the juvenile stage to tassel initiation under short days
- P2O: Critical photoperiod or the longest day length (in hours)
- P2R: Extension of the phase leading to panicle initiation for each hour increase in photoperiod beyond P2O.
- PANTH: Thermal time from the end of tassel initiation to anthesis
- P3: Thermal time from the end of flag leaf expansion to anthesis.
- P4: Thermal time from anthesis to the beginning of grain filling.
- P5: Thermal time from the beginning of grain filling to physiological maturity
- PHINT: Phylochron interval, the thermal time interval between successive leaf tip appearances.
- G1: Scalar for relative leaf size.
- G2: Scalar for partitioning assimilates to the panicle (head).

These developed genetic coefficients were used in the study to run the CERES-Sorghum model.

From the numerous runs, CSR-01, SAMSORG-44 and 2192-2N recorded the highest panicle size partitioning coefficient (G2) while SAMSORG-14, SAMSORG-17 and 12KN ICSV-188 recorded the lowest. CSR-02 and ICSV-400 got an equidistant value of (5.4 and 4.7) respectively. For the juvenile phase coefficient (P1), it was observed that SAMSORG-14, 12KN ICSV-188 and CSR-02 recorded the highest thermal time from emergence to its end of juvenile stage (P1) and the lowest was observed with SAMSORG-17 and SAMSORG-44, while ICSV-400 and CSR-01 were midway between. Values for the photoperiodism coefficients (P2R) ranges from 1-300 (GDD) $h^{-}$ SAMSORG-17 recorded the highest while ICSV-400 recorded the lowest.

Furthermore, the grain filling duration and thermal time from end of flag leaf expansion to anthesis coefficients (P3, P4 and P5), 12KN ICSV-188 and CSR-02 recorded the highest flag leaf expansion coefficients (P3) while SAMSORG-14, SAMSORG-17 and SAMSORG-17 were on the same range and CSR-01 and ICSV-400 got equidistant values of (266.2 and 289.3) respectively. In addition, it was also observed that 2192-2N, SAMSORG-17, ICSV-400 and CSR-02 recorded the highest thermal time from anthesis to the beginning of grain filling (P4) while CSR-01, SAMSORG-44, SAMSORG-14 and 12KN ICSV-188 gave a midway value that were within the acceptable range. Values for the leaf size coefficients (G1) ranges from 0-22 and all the eight (8) cultivars were with the range. For the grain filling period to physiological maturity coefficients (P5), it was also observed that SAMSORG-17, 12KN ICSV-188 and 2192-2N recorded the highest values while the remaining varieties gave values that were within the acceptable range.

**Table 7. One thousand seed weight (g), threshing % and Grain yield of 8 sorghum varieties at Minjibir and B.U.K**

| Treatment/Varieties | 1000 seed weight (g) | | Threshing (%) | | Grain Yield (kg/ha) | |
|---|---|---|---|---|---|---|
| | Minjibir | B.U.K | Minjibir | B.U.K | Minjibir | B.U.K |
| CSR-01 | 67.77b | 71.92 | 64.00ab | 66.75a | 2667 | 2500ab |
| CSR-02 | 68.40b | 70.95 | 64.50ab | 67.50a | 2533 | 2033abc |
| SAMSORG 44 | 76.52a | 71.87 | 62.25b | 72.25a | 2800 | 2800a |
| SAMSORG 14 | 69.17b | 75.15 | 66.00ab | 69.00a | 2000 | 2137abc |
| 2192-2N | 59.48d | 67.70 | 63.64ab | 67.25a | 1758 | 1240cd |
| ICSV-400 | 60.50cd | 69.67 | 74.00a | 73.25a | 2200 | 1710bcd |
| 12KN ICSV-188 | 66.22bc | 79.55 | 63.75ab | 68.00a | 2533 | 2410ab |
| SAMSORG 17 | 24.00e | 72.92 | 11.25c | 28.50b | 1778 | 770d |
| Grand mean | 61.51 | 72.5 | 58.67 | 64.1 | 2284 | 1950 |
| SED | 1.723 | 4.60 | 3.242 | 6.55 | 316.0 | 302.3 |

Means within a column having similar letter(s) are not significantly different at 5% level of probability using Tukey HSD Test

**Table 8. Generated Cultivar Coefficients of Varieties Used for Calibration in the CERES-Sorghum Modelling Trial**

| | | Varieties | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| Coefficients | Range | CSR-01 | CSR-02 | SAMSORG 44 | SAMSORG 14 | 2192-2N | ICSV-400 | 12KN ICSV-188 | SAMSORG 17 |
| P1 (GDD) $^{O}$C | 150-600 | 429.8 | 507.4 | 325.1 | 595.4 | 297.9 | 450.4 | 508.6 | 315.0 |
| P2 (Hours) | | 102.0 | 102.0 | 102.0 | 102.0 | 102.0 | 102.0 | 102.0 | 102.0 |
| P2O (Hours) | 10-17 | 11.05 | 12.37 | 11.23 | 13.28 | 13.52 | 13.18 | 12.62 | 11.81 |
| P2R (GDD) $h^{-}$ | 1-300 | 104.5 | 163.9 | 87.0 | 162.9 | 142.2 | 23.6 | 113.6 | 238.9 |
| PANTH | | 617.5 | 617.5 | 617.5 | 617.5 | 617.5 | 617.5 | 617.5 | 617.5 |
| P3 | | 266.2 | 414.1 | 224.8 | 235.4 | 337.1 | 289.3 | 444.8 | 250.1 |
| P4 | | 134.2 | 210.7 | 160.8 | 179.5 | 230.0 | 213.6 | 150.2 | 229.6 |
| P5 (GDD) $^{O}$C | 400-700 | 541.2 | 569.1 | 564.5 | 541.9 | 628.5 | 565.6 | 648.2 | 670.0 |
| PHINT | | 49.00 | 49.00 | 49.00 | 49.00 | 49.00 | 49.00 | 49.00 | 49.00 |
| G1 | 1-22 | 0.0 | 0.0 | 13.0 | 11.9 | 11.9 | 11.9 | 11.9 | 3.0 |
| G2 (g/day$^{-1}$) | 4.5-6.5 | 6.5 | 5.4 | 6.4 | 4.5 | 6.5 | 4.7 | 4.5 | 4.5 |

**Table 9. Statistical indicators of model performance of some parameters after model calibration**

| | Measured Parameter (Calibration Experiment) | | | |
|---|---|---|---|---|
| **Statistics** | **Days to Anthesis** | **Days to Phy. Maturity** | **Leaf Area Index** | **Leaf No. per/stem** |
| RMSE | 7.28 | 5.42 | 0.85 | 1.37 |
| E | -6.25 | 1.13 | -0.1 | 1.14 |
| EF | 0.91 | 0.93 | -2.57 | 0.8 |
| D-Index | 0.92 | 0.96 | 0.69 | 0.95 |
| | **Measured Parameter (Calibration Experiment)** | | | |
| **Statistics** | **Harvest Index** | **Stalk weight (kg/ha)** | **Biomass (kg/ha)** | **Yield (kg/ha)** |
| RMSE | 0.29 | 584.4 | 461.55 | 125.68 |
| E | -0.2 | 419 | 327.25 | 94.75 |
| EF | -1.04 | 0.69 | 0.86 | 0.87 |
| D-Index | 0.47 | 0.93 | 0.97 | 0.97 |

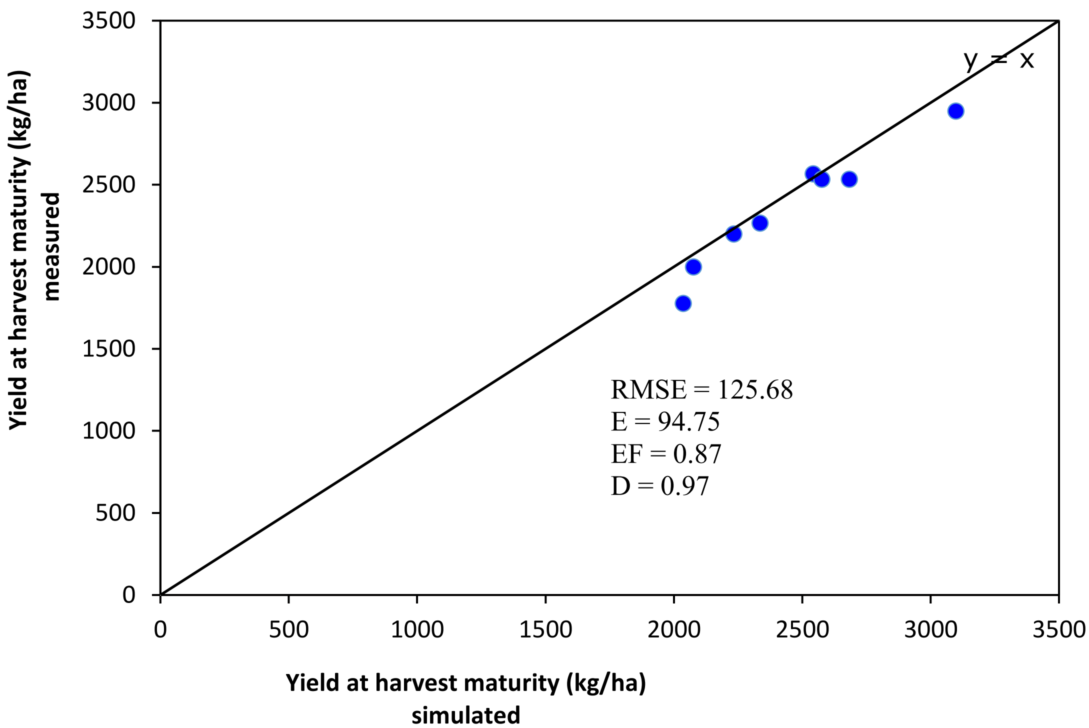


**Figure 1: Trend lines showing the relationship between Simulated and Observed grain yield**

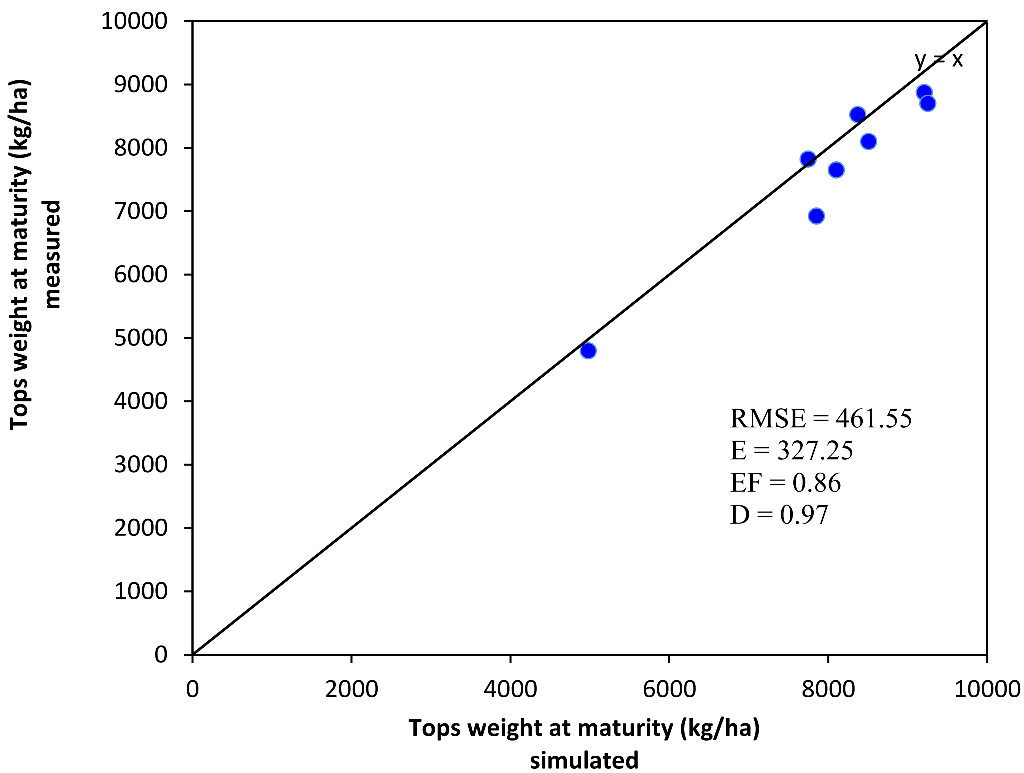


**Figure 2: Trend lines showing the relationship between Simulated and Observed Tops weight at maturity**

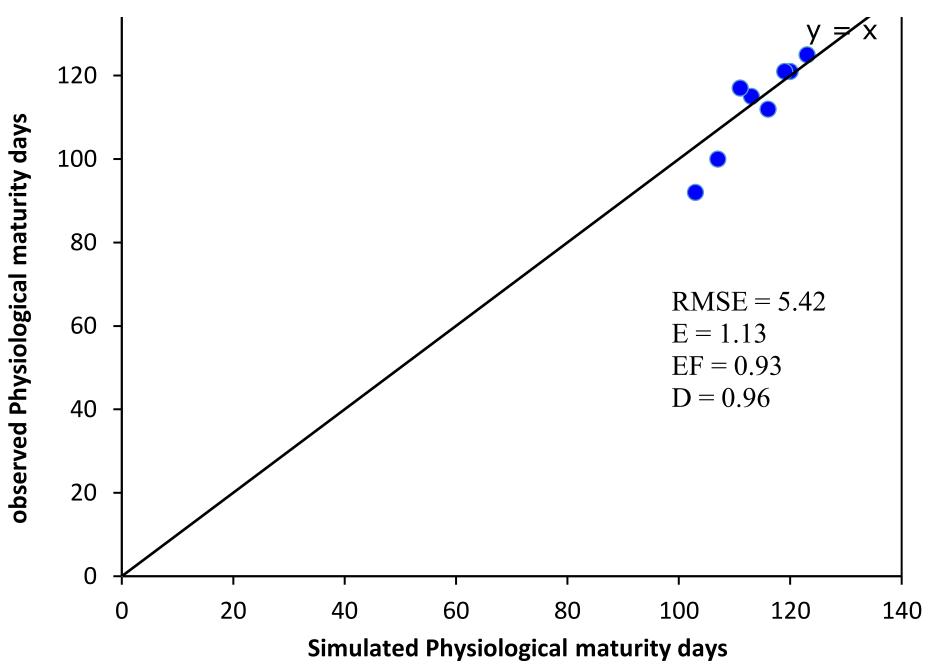


**Figure 3: Trend lines showing the relationship between Simulated and Observed days to physiological maturity**

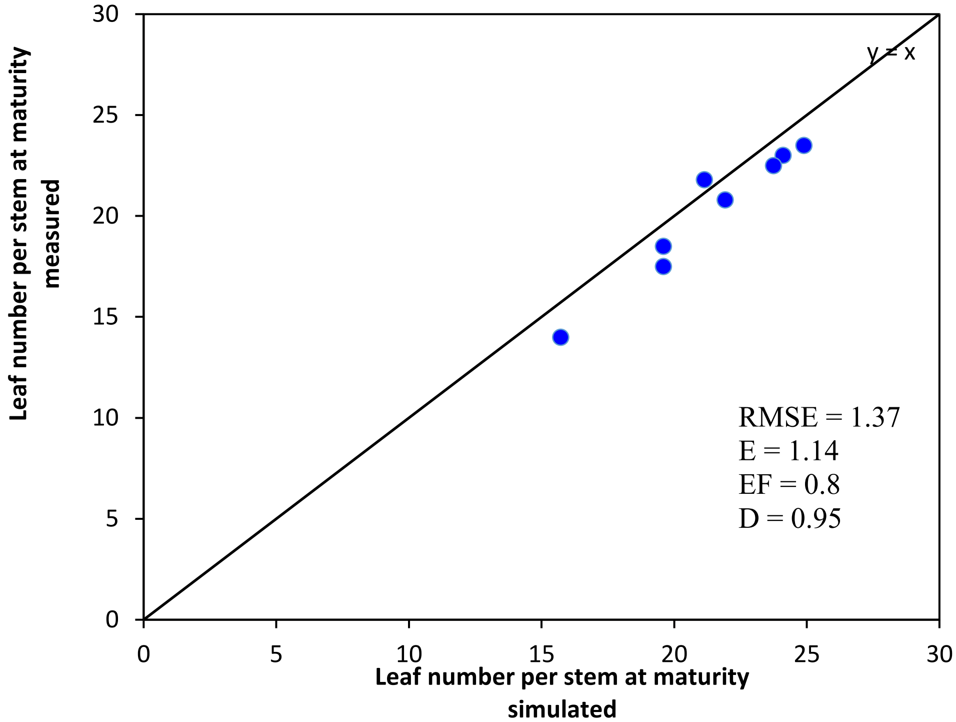


**Figure 4. Trend lines showing the relationship between Simulated and Observed Leaf number per stem**

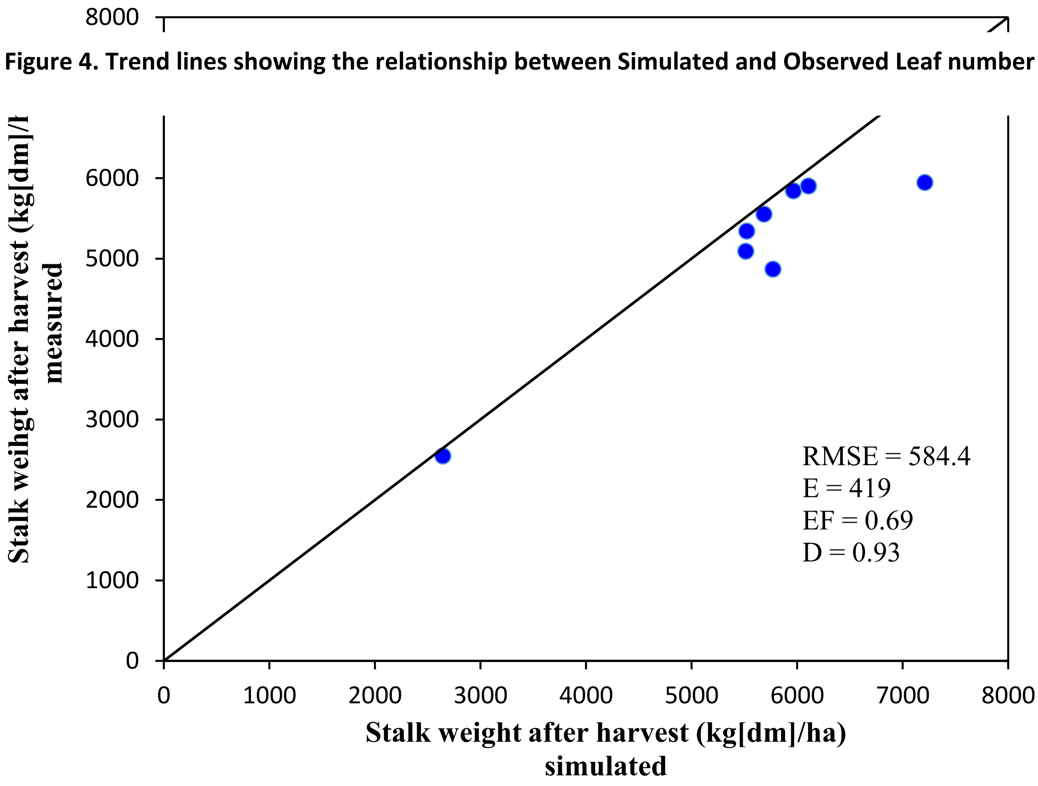


**Figure 5. Trend lines showing the relationship between Simulated and Observed Stalk weight after harvest**

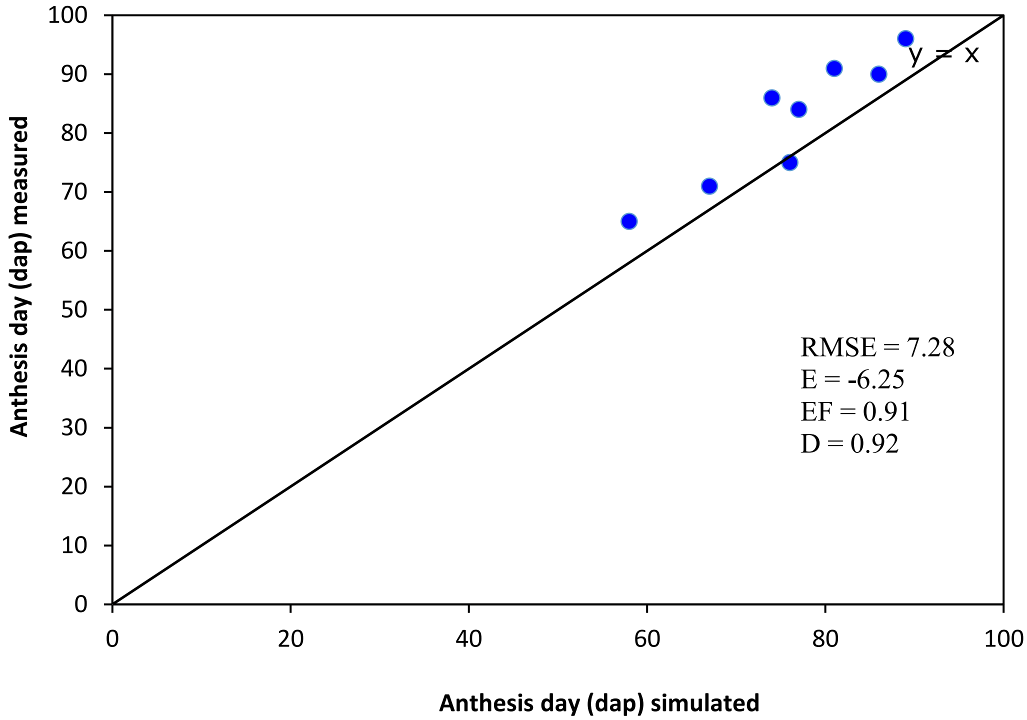


**Figure 6: Trend lines showing the relationship between Simulated and Observed days to anthesis**

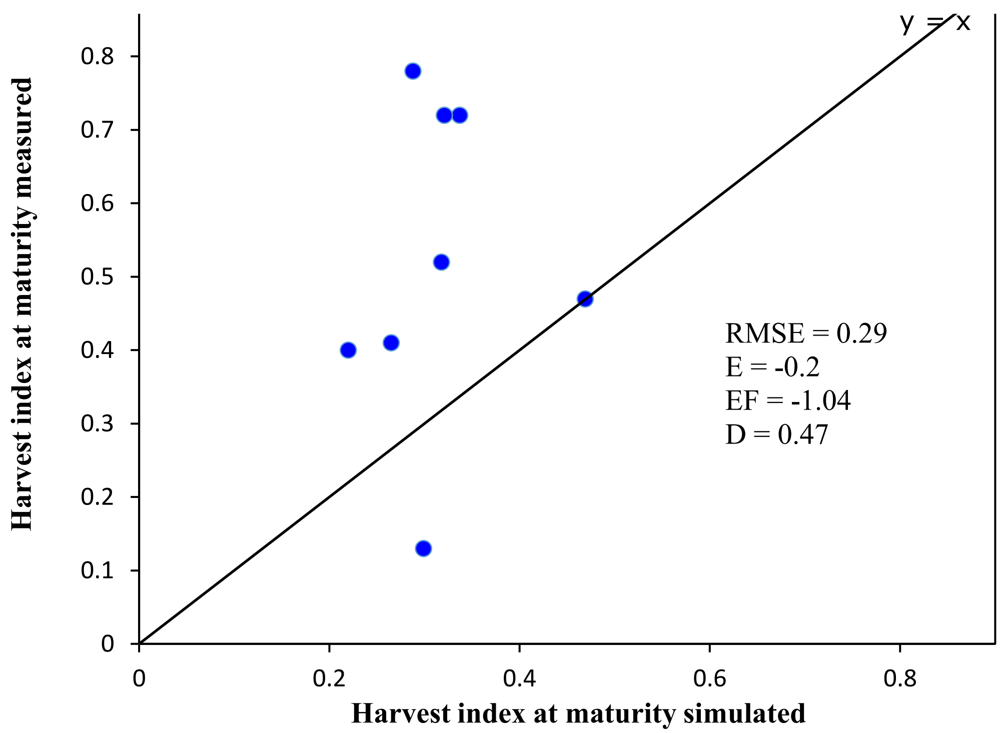


**Figure 7: Trend lines showing the relationship between Simulated and Observed Harvest index**

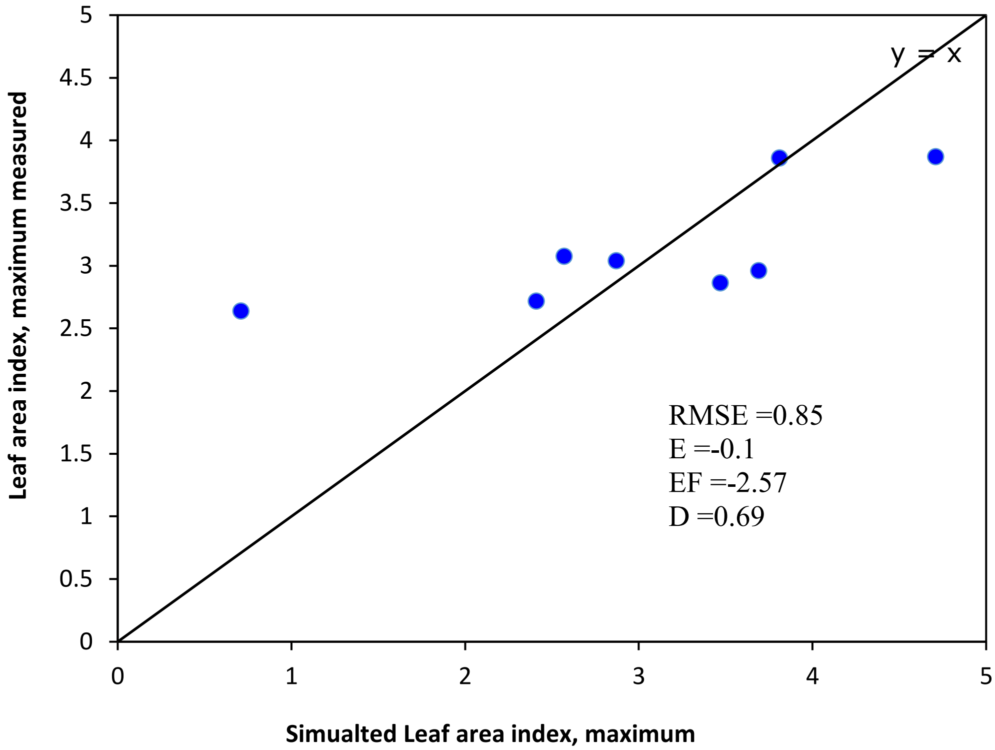


**Figure 8: Trend lines showing the relationship between Simulated and Observed Leaf area index**

**Model Evaluation**

Result of simulation studies were evaluated with data collected from field observations from Bayero University Kano, during the 2015 rainy season. Table 10, shows the comparisons, statistics and extent of agreement between simulated and observed values on days to anthesis, days to physiological maturity, maximum leaf area index (LAI), harvest index at maturity, above-ground biomass (kg $ha^{-1}$) and final grain yield (kg $ha^{-1}$). As shown in the table, simulated days to anthesis, days to physiological maturity, maximum leaf area index (LAI), harvest index at maturity, above-ground biomass (kg $ha^{-1}$) and final grain yield (kg $ha^{-1}$) closely matched with the observed with slight positive and negative prediction deviation in some instances.

A very good prediction accuracy was found for days to physiological maturity, leaf area index and harvest index for D-index and RMSE statistics (*D-index*= 0.97, 0.96, 0.96 and *RMSE* = 4.9, 1.25, 0.47). Good agreements were also found between observed and simulated values of days to anthesis with D-index of 0.94, RMSE = 5.56, EF = 0.90 and E values of -4.00.

However, the model slightly underestimated above-ground biomass and grain yield. Prediction accuracy for Harvest index and leaf area index were low when compared to other measured parameters, D-index and RMSE values were (0.90 and 0.86; 524.7and 1155.72).

**Model Evaluation Performance**

Results from the simulation studies and the model estimated cultivar coefficients, calibration and evaluation parameters of all the eight (8) varieties clearly shows that CERES-Sorghum model could serve as a sound scientific toolfor simulating sorghum growth and yield development under different scenarios and can equally be use as a tool for decision making in the Sudan Savanna agro ecological zone of Nigeria. The estimated values revealed that some simple equations could produce reasonable results withgood genetic coefficients values estimated for all the eight (8) cultivars and were incorporated into the cultivar coefficient file of the DSSAT-shell. These coefficients are required by the model to simulate the growth and yield of the sorghum varieties. The values for the estimated genetic coefficients found in this study offer the user reasonable inputs for simulating sorghum growth and yield in the Sudan Savanna agro-ecological region of Nigeria.

Furthermore, the result of the calibration and evaluation experiments found a good prediction agreement for all the tested parameters as evidenced by values from the statistical indicators of the model performance. Good agreement was found between observed and simulated grain yield and other variables measured. Even though there were some slight differences between some observed and simulated values, in particular for leaf area index (LAI), harvest index at maturity and above-ground biomass, the overall results of the model application were satisfactory. The variations in harvest index and leaf area index prediction accuracy indicate uncertainty level as shown by the statistical indicator values. To this effect, the statistical indices have revealed that the model under predicted some parameters in other instances. The goodness of fit between observed and simulated grain yield and other measured variables corroborates with previous findings from the same agro-ecology (Gavilán-Acuna *et al.,* 2024; Bregaglio *et al.,* 2023; Jagtap *et al.,* 1993; Gungula *et al.,* 2003; Jibrin *et al.,* 2012; Adnan *et al.,* 2015).

**Table 10. Comparison between some observed and simulated parameters after model evaluation (Evaluation Experiment)**

| | Days to Anthesis | | | Days to Phy. Mat. | | | Leaf Area Index | | | Harvest Index | | | Biomass (Kgha$^{-1}$) | | | Yield (Kgha$^{-1}$) | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Treatments** | Sim. | Obs. | PD | Sim. | Obs. | PD | Sim. | Obs. | PD | Sim. | Obs. | PD | Sim. | Obs. | PD | Sim. | Obs. | PD |
| CSR-01 | 86 | 90 | -3.5 | 120 | 122 | -2.25 | 3.81 | 2.47 | 1.34 | 0.30 | 0.49 | -0.19 | 5966 | 5233 | 733 | 2543 | 2500 | 43 |
| CSR-02 | 81 | 88 | -7.25 | 119 | 121 | -2.25 | 2.57 | 2.47 | 0.11 | 0.32 | 0.48 | -0.16 | 5525 | 5300 | 225 | 2576 | 2033 | 543 |
| SAMSORG 44 | 77 | 85 | -7.75 | 113 | 117 | -4.25 | 3.69 | 2.27 | 1.42 | 0.34 | 0.53 | -0.20 | 6108 | 6300 | -192 | 3099 | 2800 | 299 |
| SAMSORG 14 | 80 | 86 | -5.75 | 111 | 119 | -7.75 | 3.47 | 2.27 | 1.20 | 0.27 | 0.45 | -0.18 | 5774 | 4233 | 1541 | 2077 | 2136 | -59 |
| 2192-2N | 61 | 67 | -5.5 | 90 | 89 | 1.5 | 0.71 | 2.00 | -1.29 | 0.47 | 0.33 | 0.14 | 5645 | 4233 | 1412 | 2336 | 2240 | 96 |
| ICSV-400 | 67 | 72 | -5 | 97 | 93 | 4 | 2.41 | 2.08 | 0.33 | 0.29 | 0.23 | 0.06 | 5514 | 4633 | 881 | 2234 | 1710 | 524 |
| 12KN ICSV-188 | 76 | 71 | 5.25 | 116 | 107 | 9 | 2.87 | 2.17 | 0.70 | 0.32 | 1.55 | -1.23 | 5687 | 4566 | 1121 | 2684 | 2410 | 274 |
| SAMSORG 17 | 89 | 92 | -2.5 | 123 | 126 | -3 | 4.71 | 2.49 | 2.22 | 0.22 | 0.53 | -0.31 | 7213 | 5300 | 1913 | 2037 | 769 | 1268 |

**Statistical indicators of model performance (Evaluation Experiment)**

| **Statistics** | Days to Anthesis | Days to Phy. Maturity | Leaf Area Index | Harvest Index | Biomass (Kgha$^{-1}$) | Yield (Kgha$^{-1}$) |
|---|---|---|---|---|---|---|
| RMSE | 5.56 | 4.90 | 1.25 | 0.47 | 1155.72 | 542.7 |
| E | -4.00 | -0.63 | 0.75 | -0.26 | 954.25 | 373.5 |
| EF | 0.90 | 0.96 | 0.85 | -50.98 | 1.00 | 1.00 |
| D-Index | 0.94 | 0.97 | 0.96 | 0.96 | 0.86 | 0.90 |

Obs. = Observe value (mean values obtained from the trial), sim. = values obtained from the model calibration, PD = Prediction Deviation (Negative deviations indicate under-prediction while positive deviations indicate over-prediction)

## CONCLUSION

The findings obtained from this research has shown that CERES-Sorghum model of DSSAT 4.6 was calibrated and evaluated as such can be employed to predict future sorghum yields in Sudan Savannah of Nigeria and other areas of similar environments. The results have clearly shown that CERES-Sorghum model could serve as a suitable tool for optimizing management decisions to improve the potential grain yield and above ground biomass of sorghum in the Sudan savanna agro-ecological zone of Nigeria. To ensure increased production of the crop for enhanced food security and livelihoods, this study, quantitatively shows the current promotion of sorghum production as one of the appropriate crops to be grown in the study area.

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