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(Research Article)

Analyzing soil variability and water use efficiency in relation to variability of climate on tomato yields in Delta State, Nigeria

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Abstract

Nigeria's agriculture sector, crucial for the nation's economy, is already experiencing the effects of climate change. Notable impacts include unpredictable rainfall patterns and a decline in vegetable exports. Tomato farming, essential to Nigeria's horticultural industry, is particularly at risk due to its reliance on weather conditions. This study aims to assess the efficacy of soil and water management across various climates, examining how these elements impact tomato yields in Delta State. The study was conducted at the Federal College of Education (Technical) Demonstration Farm in Asaba, Delta State. To understand the development patterns of tomato cultivation and its water use efficiency, soil and climate data were collected and analysed. Soil samples were taken from three tomato-growing experimental plots at depths ranging from 0 to 60 cm using a soil auger. Standard analytical techniques were employed to evaluate the physico-chemical characteristics of these soil samples. The results showed that these traits positively affected tomato output and growth. During the growing season, irrigation methods were fine-tuned to match the tomato plants' growth stages. The timing and frequency of irrigation fluctuated according to the experimental design, while the total water supplied stayed uniform across treatments. Interestingly, a corresponding trend revealed that irrigation water use efficiency (IWUE) rose as irrigation volume decreased. While the study area's climate is generally suitable for tomato cultivation, increasing temperatures could lead to heat stress risks. This finding holds great promise for the tomato industry, as managing water stress effectively not only saves water but also boosts the levels of beneficial compounds like sugars and antioxidants, thus enhancing both the flavor and nutritional quality of the fruit.

Keywords: Soil variability; Water use efficiency; Climate variability; Tomato yields

1. Introduction

In Nigeria, agriculture serves as the primary source of income for most people and has a crucial role in shaping the country's economy. The agricultural industry is vital in driving food production, generating foreign revenues, creating jobs, and providing raw materials for related businesses, and adding to the GDP. Its importance cannot be overstated. According to a sector-by-sector analysis, the agriculture industry contributed around 42% of the real GDP in 2006, up from 41.2% in 2005. Similarly, the agriculture sector's growth rate in terms of GDP contribution at 1990 constant basic prices increased from 4.2% in 2002 to 7.21% in 2007, 6.2% in 2008, 5.9% in 2009, and 4.2% in 2002 to 4.12% in 2014. In 1999, more than 60% of Nigeria's workforce was employed in the agriculture sector (Agba, 2015).

Nigeria's climate has a significant role in food production, particularly in the country's rainforest region, where farmers mostly rely on rain for farming. Research shows that climate change has a detrimental impact on agriculture in Africa

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and that adaptation is one policy option to lessen that impact (Ayinde *et al.,* 2011). It is essential to recognise that Nigeria's food supply cannot keep up with population increase, and that several variables, including climate change, are major contributors to the country's food deficit. Crop production and processing account for a sizeable portion of agriculturally related businesses in Nigeria, where over 60% of the population rely heavily on these industries for survival (Agba *et al.,* 2017). On the other hand, prompt climate prediction provision can help farmers make well-informed decisions, reduce adverse effects, and enable them to take advantage of or prepare for anticipated conditions (Bernardi, 2011). Furthermore, efficient distribution of climate-related information and advisory services can significantly improve risk management associated with climate change and assist farmers in adjusting to it (Tall *et al.,* 2014).

In Nigeria, tomatoes are a significant horticultural crop. Tomato (*Solanum lycopersicum L.*) belongs to the family Solanaceae, where pepper, potato, tobacco, eggplant, and tomatillo belong, and it is one of the significant commercial vegetable crops widely grown in Nigeria. Recently ranked first in a prioritization workshop for vegetable crop value chains in the country, tomatoes are a high-value crop with considerable potential to create employment opportunities and increase incomes for those involved in the tomato value chain through commercialization. Over 30% of farmers grow tomatoes for home consumption or cash nationwide. The crop contributes 14% of all vegetable produce and about 7% of horticultural crops in the country (Olanrewaju *et al.,* 2017). However, tomatoes are highly perishable and vulnerable to the effects of climate change. Olanrewaju *et al.* (2017) observed that weather-induced seasonality in tomato production is a key factor behind market price fluctuations in Nigeria. Osunmuyiwa *et al.* (2021) detailed the trade patterns of tomatoes between Nigeria and its neighboring countries, noting that Nigeria faces seasonal low production from May to August and November to December. During these periods, Nigeria supplements its low production by importing tomatoes from Neighboring countries in Africa. Tomato plants are sensitive to water stress and show a high correlation between evapotranspiration (ET) and crop yield (Guhan *et al.,* 2020). Water is a decisive factor for crop production because of its crucial role in nutrient uptake and transport, temperature regulation, and several physiological processes, including photosynthesis.

Over the years, water-intensive agriculture has rendered this resource a limiting factor for crop production, especially in water-scarce and semi-arid areas. Considering the growing population's increasing food and nutritional demands, a significant part of agricultural research focuses on improving water use efficiency (WUE) and conserving water without yield penalties. Considering the complexity of increasing WUE through breeding owing to the trade-off between photosynthesis and transpiration, agronomic strategies are requisite (Adu *et al.,* 2018). Innovative timing involves adjusting operations to maximise advantages or minimise risks associated with climate change, taking into account factors like water availability, labor, expected temperatures, and market conditions. Few studies have investigated the patterns and trends of rainfall, temperature, relative humidity, and other parameters on the yields of cassava, yam, pepper, and tomato in Delta State, Nigeria. Previous records indicate that very few have intensively examined the relationship between climate change and crop production. Moreover, different crops may be affected unevenly. To ensure food security in south-south Nigeria in order to feeds a region more than 45% of the region population, it is essential to examine the climatic trends of this region. Therefore, the purpose of this research is to determine the coefficient of variation in climatic variables in relation to soil variability and water use efficiency on tomatoes yield in Delta State, South-South, Nigeria

2. Materials and Methods

2.1. Study Area

The study was carried out at the Demonstration Farm of the Federal College of Education (Technical), Asaba, Delta State, Nigeria. Delta State is Nigeria's oil and agricultural producing state, located in the South-South geo-political area of the Niger Delta region with a population of 4,098,291 (males: 2,674,306; females: 2,024,085) (NPC, 2006). With an approximate area of 762 square kilometers (294 sq mi), the capital city is Asaba, situated at the northern end of the state. At the same time, Ogwashi-Uku has the largest land space for any industry, Warri is the state's economic nerve and also the most populated in the southern end of the state (Umeri *et. al.,* 2016). The total land area of the state is 16,842 Km2. It is bounded north by Edo state, Anambra state to the east, Rivers state to the southeast, Bayelsa state to the south, the Atlantic Ocean, the Bay of Benin to the west, and Ondo state to the northwest. The state is confined to the east and south by the lower course and delta of the Niger River. Delta was founded in 1991 in the southern half of the former Bendel state. The state capital is Asaba, on the Niger River. In the Niger River delta, most of the state lies at an elevation below 500 feet (150 meters). Delta State lies roughly between longitudes 060 45iE and latitudes 060 30iN of the equator.

2.2. Soil Sample and Climatic Data Analysis

Samples were collected from each point at the soil profile (depths) of 0-15, 15-30, 30-45 and 45 – 60cm at a radius of 5cm with the aid of a soil auger. The surface soil samples were air-dried; rocks and pebbles will be removed before pulverisation using a mortar and pestle. The pulverised soil samples will then pass through a 2mm filter sieve to achieve uniform particle size. The sampling bags were kept inside clean plastic containers to avoid contamination. The soil samples were scooped into air-tight containers labelled according to the name of the area from which the samples were collected and the sampling point depth. The samples collected were taken to the laboratory at the Department of Soil Science and Land Management of University of Benin, Benin, Edo State, for determination of pH, bulk density, textural class, electrical conductivity, nitrogen, available phosphrous, calcium, magnesium, and potassium. The results of the soil test were subjected to appropriate statistical analyses. Temperature, precipitation, and solar radiation are the three most widely used climate variables to assess climate change and its impact. Climatic data were obtained from the Nigeria Meteorological Agency (NIMET) for 2024/2025. The data that will be obtained are Minimum and maximum temperature, Humidity, Rainfall, wind, and sunshine.

2.3. Land Preparation, Experimental Design, Treatments, and Planting

The field experiment was carried out at the Federal College of Education (Technical) Demonstration Farm, Asaba, Delta State, Nigeria, where a 1296sqm (36m x 72m) land area (Uncultivated) were ploughed with disc plough and then harrowed after a week of ploughing. According to the experimental design, the land was demarcated into blocks and plots. The experiment was carried out in a randomized complete block design (RCBD) across the general slope of the field in order to ensure as homogeneous soil conditions as possible within the blocks. The experimental set up consist of combination of two level of fertilizer amendments rate; 3 and 6t/ha; two level of poultry manure; 3 and 6.0 t/ha and two level of irrigation; 100% and 75% which will be factorially combined to form a total of ten treatments (Table 1). The experiment will be carried out with two replicates, making 20 plots for the experiments. The NPK fertilizer and poultry manure were applied at two weeks after transplanting as a treatment.

Table 1 Treatment for Field Experiment

S/N	Treatment Label	Description
1	I_{100}	No NPK + No manure + 100% irrigation (Control)
2	I_{75}	No NPK + No manure + 75% irrigation (Control)
3	N_3I_{100}	3t/ha of NPK+ 100% irrigation
4	N_31_{75}	3t/ha of NPK+75% irrigation
5	N_6I_{100}	6t/ha of NPK+ 100% irrigation
6	N_6I_{75}	6t/ha of NPK+ 75% irrigation
7	M_3I_{100}	3t/ha of manure + 100% irrigation
8	M_3I_{75}	3t/ha of manure + 75% irrigation
9	M_6I_{100}	6t/ha of manure + 100% irrigation
10	M_6I_{75}	6t/ha of manure + 75% irrigation

Water for irrigation will be pumped from a 13.71-meter well into tanks with overhead connections using a submersible pump. The overhead tanks will have a capacity of 2000 litres (L) and will be erected at 2 meters above ground level as a water reservoir. In the full irrigation treatment (100%), 100% of the water required to bring the soil water to field capacity (FC) which were applied when about 50% of FC could have been depleted in the plots. While in the deficit irrigation treatment (75%), water was applied on the same day as that of the full irrigation treatment, but the irrigation depth was reduced to 75% of the full irrigation.

2.4. Irrigation Water Application

Irrigation water was applied as per the schedule of the irrigation treatments. Soil moisture was calculated at each stage of the crop by the gravimetric method before irrigation. The depth of irrigation water was calculated by equation 1.

$$d = \left(FC - \frac{M}{100}\right) X\ 15$$

$$Where,$$

- $d = Irrigation\ water\ depth\ (cm)$
- $FC = Field\ capacity\ (\%vol.)$
- $M = Percent\ moisture\ content\ (volume\ basis)$

This depth (d) was multiplied by each plot's area to get the water volume. A calibrated bucket measured the amount of irrigation applied to the plot (other than the drip irrigated tank).

2.5. Crop Evapotranspiration

Crop evapotranspiration (ET, mm) values of different irrigation treatments were calculated using the soil water budget, as expressed in equation 3 (Garrit *et al.,* 1982).

$$ET = I + P - R - D \pm \Delta S$$

Where I is the applied irrigation water amount (mm), P is the precipitation, R is the runoff (mm), D is the drainage below the effective root depth (mm), and ΔS is the soil water content difference between two measurements (mm 90 cm^{-1}). The amount of irrigation water was measured by a water meter for each plot. The changes in soil water content between different measurements were calculated by the gravimetric method. In determining the ET, the water content in the 0-60 cm layer of the soil was taken into account (Patanè, C. & Cosentino, 2010). A possible water content increase in the layer of 60-90 cm was considered as deep percolation and neglected. The runoff is not taken into consideration in the computation for the soil water budget since irrigation water was administered in a regulated manner using the drip irrigation method.

2.6. Statistical Analysis

Data obtained from the experiments were analyzed using the Statistical Package for Social Sciences (SPSS). Both descriptive and multiple regression were employed in data analysis. In contrast, simple correlation, stepwise multiple regressions, and analysis of variance (ANOVA) were used to show the relationship between climatic parameters and crop yield and the trend and variation in crop yield.

3. Result and Discussion

3.1. Physico-Chemical Properties of Soil Samples

Research shows that the physicochemical properties of nutritional components influence their mobility, bioavailability, and plant uptake (Adaikpoh & Kaiser, 2012). The characteristics of soils collected from the experimental field included pH, electrical conductivity, available phosphorus, total nitrogen, exchangeable cations (potassium, calcium, sodium, and magnesium) and particle size (silt, clay, and sand).

3.2. Soil pH

As illustrated in Table 2, the pH levels (soil hydrogen ion concentration) for surface and subsurface soil at the study site varied from 5.5 to 6.8. This indicates that the soils possess a moderate acidity. These soils are appropriate for growing vegetables due to their slightly acidic pH. Most vegetables thrive in slightly acidic soil (Osunbitan, 2013). A pH ranging from 3.5 to 10.0 supports plant growth. Usually, a pH between 6.0 and 7.0 is considered optimal for robust plant development (Haby *et al.,* 2011). The application of inorganic fertilizers and other chemicals in the field before the study began may have contributed to the observed acidification of the soil across all study sites. This observation aligns with expectations, as the pH levels of most tropical soils typically range from acidic to slightly neutral (Abdallah *et al.,* 2011).

3.3. Textural Class

The soil at the field site showed a mostly sandy profile across the soil horizon, with sand levels ranging from 61.7% in the top layer to 78.8% in the subsurface layer. The clay content was low, between 10.6% and 12.4%, while silt content fluctuated from 20.06% to 33.8%. Sand is dominant in all layers, suggesting a coarse-textured soil, although slight differences exist between the surface and deeper samples. The variability and poor sorting of soil particles likely explain the high sand content found in all samples. This inconsistency results from the anthropogenic nature of the soil materials, which mainly include mixed and decomposed waste rather than naturally weathered parent rock. These findings are consistent with the observations of Amos-Tautua *et al.* (2014), who indicated that soils with a high sand content and low clay content are more prone to pollutant leaching due to their larger pore spaces and diminished capacity to hold contaminants.

Table 2 Physical Properties and Particle Distribution of the Soil at Different Depths

	Depth (cm)	pH	Sand (%)	Silt	Clay (%)	Bulk density (g/cm^3)
Replications				(%)		
1	00-15	6.4	67.4	32.04	11.7	1.51
	15-30	6.7	72.5	28.1	10.6	1.58
	30-45	6.4	78.8	20.06	10.7	1.6
	45-60	6.8	79.1	22.23	11.44	1.61
2	00-15	6.4	68.4	31.1	11.6	1.55
	15-30	6.2	64.4	30.1	10.12	1.6
	30-45	6.5	70.4	29.6	10.9	1.62
	45-60	5.7	72.11	28.22	10.7	1.64
3	00-15	6.4	62.7	32.6	13.4	1.53
	15-30	5.8	71.7	29.6	13.41	1.57
	30-45	5.9	68.7	27	13.6	1.6
	45-60	6.3	69.4	25.3	12.78	1.61

3.4. Bulk density (g/cm3)

Table 2 shows that the bulk density of both surface and subsurface soil at the study site ranged from 1.51 to 1.68. Dantani *et al.* (2024) note that the bulk density achieved through organic amendment application lies within the optimal range for root development. The introduction of organic amendments rich in organic matter likely aids in lowering bulk density by modifying the essential soil characteristics required for this reduction. Soil particles grouped together by organic materials are referred to as soil aggregates, and their formation is promoted by organic matter. The larger pore spaces surrounding soil aggregates enhance the soil's macro-porosity, improving both water and air flow. Adekiya & Ojeniyi (2001) indicate that increased soil bulk density can hinder root elongation when water content is low. Even though untilled soils exhibited higher water content and lower temperatures, these conditions did not beneficially influence tomato growth and yield. Thus, tomatoes grown on alfisols in the humid tropics necessitate tillage to lower soil density, facilitating improved root development, nutrient absorption, and increased yields. Implementing tillage and planting on ridges or mounds further enhances nutrient availability for tomato crops.

3.5. Electrical Conductivity

Table 3 illustrates that the soil's electrical conductivity (EC), an important indicator of salinity and nutrient levels, progressively increased with depth, from 10.5 mg/kg at the surface to 13.7 mg/kg in the subsurface. The deepest layers recorded the highest EC value of 13.9 mg/kg, likely due to leaching effects from the area's heavy rainfall. Rainwater dilutes solute concentrations at the surface while facilitating the downward movement of dissolved salts and minerals, resulting in their accumulation in deeper layers. Obianefo *et al.* (2016) note that this phenomenon accounts for the lower conductivity observed in topsoil compared to deeper lay. The soil exhibits moderate salinity, which is deemed acceptable for agricultural crop production. According to FAO guidelines, soils with an EC exceeding 16 mS/cm (or mg/kg, depending on the measurement technique) are classified as very saline, jeopardizing plant health due to ion toxicity and osmotic stress. However, the EC values recorded in this study were significantly lower than this threshold, suggesting that salinity did not impose notable growth limitations, thus rendering the soil suitable for tomato cultivation (Ademiju *et al.,* 2019).

Table 3 Variation of Chemical Properties at Different Depth

	Depth (cm)	EC	Av.P	TN	K	Na	Mg
		(mg/Kg)	(ppm)	(%)	(cmol/kg)	(cmol/kg)	(cmol/kg)
Replications							
1	00-15	13.7	0.36	0.63	0.27	0.63	3.42
	15-30	13.9	0.19	0.6	0.21	0.67	3.33
	30-45	12.5	0.12	0.96	0.42	1.91	3.43
	45-60	10.5	0.19	0.21	0.3	0.72	3.2
2	00-15	12.7	0.31	0.35	0.21	0.87	3.06
	15-30	13.1	0.11	0.23	0.27	0.59	3.93
	30-45	12.5	0.11	0.17	0.36	1.95	3
	45-60	11.6	0.08	0.13	0.47	0.76	2.97
3	00-15	11.5	0.17	0.35	0.24	0.71	2.69
	15-30	11.9	0.25	0.3	0.21	0.62	3.49
	30-45	12.8	0.18	0.38	0.27	0.98	3.06
	45-60	10.8	0.11	0.14	0.35	0.71	2.9

Electrical Conductivity (EC), Available Phosphorus (Av. P), Total Nitrogen (TN), Potassium(K), Sodium (Na), Magnesium (Mg)

3.6. Nitrogen, Potassium, Magnesium, Sodium, Phosphorus

The soils revealed elevated phosphorus (P) levels, with surface and subsurface measurements between 0.08 and 0.36 cmol/kg. This may be attributed to a considerable amount of organic detritus and plant decay (Ideriah *et al.,* 2006). Research shows that increased phosphorus concentrations enhance plant growth. Soil samples exhibiting P levels over 0.1 cmol/kg are considered suitable for agricultural use (FAO, 1976). According to Isirimah (2002), phosphorus is essential for the development of fibrous root systems in plants.

Since most waste originates from plant residues abundant in organic matter, the elevated nutrient levels in the soil, as illustrated in Table 3 may be linked to this waste composition. Research has shown that high phosphate concentrations can limit plants' access to cation metals (Obianefo *et al*., 2017). The exchangeable potassium (K) in soils varies from 0.21 to 0.42 cmol/kg for surface and subsurface layers, respectively, as indicated in Table 3. Umeri et al. (2017) note that more fertile soils often exceed 0.2 cmol/kg, which is the critical threshold for exchangeable K. This suggests that these soils are nutrient-rich and have significant potential for crop yield without the need for fertilizers. Potassium catalyzes in plants, boosting chlorophyll production in leaves and controlling the opening and closing of leaf stomata. It also contributes to disease resistance, water absorption, fruit ripening, and the synthesis and transportation of plant sugars and carbohydrates.

Table 3 indicates that the total nitrogen (N) content in the soil ranged from 0.13 to 0.96 percent for surface and subsurface layers, respectively. This study demonstrates a similar range of values (Osakwe, 2014). Nitrogen naturally enters soils through phenomena like lightning and the breakdown of plant material (Eddy *et al.,* 2006). The FDALR (2004) guidelines for tomato cultivation suggest that the total N in the soil sample was low. The waste mixture, primarily derived from farmyard and agricultural sources, likely contributed to the increased nitrogen levels in the soils. Additionally, the soil contains organic matter that supplies most of the nitrogen and phosphorus essential for enhancing soil fertility and supporting plant growth (Ideriah *et al.,* 2010).

Soil organisms play a crucial role in breaking down waste, contributing to the soil's rich nutrient content (Amos-Tautua *et al.,* 2014). The magnesium (Mg) concentrations for surface and subsurface soils range from 1.79 cmol/kg to 3.93 cmol/kg, respectively. Magnesium is essential for transporting phosphorus in plants, and its exchangeable Mg^{2+} content is vital for protein synthesis and cell division. In all locations, the exchangeable magnesium concentration met Umeri *et al.* (2017) 's threshold of 1.9 cmol/kg, indicating moderate levels. Sodium (Na) levels ranged from 0.07 cmol/kg to 0.195 cmol/kg in both subsurface and surface soils. Excessive salt can lead to wilting due to its effect on lowering water potential and reducing water uptake. Sodium, a crucial micronutrient, aids in metabolism, particularly in chlorophyll production and the regeneration of phosphoenolpyruvate (Zhu, 2001).

3.7. Irrigation Water Amount and Crop Evapotranspiration

Table 4 summarizes the total irrigation water applied to all experimental treatments and the crop evapotranspiration (ET_C) values. ETc values were calculated by multiplying the reference evapotranspiration (ETo) by the stage-specific crop coefficient (Kc) for tomato plants at various growth stages. Meanwhile, the total irrigation water was determined using the measured volume of water delivered to each experimental plot. Data analysis indicates that ETc values were relatively low during the first two weeks after transplanting, which can be attributed to the limited vegetative growth and decreased water consumption of young tomato plants. However, as the plants advanced through later developmental stages—particularly vegetative growth, blooming, and fruit development—the ETc values steadily increased, reflecting the crop's heightened water requirements.

Irrigation was scheduled at two different intervals: a 5-day cycle (Treatment A) and an 8-day cycle (Treatment B). Treatment A received 22 irrigation events throughout the growing season, ensuring more frequent water replenishment, whereas Treatment B received only 13 irrigation treatments due to the longer intervals. This difference in irrigation frequency directly impacted the total water input for each treatment, highlighting the trade-offs between water application frequency and crop water usage efficiency. The volume of irrigation water applied varied significantly throughout the experimental treatments, ranging from 345 mm to 478 mm, indicating changes in irrigation schedule and water management practices. In addition to irrigation, the total precipitation recorded throughout the growth season was 185 mm, which helped to improve overall soil moisture availability. Crop evapotranspiration (ET) values varied significantly among treatments, indicating the effect of irrigation regimes on tomato crop water consumption. The maximum evapotranspiration was reported in Treatment AT1, at 589 mm, suggesting increased water use, likely due to excellent moisture conditions promoting strong plant growth. In contrast, Treatment BT2 recorded the lowest ET value, measuring 439 mm, possibly due to water stress or reduced watering frequency, leading to lower plant transpiration rates. These discrepancies underscore the significance of irrigation management in determining crop water demand and overall yield.

The irrigation water application was carefully controlled during the growing season to align with the developmental stages of the tomato plants. Although the overall amount of water applied remained consistent for all plants, the timing and frequency of irrigation varied according to the treatment program. This approach ensured that water distribution was customised to meet crop demands at various phenological stages, including early establishment, blooming, and fruit development. Tomato irrigation requirements vary significantly based on climatic conditions, cultivar characteristics, and agricultural practices. Patanè *et al.* (2011) discovered that seasonal irrigation water needs for tomato production usually range from 325 to 464 mm under Mediterranean growing conditions. Tarı and Sapmaz (2017) found that irrigation amounts for tomato processing varied from 242 to 404 mm, with corresponding seasonal evapotranspiration (ET) values ranging from 276 to 406 mm. In contrast, Ertek *et al.* (2012) found that semi-arid conditions led to significantly higher water needs, with maximum irrigation and ET values of 811.7 mm and 863.3 mm, respectively, while the minimum recorded values were 503.7 mm (irrigation) and 516.1 mm (ET). These differences highlight the significant impact of environmental conditions, especially in dry and semi-arid regions where evaporative losses are more significant. Elmas *et al.* (2023) findings closely align with our experimental results, demonstrating similar ranges in seasonal ET and irrigation water use. This implies that our irrigation management strategy effectively matched crop water requirements while maintaining efficiency under prevailing field conditions.

Table 4 Seasonal irrigation water amount (I), crop evapotranspiration (ET) and precipitation values (P)

Irrigation Interval	Irrigation Level	Irrigation (I) (mm)	Crop Evapotranspiration (ET_C) (mm)	Precipitation (mm)
5 Days (A)	Kpc = 1.0 (T1)	478	589	138
	Kpc = 0.75 (T2)	398	501	
8 Days (B)	Kpc = 1.0 (T1)	456	491	
	Kpc = 0.75 (T2)	345	439	

3.8. Climatic Conditions on Tomato Cultivation

The primary climatic factors—including minimum temperature, maximum temperature, evapotranspiration (ET), duration of sunshine, maximum relative humidity, and rainfall—are directly related to the crucial decision rules noted in each agro-ecological zone, influencing high tomato yields. The associations highlight the specific climatic variable combinations that best support optimal tomato production in the study area, as illustrated in Table 5. This study provides essential insights into the environmental needs of a vital vegetable crop, specifically linking climatic factors to tomato yields. The results show that high productivity in tomatoes is frequently tied to moderate or average climatic conditions. This suggests that stable and balanced environments promote healthy growth, while extreme variations—either too high or too low—can hinder optimal development. Furthermore, the study presents a valuable framework for predicting tomato production based on existing weather patterns by pinpointing the specific climate-yield relationships for each agro-ecological zone. These findings can enhance crop scheduling, inform local agricultural planning, and assist in creating adaptation strategies to tackle climate change and its variability.

Table 5 Average Climatic Parameters of the Study Area from NIMET Station

Month	Min Temp	Max Temp	Humidity	Wind	Sun	Rad	ET0
	°C	°C	%	km/day	hours	MJ/m^2/day	Mm/day
Jan	17.54	31.95	50	194	6.6	19.1	5.17
Feb	18.24	32.15	52	194	7.4	21.0	5.48
March	18.54	31.35	56	185	7.1	21.0	5.27
April	18.14	29.15	65	168	6.7	20.0	4.52
May	17.64	27.85	70	168	7.1	19.5	4.11
June	17.24	27.35	69	168	6.7	18.3	3.88
July	16.84	26.65	70	185	5.6	17.0	3.67
Aug	16.74	26.95	70	168	6.2	18.7	3.89
Sept	6.84	28.35	67	168	7.0	20.5	4.38
Oct	17.14	29.45	63	168	7.5	21.2	4.69
Nov	17.24	30.15	57	194	7.2	20.0	4.89
Dec	17.34	30.65	54	211	7.3	19.8	5.08
Average	17.44	29.35	62	181	6.9	19.7	4.59

Boote *et al.* (2012) emphasize that temperature is a vital abiotic factor influencing the growth, development, and productivity of tomato plants. Young *et al.* (2004) note that high relative humidity, commonly seen during tomato-growing seasons in various regions of Africa, can significantly worsen the adverse effects of temperature stress. This interplay of heat and humidity severely disrupts optimal growing conditions for tomatoes. The results of this study suggest that the impacts of heat stress may prevent tomatoes grown during the dry season under current temperature conditions from reaching their maximum genetic yield potential. Given the already minimal stress levels observed in the current climate, this is quite concerning. Therefore, any additional temperature increases brought on by ongoing climate change may lead to even more significant declines in tomato productivity and yield (Ayankojo & Morgan, 2020). The size of individual fruits in this study was not significantly affected by the current temperature levels; however, when temperatures rose above the existing range, there was a noticeable decrease in both fruit size and quantity. These findings demonstrate the vulnerability of tomato crops to heat stress and emphasize the necessity of flexible farming practices, such as developing heat-tolerant cultivars or planning planting times, to safeguard tomato yields from rising temperatures.

The tomato crop may experience heat stress due to rising temperatures; however, a sufficient water supply for the plants to meet their evaporative requirements may also alleviate the projected increase in plant growth. Unlike a similar temperature scenario with limited available soil water and/or nutrient content, the effects of heat stress indicated in this study may be comparatively lower because the model was simulated under non-limiting water and nutrient conditions. Furthermore, linking the increase in biomass under high temperatures to a direct effect of temperature on tomato development proved impossible. This is because, compared to plants grown under ideal temperature conditions without heat stress, tomato fruit set is significantly reduced under high-temperature-induced stress, resulting in a greater allocation of resources (carbon, water, and nutrients) to vegetative biomass (Boote *et al.,* 2012). Similarly, Bhandari *et al.* (2021) found that when maximum temperatures rise above 28o°C, tomato yield per acre declines. Due to their sensitivity to heat stress, tomatoes produce fewer fruits. However, Houetohossou *et al.* (2024) discovered that temperatures in Portugal significantly affect tomato yield forecasts and that temperatures below 21°C greatly influence productivity. They also observed that yield decreased as relative humidity increased. Our findings align with Bhandari *et al.* (2021) assertion that yield increases at relative humidity levels between 75% and 95%. According to Houetohossou *et al.* (2024), humidity levels above 71% positively impacted the average tomato yield estimate. The findings align with those of Dwamena (2022), who evaluated the effects of minimum, maximum, and relative humidity fluctuations on the yields of maize, cassava, and yam in West Africa using multiple regression. The findings indicated that higher cassava yields do not result from increased rainfall. Similarly, Guo & Chen (2022) demonstrated that significant precipitation during blooming constrains tomato development. Indeed, excessive rainfall can lead to agricultural waterlogging, which impairs crop root respiration.

The study revealed a clear link between low evapotranspiration (ET) rates across all three locations and increased yields of tomatoes. ET refers to the total water lost due to plant transpiration and soil evaporation. When ET levels are elevated, tomato plants experience water stress, losing moisture faster than their roots can absorb it (Hao et al., 2019). Persisting water deficits can lead to various physiological stress responses, including wilting, stunted growth, reduced fruit size, and, in severe cases, plant death. Tomato plants frequently show a noticeable decrease in fruit output when exposed to high ET. While fruits that are already developing may desiccate and drop off too soon, water stress during crucial developmental stages can result in flower abortion, which prevents fruit set. High ET al so adversely affects fruit quality alongside yield reduction. Due to their lower water content, water-stressed tomato fruits are usually smaller, less juicy, and less flavorful, making them less appealing in the market and for human consumption (Aires *et al.,* 2022). Additionally, the tomato plant's root structure weakens with prolonged exposure to water stress, rendering it more susceptible to diseases and pathogens in the soil, such as downy mildew and root rot. The decline in crop health and productivity during high ET situations is intensified by these factors. Interestingly, the study also found that areas with higher tomato yields usually had average humidity and temperature, creating more balanced and beneficial microclimatic conditions for plant growth. These findings align with previous research that emphasized the importance of maintaining a temperate climate and regulating ET levels to maximize tomato yield.

4. Conclusion

This study aimed to evaluate the interrelations between soil variability, water use efficiency (WUE), and the variation in climatic conditions, and how they influence tomato yield in Delta State, South-South Nigeria. The investigation covered several soil parameters, including pH, electrical conductivity, available phosphorus, total nitrogen, exchangeable cations (potassium, calcium, sodium, and magnesium) and particle size distribution (silt, sand, and clay). Despite the fact that these nutrients increased soil fertility, the distribution of particle sizes did not significantly change, suggesting that soil texture remained largely constant across depths and locations. The findings highlighted the critical impact of irrigation techniques on tomato cultivation by revealing statistically significant differences ($p < 0.01$). While this approach was resource-intensive, it maximized production by delivering irrigation at 100% of the crop evapotranspiration (ETc) requirement across seasons for optimal water usage efficiency (WUE). Applying 50% ETc, on the other hand, proved to be a good alternative for cost reduction with minimal yield loss. Lastly, a clear difference in tomato yields was observed across various agro-ecological zones. Multiple factors, particularly climate variations, were significant contributors to this discrepancy. Regions characterized by moderate temperatures, adequate rainfall, and ample sunshine—conditions that enhance plant growth and fruit production—recorded higher tomato yields.

Compliance with ethical standards

Disclosure of conflict of interest

No conflict of interest to be disclosed.

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