PLASU Journal of Environmental Sciences, E-ISSN 2360-9222, Vol.2, No. 2, June 2026, Published by the Faculty of Environmental Sciences, Plateau State University, Bokkos. https://www.pjes.ng
DOI: 10.5281/zenodo.19401971

SEASONAL AND ANNUAL PATTERNS OF CLIMATIC ELEMENTS IN BENUE STATE AND THEIR IMPLICATIONS FOR YAM PRODUCTION

[1]Daniel Iorwuese Gelleh, [2]Nankap Latur Binbol

[1]National Centre for Remote Sensing Jos East LGA P.M.B 2136 Jos, Plateau State Nigeria.

[2]Department of Geography and Regional Planning, Faculty of Environmental Sciences, University of Jos, P.M.B. 2084, Jos, Plateau State, Nigeria.

Corresponding author's email: gellehdaniels@yahoo.com

https://orcid.org/0000-0001-6976-7777

ABSTRACT

Yam (Dioscorea spp.) is a critical food security crop in Benue State, Nigeria, yet production remains highly sensitive to climatic variability. This study examined the influence of climatic elements on yam growth and yield through analysis of thirty-five years (1988–2022) of climatological data. Climate elements; rainfall, maximum, minimum, and mean temperature, relative humidity, and solar radiation were analyzed using trend analysis and regression modeling to establish relationships with yam phenological development. Results revealed distinct seasonal patterns characteristic of tropical savanna climate, with rainfall concentrated between April and October (peak: 232.27mm in September) and a pronounced dry season from November to March. Annual rainfall exhibited high interannual variability (600–1600mm) with a statistically weak positive trend ($R^2 = 0.055$), indicating that year-to-year fluctuations dominate the rainfall regime. Maximum temperatures ranged between 33.0°C and 34.5°C, with peaks during March–April exceeding optimal thresholds for yam physiology, while minimum temperatures occasionally dropped below 20°C during harmattan periods, impeding metabolic processes. Relative humidity fluctuated clearly (50–95%), with extended high-humidity periods increasing pathogenic risks, while solar radiation variability approximately 4 -7 hours directly influenced photosynthetic capacity during tuber bulking phases. The study concludes that yam production is highly vulnerable to interannual climatic variability, particularly temperature extremes at critical phenological stages and erratic rainfall distribution. It is recommended that policymakers promote climate-resilient strategies including heat-tolerant yam varieties, adjusted planting schedules aligned with historical climatic windows, supplemental irrigation infrastructure, and humidity management practices to mitigate disease pressure and stabilize yields under increasing climate uncertainty.

Keywords: Variability, Yam Production, Seasonal, Annual, Benue State, Climate Elements, Trend Analysis.

1. INTRODUCTION

Climate dynamics exert profound influence on agricultural productivity in tropical regions, particularly in areas dominated by rain-fed systems. Benue State, often referred to as the "Food Basket of the Nation," serves as a major yam-producing region in Nigeria, where yam cultivation plays a central role in food security and economic livelihoods (Omena, Okwu-

Delunzu, & Idenyi, 2023; Uger, 2023). Understanding the seasonal and annual behavior of climatic variables is essential for predicting crop performance, designing adaptive interventions, and ensuring long-term sustainability. Previous researches have highlighted the strong dependence of yam cultivation on rainfall, temperature, humidity, and solar radiation, with variations in these elements directly affecting growth stages and yields (Adesiji, Ojo, & Ogunjobi, 2024; Adejuwon, Joshua, & Dada, 2024).

Despite the critical role of climate in yam production, increasing variability has rendered cultivation more unpredictable in Benue State. Farmers frequently encounter challenges such as delayed rainfall onset, heat stress during critical growth periods, waterlogging from excessive precipitation, and intermittent dry spells that disrupt tuber development (Ogunjo, Olusola, & Akinwumiju, 2023; Omonona, Ogunjobi, & Ajani, 2023). Although some studies have examined isolated climatic factors, a comprehensive analysis linking these patterns to yam production remains limited, underscoring the need for integrated research to inform adaptive strategies (Zakari, Hassan, & Iguisi, 2021; Kalu, Eze, & Ugwu, 2023).

The aim of this study is to analyze the seasonal and annual patterns of climatic elements in Benue State and interpret their implications for yam production. To achieve this, the research examines seasonal patterns of rainfall, temperature, relative humidity, and solar radiation; analyzes annual long-term trends from 1988 to 2022; interprets how these patterns influence yam growth stages; and recommends climate-smart agricultural practices for yam production. Guiding this investigation are key research questions: What are the seasonal characteristics of climatic variables in Benue State? How have annual trends of climatic elements evolved over the 35-year period? In what ways do these climatic patterns affect yam phenology and yield? And what adaptive strategies can mitigate climatic risks in yam production?

This study contributes to agricultural climatology by providing empirical evidence on the climate–crop relationship in Benue State. The findings support crop planning and extension services, yam breeding programs, policy development for climate-resilient agriculture, and evidence-based decision-making for farmers and stakeholders, aligning with broader efforts to address climate impacts in sub-Saharan Africa (Intergovernmental Panel on Climate Change [IPCC], 2022; Nigerian Meteorological Agency [NiMet], 2023; Shiru et al., 2023).

2. LITERATURE REVIEW

The Earth's climate is governed by spatiotemporal patterns driven by orbital dynamics and solar radiation, resulting in distinct seasonal and annual cycles marked by fluctuations in temperature, precipitation, and humidity. In tropical regions such as Benue State, Nigeria, these cycles manifest as pronounced wet (April–October) and dry (November–March) seasons, characteristic of the Southern Guinea Savanna's Aw Köppen climate classification. Recent analyses underscore that these patterns are increasingly influenced by global climate change, leading to heightened variability and shifts in climatic norms (Zhang et al., 2024).

Rainfall in Benue State exhibits strong seasonality, with the wet season delivering the majority of annual precipitation—often exceeding 250 mm monthly during its peak. However, significant interannual variability, influenced by teleconnections such as Atlantic Sea Surface Temperatures and the position of the Intertropical Convergence Zone, has made rainfall onset and cessation increasingly erratic. The occurrence of intra-seasonal dry spells, such as the "August break," further exacerbates moisture stress during critical crop growth stages, challenging rain-fed agricultural systems (Liu, Li, Shao, & Wang, 2025).

Temperature regimes complement this seasonal rhythm, with the hottest periods occurring in late dry season (February–March), where maxima frequently surpass 35°C. The Harmattan winds introduce temporary moderation, though a persistent warming trend of approximately 0.8°C over recent decades has been observed, intensifying heat stress and evaporative demand (Agbaje, Abiona, Awojide, Azeez, & Tayo, 2022). Relative humidity closely follows precipitation patterns, exceeding 80% during peak rainy months—a condition that supports vegetative growth but also promotes fungal pathogens. Conversely, dry-season humidity can drop below 40%, accelerating soil moisture loss and crop water stress (Adejuwon, Tewogbade, Oguntoke, & Ufoegbune, 2023).

Solar radiation demonstrates an inverse relationship with cloud cover, peaking during the dry season and moderating during the wet months. Although sufficient for photosynthesis, the Harmattan haze and cloudy periods can limit light availability, affecting biomass accumulation in photoperiod-sensitive crops such as yam (Adedugba, Adeyemo, Adetumbi, Amusa, & Ogunkanmi, 2023).

3. MATERIALS AND METHODS

The study draws on 35 years of climatic data spanning 1988 to 2022, encompassing rainfall, relative humidity, temperature (including minimum, maximum, and mean values), and solar radiation, sourced from meteorological records in Makurdi, Benue State. Additionally, yam agronomic thresholds are incorporated based on established literature to facilitate interpretation (Adebayo & Oguntunde, 2024; Eze, Onyekwelu, & Adeyemo, 2024). Analytical procedures include seasonal analysis using monthly means to delineate wet and dry season characteristics. For trend analysis, linear regression models are applied, expressed as y and x, where y represents the climatic variable and x denotes the year. Variability is assessed through metrics such as the coefficient of variation (CV), inter-annual anomaly plots, and comparisons with yam phenological thresholds. Agronomic interpretation links these climatic variables to yam growth stages, from sprouting through vegetative growth, tuber initiation, and bulking to maturation.

The variables assessed encompass rainfall in millimeters, which provides moisture essential for sprouting and tuber bulking; minimum temperature in degrees Celsius, influencing metabolic activity and sprouting; maximum temperature in degrees Celsius, associated with heat stress and evapotranspiration; mean temperature in degrees Celsius, governing physiological processes; relative humidity in percent, affecting disease risk and transpiration control; and solar radiation in hours, critical for photosynthesis and tuber formation (Omena et al., 2023; Uger, 2023). Monthly averages were calculated to delineate the intra-annual patterns of each climatic element, linking them to yam's growth stages while annual trend analysis for each element, a linear regression trend line was fitted to the annual time-series data. The slope of the trend and the coefficient of determination (R^2) were computed to quantify the magnitude and statistical strength of long-term changes, respectively.

3.1 Study Area

Benue State has a landmass of roughly 34,059 km², it is situated between latitudes 6° 25' and 8° 8 N and longitudes 7° 47' and 10° 0' E. Its elevation is 146.02 m (479.07 ft) above sea level (Ujoh, Igbawua, & Paul, 2019). The state is bordered to the north by Nasarawa State, to the east by Taraba State, to the south by Ebonyi and Cross River State, to the southwest by Enugu State, to the west by Kogi State, and to the southeast by the Republic of Cameroon as shown in Figure 1. Benue State is situated within the Southern Guinea Savanna zone of Nigeria, featuring a tropical wet–dry climate classified under the Köppen Aw system. The region typically receives between 1,200 and 1,600 mm of annual rainfall, with temperatures ranging from 17°C to 37°C. These seasonal shifts are primarily driven by the migration of the Intertropical Discontinuity (ITD), which regulates moisture inflow and determines the timing of the rainy and dry seasons (Aighewi, Asiedu, Maroya, & Balogun, 2020; Olorunfemi, Fasinmirin, & Komolafe, 2024).

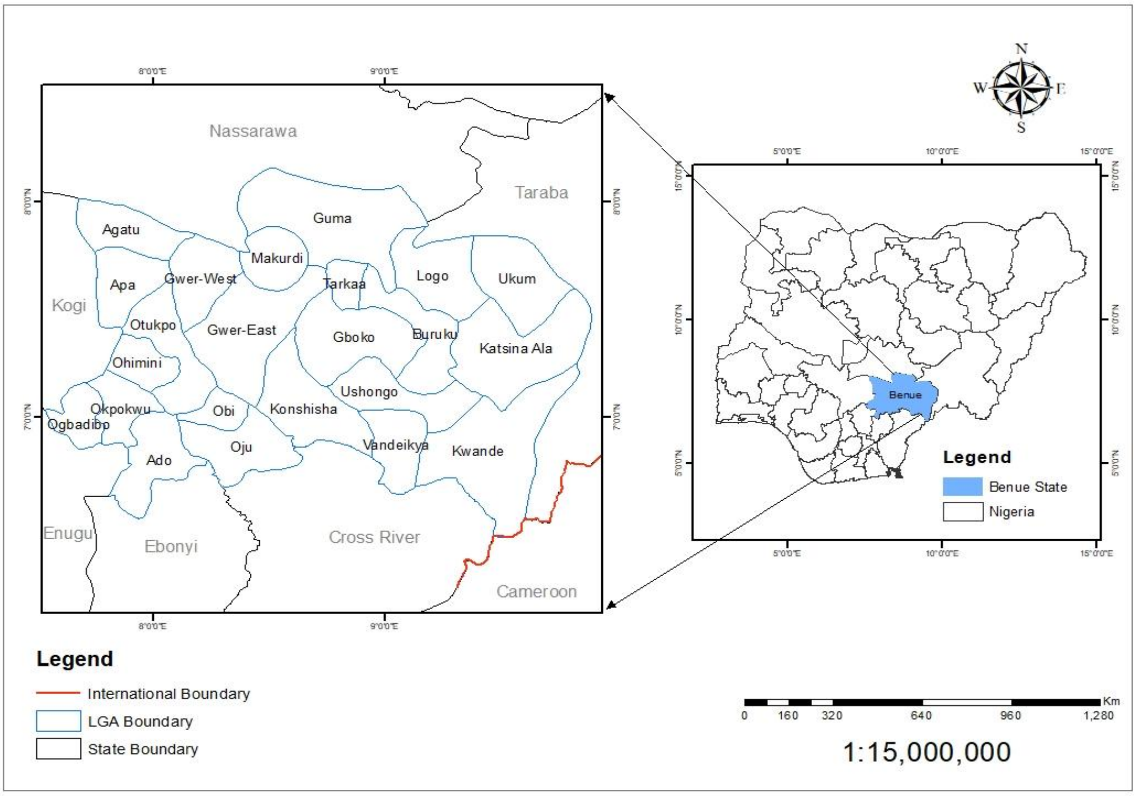

Figure 1: Benue State, Nigeria

3.2 Methods of Data Collection

The study employed a secondary data collection methodology, utilizing historical meteorological records obtained exclusively from the Nigerian Meteorological Agency (NiMet). The data was sourced from a designated and standardized weather station located in Makurdi, Benue State. This dataset encompassed continuous, instrument-derived daily measurements of rainfall, temperature, relative humidity, and solar radiation over a 35-year period from 1988 to 2022. For the purpose of analyzing annual patterns, the raw data was processed to compute mean monthly values, which were then aggregated to derive annual averages for each climatic variable across the entire study period. To delineate seasonal patterns, the raw monthly data for all years was summarized to create a composite annual cycle, illustrating the typical monthly fluctuations within a representative year. This method of utilizing a long-term, official instrumental data set from a single, consistent location ensured the temporal consistency and reliability necessary for robust trend and variability analysis.

3.3 Method of Data Analysis

The methodological approach for analyzing seasonal and annual climatic patterns centered on the aggregation and time-series analysis of long-term meteorological data. Historical data for key variables were sourced and compiled into monthly records across the 35-year study period. To elucidate annual patterns, the mean value for each climatic variable was calculated per calendar year, creating a continuous annual time series for trend examination. For seasonal analysis, the data were restructured to illustrate intra-annual cycles by computing the long-term average for each calendar month across the entire data set, thereby generating a composite annual profile that highlights the typical monthly progression. The analysis of these aggregated time-series data employed both graphical and statistical techniques. Graphical plots were essential for visualizing the distinct seasonal cycles and inter-annual fluctuations, while descriptive statistics summarized central tendencies and variability. Trend analysis was applied to the annual series to assess the presence and magnitude of long-term directional changes, complemented by measures of volatility to quantify inter-annual inconsistency, ultimately linking these climatic patterns to agricultural phases.

4. RESULTS AND DISCUSSION

This section explains the seasonal and annual patterns of climatic elements in Benue State, drawing numerical values and interpretations from the dataset, and interprets their implications for yam cultivation. Rainfall in Benue State exhibits a distinct unimodal pattern characteristic of a tropical savanna climate. During the dry season from November to March, rainfall remains extremely low, ranging from 9.71 mm to 10.43mm. The onset of rains in April brings a sharp increase to 89.17mm, supplying the moisture necessary for yam sprouting. Higher rainfall occurs in August and September, with values of 229.21mm and 232.27mm, respectively, before declining to 132.13mm in October as the rains cease. For yam production, the early dry season imposes severe moisture stress that restricts sprouting, while excessive rainfall in August and September promotes tuber bulking but heightens the risk of waterlogging, a known constraint in yam fields (Ogunjo et al., 2023; Omonona et al., 2023). The presented rainfall pattern (Figure 2) creates a defined but constrained phenological window for yam cultivation, directly linking the unimodal climate regime to specific physiological opportunities and stresses throughout the crop cycle. The onset of rains in April provides the critical moisture threshold required to break dormancy and initiate sprouting, marking the start of the growing season. However, the subsequent steep increase to high rainfall in August and September coincides with the tuber bulking phase, where high soil moisture availability supports rapid tuber expansion. This positive relationship is counterbalanced by the significant risk of root zone anoxia and fungal pathogen proliferation under waterlogged conditions, a direct consequence of the excessive precipitation during these peak months. Conversely, the preceding severe dry season imposes a hard physiological limit on the planting calendar, as soil moisture is insufficient to support sprouting. Thus, the unimodal pattern does not merely describe rainfall distribution but defines a narrow period of optimal moisture availability bookended by a moisture deficit that delays planting and a moisture surplus that threatens yield and tuber health. This results in a tight synchronization between crop phenology and climate, where deviations in the timing or intensity of the rainy season can directly compromise establishment or bulking, supporting the climate-sensitive vulnerability of the production system.

Temperature patterns display marked seasonality. In the Harmattan period from December to February, minimum temperatures range from 17°C to 23°C, maximum from 30°C to 37°C, and mean from 26°C to 31°C, resulting in cool nights that slow yam metabolic activity. The pre-rainy season in March and April sees minimum temperatures of 24°C to 25°C, maximum of 37°C to 38°C, and mean of 31°C to 32°C, introducing the highest risk of heat stress that may reduce sprouting and vine elongation. During the wet season from June to September, minimum temperatures are 22°C to 24°C, maximum 29°C to 31°C, and mean 26°C to 28°C, providing optimal conditions for vegetative growth and tuber initiation. These patterns correspond with documented thresholds, as yam thrives between 25°C and 30°C, whereas temperatures exceeding 35°C induce heat stress. Peak maximum temperatures reach 37.7°C in March, potentially impairing photosynthesis and carbohydrate translocation (Zakari, Hassan, & Iguisi, 2021; Kalu, Eze, & Ugwu, 2023).

Relative humidity follows a gradual seasonal increase, with lows in the dry season at 50.87% in January and 53.57% in February, rising to highs of 84.56 to 87.09% from June to September. Agronomically, high humidity supports leaf turgidity and canopy development but, when exceeding 85%, favors fungal diseases such as yam anthracnose. Conversely, low humidity in the dry season elevates evapotranspiration stress (IPCC, 2022; NiMet, 2023). Solar radiation inversely correlates with rainfall, peaking in the dry season at 7 hours in November and December, and dipping to lows of approximately 4 hours in August and July due to cloud cover. This dynamic is significant, as tuber bulking demands both adequate moisture and sufficient sunlight; thus, August's low sunshine emerges as a limiting factor despite abundant rainfall (Shiru et al., 2023; Olorunfemi, Fasinmirin, & Komolafe, 2024).

Comparing these seasonal patterns with yam phenology reveals specific implications. During sprouting in March and April, yam requires at least 50mm to 80 mm of rainfall and minimum temperatures above 20°C, yet maximum temperatures of 37°C to 38°C pose heat stress risks before rains stabilize. Vegetative growth from May to July benefits from moderate temperatures and rapidly climbing rainfall of 175mm to 200 mm monthly, with moderate solar radiation facilitating vine expansion. Tuber initiation in July and August necessitates abundant water and sunlight, but rainfall peaks coincide with solar radiation below 5 hours per day, potentially delaying this stage. Tuber bulking from August to October thrives under high humidity and moderate temperatures, with September's approximately 232 mm rainfall proving highly favorable, though waterlogging risks arise from over 600 mm of cumulative rainfall in August and September. Finally, maturation and harvest from October to December are aided by drying conditions that enhance tuber skin-setting and storage quality, as solar radiation increases amid declining rainfall (Aighewi, Asiedu, Maroya, & Balogun, 2020; Adebayo & Oguntunde, 2024).

The annual rainfall in Benue State from 1988 to 2022 as depicted in Figure 3, exhibits pronounced interannual variability, with values ranging from approximately 600mm to over 1,600 mm. Peak precipitation years, such as 1999 and 2019 (exceeding 1,600mm), support robust yam vegetative growth but elevate waterlogging risks, potentially impairing root respiration and increasing rot disease susceptibility. Conversely, dry years like 2003 (below 800mm) induce moisture stress, stunting development. Linear regression reveals a weak positive trend (slope = 4.75 mm/year, $R^2 = 0.055$), indicating negligible long-term increase (approximately 0.1% annually) amid dominant year-to-year fluctuations exceeding 500mm. This variability, rather than the trend, poses the primary challenge to yam production. These findings support Omonona, Ogunjobi, & Ajani, (2023) on the dual effects of rainfall extremes in yam cultivation and align with Akinsanola, Ogunjobi, and Abolude (2025) regarding intensified rainfall oscillations in West Africa.

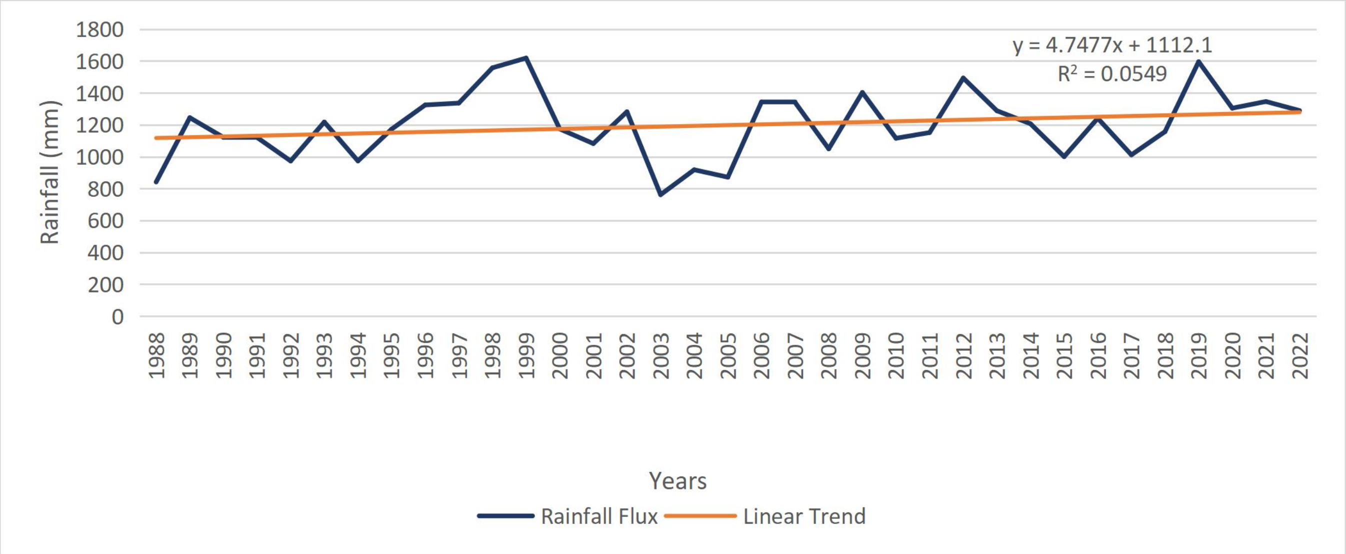

Figure 3: Annual Pattern of Rainfall in Benue State

Annual maximum temperatures in Figure 4, fluctuate between 33.0°C and 34.5°C, with a mean of 33.34°C and notable peaks in 2017 and 2021 (≥34.2°C), risking heat stress during yam's vegetative phase, and dips in 2011–2012 (<33.2°C), potentially slowing metabolic rates and delaying tuber bulking. A modest warming trend (slope = 0.0082°C/year, R^2 = 0.0596) accounts for only about 0.01°C annual increase, emphasizing interannual variability over long-term change. This pattern influences photosynthetic efficiency and yield stability. The results support Uger (2023) on variable temperature responses in the Guinea savanna zone, Adesiji, Ojo, & Ogunjobi (2024) on suboptimal temperatures reducing enzyme activity, Adejuwon, Joshua, & Dada, (2024) on heat spikes disrupting tuber stages, and Omonona, Oyekale, and Ogunjobi (2024) on volatility threatening yam yields, with no evident contradictions.

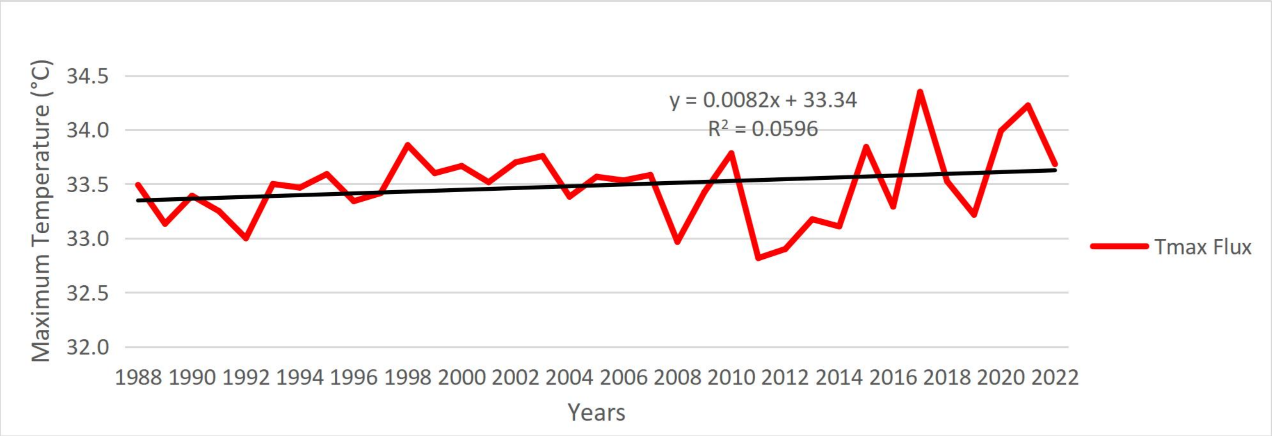

Figure 4: Annual Pattern of Maximum Temperature (T. max) in Benue State

Annual mean temperatures as reflected in Figure 5, oscillate around 27.97°C, with peaks near 28.5°C in 1998, 2007, and 2010, accelerating vegetative growth but risking moisture stress and impaired tuber allocation, and troughs below 27.5°C in 1989, 2011, and 2012, reducing photosynthesis and shortening the growing season. Linear analysis shows a negligible cooling trend (slope = –0.002°C/year), with minimal variance explained, highlighting interannual volatility as the key driver. This instability necessitates resilience strategies for yam phenology. Findings align with Okechukwu and Nwosu (2022) on thermal extremes affecting tropical root crops and support Eze, Okoro, and Nwachukwu (2023) on the need for temperature-tolerant varieties.

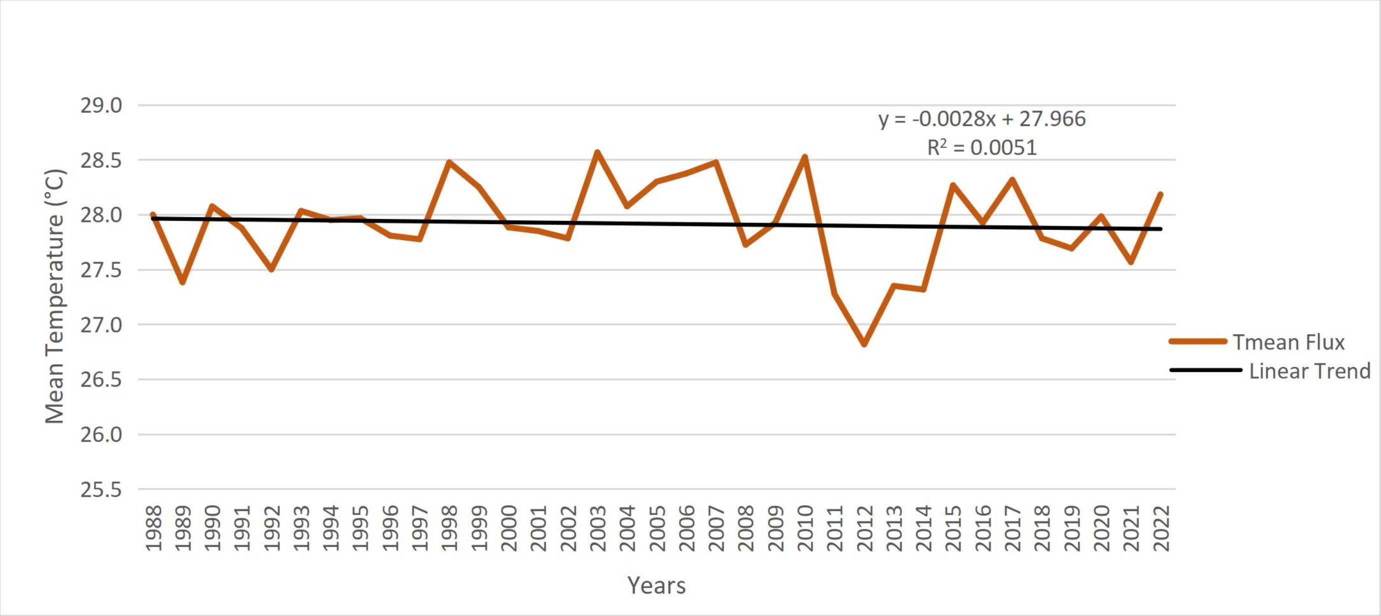

Figure 5: Annual Pattern of Mean Temperature (T.mean) in Benue State

Minimum temperatures range from 20.5°C to 23.5°C, with a mean of 22.5°C, peaks above 23.0°C in 2003 and 2007 as shown in Figure 6, enhancing metabolic activity, and dips below 21.5°C in 2012 and 2021 delaying sprouting and development. A weak cooling trend (slope = –0.0137°C/year, $R^2 = 0.0473$) indicates approximately 0.01°C annual decrease (0.5% over the period), but interannual variability dominates, influenced by regional factors like ITCZ shifts. Cyclical patterns affect soil moisture and pests during vegetative phases. Results support Oluwaseun, Adebola, and Ibrahim (2024) on combined stressors, Omena et al. (2023) on suboptimal lows impeding reactions, and Eze et al. (2023) on short-term variations dominating yam impacts.

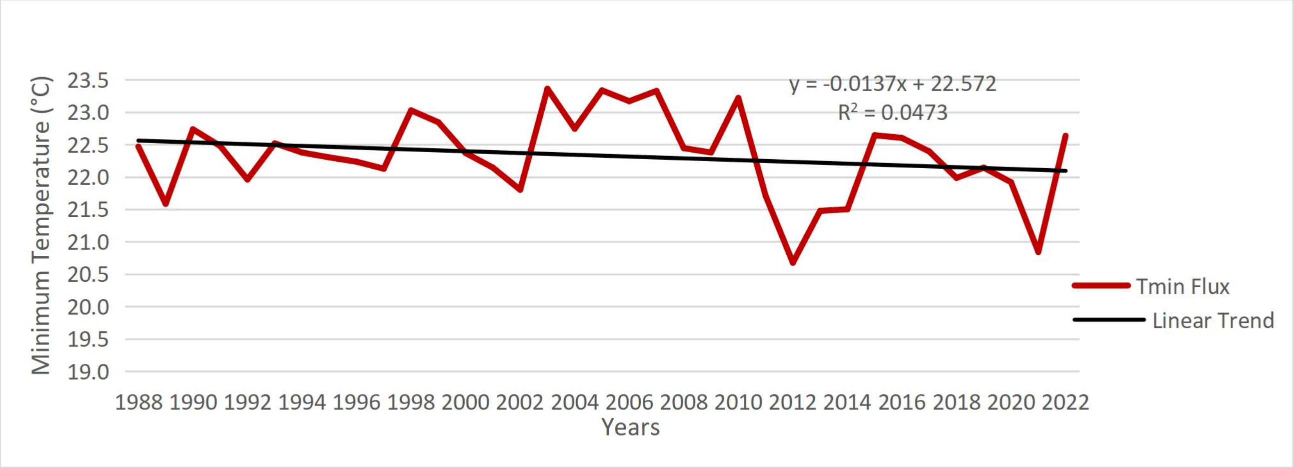

Figure 6: Annual Pattern of Minimum Temperature (Tmin) in Benue State

Relative humidity varies between 60% and 95% around a mean of 73.57%, with peaks like 95% in 2005 as demonstrated in Figure 7, promotes vegetative growth but fosters diseases such as anthracnose, and troughs below 67% in 2014 inducing transpiration stress and limiting tuber initiation. An insignificant trend (slope = 0.0155%/year, R^2 = 0.0004) underscores short-term fluctuations linked to monsoon dynamics. This volatility demands dual strategies against disease and dryness. The pattern supports Omonona, Ajani, and Oni (2022) on high humidity driving pathogen outbreaks, Adeyemi, Okeleye, and Matthew (2021) on dryness reducing assimilation, Shiru et al. (2023) on West African variability, Olagunju, Babatunde, and Ogunpaimo (2023) on resilient practices, Olorunfemi, Fasinmirin, & Komolafe (2024) on adaptive measures, and Tizhe (2024) on resilient practices, without contradictions.

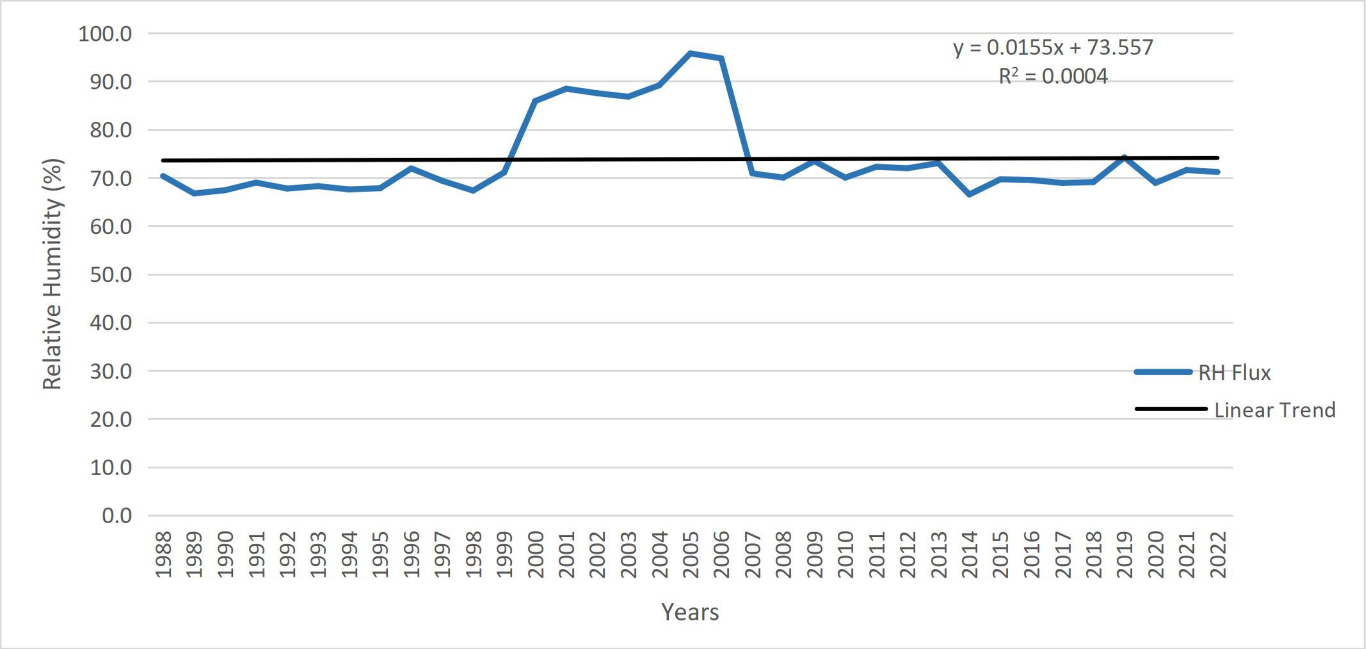

Figure 7: Annual Pattern of Relative Humidity (RH) in Benue State

Solar radiation fluctuates between 5.5 and 7.0 hours/day, with peaks in 1988 and 2006 as revealed in Figure 8, enhancing photosynthesis and tuber yield, and troughs in 1989 and 2020 limiting assimilates and increasing disease risk via prolonged cloudiness. A weak downward trend (slope ≈ –0.02 hours/year, $R^2 = 0.0184$) is negligible, with interannual variability as the primary concern for yield stability. Adaptive practices like optimized planting and shade-tolerant cultivars are recommended. Findings align with Aighewi, Asiedu, Maroya & Balogun (2020) on light demands for yam, Omonona et al. (2023) on low radiation stressing tuber development, Onwuka (2023) on maximizing interception, and Raymundo, Ogwu, and Akpenpuun (2024) on variability threatening stability, with no contradictions.

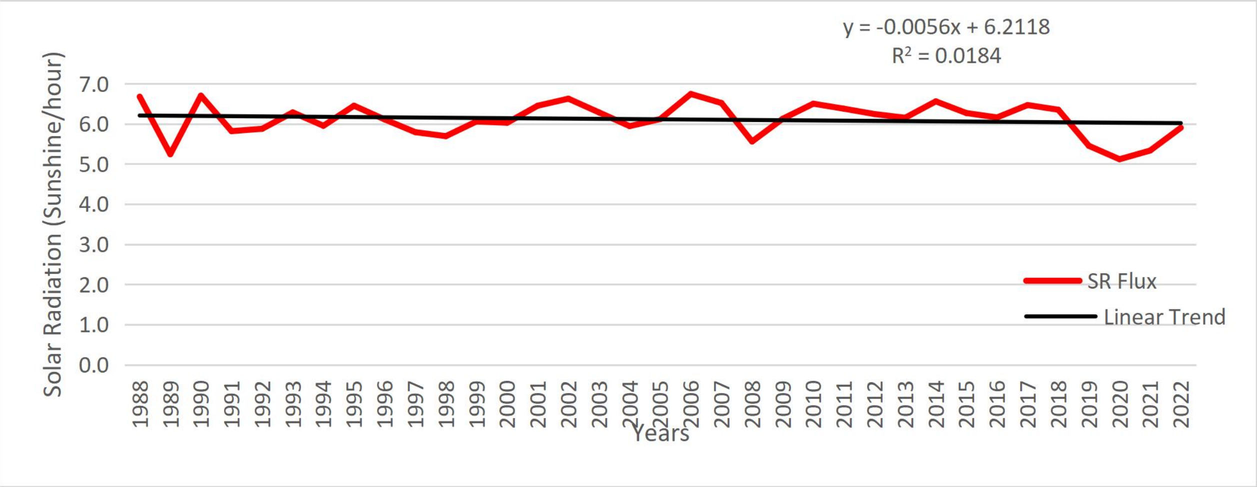

Figure 8: Annual Pattern of Solar Radiation (SR) in Benue State

Synthesizing these patterns, yam production primarily benefits from the wet season from April to October, though excessive rainfall and low solar radiation in August present challenges. Annually, climatic variables display weak or negligible trends but strong interannual variability, positioning variability rather than long-term trends as the foremost threat to yam production. Farmers contend with alternating years of dry spell, excess rainfall, heat spikes, and low-light conditions, consistent with regional climate instability (Uger, 2023; Adesiji, Ojo, & Ogunjobi, 2024).

5. CONCLUSION

Conclusively, this study offers a comprehensive evaluation of the seasonal and annual patterns of climatic elements in Benue State over the 35-year period from 1988 to 2022, alongside their implications for yam production. The results demonstrate a robust seasonal climatic regime, where rainfall and humidity peak during wet months, while temperatures and sunshine hours are highest in dry months. Nonetheless, interannual variability, rather than long-term trends, stands out as the paramount climatic challenge, profoundly affecting yam growth and yields. The weak long-term trends in rainfall, temperature, humidity, and solar radiation indicate minimal dramatic shifts in Benue State's climate over the period, yet short-term deviations such as extreme wet or dry years significantly disrupt yam production cycles. Considering yam's acute sensitivity to climatic oscillations, especially rainfall variability and heat stress, sustaining production amid evolving climate conditions demands adaptive agricultural strategies. Ultimately, the findings underscore the growing importance for resilience-oriented farming practices, enhanced climate knowledge dissemination, and regional interventions to bolster yam farmers against climatic risks.

Acknowledgments

The authors gratefully acknowledge the Nigerian Meteorological Agency (NiMet), Makurdi, for providing the meteorological data used in this study.

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