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OPTIMIZING FERTIGATION FOR GROWTH, YIELD AND RESOURCE EFFICIENCIES OF GREENHOUSE-GROWN PEPPER (*Capsicum spp*.) IN A RAINFOREST ZONE OF NIGERIA

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ABSTRACT

Interest in greenhouse system of cultivation is on the increase among pepper farmers in southwest Nigeria however, little is known about how to maximize yield using the right fertilizer and water combination. This experiment therefore assessed the effects of fertigation regimes on the growth, yield and resource-use efficiency of greenhouse-grown pepper species in a rainforest zone of Nigeria. A 3 by 2 by 2 factorial experiment was conducted using three nitrogen fertilizer rates (0, 60 and 100 kgN/ha), irrigation regimes at 100 and 70% field capacity and Capsicum species (habanero: Capsicum sinensis L.) and bell pepper: Capsicum annuum L.) laid out in a split-split plot design with four replications. Results showed that irrigation application at 70 % field capacity combined with 60 kgN/ha enhanced pepper growth, fruit yield characters and water and nutrient use efficiencies. Habanero species out-performed sweet pepper under greenhouse conditions. Irrigation application at 100 % FC and nitrogen (100 kgN/ha) did not significantly improve yield or resource efficiency compared with 70 % FC and 60 kgN/ha. Thus, findings from the study suggest that moderate fertigation regime is optimal for growth, yield and resource-use efficiency of pepper. Habanero pepper produced higher fruit yield and utilized nutrient and water more efficiently compared with bell pepper. It is therefore recommended that fertilizer rate of 60 kgN/ha, coupled with irrigation at 70 % field capacity be adopted as a strategy for greenhouse pepper cultivation in the rainforest environment of Nigeria.

Keywords: Irrigation, fertilizer, capsicum, performance, inputs, efficiency, food security.

1. INTRODUCTION

The effects of climate change such as decrease in water availability; accelerated soil erosion, nutrient depletion and others are menace to food security and call for effective mitigation and adaptation measures. One of such measures includes use of fertigation technique, a process of combining irrigation with fertilizer application, thereby enabling plants to receive essential nutrients and water simultaneously. It is widely used in crop production, particularly in horticultural crops, where precision in nutrient resources is essential for optimum growth and yield. Pepper is a typical vegetable crop that benefits from fertigation. Its growth and yield is majorly affected by water and nutrient availability.

Vegetables including peppers, are produced both on the field and indoors (indoor farming using controlled environment production facilities). Indoor farming (crop production in controlled environment facilities such as greenhouses, screenhouses, nethouses and polyculture), is gaining increasing importance and widespread adoption worldwide as an essential and widespread

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agricultural practice and viable alternative to open field cultivation (Savic & Ilin 2022). Growing crops in controlled environment facilities, offers several advantages compared to traditional open-field farming. Greenhouse systems allow growers to manipulate key environmental factors, providing a more stable and predictable environment for crops, offers protection from pests, diseases, and extreme weather conditions with positive impacts for yield, quality and resource use and the environment compared with open field cultivation. By creating a barrier between the crop and the outside environment, greenhouses reduce the need for chemical inputs like pesticides and herbicides. This contributes to more sustainable farming practices, which is becoming increasingly important in the face of global environmental challenges. However, while greenhouses offer these advantages, they also require efficient resource management. Water, nutrients, and energy must be used judiciously to minimize operational costs and environmental impacts. The development of an integrated soil, plant, and weather control system holds great potential for enhancing resource use efficiency, yield, quality and income outcomes. The introduction of precision control systems that integrate data from soil, plant, and weather conditions can improve the efficiency of greenhouse operations by optimizing resource use, yield quality and production cost. In greenhouse production systems, the control and monitoring of growing environment conditions is critical for optimizing growth conditions and resource efficiency (water, nutrients, microclimate) for enhanced productivity and income (Acedo & Buntong, 2021). Variables such as temperature, humidity, soil moisture, nutrient availability, and light intensity can be precisely monitored and controlled to ensure favourable growing environment for crops for optimal productivity. However, achieving these objectives for greenhouse-grown crops is challenging due to the complexity of managing the growing environment conditions and resources. Greenhouse crop production is an essential aspect of modern agriculture especially in seasons and regions characterized by unfavourable climates (Wang et al., 2018, Savic & Ilin 2022). The practice provides favourable (close to optimum) environmental conditions that support year-round production, optimum productivity, quality and resource efficiency. However, the success of greenhouse production depends on several factors, including fertigation regime, soil and plant health, and weather/microclimate conditions. Vegetables such as pepper, tomato, lettuce, spinach etc are candidates for indoor farming and as such widely produced in greenhouses. However, these crops are particularly sensitive to fluctuations in environmental conditions (soil, plant and microclimate). Effective, timely monitoring and control of these variables within the greenhouse system is important step to alleviate stress effects, enhance photosynthesis and plant growth, yield and quality in addition to enhanced resource use efficiency, income and environment sustainability. Advances in agricultural technologies have focused on automation of greenhouse management through dynamic monitoring, control and modification of growing environment conditions, production resources soil (water and nutrient) and weather (light, temperature, humidity, wind) according to energy prices and plant needs. Such technologies offer avenue for creating ideal growth conditions for plant growth, boost yield, quality, resource efficiency and sustainability of greenhouse production system. This is particularly important for vegetables such as peppers, which require specific growing environment conditions for growth, flowering, fruit setting, ripening and quality (Oh & Koh, 2019). For instance, maintaining optimal temperature ranges between 18-30°C and adequate relative humidity levels can enhance growth, fruit yield and quality of vegetables (Oh & Koh, 2019, Savic & Ilin, 2022).

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Pepper belongs to genus *Capsicum* of family Solanaceae. Capsicum is widely-accepted and suitable crop for countless uses as food and non-food products (Tripodi and Kumar, 2019).In terms of ecology, capsicum species are perennial shrubs in tropical regions (they can sometimes last up to ten years), but they are typically planted as annuals and herbaceous plants in temperate countries. They can also be grown as perennials in climate-regulated greenhouses (Guibben and ElTahir, 2004, *Raphael et al, 2010, Fadare et al., 2025*). Peppers like other plants, demand well-drained, moisture-holding loamy soil with ideal growth and production temperatures between 18 and 30 ^{0}C. Capsicum has over twenty varieties five of which have been domesticated (Bosland and Votava, 2013). Fruits of pepper can be taken fresh, dry and processed. Like other members of the solanaceous family such as tomatoes and eggplant, peppers are rich in calcium, phosphate, potassium and vitamin B2 (Bosland and Votava, 2000,). In Nigeria, the consumption of pepper makes up over 20% of the daily average vegetable intake per person (Alegbejo, 2002, Fadare et al., 2025). In southwest region of the country, it is used to make stews and soups, which are among the main and most important accompaniments to staple foods made from cereal and root crops. Also, pepper production is considered to be a profitable agribusiness venture particularly for commercial farmers. Many vegetable farmers have developed interest in producing the crop especially as the economic value of the crop had suddenly increased thereby making for high income.

Most pepper farmers practice open-field production which is increasingly challenged by erratic rainfall, soil degradation, and low productivity. However, greenhouse system of production proffers a controlled environment for optimum growth, yield and quality pepper (Nishad and Krupa, 2022). Compared to the situation in open-field vegetable production, protected cultivation offers numerous opportunities to increase the sustainability of growing processes and techniques due to the precise control over numerous processes (Voogt, 2005, Fadare et al., 2025). Although adoption of greenhouse production system is in its infancy in the south –west of Nigeria, it is rapidly becoming a popular farming practice among pepper farmers. According to Xiang et al. (2015), the major factors that affect output of vegetable crops in greenhouse are fertilizer and water. Inadequate irrigation results in reduction in crop yield and quality while over-irrigation and prolonged soil saturation can cause disease in plant roots and increased likelihood of blossom-end rot, a condition where the blossom end of the fruit becomes discolored and decays (Kabir et al., 2021). On the other hand, excessive or inappropriate use of fertilizer not only leads to fertilizer waste and soil acidity but also triggers environmental pollution (Zhang et al., 2018.). Improper irrigation subject crops to rootzone moisture deficits and water stress (Agele et al., 2014)

In greenhouse system of production, water and nutrient are often applied together in the process known as fertigation. Fertigation is one improved technique for achieving better water and N management practices, and involves applying soluble chemical fertilizers together with the irrigation water. Fertigation enhances improvement in the delivery of water and fertilizer especially when drip irrigation system is used since it allows for frequent but low volume irrigation treatments close to the plant base as against other systems of application. This reduces soil water evaporation thereby improving water use efficiency (WUE) without reduction in yield and quality of fruit (Locascio, 2005,). The basic principle of fertigation is that water and nutrients are applied based on crop demand (Voogt, 2005,). Compared with the broadcast fertilisation method, fertigation achieves higher nutrient use efficiency (NUE), reduced loss of fertilizer and lower labour input requirements, hence, it shows great potential for the sustainable development of agriculture (Li et al., 2021). For peppers produced in greenhouses, fertigation regime optimization entails regulating the water and fertilizer supply to improve yield, growth, and resource efficiency.

Previous study by Ningoji et al, 2024, indicated that when combined with 125 % of the recommended fertilizer dose (RDF), an irrigation schedule at 75% available soil moisture (ASM) greatly enhanced pepper growth and production characteristics. Both the overall fruit yield (60,089 kg ha^{-1}) and yield attributing metrics were significantly enhanced by this combination. Additionally, the advantage-cost ratio of 2.07, energy productivity (0.80 kg MJ^{-1}), nutrient use efficiency (79.5 kg kg^{-1}), and water usage efficiency (16.75 kg m^{-3}) all showed superiority. Another study in Northwest China demonstrated that in order to balance yield, quality, and water use efficiency (WUE), drip fertigation for sweet peppers, using 150 kg/ha of nitrogen and 75% evapotranspiration (ETC) should be deployed (Wang et al., 2022).

Poor soil and water management techniques (increasing agricultural water demand and overuse by growing populations, etc.) will make issues with water availability even worse. Making the best use of water for agriculture and implementing techniques that improve agricultural production's water use efficiency are therefore essential components of effective water management strategies. Ajayi et al. (2023) reported that strategies for the sustainable management of land and water resources must be put in place since the humid tropics' agricultural potential and sustainable exploitation of its water resources may be impacted by extreme weather events and a changing climate. Enhancements to soil and water management techniques, technological developments, and policy decisions will increase the capacity and ability to lessen the negative effects of water scarcity and finite water supplies.

Although many researches on fertigation have been carried out on other crops and regions of Nigeria, limited information exists about optimization of fertigation regimes for habanero and sweet pepper production in greenhouse in southwest Nigeria. Inadequate or excessive fertilizer and water application can result in environmental degradation and negative impact on plant growth, productivity and fruit quality. It is therefore crucial to determine the suitable fertigation that optimizes output and quality while maintaining resource efficiency. The aim of this study is to evaluate the effects of different fertigation regimes on the growth, yield and resource-use efficiency of two pepper varieties grown under greenhouse conditions in a rainforest zone of Nigeria. The objectives are to determine the optimal fertilizer and water application rates(fertigation regimes) on the performance and water and nutrient use efficiencies of habanero and sweet pepper in a rainforest zone of Nigeria

2. MATERIALS AND METHODS

2.1. Experimental materials

2.1.1 Experimental plot

The experiment was carried out in a naturally-ventilated greenhouse at the Federal College of Agriculture, Akure, in southwest Nigeria. The annual rainfall of the area ranges from 1100 -1500 mm per annum, relative humidity is 88% and temperature ranges from 28-32 ^{0}C. The greenhouse measured 24mx8m with nets on the side and polyethylene cover. Pre-cropping analysis of randomly-sampled soil was done in the laboratory and the result is presented in Table 1.

2.1.2. Irrigation equipment:

Drip lines (MICRODRIP 8) with flow rate of 2.00l/hr at 1 bar and emitters spaced at 0.30m apart were placed on two ends of each bed at 0.60m apart and 5cm depth. Six drums were set up outside the greenhouse to act as fertigation tanks which supplied nutrient- dissolved –in- water to each of the beds.

2.1.3 Experimental materials

Clair F1 variety of bell pepper and Piqante red F1 variety of habanero were used as test crop for the experiment. These crop varieties are suitable for greenhouse system of production. The fruits of these crops are green when produced but turns red at full maturity. The fertilizer used was soluble NPK 20:20:20

Table 1. Pre-cropping properties of experimental soil

Parameters	Values
pH	5.46
Organic C (%)	0.15
Organic Matter (%)	0.26
N (%)	0.06
P (mg/kg)	1.01
K (cmol/kg)	0.31
Ca (cmol/kg)	1.40
Na (cmol/kg)	0.36
Mg (cmol/kg)	0.60
Sand(%)	40.80
Clay(%)	37.20
Silt(%)	22.00
Textural Class	clay loam

2.2 Experimental design

The experiment was a 3x2x2 factorial fitted into split-split plot design and replicated four times. Fertilizer level (N0= 0kg/ha, N1= 60kg/ha and N2= 100kg/ha of soluble NPK 20:20:20) was the main factor while irrigation level (W1= 100% and W2= 70% field capacity) and Capsicum species (V1= habanero pepper and V2= sweet pepper) were sub-plot and sub-sub-plot respectively. Theses gave a total of 12 treatment combinations which were replicated 4 times.

2.3. Nursery and transplanting

Seeds of the two species of pepper were planted in seed trays filled with well-moistened coco peat in a portable greenhouse. Six raised bed of 23mx1m were made and seedlings transplanted on two sides of each bed at 0.6x0.6m apart after growing in nursery for four weeks.

2.4 Irrigation and fertigation.

The volumetric water content of the soil used was measured using Decagon sensor-probe moisture meter and the values obtained used to determine the watering regime used and irrigation quantities were adjusted in accordance with the drip emitters' flow rates, which were 2 L h^{-1} each. Water was supplied for 10 minutes per irrigation cycle, delivering roughly 0.33 L per emitter, in order to reach 100% field capacity. The irrigation time was changed to 7 minutes for

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the 70% field capacity regime, which equates to roughly 0.23 L per emitter. To ensure uniformity across all treatments, irrigation was delivered via drips, and application time was tracked using a stopwatch.

Same volume of water was applied to plants three times daily for the first 2 weeks after transplanting (2WAT) while water and fertilizer treatment were imposed as from third and fourth weeks after transplanting respectively. During fertigation, the soluble NPK 20:20:20 was given according to the treatments in 5 split doses at 14days interval beginning from 14 days after transplanting. Water was supplied to maintain 70% and 100% field capacity throughout the period of the experiment.

2.5 Data collection

Data on physiological parameters such as plant height and stem girth were taken fortnightly from 4WAT using measuring tape and veneer caliper respectively while number of branches were counted. Plant biomass was determined by partitioning plant samples into leaf, stem and root and their fresh weight taken after which the plant parts were oven-dried at 70^0C and the new weight recorded. Data on yield and yield components such as number of fruit, weight of fruit, total yield, marketable yield and others were also collected. Number of fruit per plant was counted and recorded and their weight taken with digital scale. Fruits affected by blossom end rot (BER) were also numbered and weighed. Marketable yield was obtained by deducting the weight of BER infected fruits from total yield.

2.6 Determination of water and nutrient use efficiencies

2.6.1 Watre use efficiency (WUE) was calculated using the formula below:

$$WUE = \frac{\text{Yield (kg/ha)}}{\text{Water applied (m}^3\text{/ha)}} \qquad \text{(Zhao et al., 2020)}$$

Where WUE is the water use efficiency in kg/ m^3

Yield is the weight of fruit in kg/ha

Water applied in m^3/ha

Nitrogen use efficiency (NUE) was calculated using the partial factor productivity formula below

$$PFP= \frac{\text{Yield (kg)}}{\text{N applied (kg)}} \qquad \text{(Yang et al., 2022)}$$

Where PFP = partial factor productivity

Yield= weight of fruit (kg)

N = quantity of nitrogen in fertilizer applied (kg)

Data analysis

The data collected were subjected to analysis of variance (ANOVA) using Mini tab 17 Statistical software and significant mean separated using Tukey honestly significant difference (HSD) at 5% probability level.

3. RESULTS

The results obtained from this experiment showed significant effects of water regimes, fertilizer rates and their interactions on the growth, yield and resource-use efficiency of both habanero and sweet pepper varieties cultivated under greenhouse conditions.

3.1 Treatment effect on growth parameters

3.1.1 Plant height

The height of pepper plants were not significantly influenced by the fertilizer rate at 4 weeks after transplanting (Table 2). At 6 and 8 weeks after planting, plants on I_2 (100KgN /ha) plot produced tallest plant (36.57cm and 54.31cm respectively) at $P<0.05$ although, not significantly different from values obtained from I_1 (60kgN/ha) plot. However, plants in both I_1 and I_2 were significantly taller than those in I_0 (0kgN/ha) plot. The average watering regime impacted the plant height significantly. Taller pepper plants with 25.41,39. 52 and 54.62 cm height were obtained at 4, 6 and 8 WAT respectively, at 70% field capacity watering regime. The height of the plants were not significantly influenced by the variety of pepper planted at 4WAT but Habanero pepper were significantly taller with plant heights of 36.22 and 58.79cm at 6 and 8 WAT respectively. There was significant interaction in irrigation combined with variety at both 4 and 8 weeks after transplanting and the interaction among fertilizer rate, water regime and variety was also significant at 4 weeks after transplanting indicating that optimum use of fertilizer and water regime had effect on plant height of the crop variety at that stage of growth.

3.1.2 Stem girth

The result for stem girth followed same pattern as that of plant height at 6 and 8 weeks after transplanting with exception to variety in which there was no significant difference between stem girth of V_1 (0.49cm) and V_2 (0.51cm) plots (Table2). Unlike plant height, the only significant interaction among treatments was observed at 8weeks after transplanting when irrigation was combined with watering regime. The number of branches in V_1 was slightly higher than V_2 plot although the difference is not significant.

3.1.3 *Number of branches*

Number of branches produced in I0 plot was significantly lower than those obtained from I_1 and I_2 respectively across weeks after transplanting while significantly higher number of branches were recorded in W_1 plots at 4 and 8 weeks after transplanting. Interaction between water regime and variety were significant ($P<0.05$) across weeks after transplanting which suggests that optimal water supply enhanced the number of branches produced by habanero at its vegetative phase of growth (Table 2).

Table 2: Effect of fertilizer rates, water regimes and varieties of pepper on plant growth parameters

	Plant height (cm)			Stem girth (cm)			Number of branches		
	Weeks After Transplanting								
Treatments	4	6	8	4	6	8	4	6	8
Fertilizer rate									
I_0 - 0kgN	19.66a	28.10b	38.39b	0.32a	0.44b	0.61b	2.41b	.05b	10.98b
I_1 - 60kgN	22.35a	34.27a	49.51a	0.37a	0.53a	0.73a	3.88a	10.02a	15.23a

I_2 - 100kgN	22.13a	36.57a	54.31a	0.36a	0.55a	0.75a	4.47a	10.94a	15.56a
Water Regime									
W_1 -70% FC	25.41a	39.52a	54.62a	0.42a	0.60a	0.79a	5.40a	12.00a	16.61a
W_2 - 100% FC	17.35b	26.44b	40.19b	0.28b	0.41b	0.60b	1.77b	6.67a	11.24b
Species									
V_1 – Habanero	21.30a	36.22a	58.79a	0.32b	0.49a	0.70a	3.91a	13.54a	20.39a
V_2 – Bell	21.46a	29.75b	36.01b	0.38a	0.51a	0.66b	3.26a	.13b	7.47b
Interactions									
I×W	ns	ns	ns	ns	ns	0.13s	ns	ns	ns
I× V	4.24*	ns	8.06*	ns	ns	ns	ns	ns	ns
W × V	ns	ns	ns	ns	ns	ns	1.29*	2.70*	3.16*
I ×W× V	5.17*	ns	ns	ns	ns	ns	ns	ns	ns

ns = Not Significant, * = significant at $p < 0.05$. For each factor, means followed by the same letter(s) in columns are not significantly different by Least Significant Difference (LSD) at $P < 0.05$.

3.2. Plant biomass

The biomass of dry stem was affected significantly by fertilizer rate where plant in I2 (96.60g/plant) plot had significantly higher value than plants in I1 (32.40g/plant) and I0 (25.90g/plant) plots respectively (Table 3). Although, the stem biomass obtained from I1 plot was not significantly different from that of I0, the value obtained in I1 is higher. This trend was also observed in total plant biomass. However, the leaves and root biomass were not significantly affected by fertilizer rates. Watering regime had no significant effect on biomass produced; leave, root and stem and total biomass produced on W1 and W2 plots were not significantly different. On the other hand, habanero (V1) plants had significantly higher root, stem and total biomass than bell pepper while the difference between leave biomass of V1 and V2 were not significant. Interaction effect of fertilizer rate and variety was observed to be significant for stem, root and total but not leave biomass.

Table 3: Summary of effect of fertilizer rate, watering regime and variety on biomass components of peppers

Treatments	Stem	Leaves	Root	Total biomass	Total biomass
	……….g/plant………				
Fertilizer rate					
I_0 - 0kgN	25.90b	13.80a	7.44a	47.10b	1060b
I_1 - 60kgN	32.40b	19.30a	9.19a	60.80b	1368b
I_2 - 100kgN	96.60a	82.70a	15.88a	195.1a	4390a

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Watering Regime					
W_1	47.50a	46.20a	14.08 a	104.8a	2357a
W_2	55.80a	31.00a	10.58 a	7.30a	2189a
Species					
V_1	68.40a	52.50a	14.08 a	135.0a	3037a
V_2	34.80b	24.70a	7.58b	67.10b	1509b
Interactions					
I×W	ns	ns	ns	ns	ns
IxV	27.92*	ns	8.72*	29.52*	2122*
W × V	ns	ns	ns	ns	ns
I ×W× V	ns	ns	ns	ns	ns

ns = Not Significant, * = significant at $p < 0.05$. For each factor, means followed by the same letter(s) in columns are not significantly different by Least Significant Difference (LSD) at $P < 0.05$

3.3 Treatment effects on yield and yield components

3.3.1 Days to 50% flowering

As seen in Table 4, plants in I_0 plots had significantly longer days to 50% flowering as against plants in I_1 and I_2 plots. Plants in W_1 (51.62) plot however attained 50% flowering in shorter days (51.62days) as against those in W_2 plot (65.08) so also habanero as against bell pepper.

3.3.2 Fruit yield and yield components

The cumulative number of fruits produced per plant is observed to be significantly lower in I0 plot when compared with I_1 and I_2 plots (Table 4) but in water regime, W_1 yielded more number of fruit per plant (23.3) which was significantly higher than W_2 plot (18.3). Habanero performed better than bell pepper as it produced significantly higher number of fruit than the latter. Number of fruits affected by blossom end rot (BER) was not significantly different in the three fertilizer plots, likewise the watering regime plots. However, more bell pepper were significantly infected by BER than Habanero A significant interaction ($P < 0.05$) was observed between fertilizer and variety which suggest that combination of the two treatments have significant effect on number of fruit per plant and marketable fruit

Table 4: Effect of fertilizer rate, watering regime and pepper variety on 50% flowering and fruit harvest

Treatments	Days to 50% flowering	Number of fruits/plant	BER fruits	Marketable fruits
Fertilizer rate				
I_0 - 0kgN	63.50a	11.20b	0.11a	11.10b

I_1 - 60kgN	55.50b	21.70a	0.28a	21.40a
I_2 - 100kgN	56.06b	29.60a	0.30a	29.30a
Watering Regime				
W_1 -70% Field capacity	51.62b	23.30a	0.31a	23.00
W_2 - 100% Field capacity	65.08a	18.30b	0.15a	18.20
Specie				
V_1:Habanero	54.71b	38.10a	0.04b	38.10a
V_2: Bell	62.00a	3.50b	0.42a	3.10b
Interactions				
I×W	ns	ns	ns	ns
IxV	ns	10.10*	ns	10.11*
W × V	ns	ns	ns	ns
I ×W× V	ns	ns	ns	ns

ns = Not Significant, * = significant at $p < 0.05$. For each factor, means followed by the same letter(s) in columns are not significantly different by Least Significant Difference (LSD) at $P < 0.05$.

3.3.4 Fruit yields at harvest

Fertilizer rate was observed to significantly affect fruit weight between 99 and 120 days after transplanting. I_2 plot produced fruit whose weight was significantly higher (4.23g/plant, 2.86g/plant) than those in I_1 (2.61g/plant, 1.58g/plant) and I0 (0.64g/plant, 0.28g/plant) plots at 99 and 120 days respectively (Table 5). Fruits harvested at 106 and 113 days after transplanting in I0 plot recorded weight which was significantly lower than values obtained from I_1 and I_2 plots. However, effect of fertilizer rate was not significant in weight of fruit harvested at 92, 127, 134,141, 148and 155 days after transplanting. Watering regime had no significant effect on fruit weight at all harvest days except 92days after transplanting where W_1 (0.58g/plant) out-yielded pepper treated to W_2 (0.10g/plant). In all harvest days, habanero fruits weighed significantly higher than bell pepper fruits.At 92 and 99 days after transplanting, watering regime and variety interacted significantly to give fruit weight of 0.39g/plant and 3.41g/plant respectively. The interaction effect of fertilizer rate and variety was also observed to be significant at 99, 113, 120 and 127 days after transplanting unlike other days when there was no significant effect among treatment factors with exception of 92 days after planting when interaction between watering regime and specie affected fruit weight significantly.

Table 5: Fertigation regime and species effects on fruit harvest of pepper

	Weight of fruits per harvest (g/plant)									
Treatments	92	99	106	113	120	127	134	141	148	155
	……………………..Days After transplanting…………………									
Fertilizer rate										

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I_0 - 0kgN	0.34a	0.64 c	1.03 b	1.39 b	0.28 c	0.77 b	1.06 a	1.45 a	1.81 a	2.41 a
I_1 - 60kgN	0.36a	2.61 b	3.31 a	5.38 a	1.58 b	1.38 a	1.12 a	0.88 a	1.42 a	3.63 a
I_2 - 100kgN	0.33a	4.23 a	3.31 a	5.61 a	2.86 a	3.62 a	2.30 a	1.19 a	2.16 a	3.97 a
Watering Regime										
W_1 -70% FC	0.58a	3.42 a	2.57 a	4.44 a	1.47 a	2.22 a	1.66 a	1.49 a	1.88 a	3.59 a
W_2 -100% FC	0.10 b	1.57 a	2.53 a	3.81 a	1.68 a	1.62 a	1.33 a	0.85 a	1.72 a	3.07 a
Species										
V_1 – Habanero	0.57a	4.64 a	4.81 a	7.29 a	2.81 a	3.56 a	2.61 a	2.12 a	3.38 a	6.32 a
V_2 – Bell	0.12 b	0.35 b	0.29 b	0.96 b	0.33 b	0.28 b	0.38 b	0.22 b	0.22 b	0.34 b
Interactions										
I×W	ns	ns	1.78	ns	ns	ns	ns	ns	ns	ns
I× V	ns	2.05 *	2.08 *	2.51 *	1.01 *	2.65 *	ns	ns	ns	ns
W × V	0.39 *	2.34 *	ns	ns	ns	ns	ns	ns	ns	ns
I ×W× V	nss	ns	ns	ns	ns	ns	ns	ns	ns	ns

ns = Not Significant, * = significant at $p < 0.05$. For each factor, means followed by the same letter(s) in columns are not significantly different by Least Significant Difference (LSD) at $P < 0.05$

3.3.5 Yield and marketable yield

There was no significant difference in the cumulative yield obtained from I_2 (8.44t/ha) and I_1 (6.47t/ha) plots although the two plots produced significantly higher yield than I_0 plot (Table 6). The same trend was observed whereby the yield of habanero was significantly higher than that of bell pepper. Conversely, yield produced in W_2 (7.09t/ha) plot showed no significant difference from those in W_1 (5.44t/ha) plot. The marketable yield expectedly followed the same pattern as observed in total yield since the latter formed the basis for calculating it. There was no significant difference in interaction of treatment factors on yield and marketable fruit.

3.3.6 Resources (Water and nutrient) efficiencies

There was no significant difference in the efficiency of nitrogen used both in fertilizer and watering regime treatments (Table 6) however habanero gave a significantly higher NUE (116.4t/ha) than bell pepper (75.80t/ha). I_0 plot had the least water use efficiency while I_2 (7.06 kg/ha/m^3) had the highest which was significantly higher than those of both I_1 (5.45 kg/ha/m^3) and I_0 (3.45kg/ha/m^3) plots. The WUE of W1 plot was also significantly higher than that of W2 (Table 6). In like manner, Habanero had a significantly higher WUE than bell pepper. However, there was no significant difference in interaction effect of the treatment factors.

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Table 6: Effects of fertigation regime and pepper variety on yield and recourse efficiencies

Treatments	Yield (t/ha)	Marketable Yield (t/ha)	NUE (kg/kg)	WUE (kg/ha/m^3)
Fertilizer rate				
I_0 - 0kgN	3.89b	3.79b	73.2a	3.45c
I_1 - 60kgN	6.47a	6.28a	107.8b	5.45b
I_2 - 100kgN	8.44a	8.17a	84.40a	7.06a
Watering Regime				
W_1 -70% Field capacity	7.09a	6.84a	102.70a	6.92a
W_2 - 100% Field capacity	5.44a	5.32a	89.50a	3.72b
Species				
V_{1}- Habanero	7.56a	7.54a	116.40a	6.38a
V_{2} – Bell	4.97b	4.62b	75.80b	4.26b
Interactions				
I×W	ns	ns	ns	ns
I× V	ns	ns	ns	ns
W × V	ns	ns	ns	ns
I ×W× V	ns	ns	ns	ns

ns = Not Significant, * = significant at $p < 0.05$. For each factor, means followed by the same letter(s) in columns are not significantly different by Least Significant Difference (LSD) at $P < 0.05$.

4. DISCUSSION

4.1 Treatment effects on growth parameters of pepper varieties

Optimizing agricultural techniques and facility management starts with adjusting the supply of water and fertilizer. Crop growth can be greatly enhanced by effective nitrogen and water management, which will raise economic yields, improve input efficiencies and quality of produce at a lower cost of investment. On the other hand, inadequate water and fertilizer management can result in higher expenses, wasteful use of water and nitrogen resources, and detrimental impacts on crop yields and the leaf area index the quality of the crop and the plants' resource efficiency can both be enhanced by effective water and nitrogen control. According to Gupta et al. (201), fertigation can supply crops with the best possible amounts of nutrients and water. The results obtained for growth parameters suggest that application of 60 kgN/ha was adequate to meet the pepper's growth nutritional demand under the greenhouse condition used in this research because there were no significant differences in plant height, number of branches and stem girth values obtained from 60 kgN/ha and 100Nkg/ha plot. This observation supports the theory of nitrogen sufficiency threshold, the point at which increase in nitrogen does not give a corresponding increase in vegetative development of plant (Wang et al., 2017).

In addition, the better performance of plant growth parameters in W_1 over those in W2 suggest that the moderate water stress ($W_{1:}$70%field capacity) might have assisted plants in that plot to maximize nutrient uptake and root activity. On the other hand, high application rates of water (W_2 : 100% fie ld capacity) might have inhibited growth, especially at higher N rate by reducing aeration in the soil (Geerts and Raes, 2009; Fereres and Soriano, 2007). The genotypic effects on water and nitrogen use efficiencies of Capsicum species (habanero and bell pepper) can explain the better performance (vegetative growth) of habanero over bell pepper (Kareem and Aladeselu, 2021). Habanero might have developed a more vigorous root system which allowed it to sustain superior growth attributes and efficient use of nutrient resources under moderate nutrient and water conditions.

4.2 Effect of treatment factors on yield and yield components

Nitrogen is an important element for the synthesis of nucleic acids, proteins, amino acids and others that assist transition of plant from vegetative to reproductive phase like flowering. However, mild nitrogen stress can sometimes result in early flowering. According to Zhang et al., 2021, excess application of nitrogen fertilizer for rice cultivation delays flowering while moderate rates are optimal for prompt flower induction. This supports the trend observed in this study whereby there was no significant difference in days to 50% flowering In I_1 (60 kgN/ha) and I_2 (100 kgN/ha) plots. In like manner, the non-significant difference in days to 50% flowering between 70 and 100 % field capacity treatments in this study might be due to ability of plant to adapt to moderate water regime by strengthening root growth and enhancing water use efficiency (Patane and Consentino, 2010). The microclimatic condition in the greenhouse may have also reduced water stress, making difference in days to flowering insignificant under both watering regimes. This aligns with the findings of Igbadun et al.(2012), that reported that moderate water stress has no significant effect on reproductive phase of crop under greenhouse condition. Genotypic stability of the pepper species used could also have been responsible for the insignificant difference in flowering time.

Results obtained from this study indicate that there is no significant difference in yield and NUE of pepper plants on both 60 kgN/ha and 100 kgN/ha plots under greenhouse condition. This observation can be linked to some factors peculiar to the protected environment of the greenhouse. One of such factors is the reduction in leaching, volatilization and de-nitrification due to regulated irrigation (drip system) thereby ensuring that the moderate fertilizer (60 %N kg ha) is taken-up and used by plant efficiently. In addition, the greenhouse provides microclimatic condition such as optimal temperature, relative humidity and others which minimizes plant stress and nutrient demand. Wang et al. (2025), reported similar findings when he worked on effects of various fertilizer rates on facility-based tomato production. It was observed that moderate fertilizer application enhanced yield and NUE of tomato, thereby reducing wastage of resources. The yield and NUE obtained from habanero were significantly higher than that of bell pepper. This might be linked to the lower case of blossom end rot (BER) when compared to bell pepper which is known to be more susceptible to BER. Water use efficiency (WUE) which determines how effectively crop utilize water for making useful products such as biomass or yield in relation to water consumed was also evaluated in this study. The result obtained showed that WUE was significantly higher in W_1 plot than the value obtained from W_2 plot. Moderate water stimulates extensive root development in plants which help them search widely for nutrient. In addition, partial closure of stomata to reduce transpiration may improve the water use efficiency of crop.

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Zhao et al. (2025) arrived at the same conclusion when he reported that moderate watering regime improved the WUE of peanut. In all, the results indicates that increment in nitrogen rate above 60 kg/ha under a watering regime of 70% field capacity do not give further commensurate growth and yield benefits. This demonstrates the importance of optimizing water and nutrient resources while looking out for difference in species to enhance efficiency of input utilized in greenhouse pepper cultivation.

5. CONCLUSIONS

This research demonstrated that growth, yield and resource-use efficiency are significantly affected by optimized fertigation regime in greenhouse-grown pepper in southwest Nigeria. Results obtained showed that among treatment factors considered, the application of 60 kgN/ha combined with a moderate watering regime of 70% field capacity performed better than higher nitrogen and water levels for most of the parameters measured. Habanero displayed superior ability in adjusting to deficit fertilizer rate and water regime compared to bell pepper under greenhouse condition. Habanero specie produced higher fruit yield and utilized nutrient and water more efficiently. The results indicate that application of high fertilizer and irrigation inputs does not transform to increased yield or efficiency of N and water. Rather, application of N and water at moderate levels through fertigation can enhance yield and rational use of resources. It is therefore recommended that fertilizer rate of 60 kgN/ha, coupled with watering regime of 70 % field capacity be adopted as a sustainable strategy for pepper cultivation in the greenhouse system in the rainforest environment of Nigeria

Author contributions

Conceptualization: S.O. Agele and G. O. Ajayi; methodology, S.O. Agele and A.J. Ajayi; investigation, G.O. Ajayi; data analysis, A.J. Ajayi; writing- original draft preparation, G. O. Ajayi; writing- review and editing, S.O. Agele; supervision, S.O. Agele. All authors have read and agreed to the published version of manuscript.

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Data Availability Statement

The corresponding author can be contacted for datasets used in the course of this study subject to approval of the owner of the data.

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Conflicts of Interest

The authors declare no conflict of interest.

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