

## PRECIPITATION EFFECTIVENESS AND RICE YIELD: IMPLICATIONS FOR AGROECOSYSTEM RESILIENCE IN LANGTANG SOUTH, NIGERIA

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**Background:** Climate variability significantly constrains agricultural productivity, particularly in rainfed systems where precipitation governs soil moisture and crop growth. In Nigeria, declining and erratic rainfall patterns threaten rice production, a staple crop critical for food security. Precipitation effectiveness, including rainfall timing and distribution, plays a key role in determining yield outcomes and shaping agroecosystem resilience under changing climatic conditions. **Objectives:** This study examines the influence of precipitation effectiveness indices on rice yield in Langtang South, Nigeria, aiming to identify key rainfall determinants of productivity and evaluate their implications for agroecosystem resilience under rainfed agricultural conditions. **Methods:** The study was conducted in Langtang South LGA, Plateau State, Nigeria, a tropical wet–dry climate region. Daily rainfall data (2001–2025) were obtained from the College of Agriculture Garkawa, while rice yield data were sourced from the Plateau State Ministry of Agriculture. Precipitation effectiveness indices (PEI) including hydrologic ratio, dry spells, rainfall onset, cessation, length of rainy season, and number of rainy days were computed. Descriptive statistics were used to summarize temporal patterns. Relationships between PEI variables and rice yield were examined using multiple linear regression, with additional generalized additive models (GAM) applied in R to capture potential non-linear effects and thresholds. **Results:** Results indicated onset dates typically begin in April, fluctuating slightly year to year within a narrow nine-day window. Rainfall onset was consistent across the study period. Cessation generally occurred in late October, though some years exhibited shorter growing seasons and reduced yields, while peak yields were recorded in other years (approximately 4.0 t/ha). Cessation rainfall showed high variability. Overall, intra-seasonal rainfall variability influenced agricultural outcomes more than total annual rainfall. Regression showed an observed trend between precipitation effectiveness indices and yield ( $R = 0.589$ ), explaining 34.7% variance but not significant ( $p = 0.122$ ). Relationships were predominantly linear, with no strong evidence of non-linear or threshold effects. Yield variability suggests limited agroecosystem resilience to intra-seasonal rainfall fluctuations. Only rainfall had a significant negative effect on yield ( $p = 0.048$ ); other variables were not significant. These findings advance understanding of intra-seasonal precipitation dynamics as a primary driver of rice yield variability in tropical rainfed systems, providing a framework for improved agroclimatic management and resilience assessment under variable climate conditions. **Conclusion:** The study identifies intra-seasonal rainfall variability as the dominant driver of rice yield fluctuations in Langtang South. Yield variability reflects limited agroecosystem resilience to rainfall fluctuations, with relationships largely linear and no strong evidence of non-linear or threshold effects.

**Keywords:** agroecosystem resilience; hydroclimatic variability; precipitation indices; climate variability; sustainable agriculture; SDG 2: Zero Hunger; rice yield; environmental stress; rain-fed systems.

### INTRODUCTION

The productive capacity of land resources is fundamentally constrained by climate, as climatic variability remains a major limitation to agricultural production, particularly in developing countries (Diarra et al., 2017; FAO, 2020). Crop yields are influenced by multiple indicators of climate variability, including precipitation dynamics and soil moisture availability, which directly regulate plant growth processes and productivity outcomes (Baweja, 2011; Rossato et al., 2017; Vogel et al., 2019). In rainfed agroecosystems, these hydroclimatic factors are especially critical due to the absence of supplementary irrigation systems.

Globally, approximately one-third of total crop production is affected by drought stress, the intensity and spatial-temporal variability of which remain difficult to predict due to interacting climatic drivers such as rainfall frequency, evaporative demand, and soil moisture deficits (Oladosu et al., 2019). Water limitation reduces realized yield potential of crop varieties (Blum, 2011), with drought identified as the most significant abiotic stressor, constraining up to 50% of global rice productivity annually (Nelson et al., 2014; Pandey & Shukla, 2015).

Beyond total rainfall amounts, precipitation effectiveness indices provide a more integrated representation of agroclimatic conditions by capturing rainfall timing, distribution, intensity, and resulting soil water availability (Wuyep et al., 2013;

Adebayo et al., 2012). These indices are particularly relevant in rainfed systems, where rainfall constitutes the primary determinant of crop development and yield formation (Ezenekwe et al., 2013). Accordingly, precipitation effectiveness is increasingly recognized as a more robust framework for assessing agricultural climate suitability than rainfall totals alone.

In Nigeria, agriculture supports approximately 70% of the population, with crop production heavily dependent on rainfall regimes. However, declining rainfall amounts and increasing interannual variability associated with climate change have been implicated in reduced agricultural productivity (Audu, 2012; Wuyep & Daloeng, 2020; Ishaku et al., 2021). Rice (*Oryza sativa*) is a strategic staple crop for national food security and an essential component of dietary consumption patterns in Nigeria (Mohidem et al., 2022). Given rapid population growth, cereal production is projected to increase by approximately 70% over the next three decades to meet rising demand (Baweja, 2011), intensifying pressure on rainfed production systems.

Recent increases in global food prices, particularly cereals, alongside import restrictions, have further emphasized the necessity of strengthening domestic rice production systems. In this context, declining and increasingly erratic rainfall patterns pose a direct threat to agricultural output, food security, and rural livelihoods, despite Nigeria's extensive arable land resources (Audu, 2012). This challenge is particularly acute in Langtang South, where agricultural production is predominantly

rained and highly sensitive to intra-seasonal rainfall variability, underscoring the need for localized hydroclimatic assessment to support adaptive agricultural planning.

Key rainfall characteristics influencing agricultural productivity in tropical environments include rainfall onset, cessation, length of rainy season, and dry spell frequency (Ezenekwe et al., 2013). Previous studies in Nigeria have applied agroclimatological approaches to quantify these variables using methods such as the Ogive approach (Adefolalu, 1993) and wind shear models (Abdulhamid & Abubakar, 2002; Omotosho et al., 2000). Rainfall onset is generally defined as the period when accumulated precipitation becomes sufficient to support germination and early crop growth, typically marked by two to four effective rainfall events (Omotosho et al., 2000; Wuyep, 2011; Danladi, 2012). Conversely, rainfall cessation marks the termination of agriculturally effective rainfall, while the length of the rainy season is defined as the interval between onset and cessation (Danladi, 2012; Zemba et al., 2013). These indices are essential for optimizing planting calendars and improving rainwater utilization efficiency (Ati et al., 2009).

Empirical evidence consistently demonstrates the sensitivity of crop yields to precipitation timing and variability. Wuyep et al. (2013) reported that early rainfall onset enhances Irish potato yields in Jos-Plateau, while delayed onset significantly reduces productivity. Similarly, Adebayo & Adebayo (1997) showed that hydrological ratio, rainfall onset, length of rainy season, dry spell frequency, and early-season rainfall jointly explained 73.5% of variation in upland rice yield in Adamawa State. In Sokoto, adaptive responses among farmers highlighted rainfall variability, particularly in onset and cessation dates, as a major constraint to optimal rice production (Ikpe, 2014).

Despite these contributions, existing studies remain limited in three key aspects. First, most analyses focus on linear relationships between rainfall variables and yield, with insufficient consideration of potential non-linearities and threshold effects in precipitation–yield dynamics. Second, there is limited integration of multiple precipitation effectiveness indices into a unified analytical framework for rainfed rice systems in Nigeria. Third, few studies explicitly link

interannual precipitation variability and extreme rainfall events to yield stability and agroecosystem resilience.

Addressing these gaps, this study examines the influence of precipitation effectiveness indices on rice yield in Langtang South, Plateau State, Nigeria, with particular emphasis on both linear and non-linear rainfall–yield relationships. The study further seeks to improve understanding of the ecological mechanisms through which rainfall variability affects agroecosystem resilience and productivity under rainfed conditions using multi-decadal climatic and yield datasets. In particular, the study focuses on intra-seasonal rainfall distribution and its effects at key phenological stages, hypothesizing that variability in rainfall timing within the season may exert greater influence on rice yield than total seasonal precipitation.

Accordingly, the study tests the following hypotheses:

H1: Intra-seasonal variability in rainfall, particularly during onset, cessation, and early growth stages, exerts a stronger influence on rice yield than seasonal totals.

H2: Precipitation effectiveness indices, capturing timing, distribution, and intensity of rainfall within the growing season, are reliable predictors of rice productivity, with higher effectiveness corresponding to increased yield.

## MATERIALS AND METHODS

### Study area

Langtang South Local Government Area (LGA), Plateau State, Nigeria, covers 838 km<sup>2</sup>, with its administrative headquarters in Mabudi town. The area is characterized by a tropical wet and dry climate with distinct rainy (April–October) and dry (November–March) seasons (Choji, 2025). Geographic coordinates range approximately from 8°22'13"–8°52'30" N latitude and 9°42'00"–10°30'00" E longitude (Figure 1). Mean monthly temperatures vary between 26°C (December–January) and 38°C (April) (Choji, 2025). The hydrological system is dominated by the Wase and Shemankar rivers and their dendritic tributaries, including Pil-Gani, Bakwai, and Zamko (Choji, 2025; Ogbale et al., 2025). The projected population is 304,785 (NPC, 2024).

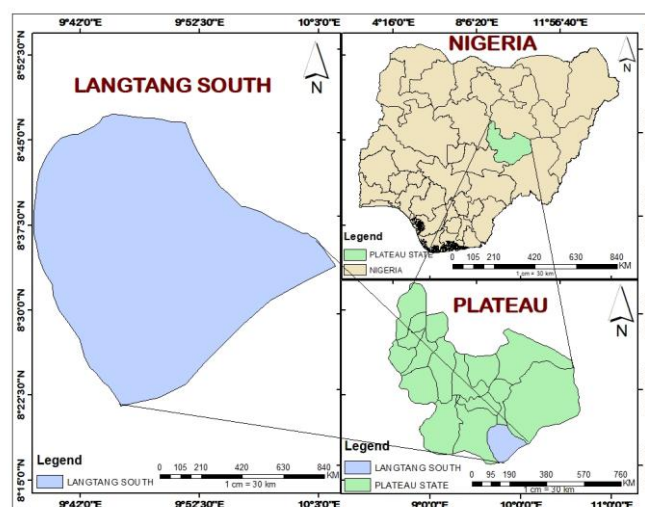


Figure 1. Map of the study area

### Data collection

Daily rainfall data for the period 2001–2025 were obtained from the College of Agriculture Garkawa, Mikan LGA. Annual rice yield data (ton/ha) were sourced from the Plateau State

Ministry of Agriculture. All datasets were screened for missing values, inconsistencies, and outliers prior to analysis. No imputation was applied; only complete and verified records were used to ensure data integrity.

## Precipitation effectiveness indices (PEI)

Precipitation effectiveness was assessed using a suite of agroclimatic indices commonly applied in tropical agricultural climatology (Walter, 1967; Adefolalu, 1993), including hydrologic ratio, rainfall onset and cessation, length of rainy season, number of rainy days, and dry spell characteristics.

### Hydrologic ratio (HR)

Hydrologic ratio was computed as:

$$HR = P / PE, \quad (1)$$

where P is mean annual precipitation (mm), and PE is potential evapotranspiration (mm) (Walter, 1967). HR is used as an indicator of climatic water availability and general suitability for rainfed rice cultivation.

### Dry spells

Dry spells were defined as periods of at least 15 consecutive days (three pentads) receiving <2 mm of rainfall during the growing season (Adefolalu, 1993). This threshold is widely used in agroclimatological studies to represent agriculturally significant water stress periods.

### Rainfall onset and cessation

Rainfall onset was defined as the first month in which accumulated rainfall reaches or exceeds 51 mm following antecedent conditions below this threshold (Walter, 1967; Adefolalu, 1988). Rainfall cessation was defined analogously as the last month meeting the same criterion. These definitions ensure consistency with established agro-meteorological standards for crop-growing season delineation.

### Length of rainy season (LRS)

The length of the rainy season was computed as:

$$LRS = \text{Cessation DOY} - \text{Onset DOY}, \quad (2)$$

where DOY refers to day of year.

### Number of rainy days

Rainy days were defined as days receiving  $\geq 2$  mm of rainfall, and the total number of such days within the rainy season was computed annually.

### Statistical analysis

All precipitation effectiveness indices (onset date, cessation date, length of rainy season, number of rainy days, dry spells, hydrologic ratio), together with total annual rainfall, were analysed alongside rice yield (ton/ha).

### Descriptive analysis

Initial analysis involved computation of mean, standard deviation, and variance to characterize interannual variability in both climatic and yield data.

### Multiple linear regression

The relationship between rice yield and precipitation effectiveness indices was examined using multiple linear regression of the form:

$$Y = \alpha + \beta_1 X_1 + \beta_2 X_2 + \beta_3 X_3 + \dots + \beta_6 X_6 + \varepsilon, \quad (3)$$

where Y is rice yield (ton/ha);  $\alpha$  is intercept;  $\beta_1$ – $\beta_6$  is regression coefficients;  $\varepsilon$  is error term; predictor variables included:  $X_1$  is total rainfall (mm);  $X_2$  is number of dry spells (April–August;  $\geq 15$  consecutive days with <2 mm rainfall);  $X_3$  is rainfall onset date;  $X_4$  is rainfall cessation date;  $X_5$  is length of rainy season;  $X_6$  is number of rainy days.

Model assumptions (linearity, independence, homoscedasticity, and normality of residuals) were evaluated prior to interpretation of results.

### Generalized additive models (GAM)

To account for potential non-linear relationships and threshold responses between precipitation variables and yield, Generalized additive models (GAMs) were implemented using the mgcv package in R (version 4.4.1). GAMs were applied as a robustness check to complement linear regression and to detect possible non-linear response curves in yield sensitivity to rainfall variability.

### Extreme event analysis

Extreme hydroclimatic conditions were quantified using dry spells of  $\geq 15$  consecutive days with <2 mm rainfall. Interannual variability and potential trends in extreme events were analysed to identify changes in rainfall stress exposure over time.

### Yield stability and agroecosystem resilience

Yield stability was assessed using two complementary metrics.

Coefficient of variation (CV):

$$CV = (\sigma / \mu) \times 100. \quad (4)$$

Yield stability index (YSI): computed as interannual deviation of yield from long-term mean yield.

These indices were used to quantify interannual yield variability as a proxy for agroecosystem resilience under rainfall variability conditions.

### Data analysis framework

Relationships between precipitation effectiveness indices, extreme events, and yield stability metrics were evaluated using correlation and regression analyses. This integrated framework allows assessment of both direct yield responses and stability-based resilience outcomes under climate variability.

## RESULTS AND DISCUSSION

### Onset and cessation trends between 2001 and 2025

Figure 2 illustrates the seasonal dynamics of rainfall onset and cessation over the study period, providing insight into the agricultural calendar and climatic stability of the study area.

The lower line in the figure, representing rainfall onset dates (day of year, DOY 91–100), indicates that the rainy season typically begins in April. Although interannual fluctuations in onset timing are observed, these remain within a relatively narrow range of approximately nine days, indicating moderate variability in the commencement of the rainy season. This pattern ensures the availability of pre-sowing soil moisture, which is essential for seed germination, plant growth, and optimal yield (Emeghara, 2015). Wuyep (2011) emphasized that the antecedent soil moisture condition at planting is more important for successful germination and sustained seedling growth. In addition, Ndomba (2010) reported that early rainfall onset contributes to improved yields by ensuring adequate moisture availability during germination.

In contrast, the upper line, representing rainfall cessation dates (DOY 297–304), shows that rainfall generally ends in late October. Compared to onset, cessation timing is more stable, with most years clustering around DOY 300–304 (Figure 2).

This indicates that the end of the rainy season is more predictable than its onset. The vertical distance between the onset and cessation lines represents the length of the growing

season (LGS), and variation in this interval reflects changes in growing season duration. Notably, 2010 and 2017 exhibit earlier cessation dates, resulting in shorter growing seasons,

which likely contributed to reduced rice yields. These years correspond to the lowest recorded yields in the study area (1.76 t/ha and 2.1 t/ha, respectively; Figure 3).

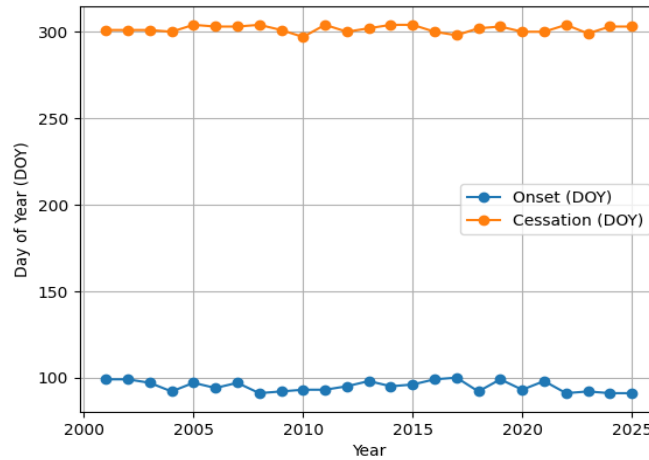


Figure 2. Onset and cessation trends between 2001 to 2025

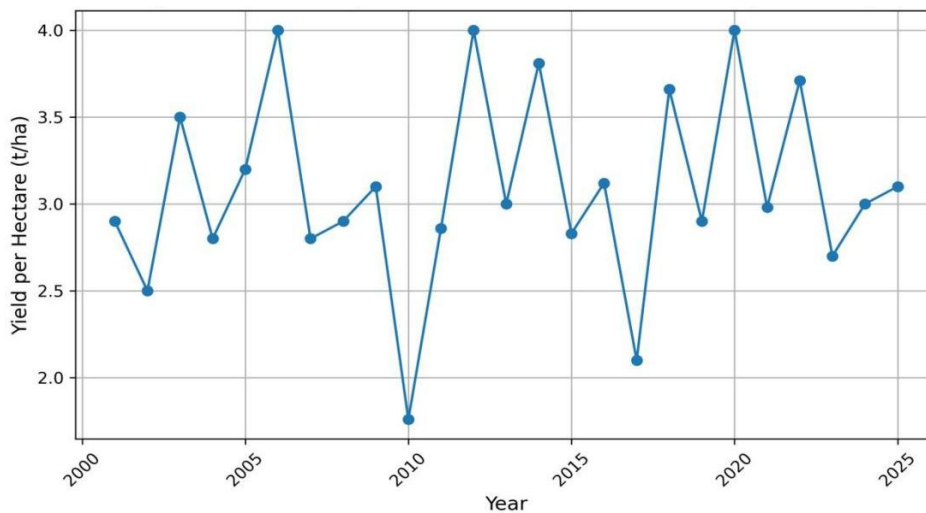


Figure 3. Trend of yield per hectare (2001–2025)

### Trend of yield per hectare (2001–2025)

Figure 3 shows marked variability in rice yield over the study period. The years with the highest yields were 2006, 2012, 2014, and 2020, while the lowest production occurred in 2010 and 2017 (Figure 3). The average yield of rice is 3.1 t/ha. Overall, the trend indicates a slight decline in yield during the period under review.

### Trend between the yield of rice and precipitation effectiveness indices

The overall trend in rainfall onset and cessation appears relatively stable over the study period, with no clear long-term directional change. However, onset dates exhibit greater interannual variability than cessation dates (Figure 2). Season length variability is primarily controlled by onset timing.

The analysis of rainfall onset indicates a mean day of year (DOY) of 94.96, corresponding to early April (Table 1). Onset dates ranged from DOY 91 to 100, with a standard deviation of 3.12 days. This narrow range and low variability indicate that rainfall onset was highly consistent throughout the study period. Such stability implies a predictable start to the growing season, which is beneficial for rice cultivation, particularly in optimizing planting dates.

Similarly, rainfall cessation exhibited high temporal stability. The mean cessation date was DOY 301.64, corresponding to late October, with values ranging from DOY 297 to 304. The standard deviation was 2.04 days, indicating very low interannual variability. This consistency suggests that the end of the rainy season is highly reliable, allowing farmers to anticipate harvest periods with minimal uncertainty. Together, the stability of onset and cessation defines a well-established and predictable seasonal rainfall window.

In contrast, rainfall amounts at the onset of the season showed considerable variability (Table 1). Mean onset rainfall was 12.92 mm, ranging from 0.74 mm to 38.17 mm, with a relatively high standard deviation of 8.87 mm. This indicates that although the timing of rainfall onset is predictable, the intensity of rainfall at the beginning of the season varies substantially between years. In some cases, low rainfall at onset may have been insufficient to support effective seed germination. Oteng-Darko et al. (2012) reported that between 1989 and 2006, rice yields declined due to erratic rainfall patterns affecting germination processes. In other years, higher rainfall may have improved soil moisture availability, although it could also have resulted in runoff and nutrient leaching.

A similar pattern was observed for rainfall at cessation (Table 1). The mean cessation rainfall was 10.50 mm, with values ranging

from 0.02 mm to 28.67 mm and a standard deviation of 9.26 mm. This high variability indicates that, although cessation timing is stable, rainfall amounts toward the end of the growing season fluctuate considerably. Such variability may significantly affect rice maturity and grain filling, as insufficient moisture can induce water stress. Upadhyaya & Panda (2019) and Aswani et al. (2025) noted that low rainfall can induce drought conditions leading to permanent damage in rice growth and development. They further reported that drought alters morphological and physiological traits, resulting in yield reductions, particularly in rainfed systems. Under drought stress, stomatal closure and a reduced leaf carbon dioxide–oxygen ratio occur, leading to inhibited photosynthesis. Conversely, excessive rainfall may delay harvesting or reduce rice yield. Early seedling and tillering stages are particularly sensitive, where water deficit causes wilting and leaf desiccation, directly impairing photosynthesis and nutrient uptake (Serraj et al., 2009; Matsunami et al., 2022; Hassan et al., 2023).

Total annual rainfall exhibited comparatively lower variability than onset and cessation rainfall amounts (Table 1). The mean annual rainfall was 1181.59 mm, ranging from 980.80 mm to 1320.12 mm, with a standard deviation of 97.34 mm. This indicates that total annual precipitation was relatively stable.

However, when considered together with variability in rainfall distribution within the growing season, it becomes evident that intra-seasonal rainfall variability is more pronounced than annual totals. This suggests that rainfall distribution during the season may be more critical for rice yield than total annual rainfall.

The length of the growing season (LGS) was also relatively stable, with a mean duration of 206.68 days (range: 198–213 days) and a standard deviation of 4.04 days (Table 1). This limited variability reflects the stability observed in both onset and cessation dates. The consistency of the growing season length indicates that crop developmental periods remained relatively uniform across years, suggesting that yield variability is unlikely to be driven by seasonal duration.

Rice yield per hectare showed moderate variability, with a mean value of 3.06 t/ha, ranging from 1.76 t/ha to 4.00 t/ha and a standard deviation of 0.60 t/ha (Table 1). This indicates that production was relatively stable but subject to notable interannual fluctuations. Given the stability of growing season length and total annual rainfall, these yield variations are more likely driven by variability in rainfall amounts at critical phenological stages, particularly during onset and cessation periods.

Table 1. Descriptive statistics of precipitation effectiveness indices

Parameter	N	Range	Min	Max	Sum	Mean	Standard deviation
Onset (DOY)	25	9.00	91.00	100.00	2374.00	94.9600	3.11555
Onset rainfall, mm	25	37.43	0.74	38.17	323.01	12.9204	8.86783
Cessation DOY	25	7.00	297.00	304.00	7541.00	301.6400	2.03879
Cessation rainfall, mm	25	28.65	0.02	28.67	262.50	10.5000	9.26253
Total annual rainfall	25	339.32	980.80	1320.12	29539.78	1181.5912	97.34463
Length of growing season	25	15.00	198.00	213.00	5167.00	206.6800	4.03856
Yield per hectare	25	2.24	1.76	4.00	76.44	3.0576	0.60069

### Onset and cessation days of rainfall and yield of rice

Analysis of the results shows that the duration of the growing season varies slightly across the years but remains within a relatively narrow range (Figure 4). The shortest growing season was observed in 2017, lasting 198 days, which is attributable to late rainfall onset and early cessation. In contrast, the longest growing seasons occurred in 2008 and 2022, each lasting 213 days, driven by earlier rainfall onset and later cessation.

For most years, the length of the growing season (LGS) ranges between 202 and 210 days, indicating a generally stable growing season duration (Figure 4). This consistency suggests a relatively reliable climatic window for rice cultivation planning, although

occasional shorter seasons, such as in 2017, may pose risks to rice yield. The observed variability in LGS is modest and is primarily influenced by shifts in the timing of rainfall onset and cessation. This implies that the adequacy of rainfall during the growing period is critical for rice growth and yield. These findings corroborate Odeniyi et al. (2020), who reported that sufficient rainfall is associated with increased rice yield. In the same vein, previous studies have shown that early onset and early cessation of rainfall negatively affect rice yield, whereas late cessation does not have a significant effect on rice production. For instance, rainfall analysis indicated that in 2017 and 2020, rainfall ceased earlier, without extending into the latter half of October or November, which is typically the last rainy month in Kogi State, Nigeria (Folorunsho & Ajiwoju, 2024).

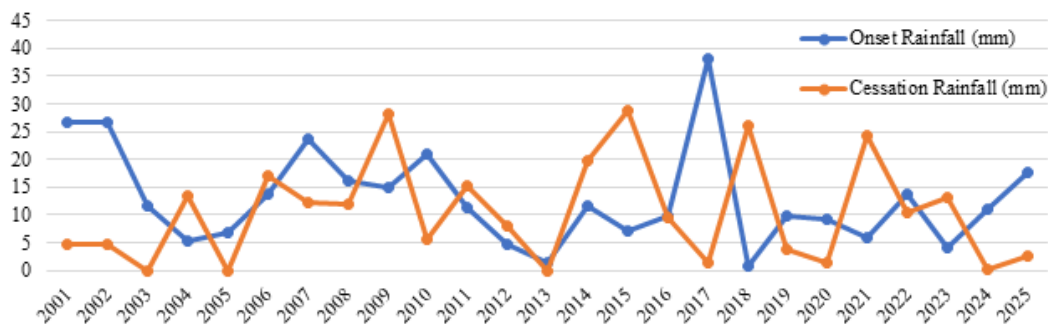


Figure 4. Onset and cessations days of rainfall

## Regression of yields with precipitation effectiveness indices

The regression analysis indicates a moderate association between precipitation effectiveness indices and rice yield ( $R = 0.589$ ), explaining 34.7% of the variance; however, the overall model was not statistically significant ( $F = 2.016$ ,  $p = 0.122$ ), suggesting limited explanatory power of the selected climatic predictors when considered jointly (Table 2). After adjustment for the number of predictors, the explanatory capacity declined further (adjusted  $R^2 = 0.175$ ), reinforcing the weak robustness of the model.

Among all variables included, only rainfall at the onset of the growing season showed a statistically significant effect, with a negative coefficient ( $p = 0.048$ ), indicating that higher rainfall during this period was associated with reduced rice yield. Other climatic factors, including cessation timing, total annual rainfall, rainfall during later stages, and the length of the growing season, did not exhibit statistically significant relationships with yield.

The limited significance of most temporal variables can be partly attributed to their low interannual variability, which reduces their capacity to explain yield fluctuations. This is consistent with the descriptive analysis, where onset and cessation dates showed relatively stable patterns across years. In contrast, rainfall at the onset stage exhibited substantial variability, making it the dominant climatic driver captured in the model.

From an agronomic perspective, the negative effect of excessive early-season rainfall is plausible, as it may induce waterlogging, delay planting operations, and enhance nutrient leaching, all of which can suppress crop establishment and early growth. These mechanisms are well documented in rice agroecosystems and are known to affect both vegetative development and final yield formation (Ye et al., 2018; Malik et al., 2002; Liu et al., 2023; Xiong, 2024).

Although total annual rainfall showed a weak and non-significant trend toward influencing yield ( $p = 0.088$ ), its effect appears less relevant than intra-seasonal rainfall distribution. This supports the interpretation that temporal allocation of precipitation is more critical for rice productivity than aggregate annual totals. Similarly, rainfall at the cessation stage did not significantly affect yield, possibly due to the moderating influence of management practices, varietal differences, and soil moisture retention capacity during late growth stages.

Overall, the findings suggest that yield variability is driven more by rainfall dynamics during key phenological phases than by season length or total precipitation. However, the absence of overall model significance and the relatively low adjusted explanatory power indicate that additional non-climatic factors, such as soil properties, temperature variability, and agronomic management, are likely required to more fully explain yield variation in the study area.

Table 2. Regression of yields with precipitation effectiveness indices

Component	Statistic	Value	Interpretation
Model summary	R	0.589	Moderate correlation between predictors and yield
	$R^2$	0.347	34.7% of yield variation explained
	Adjusted $R^2$	0.175	Weak adjusted explanatory power
	Std. Error	0.546	Moderate prediction error
ANOVA	F-value	2.016	Model not statistically significant
	p-value	0.122	No overall model significance
Significant predictor	Rainfall (onset)	$p = 0.048$	Significant negative effect on yield
Non-significant predictors	Cessation DOY	$p = 0.180$	No significant effect
	Rainfall (late stage)	$p = 0.712$	No significant effect
	Total annual rainfall	$p = 0.088$	Weak, non-significant effect
	Length of growing season	$p = 0.917$	No effect

## Precipitation effectiveness indices and their relationship with rice yield

Descriptive statistics (Table 1) indicate relatively low variability in rainfall timing parameters compared with higher variability in rainfall amounts during key phenological stages. Onset rainfall exhibits substantial variability (mean = 12.92 mm; range = 0.74–38.17 mm; SD = 8.87 mm), indicating inconsistent moisture availability at the beginning of the growing season. Cessation rainfall also shows considerable variability (mean = 10.50 mm; range = 0.02–28.67 mm; SD = 9.26 mm), reflecting fluctuating end-of-season moisture conditions.

In contrast, total annual rainfall (mean = 1181.59 mm; SD = 97.34 mm) and the length of growing season (LGS) (mean = 206.68 days; SD = 4.04 days) display relatively low variability, indicating that both cumulative rainfall and seasonal duration remained stable throughout the study period. Yield per hectare exhibits moderate variability (SD = 0.60 t/ha), suggesting

that interannual fluctuations in production occur despite a relatively stable seasonal framework. Overall, these patterns suggest that intra-seasonal rainfall distribution, rather than total rainfall or season length, represents the primary source of climatic variability relevant to yield outcomes.

The multiple linear regression model indicates a moderate relationship between precipitation effectiveness indices and rice yield ( $R = 0.589$ ), explaining 34.7% of the total variance (Table 2). However, the model is not statistically significant ( $F = 2.016$ ,  $p = 0.122$ ), indicating limited collective explanatory power of the selected climatic variables. The adjusted  $R^2$  further confirms that a substantial proportion of yield variability remains unexplained after accounting for the number of predictors, suggesting that additional agronomic and environmental factors not included in the model likely contribute to yield variation.

Among all predictors, only rainfall shows a statistically significant negative relationship with yield ( $p = 0.048$ ),

indicating that increased rainfall, particularly during critical phenological stages, is associated with reduced rice yield. This effect may be attributed to excessive moisture conditions such as waterlogging and nutrient leaching, which are known to impair rice development (Ye et al., 2018; Asamoah, 2022; Liu et al., 2023). Waterlogging is widely recognized as a major constraint in rice systems, as it disrupts physiological processes and reduces photosynthetic efficiency and plant growth (Manik et al., 2022; Xiong, 2024).

Other variables, including cessation date, total annual rainfall, and length of the growing season, are not statistically significant. Total rainfall exhibits only a marginal effect ( $p = 0.088$ ), reinforcing the interpretation that cumulative precipitation alone is not a strong determinant of yield variability in the study area.

Onset date is excluded from the model due to multicollinearity, indicating redundancy with other precipitation variables. This suggests interdependence among precipitation effectiveness indices, which may limit their individual explanatory contribution within the regression framework.

Overall, the results indicate that, although precipitation effectiveness indices collectively explain a moderate proportion of rice yield variability, their explanatory power remains limited. Yield responses are driven more strongly by rainfall intensity during critical growth stages than by seasonal timing or total rainfall, highlighting the importance of intra-seasonal precipitation dynamics under rainfed rice production systems.

### Non-linear effects, yield stability, and integrated interpretation

To assess potential non-linear relationships between precipitation indices and rice yield, Generalized Additive Models (GAM) were applied as an exploratory robustness check. The results suggest that the inclusion of smooth terms does not materially change the interpretation obtained from the linear model. Visual inspection of the fitted smooth functions indicates the absence of pronounced curvature or clear threshold behaviour across key variables, including rainfall onset, cessation, total rainfall, and dry spell frequency.

The effective degrees of freedom for smooth terms were close to one, suggesting that relationships between precipitation variables and yield are predominantly linear or only weakly non-linear within the observed data range. However, this interpretation is based on the observed model structure rather than formal model comparison metrics, as no AIC or deviance-based comparison was conducted. Therefore, the GAM results should be interpreted as supportive qualitative evidence rather than a statistically superior alternative to the linear model.

Overall, the GAM analysis provides no indication of strong non-linear responses in rice yield to precipitation variability, suggesting that yield responses are largely linear or weakly curved under the current climatic conditions.

Yield stability analysis based on the coefficient of variation (CV) indicates moderate interannual variability in rice production, suggesting partial stability of the agroecosystem under relatively consistent seasonal rainfall patterns. Despite stable onset and cessation dynamics, yield fluctuations persist, indicating that seasonal structure alone does not fully explain productivity variability. The Yield Stability Index (YSI) further highlights interannual deviations from the long-term mean, with reduced stability observed in years characterized by suboptimal rainfall distribution during critical phenological stages. These patterns suggest that agroecosystem resilience in the study area is moderately constrained, with productivity more sensitive to intra-seasonal rainfall variability than to total

seasonal rainfall. In particular, years with disrupted rainfall distribution correspond to lower stability, reinforcing the importance of rainfall timing and intra-seasonal consistency in maintaining yield reliability under rainfed conditions.

Overall, the results indicate that precipitation effectiveness indices are important but not sufficient predictors of rice yield variability in Langtang South. While rainfall timing (onset and cessation) and growing season length are relatively stable, variability in rainfall intensity during key phenological stages plays a more dominant role in determining yield outcomes.

Taken together, the regression results and the exploratory GAM analysis suggest that rice yield is influenced by multiple interacting factors beyond precipitation alone. These likely include soil properties, crop management practices, and additional climatic variables not included in this study.

Nevertheless, the findings consistently indicate that intra-seasonal rainfall variability, rather than total annual rainfall, is the primary hydroclimatic driver of yield fluctuations in the study area. This has important implications for climate-smart agricultural planning and adaptive management strategies aimed at improving rice productivity under rainfed conditions. Overall, rice yield in Langtang South appears to be governed less by total seasonal rainfall and more by the timing and distribution of rainfall within the growing season, with both productivity and stability reflecting the sensitivity of the rainfed agroecosystem to intra-seasonal precipitation dynamics.

In the context of the stated hypotheses, the study results generally support H1, indicating the importance of intra-seasonal rainfall variability for rice yield formation. Despite relatively stable onset and cessation dates, significant interannual variability in rainfall amounts during key growth stages, particularly at the start of the season, was closely associated with yield fluctuations. Years with insufficient or excessive early-season moisture (e.g., 2010 and 2017) exhibited reduced yields, highlighting the critical role of intra-seasonal rainfall distribution for effective crop development. Thus, H1 is largely confirmed: it is the distribution of rainfall, rather than the calendar length of the season, that constitutes the key hydroclimatic factor influencing rice productivity.

Regarding H2, the multiple regression and GAM analyses indicate that precipitation effectiveness indices do have predictive value, although their explanatory power is limited. Among all the indices considered, only rainfall at the onset stage was statistically significant, showing a negative relationship with yield. This suggests that precipitation effectiveness indices can partially explain yield variability, but a full assessment of rice productivity requires consideration of additional factors such as soil properties, agronomic practices, and temperature conditions. Therefore, H2 is partially confirmed: the indices provide important information, but their use as the sole predictor of yield is limited.

### CONCLUSION

In Langtang South, rice yield variability is driven primarily by intra-seasonal rainfall distribution rather than seasonal onset, cessation, or total annual precipitation. Fluctuations in rainfall intensity during critical phenological stages, particularly at the start of the growing season, emerge as the dominant factor influencing crop performance.

Total seasonal rainfall and growing season length exert comparatively minor effects, indicating that fine-scale precipitation dynamics within the season determine yield outcomes more than aggregate climatic parameters. Yield responses were largely linear, with no strong evidence of non-

linear or threshold effects, and stability analysis shows moderate agroecosystem resilience to intra-seasonal variability.

The study establishes a direct link between within-season rainfall heterogeneity and rice productivity, providing a quantitative perspective on precipitation effectiveness in rainfed tropical agroecosystems. This highlights the need to consider rainfall distribution at critical growth stages as a key hydroclimatic driver of crop yield, extending conventional assessments based solely on seasonal totals or structural metrics.

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## Author's statements

### Contributions

All authors contributed to the study's conception and design. Conceptualization: S.Z.W.; Data curation: A.S.O.; Formal analysis: S.Z.W.; Investigation: A.S.O.; Methodology: W.J.; Project administration: W.J.; Visualization: all authors; Writing – original draft: S.Z.W.; Writing – review & editing: A.S.O.

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## Declaration of conflicting interest

The authors declare no competing interests.

## Financial interests

The authors declare they have no financial interests.

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## Data availability statement

All raw rainfall and yield datasets, computed indices, and analytical scripts (regression, GAM, and stability analyses) will be available from the corresponding author to ensure full reproducibility.

## AI Disclosure

The authors declare that generative AI was not used to assist in writing this manuscript.

## Ethical approval declarations

This study adhered to ethical guidelines for research involving human participants, as approved by the Institutional Research Committee. Informed consent was obtained from all individuals who participated in the study.

## Additional information

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## REFERENCES

- Abdulhamid, A. I. & Abubakar, G. Z. (2002). Application of Agro-Climatology to Agricultural Planning in Katagum Zone, Bauchi State – Nigeria. *Azare Journal of Education*, (61), 8–14.
- Adebayo, A. A., & Adebayo, E. F. (1997). Precipitation effectiveness indices and upland rice yield in Adamawa State. *Annals Borno*, 13(14), 266–276.
- Adebayo, A. A., Onu, J. I., Adebayo, E. F., & Anyanwu, S. O. (2012). Farmers' awareness, vulnerability and adaptation to climate change in Adamawa State, Nigeria. *British Journal of Arts and Social Sciences*, 9(2), 104–115.
- Adefolalu, D. O. (1993). Rainfall climatology and agricultural extension. *Nigeria, NGA Journal*, 5, 32–36.
- Aswani, S., Anitha, S., Prameela, P., Parvathy, M. S., Prashanthi, P., & Santhoshkumar, A. V. (2025). Drought responses and its management in rice: A review. *International Journal of Research in Agronomy*, 8(3), 107–111. <https://www.doi.org/10.33545/2618060X.2025.v8.i3b.2599>.
- Ati, O. F., Stigter, C. J., Igusi, E. O., & Afolayan, J. O. (2009). Profile of rainfall change and variability in the northern Nigeria, 1953–2002. *Research Journal of Environmental and Earth Sciences*, 1(2), 58–63. <https://www.airitilibrary.com/Article/Detail?DocID=20410492-200910-201009060085-201009060085-58-63>.
- Audu, E. B. (2012). A descriptive analysis of rainfall for agricultural planning in Lokoja local government area of Kogi state, Nigeria. *International Journal of Science and Technology*, 2(12), 850–855.
- Baweja, P. K. (2011). Rainfall variability and probability for crop planning in Solan, Himachal Pradesh. *Journal of Farm Science*, 1(1), 75–88. <https://indianjournals.com/api/article-view/ijfs-1-1-012>.
- Blum, A. (2011). Plant breeding for water-limited environments. In *Plant Breeding for Water-Limited Environments* (pp. 1–255). <https://doi.org/10.1007/978-1-4419-7491-4>.
- Choji, V. (2025). Assessing land cover change in Langtang–South Local Government Area, Plateau State, Nigeria using GIS and remote sensing tools: a case study approach. *PLASU Journal of Environment Sciences*, 1(1), 170–192. <https://doi.org/10.5281/zenodo.14706410>.
- Danladi, B. E. L. L. O. (2012). *Precipitation effectiveness indices and millet yield in two local government areas of Kano State, Nigeria* (Doctoral dissertation). <https://kubanni.abu.edu.ng/handle/123456789/605>.
- Diarra, A., Barbier, B., & Yacouba, H. (2017). Impact of climate change on cotton production in Burkina Faso. *African Journal of Agricultural Research*, 12(7), 494–501. <https://doi.org/10.5897/AJAR2015.10763>.
- Emeghara, S. I. (2015). *Effect of precipitation effectiveness indices on the yield of some selected cereal crops in Sokoto State, Nigeria* (Doctoral dissertation). <https://kubanni.abu.edu.ng/handle/123456789/7449>.
- Ezenekwe, L. N., Ezemonye, M. N., & Emeribe, C. N. (2013). An appraisal of the characteristics of rainfall in Kano. *British Journal of Advance Academic Research*, 2(1), 20–28.
- FAO. (2020). *Food Outlook – Biannual Report on Global Food Markets: June 2020*. Food Outlook, June 2020. Rome. <https://doi.org/10.4060/ca9509en>.
- Folorunsho, J. O., & Ajiwoju, M. (2024). Analysis of Perceived Effects of Rainfall Variability on Rice Yield in Lokoja, Kogi State, Nigeria. *ABUJ Journal of Social and Management Sciences*, 5(1), 136–151. <https://doi.org/10.53982/ajsms.2024.0501.07-j>.
- Hassan, M. A., Dahu, N., Hongning, T., Qian, Z., Yueming, Y., Yiru, L., & Shimei, W. (2023). Drought stress in rice: morpho-physiological and molecular responses and marker-assisted breeding. *Frontiers in Plant Science*, 14, 1215371. <https://doi.org/10.3389/fpls.2023.1215371>.
- Ikpe, E. (2013). *Adaptation strategies to climate change among grain farmers in Goronyo Local government area of Sokoto State* (Doctoral dissertation, Ahmadu Bello University, Zaria).

- Ishaku, P. A., Binbol, N. L., Ishaya, S. K., Danjuma, M. N., & Wuyep, S. Z. (2021). Analysis of Rainfall Onset, Cessation and Length of Rainy Season in the Guinea Savanna Region of Nigeria. *African Journal of Geographical Sciences*, 2(1), 105–116.
- Liu, D., Song, C., Xin, Z., Fang, C., Liu, Z., & Xu, Y. (2023). Agricultural management strategies for balancing yield increase, carbon sequestration, and emission reduction after straw return for three major grain crops in China: A meta-analysis. *Journal of Environmental Management*, 340, 117965. <https://doi.org/10.1016/j.jenvman.2023.117965>.
- Malik, A. I., Colmer, T. D., Lambers, H., Setter, T. L., & Schortemeyer, M. (2002). Short-term waterlogging has long-term effects on the growth and physiology of wheat. *New Phytologist*, 153(2), 225–236. <https://doi.org/10.1046/j.0028-646X.2001.00318.x>.
- Matsunami, M., Hayashi, H., Murai-Hatano, M., & Ishikawa-Sakurai, J. (2022). Effect of hydropriming on germination and aquaporin gene expression in rice. *Plant Growth Regulation*, 97(2), 263–270. <https://doi.org/10.1007/s10725-021-00725-5>.
- Mohidem, N. A., Hashim, N., Shamsudin, R., & Che Man, H. (2022). Rice for food security: Revisiting its production, diversity, rice milling process and nutrient content. *Agriculture*, 12(6), 741. <https://doi.org/10.3390/agriculture12060741>.
- National Population Commission (NPC). (2024). *Nigerian population data sheet. Abuja, Nigeria: National Population Commission*. <https://www.population.gov.ng>.
- Ndomba, P. M. (2010). Development of rainfall curves for crops planting dates: A case study of Pangani River Basin in Tanzania. *Nile Basin Water Science and Engineering Journal*, 3, 13–27.
- Nelson, G. C., Valin, H., Sands, R. D., Havlík, P., Ahammad, H., Deryng, D., ... & Willenbockel, D. (2014). Climate change effects on agriculture: Economic responses to biophysical shocks. *Proceedings of the National Academy of Sciences*, 111(9), 3274–3279. <https://doi.org/10.1073/pnas.1222465110>.
- Odeniyi, K., Ibitunde, I. O., & Olaniyi, G. B. (2020). Effects of rainfall and temperature on rice production in Nigeria. *Nigerian Journal of Rural Sociology*, 20(2), 21–26. <https://doi.org/10.22004/ag.econ.347353>.
- Ogbole, A. S., Benson, N., & Ugese, A. A. (2025). Flood vulnerability assessment and mapping in selected communities of Langtang South Nigeria, using analytical hierarchy process and geographic information system. *Discover Water*, 6, 5. <https://doi.org/10.1007/s43832-025-00326-7>.
- Oladosu, Y., Rafii, M. Y., Samuel, C., Fatai, A., Magaji, U., Kareem, I., ... & Kolapo, K. (2019). Drought resistance in rice from conventional to molecular breeding: a review. *International Journal of Molecular Sciences*, 20(14), 3519. <https://doi.org/10.3390/ijms20143519>.
- Omotosho, J. B., Balogun, A. A., & Ogunjobi, K. (2000). Predicting monthly and seasonal rainfall, onset and cessation of the rainy season in West Africa using only surface data. *International Journal of Climatology: A Journal of the Royal Meteorological Society*, 20(8), 865–880. [https://doi.org/10.1002/1097-0088\(20000630\)20:8<865::AID-JOC505>3.0.CO;2-R](https://doi.org/10.1002/1097-0088(20000630)20:8<865::AID-JOC505>3.0.CO;2-R).
- Oteng-Darko, P., Kyei-Baffour, N., & Ofori, E. (2012). *Simulating rice yields under climate change scenarios using the CERES-Rice model*. <http://hdl.handle.net/1807/47602>.
- Pandey, V., & Shukla, A. (2015). Acclimation and tolerance strategies of rice under drought stress. *Rice Science*, 22(4), 147–161. <https://doi.org/10.1016/j.rsci.2015.04.001>.
- Rossato, L., Alvalá, R. C. D. S., Marengo, J. A., Zeri, M., Cunha, A. P. D. A., Pires, L. B., & Barbosa, H. A. (2017). Impact of soil moisture on crop yields over Brazilian semi-arid. *Frontiers in Environmental Science*, 5, 73. <https://doi.org/10.3389/fenvs.2017.00073>.
- Serraj, R., Kumar, A., McNally, K. L., Slamet-Loedin, I., Bruskiewich, R., Mauleon, R., ... & Hijmans, R. J. (2009). Improvement of drought resistance in rice. *Advances in Agronomy*, 103, 41–99. [https://doi.org/10.1016/S0065-2113\(09\)03002-8](https://doi.org/10.1016/S0065-2113(09)03002-8).
- Upadhyaya, H., & Panda, S. K. (2019). Drought stress responses and its management in rice. In *Advances in rice research for abiotic stress tolerance* (pp. 177–200). Woodhead Publishing. <https://doi.org/10.1016/B978-0-12-814332-2.00009-5>.
- Vogel, E., Donat, M. G., Alexander, L. V., Meinshausen, M., Ray, D. K., Karoly, D., ... & Frieler, K. (2019). The effects of climate extremes on global agricultural yields. *Environmental Research Letters*, 14(5), 054010. <https://doi.org/10.1088/1748-9326/ab154b>.
- Walter, M. W. (1967). Length of the rainy season in Nigeria. *The Nigerian Geographical Journal*, 10(2), 123–128.
- Wuyep, S. Z. (2011). *Effect of climate on growth and yield of Irish potato in Jos South, Nigeria* (Unpublished master's thesis). Modibbo Adama University, Yola, Nigeria.
- Wuyep, S. Z., & Daloeng, H. M. (2020). Climate Change, Rainfall Trends and Variability in Jos Plateau. *Journal of Applied Sciences*, 2, 76–82. <https://doi.org/10.3923/jas.2020.76.82>.
- Wuyep, S., Zemba, A., & Jahknwa, C. J. (2013). Effects of precipitation effectiveness on the yield of Irish potato (*Solanum tuberosum*) in Jos-plateau, Nigeria. *International Journal of Research in Applied, Natural and Social Sciences*, 1(5), 27–32.
- Xiong, D. (2024). Perspectives of improving rice photosynthesis for higher grain yield. *Crop and Environment*, 3(3), 123–137. <https://doi.org/10.1016/j.crope.2024.04.001>.
- Ye, H., Song, L., Chen, H., Valliyodan, B., Cheng, P., Ali, L., ... & Nguyen, H. T. (2018). A major natural genetic variation associated with root system architecture and plasticity improves waterlogging tolerance and yield in soybean. *Plant, Cell & Environment*, 41(9), 2169–2182. <https://doi.org/10.1111/pce.13190>.
- Zemba, A., Wuyep, S., Abel, A., & Jahknwa, C. (2013). Growth and yield response of Irish potato (*Solanum Tuberosum*) to climate in Jos-South, Plateau State, Nigeria. *Global Journal of Human Social Science (B)*, 13(5), 13–18.