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Research paper

Influence of *El Niño*-Southern Oscillation on Rainfall Variability and Cereal Crop Yields in Northwestern Nigeria

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ABSTRACT

This study assessed the influence of the *El Niño*-Southern Oscillation (ENSO) on rainfall variability and cereal crop yields using monthly rainfall data (1983–2024) sourced from the NASA Prediction of Worldwide Energy Resources; annual rice, millet and sorghum yield data (2000–2024) from the National Agricultural Extension and Research Liaison Services (NAERLS); and El Niño-Southern Oscillation (ENSO) indices (1983–2024) obtained from NOAA. Rainfall anomalies were computed to characterise interannual variability, while linear regression and one-way analysis of variance (ANOVA) with eta-squared (η^2) effect size were used to evaluate crop yield trends and ENSO effects. Annual rainfall averaged 862.26 mm (CV = 37.14%) and varied significantly among ENSO phases ($F = 5.32$, $p = 0.0052$), with pronounced wetter conditions during some *La Niña* years (2021 and 2022). Rice ($p = 0.013$) and millet ($p < 0.001$) yields exhibited significant increasing trends, whereas sorghum ($p = 0.002$) showed a slight significant decline. However, ENSO had no significant influence on all the yields. These findings indicate that ENSO is a significant driver of rainfall variability but a weak predictor of annual cereal yields, highlighting the need to integrate ENSO-based seasonal climate forecasts with climate-smart agricultural practices to strengthen agrometeorological advisory services.

Keywords: *El Niño*-Southern Oscillation; Rainfall variability; Cereal crop yield; Climate variability; Northwestern Nigeria

Rainfall variability remains one of the most persistent constraints to crop production in the semi-arid regions of sub-Saharan Africa, where farming systems are predominantly rain-fed and highly sensitive to climatic fluctuations (Dagona *et al.,* 2024; Dogondaji & Magawata, 2024). In northwestern Nigeria, cereal crop production, particularly rice, millet, and sorghum, forms a major livelihood activity and constitutes a central focus of agricultural extension services (Amare & Balana, 2023; Lawrence & Elisha, 2022). However, increasing irregularity in rainfall amount, timing, and seasonal distribution has heightened production risks (Pienaah *et al.,* 2023; Rilwanu & Adamu, 2022), making it more difficult for extension agents to provide reliable advisory support to farmers operating under uncertain climatic conditions. Beyond local atmospheric processes, growing evidence indicates that rainfall variability in the tropics is partly influenced by large-scale ocean-atmosphere interactions, among which the *El Niño*-Southern Oscillation (ENSO) is the most prominent and widely studied (Cao *et al.,* 2024; Singh *et al.,* 2021). ENSO has been linked to rainfall anomalies across West Africa through its modulation of global circulation patterns, with *El Niño* and *La Niña* phases often associated with contrasting rainfall outcomes (Hashidu & Badaru, 2021; Umar & Kehinde, 2020). Despite this recognition, the practical relevance of ENSO-related rainfall variability to climate-responsive agricultural planning and agrometeorological risk assessment at sub-regional scales in Nigeria remains underexplored.

Existing studies in Nigeria, such as Ati *et al.,* (2010); Shehu *et al.,* (2016); and Umar & Kehinde (2020), have focused on national-scale rainfall variability or single-state analyses, often emphasising climatological interpretation with no attention to agricultural outcomes and planning, and also overlooking the unique climatic dynamics of the northwestern region. This gap

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limits extension systems' ability to integrate climate information into advisory services, particularly in regions such as northwestern Nigeria, where rainfall variability affects cereal yield stability (Dogondaji & Magawata, 2024; Okon *et al.,* 2021). Therefore, understanding rainfall, ENSO, and cereal crop yield variability over time, and how ENSO phases relate to these dynamics, is critical for strengthening agricultural planning in the region. Such knowledge can support the development of climate-informed advisory services that move beyond generalised recommendations to more context-specific guidance. Against this background, this study examines rainfall variability and cereal crop yield dynamics in northwestern Nigeria, with particular emphasis on the influence of ENSO phases and their implications for agricultural planning. The study analysed rainfall anomalies, crop yield trends, and ENSO-related variability to provide empirical evidence to inform agricultural planning and support resilient cereal production in the region.

MATERIALS AND METHODS

Study area

The study was conducted in northwestern Nigeria, comprising Kaduna, Kano, Katsina, Kebbi, Sokoto, Zamfara, and Jigawa States (Fig. 1). The region lies within the Sudan-Sahel ecological zone and is characterised by a semi-arid to sub-humid climate with a unimodal rainfall regime extending from May to October, followed by a dry season from November to April (Gbode *et al.,* 2019; Olalere *et al.,* 2021). Agriculture is predominantly rain-fed, with rice, millet, and sorghum representing the principal cereal crops cultivated by smallholder farmers (Abdullahi *et al.,* 2023; Federal Republic of Nigeria, 2024). Rainfall exhibits a marked south-to-north decreasing gradient and considerable interannual variability (Olalere *et al.,* 2021), making the region particularly vulnerable to climate variability and suitable for investigating the influence of the *El Niño*-Southern Oscillation (ENSO) on rainfall and cereal crop yields.

Data sources

Monthly rainfall data for the period 1983-2024 were obtained from the National Aeronautics and Space Administration Prediction of Worldwide Energy Resources (NASA POWER) database. Monthly *Niño* 3.4 sea surface temperature (SST) anomalies covering the same period were obtained from the National Oceanic and Atmospheric Administration (NOAA) Climate Prediction Centre. Annual yield data for rice, millet, and sorghum for the period 2000-2024 were obtained from the National Agricultural Extension and Research Liaison Services (NAERLS), Ahmadu Bello University, Zaria, Nigeria.

Climate data aggregation

Monthly rainfall totals were aggregated to obtain annual rainfall totals for each year, while monthly *Niño* 3.4 SST anomalies were averaged to obtain annual mean anomalies, which were used to classify individual years into *El Niño,* Neutral, and *La Niña* phases. This aggregation enabled direct comparison between annual rainfall, annual crop yield, and annual ENSO conditions. To illustrate the spatial pattern of rainfall across northwestern Nigeria, mean annual rainfall values for the selected meteorological stations were interpolated using the Inverse Distance Weighting (IDW) method in QGIS (version 3.44) to generate the rainfall distribution map.

Rainfall anomaly and ENSO phase classification

Rainfall variability in northwestern Nigeria was assessed using annual rainfall anomalies computed relative to the long-term mean annual rainfall for the period 1983–2024. Rainfall anomalies provide a direct measure of departures from average climatic conditions and are widely used to evaluate interannual rainfall variability. Positive anomaly values indicate wetter-than-average years, whereas negative values indicate drier-than-average years. The computed rainfall anomalies were subsequently analysed by ENSO phases to evaluate their influence on rainfall behaviour in northwestern Nigeria. The annual rainfall anomaly was calculated as:

$$RA_i = R_i - \bar{R} \text{……………………. (1)}$$

Where: RA_i is the rainfall anomaly for year i (mm); R_i is the observed annual rainfall (mm); and $\bar{R}$ is the long-term mean annual rainfall (mm).

To investigate the influence of ENSO on rainfall anomaly and crop yields, each year was classified into an ENSO phase using the annual mean *Niño* 3.4 sea surface temperature anomaly derived from the monthly NOAA *Niño* 3.4 dataset. Annual ENSO phases were assigned using the annual mean *Niño* 3.4 sea surface temperature anomaly. Years with anomalies ≥ +0.5°C were classified as *El Niño*, years with anomalies ≤ −0.5°C as *La Niña*, while years with anomalies between −0.5°C and +0.5°C were classified as Neutral. This annual classification was adopted to enable direct comparison with annual rainfall totals and annual crop yields. The classified ENSO phases were subsequently used to evaluate differences in rainfall anomalies and cereal crop yields among *El Niño*, Neutral, and *La Niña* years.

Crop yield trend analysis

Trends in rice, millet, and sorghum yields from 2000 to 2024 were evaluated using simple linear regression. The regression analysis was used to determine the direction and magnitude of changes in crop yields over time and to identify whether crop yields exhibited increasing or decreasing trends during the study period. The linear regression model is expressed as:

$$CY_t = \alpha + \beta_t + \epsilon_t \text{ ……………….. (2)}$$

Where: CY_t represents the crop yield (t/ha) in year t; α is the intercept; β_t is the regression coefficient representing the average annual change in yield; ϵ_t is the random error term.

Analysis of ENSO influence on rainfall and crop yield variability

The influence of ENSO on rainfall variability was evaluated by comparing annual rainfall anomalies among *El Niño*, Neutral, and *La Niña* years using one-way analysis of variance (ANOVA). Similarly, the effects of ENSO on rice, millet, and sorghum yields were assessed by comparing mean annual crop yields

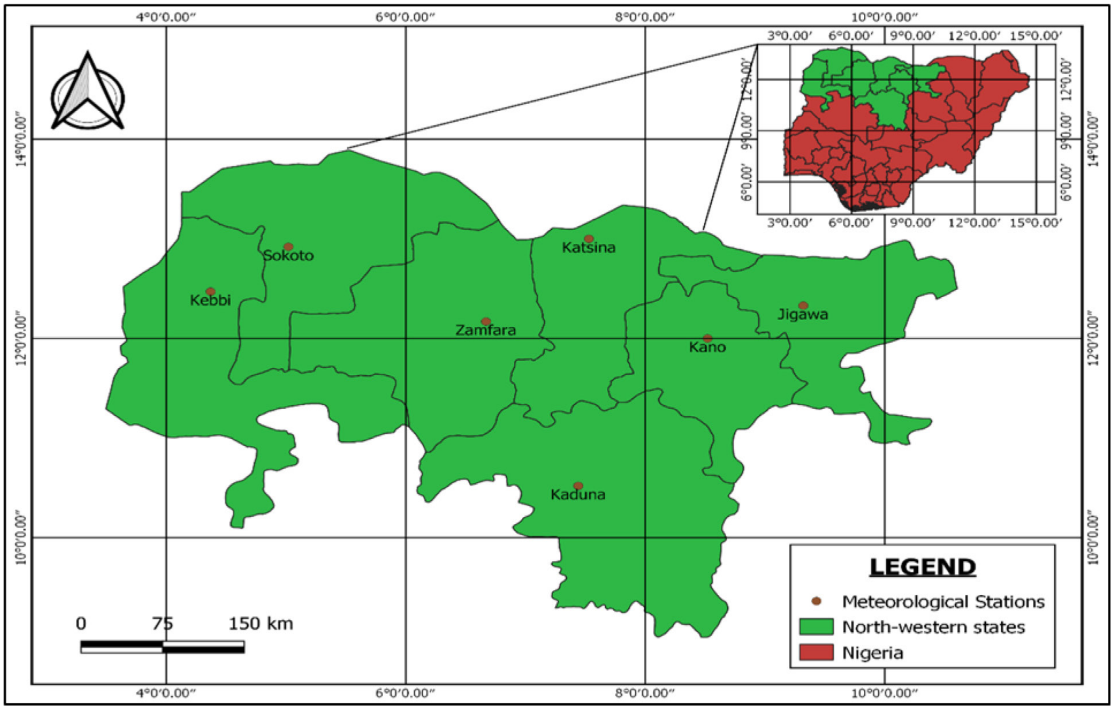

Fig. 1: Study Area (Northwestern Nigeria)

across the three ENSO phases. Before conducting the ANOVA, the assumptions of normality and homogeneity of variances were assessed using the Shapiro-Wilk and Levene's tests, respectively. Statistical significance was evaluated at the 5% probability level ($p < 0.05$). To complement the significance tests, effect sizes (η^2; eta squared) were calculated for each ANOVA to quantify the proportion of total variance in rainfall anomalies and crop yields attributable to ENSO phase. Effect sizes were interpreted following Cohen's guidelines, where η^2 values of approximately 0.01, 0.06, and 0.14 represent small, moderate, and large effects, respectively. Reporting both p-values and effect sizes provided a more comprehensive assessment of the practical significance of ENSO-related differences. Box-and-whisker plots were used to illustrate the distribution of rainfall anomalies and crop yields under the different ENSO phases. The boxplots display the median, interquartile range (IQR), whiskers representing data dispersion, and outliers, thereby facilitating visual comparison of rainfall anomalies and crop yield variability among *El Niño*, Neutral, and *La Niña* conditions. The combined use of ANOVA, effect size estimation, and box-and-whisker plots provided both quantitative and graphical evaluation of the influence of ENSO on rainfall variability and cereal crop yields in northwestern Nigeria, thereby strengthening the interpretation of the implications of rainfall variability and ENSO phases for agricultural planning.

RESULTS

Rainfall characteristics of the study area

The rainfall characteristics of the study area are presented in Table 1. Mean annual rainfall varied considerably across northwestern Nigeria. Kaduna State recorded the highest mean annual rainfall (1739.15mm), whereas Sokoto (645.75mm), Katsina (662.41mm), and Jigawa (684.16mm) recorded the lowest values. Kaduna exhibited the highest coefficient of variation (59.07%), indicating substantial interannual rainfall fluctuations despite receiving the greatest annual rainfall. In contrast, Zamfara recorded the lowest coefficient of variation (28.38%), suggesting relatively more stable rainfall conditions. Kano, Katsina, and Jigawa displayed moderate rainfall variability, with coefficients of variation ranging from approximately 42% to 46%. The results further indicate that the regional mean annual rainfall in northwestern Nigeria from 1983 to 2024 was 862.26mm, with annual totals ranging from 427.90mm to 2,199.82mm. The relatively high standard deviation (320.26mm) and coefficient of variation (37.14%) indicate substantial interannual variability in rainfall across the study period.

The spatial distribution of mean annual rainfall across northwestern Nigeria is presented in Fig. 2. The map reveals a south-to-north rainfall gradient characteristic of the Sudan-Sahel ecological zone, with annual rainfall exceeding 1,700mm in southern Kaduna but decreasing to less than 700mm across the deeper northern states of Sokoto, Katsina, and Jigawa. Intermediate rainfall amounts occur over Kebbi, Zamfara, and Kano. This spatial pattern agrees with the descriptive statistics presented in Table 1 and reflects the progressive weakening of monsoonal moisture northwards across the region. The observed spatial differences in rainfall amount and variability demonstrate the heterogeneous climatic conditions across northwestern Nigeria and provide the climatic background for assessing the influence of ENSO on rainfall anomalies and cereal crop yields.

Rainfall anomaly characteristics and influence of ENSO

The temporal variation in annual rainfall anomalies and their relationship with ENSO phases in northwestern Nigeria

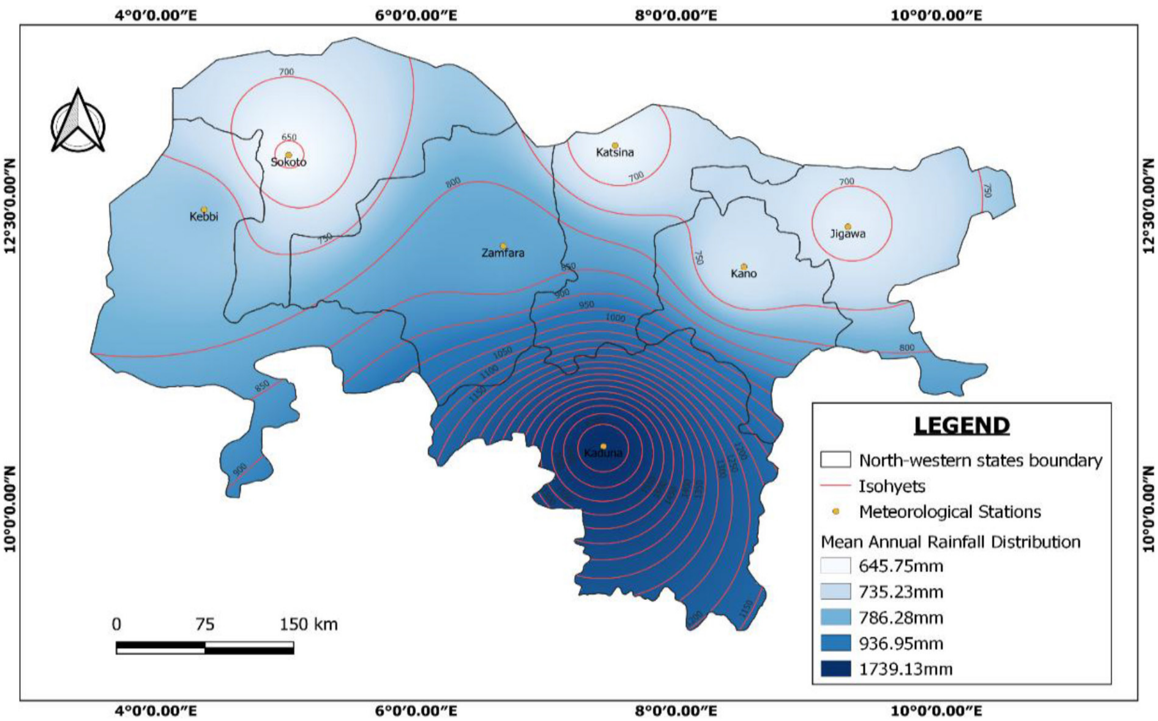

Fig. 2: Spatial distribution of mean annual rainfall across northwestern Nigeria (1983–2024)

Table 1: Rainfall Information of the Selected Stations (1983–2024)

State	Longitude (°E)	Latitude (°N)	Maximum (mm)	Minimum (mm)	Mean Rainfall (mm)	SD (mm)	CV (%)
Kaduna	7.44	10.52	6360.63	664.45	1739.15	1027.29	59.07
Kano	8.52	12.00	1845.69	200.39	710.31	299.23	42.13
Katsina	7.53	13.00	1784.55	374.41	662.41	304.08	45.91
Kebbi	4.37	12.47	2202.76	485.16	767.30	259.35	33.80
Sokoto	5.02	12.92	1403.83	342.77	645.75	240.07	37.18
Zamfara	6.67	12.17	1542.85	300.59	819.83	232.64	28.38
Jigawa	9.32	12.33	1693.74	210.94	684.16	289.51	42.32
Northwestern Nigeria	-	-	2199.82	427.90	862.26	320.26	37.14

Source: Computed from NASA POWER rainfall data (1983–2024)

between 1983 and 2024 is illustrated in Fig. 3. The rainfall anomaly series (Fig. 3a) showed no sustained monotonic trend but rather a succession of wet and dry years, highlighting the highly variable nature of the regional rainfall regime. Most years before 2019 were characterised by small to moderate rainfall anomalies, whereas the period between 2020 and 2022 recorded exceptionally large positive anomalies, with 2021 representing the wettest year during the study period. Conversely, several years during the late 1990s and late 2000s experienced pronounced negative rainfall anomalies, indicating substantial rainfall deficits. Although positive and negative rainfall anomalies occurred under all ENSO phases, some years (2021 and 2022) classified as *La Niña* exhibited pronounced positive rainfall anomalies. Several Neutral years, such as 1994, 2004 – 2006, 2009, 2013, 2020, and 2024, experienced substantial departures from the long-term mean, indicating that multiple climatic drivers beyond ENSO influence rainfall variability in the region.

The annual mean *Niño* 3.4 index (Fig. 3b) shows substantial fluctuations in ENSO conditions during the study period, with pronounced warm-phase events occurring in the late 1980s, 1997–1998, 2015–2016, and 2023–2024, and persistent cold-phase episodes during the mid-1980s, 1999–2001, 2010–2012, and 2020–2022. These alternating warm and cold phases corresponded with noticeable changes in rainfall anomalies, suggesting that Pacific sea surface temperature variability exerts a measurable influence on rainfall over northwestern Nigeria. However, the occurrence of both wet and dry years during Neutral conditions further suggests that the regional rainfall regime is also modulated by other large-scale climate systems, including variations in the West African Monsoon, tropical Atlantic sea surface temperatures, the African Easterly Jet, and land-atmosphere interactions.

The distribution of rainfall anomalies across ENSO

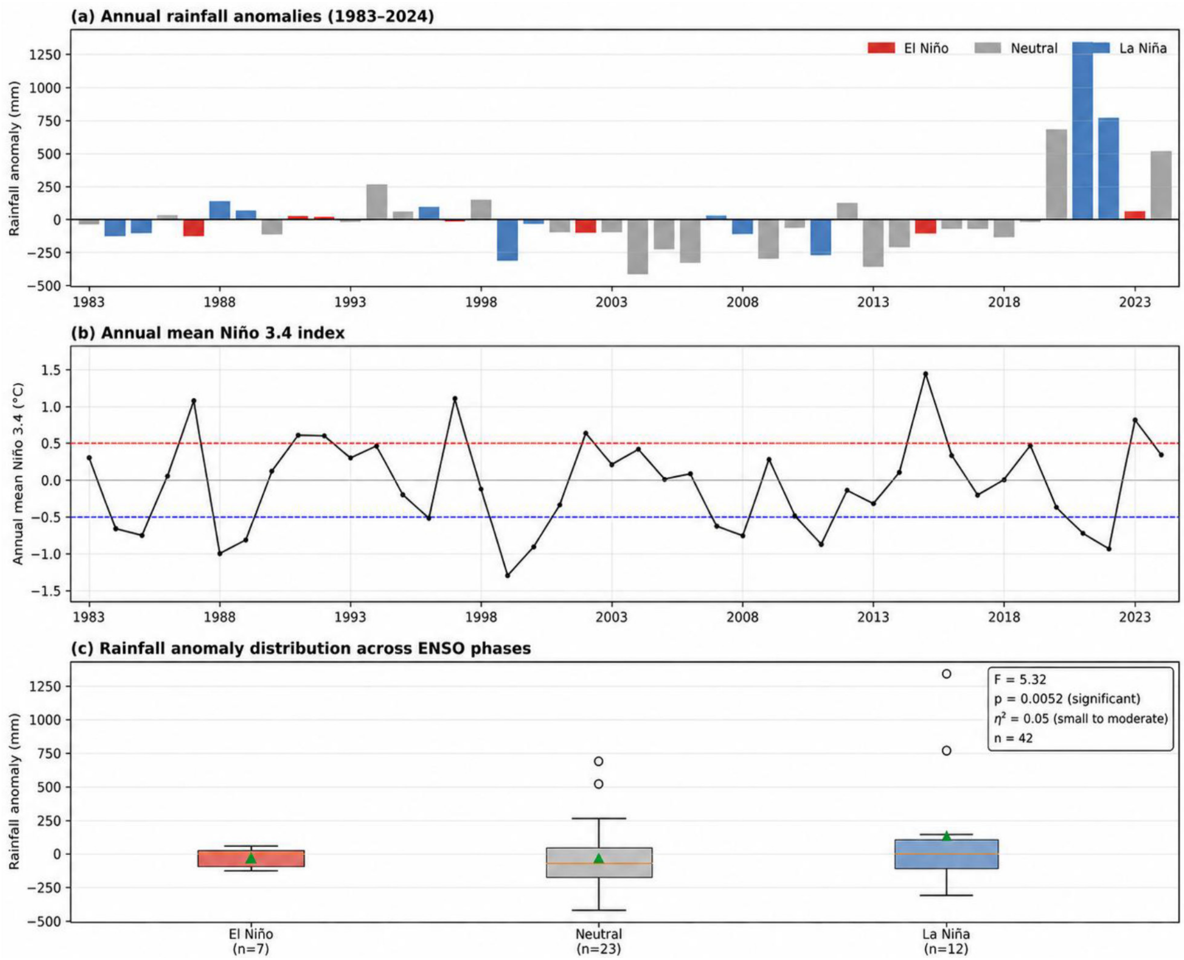

Fig. 3: Annual rainfall anomalies and ENSO variability in northwestern Nigeria (1983–2024) (a) Annual rainfall anomalies relative to the long-term mean, with bar colours indicating ENSO phase (b) Annual mean *Niño* 3.4 anomalies showing El N*iño* (≥+0.5 °C), Neutral (-0.5 to +0.5 °C), and La *Niña* (≤-0.5 °C) conditions. (c) Distribution of rainfall anomalies across ENSO phases

phases is further illustrated by the box-and-whisker plots (Fig. 3c). *La Niña* years were characterised by relatively higher median rainfall anomalies and a wider range of variability, reflecting the occurrence of some exceptionally wet years like 2021 and 2022. Conversely, *El Niño* years generally exhibited lower median rainfall anomalies, indicating a tendency towards slightly drier conditions. Although the interquartile ranges of the three ENSO categories overlap, clear differences in their central tendencies are evident. The one-way analysis of variance confirmed that rainfall anomalies differed significantly among ENSO phases ($F = 5.32$, $p = 0.0052$), demonstrating that ENSO exerts a statistically significant influence on annual rainfall variability in northwestern Nigeria. The estimated effect size ($\eta^2 = 0.05$) is climatically meaningful because it indicates that ENSO accounted for a small to moderate influence on the total variance in annual rainfall anomalies. This suggests that while ENSO contributes moderately to interannual rainfall variability, a significant proportion of rainfall variation arises from other regional and global climatic processes operating over West Africa.

Trends in cereal crop yields

The temporal trends in the average yields of rice, millet, and sorghum, and in aggregate cereal production in northwestern Nigeria from 2000 to 2024 are presented in Fig. 4. Linear regression analysis revealed contrasting long-term productivity trends among the three cereal crops, reflecting differences in crop performance over the study period.

Rice yield exhibited a significant positive trend, increasing from 1.68 t/ha in 2000 to 1.91 t/ha in 2024 (Fig. 4a). The fitted regression model ($y = 0.0088x + 1.660$) explained 28.1% of the temporal variation in rice yield ($R^2 = 0.281$, $p = 0.013$), indicating a modest but statistically significant improvement in productivity over time. Although annual fluctuations were evident, particularly after 2017, the overall trend suggests gradual gains in rice production across the region. Millet recorded the strongest positive trend among the cereal crops (Fig. 4b). Average yield increased from 1.17 t/ha in 2000 to 1.51 t/ha in 2024, with regression analysis indicating a significant increase ($y = 0.0136x + 1.094$; $R^2 = 0.594$, $p < 0.001$). Time explained 59.4% of the variation in millet yield ($R^2 = 0.594$), demonstrating that millet experienced the most consistent and sustained productivity improvement during the study period. In contrast, sorghum exhibited a significant declining trend (Fig. 4c). Although yields increased during the early years of the study and

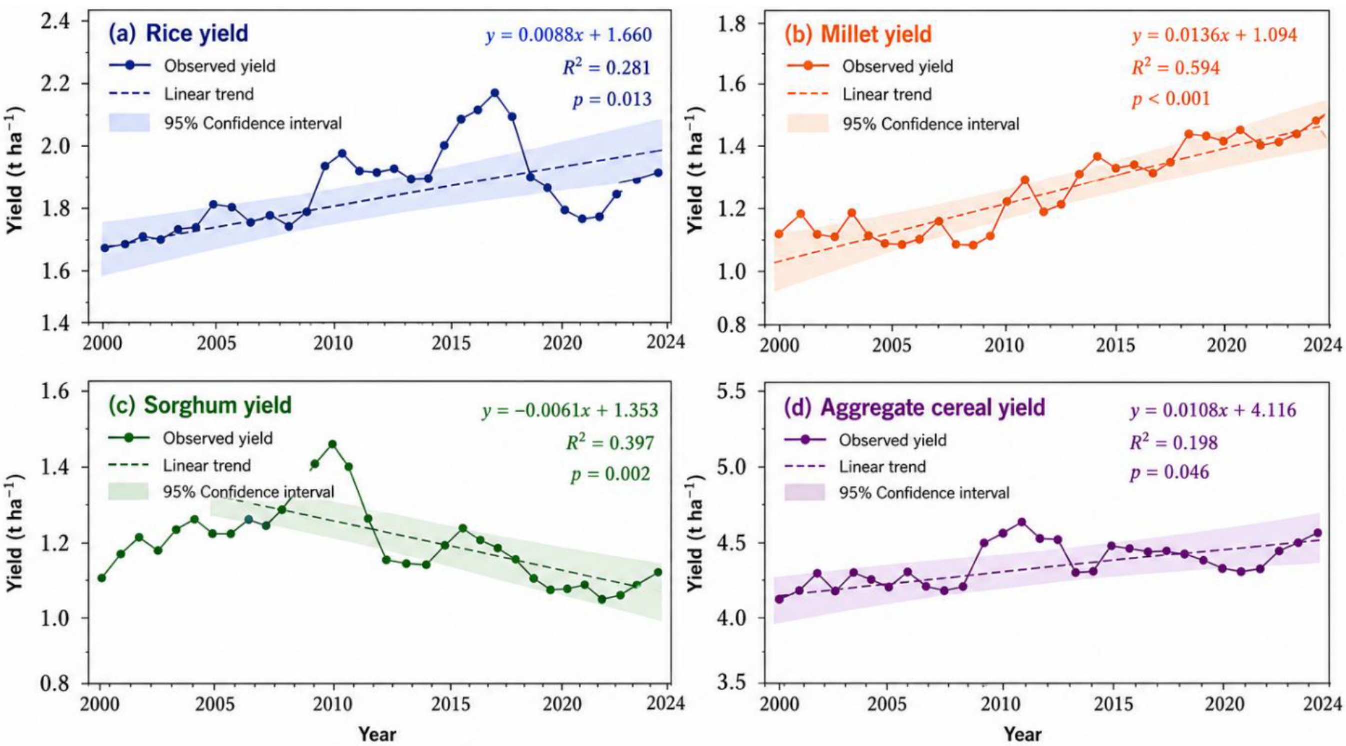

Fig. 4 (a-d): Temporal trends in the average yields of rice, millet, sorghum, and aggregate cereal production in northwestern Nigeria (2000-2024)

reached a maximum around 2010, productivity declined thereafter, resulting in a negative regression slope (y = –0.0061x + 1.353). The regression model accounted for 39.7% of the observed variation (R^2 = 0.397, p = 0.002), indicating a statistically significant reduction in sorghum yield over the 25-year period. Despite the contrasting responses of the individual crops, the aggregate cereal yield showed a slight but significant increasing trend (Fig. 4d). Average combined yield increased from 4.11 t/ha in 2000 to 4.56 t/ha in 2024, with the regression equation (y = 0.0108x + 4.116) explaining 19.8% of the temporal variation (R^2 = 0.198, p = 0.046). Although the coefficient of determination was relatively low, the positive and statistically significant slope indicates a gradual improvement in overall cereal productivity across northwestern Nigeria.

Cereal crop yield response to ENSO phases

The distribution of rice, millet, and sorghum yields across *El Niño*, Neutral, and *La Niña* phases in northwestern Nigeria from 2000 to 2024 is presented in Fig. 5. Although slight differences in yield distributions were observed among ENSO phases, one-way ANOVA indicated that these variations were not statistically significant for any of the cereal crops. Rice yield exhibited the largest between-group variability ($F(2,22) = 1.15$, p = 0.338), followed by millet ($F(2,22) = 0.39$, p = 0.683) and sorghum ($F(2,22) = 0.29$, p = 0.749). The corresponding effect sizes were small ($\eta^2 = 0.09$ for rice and $\eta^2 = 0.03$ for both millet and sorghum), indicating that ENSO phase explained only a negligible proportion of the observed interannual variation in cereal yields.

The rice boxplots (Fig. 5a) show a tendency towards slightly higher median yields during *La Niña* and Neutral years compared with *El Niño* years. However, the considerable overlap in the interquartile ranges and whiskers demonstrates that year-to-year variability within each ENSO phase exceeded the variability among phases. Similarly, millet yields (Fig. 5b) exhibited nearly identical median values and dispersion across all ENSO categories, indicating a highly stable response irrespective of ENSO conditions. Sorghum yields (Fig. 5c) also displayed substantial overlap among the three ENSO phases, with only minor differences in central tendency and variability. This implies that while ENSO-related climatic variability may influence rainfall patterns, these differences were not translated into statistically distinguishable differences in cereal yields. The overlap in yield distributions among *El Niño*, Neutral, and *La Niña* years suggests that cereal production in northwestern Nigeria is influenced by a wider range of interacting factors than ENSO phase alone. These include intra-seasonal rainfall distribution, soil moisture availability, crop management practices, varietal improvements, fertiliser use, and other socio-economic and environmental factors that may buffer the effects of large-scale climate variability on cereal crop production.

DISCUSSION

ENSO as a driver of rainfall variability in northwestern Nigeria

The significant differences in rainfall anomalies among ENSO phases demonstrate that ENSO is an important driver of interannual rainfall variability in northwestern Nigeria, as evidenced by the significant differences in rainfall anomalies among *El Niño,* Neutral, and *La Niña* years (Fig. 3; F = 5.32, p = 0.0052). This pattern is consistent with the influence of ENSO on tropical atmospheric circulation, whereby changes in Pacific sea surface temperatures modify the Walker Circulation and affect the strength of the West African Monsoon and moisture transport into the Sudan-

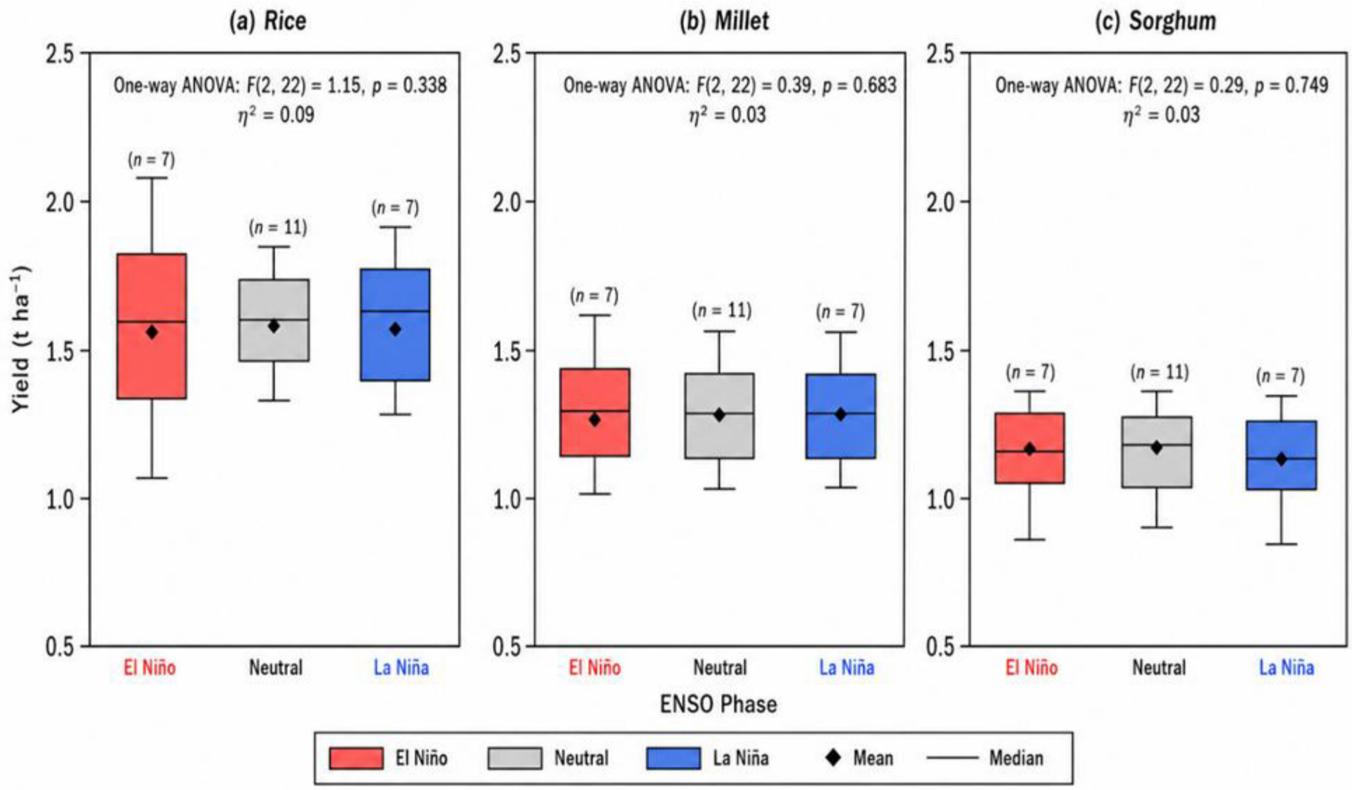

Fig. 5 (a-c): Yield distribution of rice, millet, and sorghum across ENSO phases in Northwestern Nigeria (2000–2024)

Sahel (Okumura, 2019). Similar relationships between ENSO, sea surface temperature anomalies, and rainfall variability over Nigeria have been reported by Egbuawa *et al.,* (2017) and Salau *et al.,* (2016). Despite the significant relationship, the relatively small effect size ($\eta^2 = 0.05$) indicates that ENSO explained only a modest proportion of the observed rainfall variability. This suggests that rainfall in northwestern Nigeria is also influenced by other large-scale and regional climatic processes, including tropical Atlantic sea surface temperature anomalies, the Intertropical Convergence Zone, the African Easterly Jet, and land–atmosphere interactions (Dia-Diop *et al.,* 2020; Nicholson, 2013). Consequently, substantial rainfall anomalies may occur within the same ENSO phase owing to the influence of other climatic drivers. Similar conclusions have been reported by Hashidu & Badaru (2021) for northern Nigeria and Ta *et al.* (2016) for West Africa, where ENSO was found to influence rainfall but was not the sole climatic driver. These findings have important implications for agricultural planning in the predominantly rain-fed farming systems of northwestern Nigeria. Although ENSO alone cannot fully predict seasonal rainfall, its significant influence suggests that ENSO-based seasonal climate forecasts can provide useful early warning information for crop management (Bello & Mamman, 2018; Tanko *et al.,* 2026). Integrating ENSO forecasts with regional climate monitoring and local meteorological observations would improve the reliability of seasonal forecasts and strengthen climate adaptation strategies for crop production.

ENSO influence on cereal crop yields in northwestern Nigeria

Although ENSO significantly influenced rainfall variability, its effects on rice, millet, and sorghum yields were not statistically significant (Fig. 5). The one-way ANOVA showed no significant differences in mean yields among *El Niño*, Neutral, and *La Niña* years for rice ($p = 0.338$), millet ($p = 0.683$), and sorghum ($p = 0.749$). Similarly, the box-and-whisker plots revealed considerable overlap in yield distributions across the three ENSO phases, indicating that annual cereal productivity remained relatively stable despite differences in ENSO conditions. The absence of significant yield differences suggests that ENSO-related rainfall variability alone was insufficient to produce measurable changes in cereal productivity. Cereal productivity is influenced by multiple interacting factors, including rainfall distribution, temperature, soil fertility, improved crop varieties, and farm management practices (Ngoune-Tandzi & Mutengwa, 2020). Consequently, the effect of ENSO on cereal crop yields may have been moderated by farmers' adaptation strategies and improvements in agricultural practices over time. These findings are consistent with the small effect size ($\eta^2 = 0.05$) obtained for rainfall, indicating that ENSO explained only a limited proportion of rainfall variability in the region. Therefore, while ENSO remains useful for seasonal climate forecasting, it should not be considered an independent predictor of cereal yields in northwestern Nigeria. Consequently, improving agricultural resilience in the region should focus on integrating ENSO-based seasonal climate forecasts with climate-smart agronomic practices, such as improved crop varieties, efficient soil fertility management, and appropriate water conservation measures. Such an integrated approach would strengthen farmers' capacity to cope with increasing climate variability and enhance sustainable cereal production in northwestern Nigeria.

CONCLUSIONS

This study examined rainfall variability, ENSO phases, and cereal crop yields in northwestern Nigeria. Annual rainfall exhibited substantial interannual variability, with significant differences among ENSO phases. However, the small effect size indicates that ENSO explained only a limited proportion of rainfall variability, suggesting the influence of other regional climatic drivers. Rice and millet yields showed gradual improvement over the study period, whereas sorghum remained relatively stable. Despite the significant influence of ENSO on rainfall, no significant differences were observed in rice, millet, or sorghum yields across ENSO phases, indicating that crop productivity is shaped by both climatic and non-climatic factors, including improved management practices and farmers' adaptation strategies. The study concludes that ENSO provides predictive information for anticipating rainfall variability when integrated with local weather forecasts. Such a forecast could support sustainable cereal production and climate adaptation in northwestern Nigeria.

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Authors Contributions: **Isah Abdullahi Tanko:** Conceptualisation, methodology, data collection, statistical analyses, interpretation, visualisation, and drafting; **Tayo Iyanda Yahaya:** Supervision, intellectual guidance during the conceptualisation and design of the study, and manuscript revision; **Aishetu Abdulkadir:** Supervision, methodological guidance, and manuscript revision; **Joel Aghaegbunam Ezenwora:** Supervision, technical advice, and model framework review; **Ishiaku Ibrahim:** Data curation and manuscript editing; **Abdulrazak Tijjani Kura:** Data curation, input to discussion, and proofreading of the manuscript.

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