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Fertigation Regime Effects on Growth, Yield, Nutrition and Active Metabolites of Greenhouse-Grown Pepper in A Rainforest Environment

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ABSTRACT

Pepper is an important vegetable crop consumed for its nutritional benefits. However, there is a need for efficient nutrient and water management for the purpose of improving yield and nutritional benefits of both leaves and fruits of greenhouse-grown peppers in a rainforest environment. This study evaluated the influence of varying fertigation regimes on growth, yield, mineral and proximate composition as well as active metabolites of greenhouse-grown peppers. The greenhouse experiment was carried out using factorial experimental design which consisted of three fertilizer levels, (0, 60 and 100kgN/ha), two watering regimes (70% and 100% field capacity) and two pepper varieties (habanero and sweet/bell pepper) giving a total 12 treatments with four replications. The growth parameters, yield traits, mineral composition, proximate contents and active metabolites were determined using standard procedures. Data collected were analyzed using analysis of variance (ANOVA) and mean separated at 5% probability level. Results obtained showed significant effects of fertigation regime on mineral and proximate compositions and also active metabolites while for growth and yield traits, the effects were insignificant. Plants fertilized with 100kgN/ha + 70% field capacity produced higher concentrations of minerals and proximate compositions including K, Ash and Crude proteins in both fruits and leaves of pepper. In contrast, accumulation of active metabolites was highest under 60kgN/ha +70% field capacity. This difference in response of metabolites and nutritional contents to fertigation regimes suggests a trade-off between growth-prioritized nutrient partitioning and synthesis of secondary metabolites. Habanero outperformed bell pepper in production of phenols, DPPH, FRAP, ABTS and NO by 1.36%, 299% and 37.5%, 4.18%respectively which indicates that response to fertigation was genotype-dependent. The study shows that fertigation management for greenhouse pepper production under greenhouse conditions should be based on production objectives. Higher nitrogen rate under moderate fertigation can be beneficial for maximizing minerals and nutritional content while nutraceuticals of pepper can be improved when a moderate nitrogen rate is supplied under mild water deficit conditions.

Keywords: *fertigation, active metabolites, proximate composition, greenhouse-grown pepper, rainforest environment.*

Introduction

Awareness is on the rise in the nexus between quality of food consumed and state of health among consumers which makes them carefully select foods that are rich in bioactive compounds and nutritional value, especially vegetables. Vegetables are essential to food and nutrition security [1] Their dietary fibre content, vitamins, minerals, and phytochemical substances make them vital for human health [2]. Consuming vegetables is positively associated with a lower death risk from heart disease, cancer, and other degenerative diseases, as well as aging, according to epidemiological research [3]. One of such widely consumed vegetable is pepper (*Capsicum spp*). Capsicum is one of the globally grown horticultural crops, esteemed not just for its culinary traits but also for its essential nutrients and bioactive compounds. It is an herbaceous plant that belongs to the Solanaceae family. Only five of more than thirty capsicum species have been domesticated and cultivated widely. They are *Capsicum annuum, Capsicum frutescens, Capsicum baccatum, Capsicum chinense and Capsicum pubescens* [4].

Several varieties of capsicum species can be distinguished by the fruit attributes, which include, flavor, color, pungency, and size. The fruits of the capsicum plant are used as spices, coloring, cardiovascular protection, anti-inflammatory, antioxidants and anti-cancer compounds in a variety of sectors. In Nigeria, southwest in particular, *C. annuum, C. frutescens and C. chinense* are the commonly cultivated and mostly consumed species. Although the fruit of pepper is the portion eaten by most consumers in their fresh, dry or powdery form, the leaf is consumed as a vegetable in some localities in the southeast of Nigeria [5]

Pepper species, both pungent and non-pungent are rich in bioactive phytochemicals which such as carotenoids, capsaicinoids, flavonoids, phenolic compounds, and vitamins [6,7]. Capsaicin, an important member of capsaicinoids is responsible for the pungency of hot peppers. and have been connected to their anti-inflammatory, antioxidant and anti-microbial properties [8,9].

Capsaicinoids have shown a wide range of bioactivities, including anti-inflammatory, anticancer, analgesic, antibacterial, hypotensive, and the ability to reduce body temperature or adipogenesis either alone or in combination with other substances [10,11]. Vitamins (C and E) support a healthy metabolism, strengthen the immune system, and have antioxidative properties [12]. Phenolic acids and flavonoids, the two phenolic phytochemicals found in peppers contribute to the antioxidant attribute of pepper for prevention of disease [13]. Carotenoids which are isoprenoids, contribute to biological processes in plant particularly capsanthin and β-carotene which are responsible for pigmentation in fruits and prevention of oxidative stress in consumers [14]. Besides these metabolites, proximate composition of pepper determines its nutritional value. Carbohydrate, crude protein, crude fiber, fat, moisture content. etc. are proximate components which enhances dietary value of peppers [15]. Proteins provide cells and tissues with support and enhances immunity while carbohydrates supply the body with energy. Crude fiber rare plant portions that are edible but not easily digested. They enhance gut health and digestion [16]. The presence of these phytochemicals together with proximate attributes determine the nutritional value and functional attributes of pepper.

However, one of the factors that influence the expression of these attributes in pepper is the management practice deployed, especially nutrient and water management. A popular and effective method of regulating nutrient and water supply, particularly in greenhouse vegetable production, is fertigation which refers to the simultaneous application of water and nutrients to plant mostly through a pressurized irrigation system [17]. Nitrogen and soil moisture are essential inputs that influence pepper growth, yield and quality. Nitrogen is a key component of chlorophyll, proteins and enzymes. It therefore regulates the vegetative and reproductive phases as well as the nutritional composition of plants [18]. [19] evaluated the effect of an increase in nitrogen on hot pepper and observed that a steady increase in nitrogen fertilizer rate resulted in high values of minerals and proximate components of the pepper. Soil water at varying field capacity affects availability of nutrients, mass flow to roots, hence, regulating nitrogen uptake and use. Fertigation ensures that water and nutrients are supplied directly to the root zone of the plants thereby enhancing water and nutrient use efficiencies [20]. It likewise allows precision control over the micro-climatic factors of the greenhouse environment. In addition to influencing the vegetative growth and output of crop, fertigation also determines the dietary value and bioactive compounds in produce [21,22]. While proper nutrient scheduling may enhance accumulation of some metabolites such as carotenoid, imbalance condition may result in changes in the build-up of other metabolites, including flavonoids and phenolics [23]. According to [24], fertigation of greenhouse-grown vegetable crops showed improvements in quality parameters (such as ascorbic acid, soluble sugars, etc.) and fertilizer savings of 20-60% [25]. Moreover, irrigation regime affects nutraceuticals in crops as biosynthesis of these compounds can be stimulated by moderate water stress, whereas excess irrigation may weaken nutrient and metabolite concentrations [26]. The interaction in water and nutrient management emphasises the necessity of optimization of fertigation regime to balance fruit yield with quality.

Although, the importance of fertigation to improved crop performance is recognised most research on pepper have fixated on growth and yield responses, with little focus are placed on quality parameters such as bioactive metabolites including antioxidants. Moreover, there is limited information on how fertigation affects the nutritional and active metabolite constituents of pepper species under greenhouse conditions, particularly in rainforest tropics. This study was designed therefore to evaluate the effects of fertigation regimes on the metabolites and proximate composition of pepper species under greenhouse conditions. The objectives were to determine the influence of fertigation on the yield, mineral, proximate composition and active metabolite constituents of pepper species. The hypothesis for this study was that fertigation regime would significantly influence the metabolites and proximate compositions of pepper fruits and leaves with variations between species considered. The outcomes of this study are expected to improve knowledge of how irrigation and nutrient management enhance nutritional and functional quality of greenhouse-grown peppers in the humid tropics.

2.0 Materials and methods

2.1 Establishment and management of pepper in greenhouse

The study was conducted in an established greenhouse of about 24m x 8m size in the Residential East Campus of the Federal College of Agriculture, Akure, Nigeria which lies within longitude 5.2381189^{0}E and latitude 7.2655701^{0}N. The temperature of the location varies between 25^{0}C-30^{0}C with annual rainfall of 1100-1500mmm per annum and relative humidity of 88%. Samples of soil were collected randomly from the greenhouse and bulked for pre-cropping soil analysis.

The experiment was a three-factorial experiment fitted into split-split plot design in four replicates. The main factor, fertilizer rate had three levels namely I_0 (0kgN/ha), I_1(60kgN/ha) and I_2 (100kgN/ha) while irrigation level (W_1= 100% and W_2= 70% field capacity) and Capsicum species (V_1= habanero pepper and V_2= sweet pepper) were sub-plot and sub-sub-plot, respectively. The variety of sweet pepper used was Mekong F1, while that of habanero was Piqante red F1; fertilizer used was soluble NPK 20-2020. Seedlings were raised in trays in a mini-screenhouse till they attained the five-leaf stage. Six beds, each with dimensions of 23m x 1m were made in the greenhouse and seedlings were transplanted on both sides of the beds on 24th of February, 2024 at 0.6m x0.6m spacing. Six drums were erected to supply nutrients and water simultaneously during fertigation. The drip lines used were connected to the main trunks from the reservoir, and through emitters on the drip lines, water was delivered to each plant. A ball gauge was built to control the flow of water from the mains to the drip line, thereby achieving the appropriate irrigation level. The drip lines (Microdrip 8) with a flow rate of 2.0 l/hr. were installed on both ends of each bed at a distance of 0.60m and emitters were spaced 0.30m apart. For two weeks following transplanting (WAT), the plants received the same amount of water three times a day while water and fertilizer treatments were imposed as from third and fourth weeks after transplanting, respectively. The soluble NPK 20:20:20 was administered in five divided doses at 14-day intervals throughout fertigation, starting 14 days after transplanting. Water was supplied to sustain field capacity treatments at 70% and 100% every irrigation time throughout the trial.

2.2. Preparation of Samples for Analysis

2.2.1 Evaluation of Metabolite Content in Pepper Fruit and Leaf

At 12 weeks after transplanting, three fruits of pepper were randomly harvested per treatment plot and analysed in the laboratory for total phenol and flavonoid content, ferric reducing property (FRAP), free radical scavenging ability, ABTS scavenging ability, NO radical scavenging ability, terpenoid and vitamin C content.

- The Folin-Ciocalteu method, modified by [27] and [28], 2014, was used to determine the total phenol content of the prepared extract of pepper fruit. 0.2ml of the extract was mixed with 2.5ml of 10% Folin-ciocalteau's reagent and allowed to stand for 5 minutes before adding 2ml of Sodium carbonate. The reaction mixture was then incubated at 45^0C for 40mins and the absorbance was measured at 700 Nm in the spectrophotometer. The values obtained were then compared to a gallic acid calibration curve to determine the total phenol content and results expressed in micrograms of gallic acid equivalent (GAE) per milliliter (µg·100 mL−1). It should be noted that while fruit was used in its fresh form, the leaves were dried and ground to a fine powder when preparing the extract.
- Total flavonoid content of the extract was evaluated using a colourimeter assay developed by Bao. (2005. About 0.2ml of the extract was added to 0.3ml of 5% $NaNO_3$ at zero time. After 5min, 0.6 ml of 10% $AlCl_3$ was added and after 6min, 2ml of 1M NaOH was added to the mixture, followed by the addition of 2.1ml of distilled water. Absorbance was read at 510nm against the reagent blank, and flavonoid content was expressed as mg rutin equivalent.
- The reducing property of the extract was assessed using modified method of [29], 2000 wherein 0.25ml of the extract was mixed with 0.25ml of 200mM of Sodium phosphate buffer pH 6.6 and 0.25ml of 1% KFC. The mixture was incubated at 50^0C for 20min, thereafter 0.25ml of 10% TCA was also added and centrifuge at 2000rpm for 10min, 1ml of the supernatant was mixed with 1ml of distilled water and 0.1% of FeCl3 and the absorbance was measured at 593nm. $FeSO_4$ dilution was run, as a standard, in the same manner to build calibration curve (absorbance µM Fe^{2+}). The free radical scavenging ability of the extract against DPPH (1, 1- diphenyl-2-picryhydrazyl) was determined using the [15] and [30] modified method. 1ml of the extract was mixed with 1ml of the 0.4mM methanolic solution of DPPH the mixture was left in the dark for 30min before measuring the absorbance at 516nm.
- 2, 2'-azino-bis (3-ethylbenthiazoline-6-sulphonic acid) (ABTS) scavenging ability of the extract was determined according to the method described by [31] and modified by [32] 2020. The ABTS was generated by reacting an (7mM). ABTS aqueous solution with $K_2S_2O_8$ (2.45 mM/l, final conc.) in the dark for 16hours and adjusting the absorbance at 734 nm to 0.70 to ethanol (0.2 of the appropriate dilution of the extract was then added to 2.0ml of ABTS solution and the absorbance was read at 732nm after 15 minutes. The TROLOX equivalent antioxidant capacity was subsequently calculated.
- Sodium Nitroprusside in aqueous solution at physiological pH spontaneously generates NO, which interacts with oxygen to produce nitrite ions that can be estimated by use of Griess reagent. Scavengers of NO compete with oxygen, leading to reduced production of NO.
  Briefly 5nM sodium nitroprusside in phosphate- saline was mixed with the extract, before incubation at 25^0C for 150min. Thereafter, the reaction mixture was added to 0.5 ml Greiss reagent before measuring the absorbance at 546nm, relative to the absorbance of a standard solution of potassium nitrate treated in the same way with Greiss reagent [33]
- The procedure described by [34] as adopted by [35] was used to determine the monoterpenoid content of the extract. 0.5g of finely grounded sample was weighed into a 50ml conical flask. 20ml of chloroform: methanol 2:1 was added to the mixture, shaken thoroughly and allowed to stand for 15min at room temp. The suspension was centrifuged at 3000rpm and the supernatant discarded. The precipitate was re-washed with 20ml chloroform: methanol 2:1 and then re-centrifuged again then the precipitate was dissolved in 40ml of 10% SDS solution. 1ml of 0.01M ferric chloride was added and allowed to stand for 30min before taking the absorbance measurement at 510nm. The STD Terpenoid (alpha-terpineol). Concentration ranging from 0-5mg/ml from the stock solution
- The vitamin C content was determined using the DNPH hydrazone method as described by [36] and [37] with ascorbic acid as the reference compound. 200ml of the extract was pipette and mixed with 300 ml of 13.3% of TCA and 75microliter of DNPH. The mixture was incubated at 37^0C for 3hrs and 500ml of H_2SO_4 was added and the absorbance was read at 520nm

2.4 Determination of proximate composition and mineral content of pepper

The proximate composition analysis was done in the laboratory to determine the moisture, crude fat, crude protein, ash, crude fiber and carbohydrate content of pepper fruit and leaf. Samples of habanero and sweet pepper fruits were washed with distilled water, sliced thinly and then treated with concentrated chlorine solution. The treated samples were then dried in the oven at 60^0C temperature for 24 hours. The dried sample were grinded and stored in air-tight container. The samples used in their fresh state were washed and ground to paste. Exactly one (1) g of the pepper was measured and homogenized with sterile distilled water of 10ml. The solution was filtered and the filtrate was used in the analysis. The moisture content was evaluated by oven-drying the samples till a constant weight was obtained and the dry weight was deducted from fresh sample weight and the result divided by fresh weight. Crude fat was determined by extracting fat from sample with the aid of an organic solvent using the Soxhlet extraction method as applied by [38]. The solvent was evaporated and the dry fat was measured and reported as % of dry pepper sample. The standard Kjeldahl (AOAC) method was used to evaluate the crude protein of the samples. It involved determination of the total nitrogen in the samples and multiplying by a common factor (6.25) which converts nitrogen to protein. The ash content of the samples was determined using the AOAC method whereby samples were incinerated in muffle furnace at 550^0C until a constant weight of ash was achieved [39]. The carbohydrate content of the samples was assessed by deducting the sum of moisture, crude fat, crude fiber, crude protein, ash from 100%. The nitrogen, phosphorus and potassium content of the pepper fruits and leaves were analysed in the laboratory. The AOAC Kjeldahl digestion, distillation and titration method was used determine the nitrogen content, while [40] method was used to quantify the phosphorus content. Potassium content, on the other hand was measured using a flame photometer.

Data collected were subjected to Analysis of Variance (ANOVA) test with the aid of Statistical Analysis System (SAS) software and Tukey's honestly significant difference (HSD) was used to separate significant means at 5% probability level.

3.0 Results

The physical and chemical properties of soil prior to cropping are shown in Table 1. The textural class of the soil was clay loam and it contained low proportion of nitrogen and organic matter. Exchangeable cations such as potassium was optimum while others like calcium and magnesium were in low quantity.

Effects of fertigation regime on growth and yield parameters of pepper plants

The effect of fertigation regime on few growth and yield parameters across sampling periods was significant at $p<0.05$ (Table 2a). Although varying nitrogen fertilizer rates had no significant effect on plant height of both bell and habanero peppers, irrigation at 100% field capacity produced taller bell and habanero pepper at 8WAT. Stem diameter of both bell and habanero peppers was not significantly affected by nitrogen rate but the watering regime of 70% field capacity significantly increased the stem diameter of bell pepper by 4WAT. The number of branches of bell and habanero pepper were not significantly affected by nitrogen rate however, watering regime had significant impacts on the number of branches. Irrigation at 70% field capacity increased the number of branches by 219.64% and 61.13%% in bell pepper at 4WAT and 6WA respectively. In contrast, habanero plants produced more branches att a watering regime of 100% at 4WAT while the effect of watering regime at 6WAT was not significant. The interaction effect of fertilizer rate and watering regime were only significant for stem diameter of bell pepper and habanero pepper at 6 and 8WAT.

Table 2b shows the effects of nitrogen fertilizer rate, watering regime and pepper species on plant height, stem diameter and number of branches of pepper. N fertilizer rate had no significant effect on plant height across the period of measurement, while plants that received no fertilizer produced thickest stem at 4WAT and 8WAT. The number of branches fertilized with 100kgN/ha was significantly higher at 4 WAT, however, the treatment effect was insignificant at 6WAT and 8WAT. Although the watering regime made no significant difference on the physiological parameters measured, pepper species significantly influenced growth parameters at varying weeks after transplanting. Plants of bell pepper were significantly taller than habanero pepper by 17.81% and 13.74% at 4WAT and 6WAT, respectively. Bell pepper also outperformed habanero in stem diameter at 4WAT and 8WAT as well as in number of branches produced at 6WAT. While the interaction between fertilizer rate and watering regime was significant on stem diameter at 6 and 8 WAT, number of branches was significantly affected by the interaction effect between watering regime and pepper species across the measurement intervals. Watering regime and species interaction also influenced plant height at 8WAT and stem diameter at 4WAT.

Effects of fertilizer rate, watering regime and species on minerals and proximate components of pepper fruits

Minerals and proximate content of pepper fruits were significantly affected by fertilizer rate, watering regime and pepper species at $p<0.05$ as seen in Table 3a.

Nitrogen (N) and potassium (K) in bell pepper fruit increased significantly (1.04% and 74.86mg/kg respectively) with application of 100kgN/ha while phosphorus (P) was highest (224mg/kg) at 60kgN/ha. Ash and crude protein of bell pepper fruit were significantly highest at 100kgN/ha while 60kgN/ha treatment significantly enhanced crude fat and moisture content. Similarly, habanero fruits were significantly high in nitrogen, potassium, ash, crude fiber, and crude protein when treated with100kgN/ha while application of 60kgN/ha boosted phosphorus, moisture content, carbohydrate and crude fiber significantly.

The effect of watering regime on all minerals and proximate components of bell pepper were significant under the watering regime of 70% field capacity with the exception of ash and carbohydrate. Habanero likewise produced fruits with high mineral and proximate components under 70% field capacity except for moisture content, crude fiber and carbohydrate. The effects of fertilizer rate x watering regime on phosphorus, potassium, ash, crude protein and crude fat were significant for both bell and habanero pepper species.

Fruit minerals and proximate components of pepper were significantly influenced by nitrogen fertilizer rate, watering regime and species of pepper at $p<0.05$ (Table 3b). Pepper plants fertilized with 100kgN produced fruits containing significantly high nitrogen (1.00%) and potassium (74.66mg/kg). The ash, crude fiber, crude protein and carbohydrate content of pepper fruit were also enhanced with 100kgN/ha application rate. Conversely, phosphorus, moisture content and crude fat of pepper fruits improved under 60kgN/ha treatment. The effects of watering regime were pronounced on all minerals and proximate components measured at 70% field capacity, with the exception of carbohydrate and moisture content. Habanero pepper significantly outperformed bell pepper in number of fruits/plants, moisture content, crude protein and crude fat at $p<0.05$. There were significant interaction effects of the three treatments (fertilizer rate x watering regime x pepper species) on all minerals and proximate components measured except nitrogen.

Effects of N rate, watering regime and species on minerals and proximate composition of pepper leaves

The effects of fertigation regime on most minerals and proximate components of pepper leaves were significant at $p<0.05$ (Table 4a). Fertilizer application rate of 100kgN/ha significantly boosted the nitrogen, phosphorus, ash, crude protein, carbohydrate and crude fat in bell pepper leaves. A similar trend was observed in habanero, wherein all mineral and proximate compositions in leaves except carbohydrate were significantly enhanced at 100kgN/ha. Irrigation at 70% field capacity increased most of the minerals and proximate contents in leaves of both bell and habanero pepper significantly. The effect of interaction between fertilizer rate and watering regime was significant for all minerals and proximate components of both bell and habanero pepper leaves.

Table 4b shows the significant effects of fertilizer rate, watering regime and species on the minerals and proximate composition of pepper leaves at $p<0.05$. Application of 100kgN/ha and reduction in irrigation water by 30%significantly enhanced most of the mineral and proximate contents in pepper leaves. While nitrogen, potassium, moisture content and crude fiber were significantly higher in bell pepper leaves, habanero produced leaves with significantly higher phosphorus, ash, carbohydrate, crude protein and crude fat contents.

All combinations of treatments produced significant effects on all leaf minerals and proximate compositions.

Fertigation regime effects on metabolite constituents of pepper fruits

The effects of fertigation regime on bioactive metabolites were significant at p<0.05 (Table 4a). DPPH radical scavenging activities (48.42% inhibition), FRAP (4.21mg/g) and Vitamin C (244.63mg/g) and monoterpenoids were significantly high at 60kgN rate in bell pepper fruits. Flavonoids, however, was not significantly influenced by fertigation treatments. Moderate watering regime (70% field capacity) significantly influenced phenols, ABTS, NO and monoterpenoid accumulation in bell pepper. Habanero followed same trend, with 60kgN/ha significantly enhanced the metabolites. However, vitamin C was higher for 70 %FC watering treatment of pepper fruits. The interaction effect between fertilizer rate and watering regime of both habanero and bell pepper were significant for all metabolite components measured.

Table 4b shows that fertilizer rate, watering regime and pepper species significantly influence active metabolites at p<0.05. DPPH, FRAP and Vitamin C were increased significantly at 60kgN/ha while ABTS was highest at 100kgN/ha. Watering regime of 70% field capacity produced higher phenol, FRAP and ABTS. Pepper species also affected metabolite concentration significantly with habanero pepper recording higher phenol (22.88 mg/kg), DPPH (4.88% inhibition), FRAP (9.22 mg/kg) and ABTS (4.88 mg/kg), NO and flavonoids. Interaction effects were significant at all levels of treatment combinations for all parameters measured except for Wr x spp effect on phenol.

Discussion

The insignificant difference recorded in physiological and yield parameters indicates that nutrient supply was beyond the minimum level of nutrient required for vegetative growth leading to equal response in physiological characters across the fertilizer rates (Table 2a). This observation is also attributable to since plants received balanced nutrients from the compound NPK fertilizer applied, the effect of varying fertilizer rate on growth and yield parameters was not pronounced. [41] reported a similar finding whereby increase in fertilizer input did not significantly vegetative growth of tomato under greenhouse cultivation. In contrast, [42] observed increase in vegetative development with increasing fertilizer in a growth medium of initial lower nutrient content. The insignificant response of pepper yields to fertilizer rates suggests that the native status of soil nutrients in greenhouse environment may have sustained high fruit yield (approaching the optimum) under fertigation. The yield of crop typically declines when nitrogen fertilizer rate exceeds the optimum level, hence, there is a need to balance fertigation [43].

The increase in some growth variables of peppers measured at 8WAT under 100% field capacity irrigation shows that watering regime wielded a greater influence over the growth and development than fertilizer rate. Water plays a critical role in translocation of nutrient, sustaining stomatal conductance and cell turgidity and others. Non-limiting soil moisture aids cell enlargement and canopy establishment and this may be responsible for the improved growth in bell pepper at 100%field capacity. Effect of watering regime on habanero was insignificant which may be attributed to its inherent ability to adapt to moderate water deficit condition.

The significance of interaction effects specifically on stem diameter suggests that stem development may be more sensitive to synchronized nutrient and water supply than other physiological variables. Stem growth reflects cumulative carbon assimilation and vascular development, both of which depend on coordinated water–nutrient availability. Irrigation enhances nutrient translocation and uptake efficiency; however, excessive watering can result into nutrient dilution and soil pores may be filled with water, cutting off aeration. This, in turn, can reduce conversion of absorbed nutrient into fruit biomass. In contrast, mild water deficit may enhance assimilate production without severe limitations to photosynthesis. Genetic variation in pepper species is reflected in number of fruits produced by both species. Bell pepper partitions assimilates into larger, though fewer fruits while habanero typically yields numerous smaller fruits. These findings indicate that optimization of fertigation regime enhances resource efficiency and cuts cost of fertilizer and nutrient wastage. The significant interaction between fertilizer rate and watering regime indicates that fruit development was as a result of combined effect of nutrient and irrigation supplied rather than individual effect of treatments

The insignificant effects of irrigation level suggests that mild water stress may sustain physiological activities of plant under greenhouse condition with the benefit of reduction in water required for irrigation (Table 2b). Variation in pepper species and genetic composition affected physiological traits. The enhanced vegetative growth of bell pepper suggests greater initial biomass build-up although increased above-ground biomass does not usually translate to higher yield since yield is determined by efficiency of dry matter partitioning. Interaction of irrigation, fertilizer rate and pepper species responses appear is specie-specific. However, insignificant interaction among fertilizer rate, watering regime and pepper species (Fr x Wr x Spp) indicates that the combined effect of these factors did not influence growth, yield and quality variables measured.

The increase in fruit contents of N, K and crude proteins at 100kgN/ha fertilizer application could have resulted from increased soil nutrient status, improved nutrient uptake and enhanced protein synthesis (Table 3a). Nitrogen, an essential macro-nutrient, aids the formation of acid while potassium boosts enzyme activity and allocation of assimilates to fruits in early stage of development [18]. However, the lower value of phosphorus recorded at 100kgN/ha suggests nutrient imbalance. Increase in potassium supply from the highest rate of NPK fertilizer used may have caused an antagonistic effect thereby suppressing phosphorus concentration in the tissue of pepper fruit.

The significant increase observed in most minerals and proximate contents at 70% field capacity irrigation suggests that mild water deficit enhanced concentration of nutrient in pepper fruit tissues and assimilate allocation to structural biomass. The effect of dilution usually reduces with decrease in water used for irrigation resulting into improved nutrient uptake efficiency via improved root-soil interface and osmoregulation and since less water accumulates in the cell, concentrations of minerals and proximate components increase per dry weight become more concentrated per dry weight. This observation is in tandem with the findings of [44] who reported that sustained- deficit irrigation (SDI) approach enhanced almond quality parameters while saving between 25% and 35% of irrigation water. However, watering regime of 100% field capacity produced fruit with higher carbohydrate content.

This may indicate greater photosynthetic activity and synthesis of carbohydrates from assimilates when moisture is adequately available. These findings imply that the nutritional value of pepper fruit can be enhanced using mild irrigation deficit as a management strategy while saving irrigation water in greenhouse production.

Genetic variation in pepper species is reflected in number of fruits produced by both species. Bell pepper partitions assimilates into larger, though fewer fruits while habanero typically yields numerous smaller fruits. These findings indicate that optimization of the fertigation regime enhances resource efficiency and cuts cost of fertilizer and nutrient wastage. Habanero yielded fruits with higher potassium and crude protein at 100kgN/ha than bell pepper with potassium of and crude protein of at same N-fertilizer rate (Table 3b). This suggests that habanero has inherent capacity for higher nutrient use efficiency and accumulation compared to bell pepper under similar fertigation regime. Our results are consistent with the findings of [45] who obtained differences in the responses of pepper species capacity for mineral absorption, and such differential responses of the pepper species could have stemmed from differences in genetic composition. This observation agrees with reports of [46] that genotype and environmental conditions both control proximate compositions of pepper fruits. This indicates that there might be a need to adopt fertigation regime separately for the production of bell and habanero pepper rather than a single recommendation approach.

The significant interaction between fertilizer rate and watering regime indicates that fruit development was as a result of combined effect of nutrient and irrigation supplied rather than individual effect of treatments. For minerals and proximate components, the significant interaction among fertilizer rate, watering regime and pepper species found for almost all quality variables shows that nutrient and water management acted in synergy to determine proximate and mineral composition of pepper fruits. Taken together, the results indicates that moderate fertilizer application and mild water deficit can enhance mineral and nutritional composition of pepper fruits thereby ensuring efficient resource use.

The mineral and proximate composition of leaves generally indicates nutrient uptake, assimilation and physiological response of plant and not necessarily edible yield (Table 4a). Nitrogen accumulation in leaves plays a central role in chlorophyll synthesis, photosynthetic enzyme formation and protein production, thereby improving photosynthetic efficiency and biomass accumulation. Nitrogen deficiency has been reported to reduce chlorophyll content, disrupt chloroplast structure and decrease photosynthetic performance in pepper plants [47]. Potassium contributes to stomatal regulation, enzyme activation and translocation of assimilates produced during photosynthesis, which supports vegetative growth and subsequent reproductive development [48]. However, increase in fertilizer rate did not translate to a commensurate increase in leaf phosphorus while the value even decreased at higher fertilizer rate especially in bell pepper. This may be due to the antagonistic effect of nutrient and differential efficiency of nutrient absorption since NPK fertilizer was used for the research. Therefore, application of high rate of the fertilizer may have enhanced accumulation of nutrients in vegetative plant parts without optimizing nutrient balance ([49].

In addition, variations in mineral accumulation among pepper tissues reflect differences in nutrient uptake and utilization efficiency among genotypes [46]. By implication, these responses demonstrates that whenever the nutritional composition of leaf improves, nutrient-use efficiency increases and there is improvement in photosynthetic capacity and the ability of plant to sustain biomass production.

The significant effects of reduction in irrigation application by 30% on minerals and proximate components of leaf suggest an increase in nutrient concentration from the reduced dilution effects while adequate watering regime (100% field capacity) enhanced carbohydrate storage in leaf. (Table 4b). Bell pepper produced leaves with higher nitrogen, crude fiber and moisture content while habanero was high in leaf phosphorus, crude protein and fat contents. This differential performance indicates genotypic variation in nutrient uptake and distribution patterns. The significant interaction between fertilizer rate x pepper species and watering regime x pepper species further suggests that fertigation should be species-specific and not uniform approach. In essence, findings from the results demonstrate that a fertigation strategy in which adequate fertilizer is supplied in combination with moderate watering regime can enhance leaf nutritional composition in pepper under greenhouse conditions.

Active metabolite components were significantly influenced by fertilizer, watering regime and pepper species (Table 5a). The high significant effects of the metabolite composition at 60kgN/ha fertilizer rate indicate that application of fertilizer at a moderate rate (60kgN/ha) enhanced the synthesis of secondary metabolite without excessive shoot growth. Nitrogen promotes enzyme synthesis and carbon fixation which are essential for the production of antioxidants and phenolic compounds. However, application of nitrogen in excess may switch plant metabolic processes towards growth activities and limit carbon partitioning into defense and antioxidant pathways. Previous studies on pepper indicate that accumulation of ascorbic acid, for example, can be altered under excessive fertilizer rate [50].

The significant effect of irrigation at 70% field capacity on FRAP, ABTS, NO, monoterpenoids, and phenols (Table 5b) suggests that mild water stress acted as a eustress, inducing defence mechanism of antioxidants. Moderate water deficit usually enhances reactive oxygen species (ROS) production, stimulate phenolics synthesis and antioxidant enzyme as protective compounds with minimal effect on yield. Pepper species accumulated metabolite differently. Habanero outperformed bell pepper in phenols, FRAP and ABTS while bell pepper recorded a significantly higher vitamin C. These variations may be attributed to genetic differences in secondary metabolism and biochemical pathways. Oftentimes, habanero peppers accumulate higher concentrations of bioactive compounds related to antioxidant potential as opposed to bell pepper, which may prioritize ascorbic acid accumulation [2]. These findings suggests that moderate irrigation and fertilizer fertigation rates for greenhouse-grown pepper might be a sustainable strategy to optimize resource use efficiency and enhance fruit yields and antioxidant characteristics.

Conclusions

This study demonstrated the influence of fertigation regime on productivity and nutritional quality of two pepper species in the greenhouse in a rainforest environment.

The findings showed that fertilizer rate, though did not affect growth and yield significantly, 100kgN/ha enhanced mineral and proximate composition of pepper fruits and leaves while active metabolites recorded a boost under 60kgN/ha treatment. Across pepper variables measured, irrigation at 70% field capacity improved metabolite constituents as well as mineral and proximate contents of the peppers Habanero pepper exhibited superior performance in fruit yields and active metabolite contents and for most proximate constituents evaluated,

The study recommended 100kgN/ha for enhancing mineral and proximate composition of pepper fruits and leaves and 60kgN/ha for boosting active metabolites production of pepper. The impacts of fertigation on pepper performance appear to be species-specific, following from differential response of yield, mineral elements, proximate composition and active metabolite constituents of bell and habanero peppers. Moderate irrigation and fertilizer fertigation rates enhanced the performance (growth, yield, proximate composition and active metabolite constituents) of greenhouse-grown pepper, this might be a sustainable strategy for optimizing resource use and enhancing fruit yields and antioxidant characteristics. Further studies are recommended to substantiate findings from this study which was based on a planting cycle) and in other agroecology and longer time periods.

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