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Research Article

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Integrating soil, plant and microclimate variables for optimizing resource use and yield of greenhouse grown pepper in a rainforest environment

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ABSTRACT

An experiment was conducted to evaluate microclimate, growth, yield and water use (evapotranspiration: ET) of peppers (*Capsicum* species: Bell and Habanero) under greenhouse condition. Pepper plants were drip fertigated (irrigation at 100 and 70% field capacity) and soluble nutrient formulation (0, 60 and 100 of recommended rates of N P K compound fertilizer). A mobile weather station was installed with sensor networks for monitoring microclimate variables (solar radiation, minimum and maximum temperatures, humidity, wind speed and photosynthetic active radiation: PAR) as well as methane (CH_4) and carbon dioxide (CO_2). Pepper evapotranspiration was determined using Penman-Monteith and Hargreaves equations. Agronomic parameters were taken on pepper plants (height and leaf development, number and weight of fruits). Correlation and regression analyses were conducted between some weather and pepper yield variables. A diagnostic algorithm was evaluated using python programming language for yield simulation. Data collected were subjected to statistical analysis using ANOVA test and e significant treatment means were separated at 5% level of probability. Results showed that the fertigation regimes significantly influenced the growth and yield of both habanero and bell peppers. Habanero performed best with F_2W_1 (100 kg N/ha + 70% Fc), while Bell pepper benefits from moderate irrigation F_1W_1 (60 kg N/ha + 70% Fc). Tailoring fertigation regimes will enhance productivity and resource efficiency of greenhouse cultivation. Habanero performed best with F_2W_1 (100 kg N/ha + 70% Fc), while Bell pepper benefits from moderate irrigation F_1W_1 (60 kg N/ha + 70% Fc). These findings confirm the critical role of regulated fertigation for optimizing pepper growth and yield in the greenhouse Maximum fertigation rates (100 kg ha^{-1} NPK and 100% field capacity watering) produced best growth and yield variables of peppers followed by 100 kg ha^{-1} and 70% Fc. High fertilizer rate combined with moderate watering (70% Fc) was optimal conditions for pepper under greenhouse condition. The time course of microclimate variables (temperature, humidity, PAR and wind speed) differed during the period of observation (March to June, 2024). Pepper water use (ET) was 4.6 mm day^{-1} (Penman Monteith) and 5.1 mm day^{-1} (Hargreave) while CH_4 and CO_2 were 29.4 and 8.7 ppm respectively. There were both positive and negative associations between pepper yield and water use and weather factors with correlation coefficients (R^2) ranging from 0.90 (strong and positive) and 0.023 (weak and positive) and -0.62 (moderate negative) to -0.023 (very week negative). In particular, there were strong but negative correlations between temperature-related variables (maximum temperature (Tmax) and growing degree days (GDD) and fruit weight and water use (ET) and between humidity and Tmax and GDD. The Gradient Boosting Model predicted pepper yield in the greenhouse based on metrics of Mean Absolute Error (MAE: 18.34) and Root Mean Squared Error (RMSE: 24.01). Both MAE and RMSE were used to assess the predictive performance of the model. Information generated on weather, soil and plant can serve as inputs in the development of control system for improving crop yield and resource efficiency of greenhouse practice. Integration of sensor networks with machine learning algorithm offer opportunity for improving real-time decision-making for greenhouse crop production.

KEYWORDS: Greenhouse, Capsicum, Fertigation, Sensors, Microclimate, Growth, Yield, Algorithm, Rainforest

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INTRODUCTION

Peppers, a member of the family *Solanaceae*, are valued for their economic importance and nutritional benefits, including high levels of vitamins A and C, antioxidants and phytonutrients (Rouphael *et al*., 2010; González-Chavira *et al*., 2018; Acedo Jr & Buntong, 2021). Global demand for peppers continues to rise due to their use in various culinary and medicinal applications.

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 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 Jr & 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).

Soil properties, plant attributes and weather/microclimate variables affect growth, yield, quality and resource efficiencies of greenhouse crop production systems especially, irrigation and fertilizer management (Saliu & Deari, 2023). It is imperative to understand the influence of soil, plant and weather/microclimate variables on the fertigation efficiency, growth, yield and quality of crops. Thus, in greenhouse crop cultivation, the focus is to maximize productivity, resource use and profitability through the efficient control of environmental conditions and production resources. There is however limited information with respect to the interactions of soil, plant and microclimate variables with fertigation regimes and productivity of greenhouse-grown vegetables in the rainforest environment of the tropics including Nigeria.

Therefore, this study was designed to evaluate the responses of soil, plant, and weather/microclimate variables to fertigation regimes, growth and yield of pepper in the greenhouse. The aim is to improve insight on the relevance of such interaction for optimizing fertigation regime, yield and resource efficiency of pepper cultivation using greenhouse production system. Findings will be useful to the development of smart environment monitoring system of greenhouse facility built on sensor networks for collection of soil, plant and microclimate data and the relevance of such system diagnostic tool for automation and improved efficiency of greenhouse management practice. Findings of this study will provide insights into the optimal fertigation regime for improving yield, quality, and nutrient use efficiency for optimizing greenhouse management practice for sustainable vegetable production

MATERIALS AND METHODS

Study Area

The study was conducted at Federal College of Agriculture, Akure, Nigeria. Akure lies between latitude 7.2571° N, and longitude 5.2058° E with altitude of 405.51 m above sea level (Figure 1). Annual rainfall is between 1300 and 1850 mm with relative humidity of 85%.

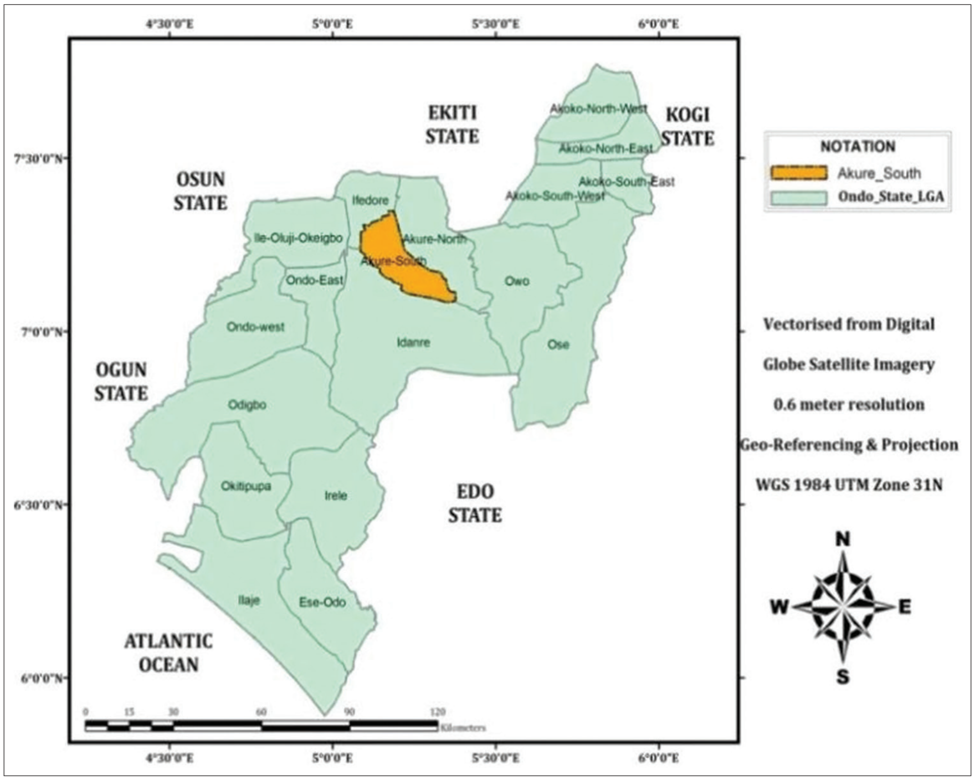

Figure 1: Map of Akure South Local government

Materials

The Greenhouse: A medium cost greenhouse was constructed. The greenhouse measuring 25 x 8 m (192 m^2) was constructed, using matured bamboo stems as frame and green house cladding materials (UV protected solar cover and insect proof net). The greenhouse was partitioned into two chambers 12 x 8 m (96 m^2) each to accommodate two concurrent greenhouse experimental set-up.

Pepper Seeds and Fertilizers

Seeds of two pepper varieties bell pepper (MEKONG F1) and habanero pepper (PIQUANTE F1) packaged by East- West seeds were obtained from an Agro-allied company in Akure. Soluble N.P.K. 20:20:20 (Agrovert) fertilizers were obtained from the same source for the experiment.

The Sensor Networks

A mobile weather station equipped with sensors and a data logger was installed for the collection of data on weather variables of temperature, relative humidity, wind speed and direction, global radiation and PAR within and outside the greenhouse.

Experimental Design and Layout

Experimental plots were divided using spit by split design the treatments were 3 x 2 x 2 factorial combination of fertilizer rates, irrigation regimes and pepper species (Figure 2). Fertilizer rates is the main plot, irrigation regime is the sub-plot treatment, and Capsicum species, the sub-sub plot factor while treatments were replicated four times. Fertilizer levels evaluated are: F_0=0 kg N/ha F_1=60 kg N/ha, F_2=100 kg N/ha, irrigation regimes are: W_1=70% field capacity moisture content and W_2=100% field capacity moisture content while pepper species evaluated are: V_1=Habanero Pepper (*Capsicum sinensis* L.) and V_2=Bell pepper (*Capsicum annum* L.).

Experimental Procedures

Pepper seedlings were raised in plastic seed trays using potting mixture as planting medium under a small screen house nursery. Prior to transplanting, calibration of drip lines was carried out for water delivery to the root zone of the plants. Also, 2 g of Furadan granules, a nematicide, was added to the hole for transplanting and mixed with the soil. Transplanting of pepper seedlings was done when plants were at 4-5 leaves stage at the rate of one seed per hole. Seedlings were removed from the seed trays with the ball of root mass intact and transplanted in planting hole. The seedlings were transplanted on the two rows on each bed at a spacing of 0.4 x 0.6 m. Adequate watering was done regularly to ensure good germination and development of the seedlings. Specifically, daily irrigation was done by split-water application thrice a day. Basal N.P.K 15:15:15 fertilizer was applied as starter for the plants at 2 weeks after transplanting (WAT).

Insect pests were controlled using recommended insecticide (Punch insecticide; Abamectin) 1.8% E.C.), Imiforce

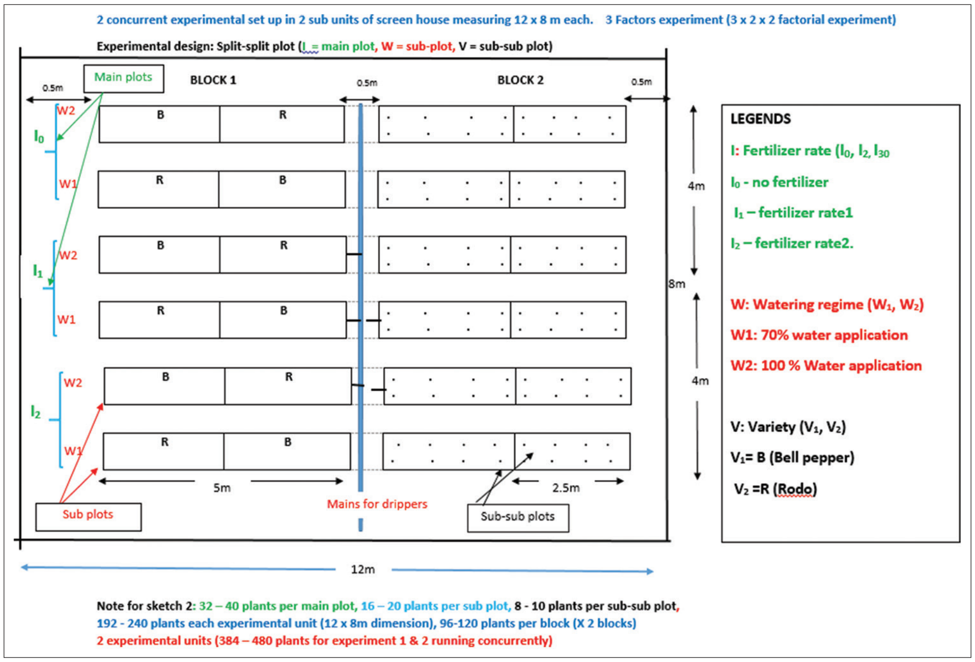

Figure 2: Experimental plot layout

(Imidaclorid 200 g/L), Mite force (Abamectin 3 g/L + Acetamiprid 15 g/L EC) and Hallakat (Emamectin benzoate 48 g/L + Acetamiprid 64 g/L EC). Fungal wilt and other fungal diseases were managed using (copper-containing fungicide eg. Mancozeb) were used for soil drenching. Pepper plants were trained on a line trellis to provide support and prevent lodging. Pruning of old and excessive leaves below the first branching point was done at flower initiation. Fertigation schedule was carried out fortnightly from 4 weeks after transplanting to deliver the required N-rates in equal splits for each treatment. The NPK (20:20:20 Agrovert) soluble fertilizer equivalent of N-rate was dissolved in irrigation reservoir for fertigation. Emerging weeds on the beds were hand pulled fortnightly to ensure beds were weed-free.

Data Collection

Soil moisture, temperature and electrical conductivity were measured at an interval of 20 minutes using ECH_2O logger. Soil moisture contents were measured weekly (before and a day after irrigation). Data were collected on the pepper growth and yield variables.

Soil Physical and Chemical Properties

Soil physiochemical properties such as soil moisture content, soil PH, organic matter, soil porosity, and water holding capacity were measured and determined.

Plant Growth and Yield Variables

Pepper growth parameters such as plant height, stem girth, number of leaves and fruit per plant, and weight of fruits were determined.

Weather Variables

Weather variables within the greenhouse and immediate environment (such as temperature, relative humidity, carbon dioxide (CO_2), Methane, (CH_4), windspeed, and pressure were recorded using the weather sensors. Ambient air temperature was measured using Track-it Data logger when sun was at its peak.

Crop water use (evapotranspiration ET) was calculated using Penman Monteith and Samani equations.

The Penman-Monteith Combination Equation:

Where $ET = \dfrac{0{,}408s(R_n - G) + \frac{\gamma 900 U_2 (e_s - e_a)}{T+273}}{s + \gamma(1 + 0{,}34U_2)}$ AQ1

ET = Evapotranspiration (mm/day),
Rn = total daily net radiation (MJ $m^{-2\ day-1}$),
G = soil heat flux (MJ/m^2/day),
γ = Psychrometric constant (kPa °C^{-1}),
T = mean air temperature (°C),
U_2 = wind speed at 2 m high (m/S),
e_s = vapour saturation pressure (kPa),
e_a = vapour partial pressure (kPa)
s = slope of the vapor pressure curve at air temperature (kPa/°C).

Hargreaves and Samani Equation

$$ET_{HARG} = 0.0023 * R_a * (T+17.8) * (T_{max} - T_{min})^{0.5}$$

ET_{HARG} = Evapotranspiration (mm/day)
R_a = Solar radiation

T = air temperature

T_{max} = maximum temperature

T_{min} = minimum temperature

Statistical Analysis

Statistical analysis was performed using statistical tool such as ANOVA at 5% probability level to determine the significance of treatment effects on the growth and yield a of pepper under greenhouse condition.

RESULTS

Soil Temperature

The results presented in Table 1, showed the mean soil temperatures recorded during pepper growth in the greenhouse. Soil temperatures differed during measurement dates but not significantly indicating relatively uniform thermal environment for habanero pepper within the greenhouse under the fertigation regimes. The no fertilizer + 100% Fc irrigation treatment recorded the lowest mean soil temperature (28.88 °C), which was significantly different from no fertilizer and 100% FC irrigation (F0W1) (29.65 °C). Other treatments (F_1W_1, F_1W_2, F_2W_1, and F_2W_2) showed soil temperatures ranging from 29.1 to 29.5 °C. The relatively stable soil temperatures across treatments indicate that the fertigation regimes moderated thermal environment within the greenhouse for pepper.

Soil Electrical Conductivity

In Table 2, the soil electrical conductivity (EC) for drip fertigated pepper species differed. For Habanero (V1), the soil EC values ranged from 0.024 to 0.040 ms/cm while the lowest EC was recorded under the F_2W_1 (100 kg N/ha + 70% Fc) treatment (0.024). The high EC value observed under the F_0W_2 (No fertilizer + 100% Fc) treatment (0.040), suggest high soil salinity. This indicates that the F_0W_2 (No fertilizer + 100% Fc) treatment notably increases electrical conductivity in the soil compared to the other treatments. The values for the F_0W_1 (0.035), F_1W_2 (0.031), and F_2W_2 (0.027) treatments fall within moderate range, with no significant differences among the treatments. This implies that, while the F_0W_2 (No fertilizer + 100% Fc) treatment produced elevated soil EC, other treatments have comparable effects on soil salinity for Habanero.

In contrast, for Bell pepper, soil EC values ranged from 0.028 to 0.037 ms/cm while the EC values for F_0W_1 (0.028) and F_0W_2 (0.037) differed significantly while for F_1W_1 (60 kg N/ha + 70% Fc) (0.028) and F_2W_1 (0.028) and F_1W_2 (0.033) and F_2W_2 (0.033) there were nonsignificant differences for soil EC, notably, the F_1W_2 (0.033) and F_2W_2 (0.033). These results underscore the differential impact of fertigation on electrical conductivity for the two pepper species. Bell pepper (V2) shows less variation and a lower overall conductivity, which could have implications for soil management and crop performance for each pepper type.

Soil Moisture

The results in Table 3 highlight the dynamics of soil moisture under pepper plant. The ANOVA results show no statistical significance for soil moisture contents (P<0.05) under habanero and bell peppers. For Habanero (V1), the soil moisture contents ranged from 0.164 and 0.230 cm^3/cm^3 and lowest moisture (0.164 cm^3/cm^3) was recorded under the F_1W_1 (60 kg N/ha + 70% Fc) and highest (0.230 cm^3/cm^3) for F_2W_2 (100 kg N/ha + 100% Fc). Specifically, the F_0W_1 and F_0W_2 (No fertilizer + 100% Fc) treatments produced soil moisture ranging from 0.213 and 0.223 cm^3/cm^3 and F_1W_2 (0.212) and F_2W_1 (0.179) which were not different significantly. Soil moisture contents under bell pepper ranged from 0.177 to 0.216 cm^3/cm^3. The lowest moisture content (0.177 cm^3/cm^3) was recorded for F_1W_1 (60 kg N/ha + 70% Fc) while highest (0.216 cm^3/cm^3) was observed under F_0W_2 (No fertilizer + 100% Fc). Although there appear to be some differences in soil moisture content across treatments, the lack of statistical significance at P<0.05 suggests that the observed differences may be due to random variation rather than the treatment effects. For example, the treatments F_1W_1 (60 kg N/ha + 70% Fc) and F_1W_2, which recorded moisture contents

Table 1: Effects of fertigation regime on soil temperature during pepper growth

Treatments	Habanero (V1)	Bell Pepper (V2)
F_0W_1 (No fertilizer+70% Fc)	29.65	29.20
F_0W_2 (No fertilizer+100% Fc)	28.88	28.83
F_1W_1 (60 kg N/ha+70% Fc)	29.45	29.42
F_1W_2 (60 kg N/ha+100% Fc)	29.29	29.26
F_2W_1 (100 kg N/ha+70% Fc)	29.05	30.42
F_2W_2 (100 kg N/ha+100% Fc)	29.15	29.11

Values within a column with different letters are statistically significant at P<0.05

Table 2: Effects of fertigation regime on soil electrical conductivity (ms/cm)

Treatments	Habanero (V1)	Bell Pepper (V2)
F_0W_1 (No fertilizer+70% Fc)	0.035	0.028
F_0W_2 (No fertilizer+100% Fc)	0.040	0.037
F_1W_1 (60 kg N/ha+70% Fc)	0.229	0.028
F_1W_2 (60 kg N/ha+100% Fc)	0.031	0.033
F_2W_1 (100 kg N/ha+70% Fc)	0.024	0.028
F_2W_2 (100 kg N/ha+100% Fc)	0.027	0.033

Values within a column with different letters are statistically significant at P<0.05

Table 3: Effects of fertigation regime on soil moisture (cm^3/cm^3)

Treatments	Habanero (V1)	Bell Pepper (V2)
F_0W_1 (No fertilizer+70% Fc)	0.213^b	0.201
F_0W_2 (No fertilizer+100% Fc)	0.223^b	0.216^b
F_1W_1 (60 kg N/ha+70% Fc)	0.164^a	0.177^a
F_1W_2 (60 kg N/ha+100% Fc)	0.212^a	0.194
F_2W_1 (100 kg N/ha+70% Fc)	0.179^b	0.194
F_2W_2 (100 kg N/ha+100% Fc)	0.230^b	0.203

Values within a column with different letters are statistically significant at P<0.05

of 0.177 and 0.194 cm^3/cm^3, respectively, were not significantly different despite the numerical variation. Although different treatments were applied, the data suggests that the fertilizer levels (F_0, F_1, F_2) and water management practices (W_1, W_2) did not lead to meaningful variations in soil moisture retention for either pepper crop. This could imply that under the specific experimental conditions, factors other than the irrigation and water management regimes might be influencing soil moisture levels. For example, environmental factors such as temperature, humidity, soil type, or even the inherent water retention capabilities of the soil could be playing a more dominant role in determining moisture levels.

Soil Chemical Properties

On the average, soil organic carbon contents under drip fertigated pepper ranged from 0.15 to 0.26%, these values are low, total N content was 0.35% (slightly low, but within a range that may support moderate plant growth), phosphorus was 1.01 mg/kg (notably low), K, Ca, Na and Mg were respectively 0.31, 1.40, 0.36 and 0.60 cmol/kg respectively. Sodium in the soil will not pose an immediate concern for salinity (Table 4).

Table 4: Effects of fertigation regime on soil chemical properties

Soil Properties	Values
pH	5.46
Organic C (%)	0.15
Organic Matter (%)	0.26
N (%)	0.35
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	37.30
Slit	21.9
Textural class	Sandy loam

Microclimate of Greenhouse

Pepper evapotranspiration (ET)

Pepper crop evapotranspiration (ET) was calculated using Penman-Monteith and Hargreaves-Samani equations (Figure 3). Evapotranspiration calculated by P-M ET_0 was averagely 5.0 mm/day at 2 WAT followed by gradual decreases to approximately 3.3 mm/day at 16 WAT. This downward trend likely reflects changes in weather conditions: reduction in temperature, solar radiation, or wind speed over time, leading to a decrease in the rate of evapotranspiration. The consistent decline suggests that the environmental factors affecting evapotranspiration are becoming less intense as the season progresses, reducing the demand for water by crops or vegetation. Hargreaves-Samani equation also showed declining trend for ET values from about 6.0 mm/day at 1 WAT to 4.1 mm/day at 16 WAT. Like the Penman-Monteith values, the ET_0 values calculated using the Hargreaves-Samani method show a peak in the early weeks and a steady reduction over time. However, the magnitude of the ET_0 values is higher across period of observation were comparable to those of Penman-Monteith. This difference is especially noticeable in the first few weeks when the environmental conditions that drive evapotranspiration, such as temperature and solar radiation, are likely stronger. The differences in ET values between the two methods can be attributed to the fact that the Penman-Monteith equation accounts for a more comprehensive set of climatic factors, including wind speed and relative humidity, while the Hargreaves-Samani equation relies primarily on air temperature and solar radiation. As a result, the Penman-Monteith model provides a more nuanced reflection of the overall environmental conditions influencing evapotranspiration. In contrast, the Hargreaves-Samani equation gives consistently higher ET_0 values, which may indicate its more sensitivity to temperature-driven effect on crop evapotranspiration, especially during warmer periods.

Figure 4 shows the trend in relative humidity over a 16-week period, there were noticeable fluctuations throughout the period of observation. At the start of the period, relative humidity is around 86%, which sees a slight dip in Week 2. This initial decline is followed by a moderate rise through Weeks 3 and 4, where relative humidity stabilises around 88%. The early weeks present a stable but gradually increasing humidity level, indicating mild atmospheric changes. By Week 6, a small dip was observed, but from Week 7 onward, the relative humidity begins to rise more significantly. This steady upward trend continues until Week 9, where the percentage of relative humidity reaches 90%. The graph shows a temporary stabilisation through Week 10 to Week 12 before a sharp increase occurs in Week 13, reaching a peak of approximately 94% suggesting a period of high atmospheric moisture However, the high value was followed by drop as the relative humidity falls to 86% at 15 WAT which continued to 16 WAT. This trend in humidity highlight rapid shift in atmospheric conditions.

Figure 5 presents the temperature values recorded in the greenhouse over 16 week period of observation. From the first to 4 WAT, air temperature ranged from 28.27 to 28.95 °C suggesting relatively warm atmospheric conditions. These values decreased to 27.94 °C by 5 WAT and 27.88 °C at 10 WAT. These consistent oscillations highlight a period of instability in temperature within this mid-phase of the 16-week period. Air temperature continues to decline from 11 WAT (27.34 °C) to 12 WAT (27.06 °C) and dropped further to 25.53 °C (lowest recorded temperature in the entire data set) at 13 WAT. This notable drop could point to a shift in environmental conditions affecting the system. However, at 14 WAT, the value was 25.98 °C followed by slight rise to 26.49 and 26.45 °C at 15 and 16 WAT respectively. These temperature values suggest that the environment was not stable, generally, the temperature trends showed that the early growth phase, pepper grew under fairly warm conditions followed by a marked cooling towards the end of measurement period. The fluctuations in temperature suggest a response to the dynamic weather conditions of the site of study.

The pattern of wind speed over 16-week period of observation outside the greenhouse facility is shown in Figure 6. The data set showed the variations in wind speed of periods of relatively strong winds, followed by gradual reductions and increases towards the end of observation. At the beginning of the observation

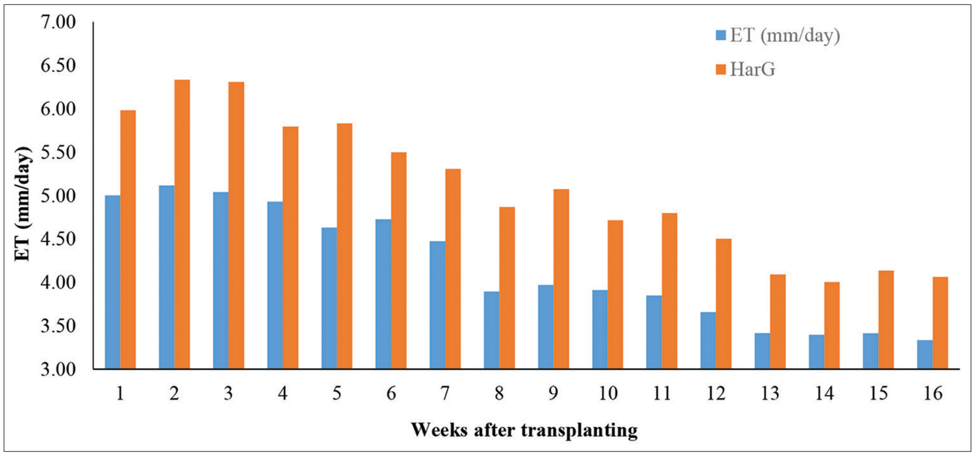

Figure 3: Time course of weekly evapotranspiration

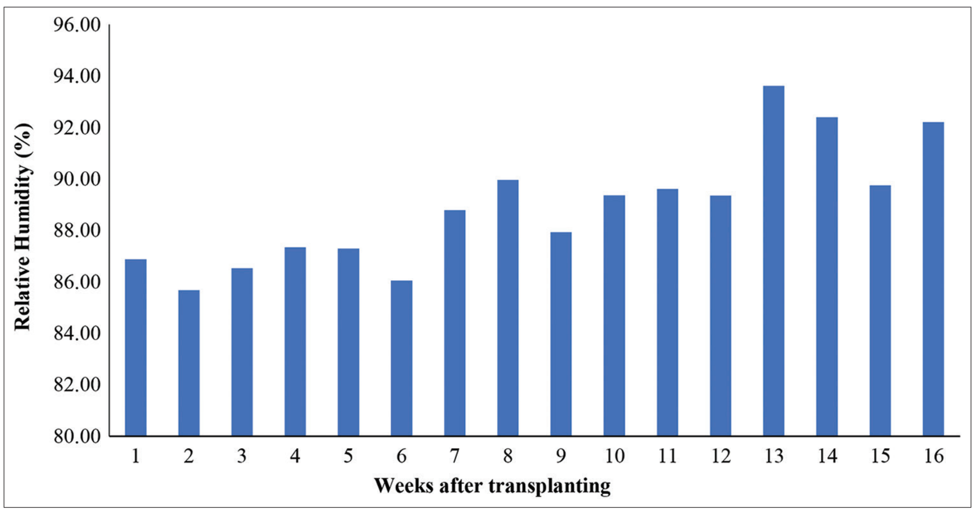

Figure 4: Time course of relative humidity in the greenhouse

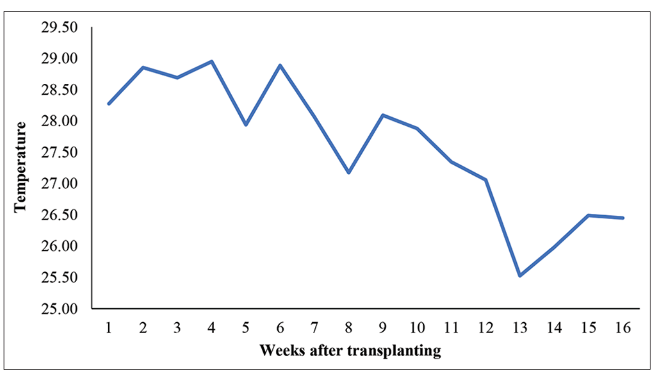

Figure 5: Weekly trend of temperature within the greenhouse

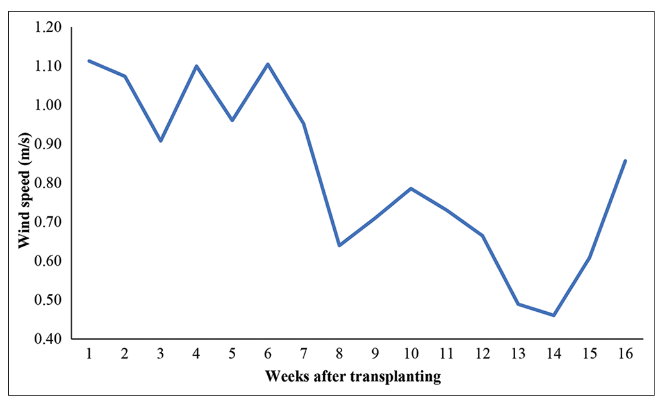

Figure 6: Weekly trend of wind speed outside greenhouse

(1 WAT,) wind speed was averagely 1.15 m/s, indicating relatively strong winds followed by slight decreases for 2 WAT (1.0 m/s). Wind speed dropped to around 0.9 m/s and rose afterwards to 1, 1 and 1.0 m/s from the 4 and 7 WAT followed by continuous drop in values to 0.6 m/s at 8 WAT. Wind speed pattern showed increases especially by 16 WAT to a value of 0.9 m/s. The trends observed suggest calmer and turbulent atmospheric conditions during period of observation.

Concentrations of Methane (CH_4) and Carbon Dioxide (CO□)

The concentrations of methane (CH_4) and carbon dioxide (CO_2), measured in parts per million (ppm), over three months using an MQ-CO_2 sensor, a common sensor used for detecting gases like carbon dioxide (CO_2) and other related gases.

Methane (CH_4) gas within the greenhouse was measured, the values showed that in April, methane concentration was high at 42.27 ppm, suggesting that there were substantial methane emissions within the greenhouse (Figure 7). This level of methane can be linked to factors such as agricultural activities nearby (livestock husbandry) or anaerobic decomposition of organic matter in soils or from organic waste materials. Methane concentration dropped by May sharply to 6.04 ppm and such reduction could be attributed to changes in the local environmental conditions, such as cooler temperatures, increased wind or rainfall which would facilitate dispersion of methane within the atmosphere. Additionally, reduced human activity, such as fewer agricultural operations or a pause in organic waste decomposition, could have contributed to the lower levels. By June, methane concentrations rose to 16.41 ppm but not comparable to level observed for April. This increase can be attributed to resurgence of methane-emitting activities, such as renewed agricultural practices, organic material breakdown, or increased microbial activity in the soil.

In April CO_2 concentration was 11.79 ppm which dropped to 5.29 ppm in June. These fluctuations in CO_2 concentrations indicate variations in environmental conditions or activities that influence carbon dioxide emission. In the high CO_2 concentration in April is attributable to increased emissions from nearby anthropogenic sources such as vehicle exhaust, industrial activities, or combustion processes. Additionally, environmental factors such as limited air circulation or temperature inversions may have trapped CO_2 near the surface, preventing it from dispersing and leading to a build-up in concentration. The elevated level might also suggest a period of intense human or biological activity, such as plant respiration or decaying organic material, which can contribute to CO_2 emissions. By May, the CO_2 concentration decreases to 2.28 ppm, indicating a significant reduction in emissions or enhanced dispersion of CO_2 in the atmosphere. This sharp decline could be due to cooler weather conditions, increased (wind, rainfall, plant uptake of CO_2 or other meteorological factors that improved air circulation, allowing CO_2 to disperse more efficiently. It is also possible that human activities contributing to CO_2 emissions, such as traffic or industrial operations, were reduced during this month, leading to the lower concentration. In June, the CO_2 concentration rises again to 5.29 ppm, though it remains lower than in April. This moderate increase could be linked to the resurgence of certain activities that release CO_2, such as vehicular traffic or decreased photosynthetic. Additionally, changing seasonal or climatic conditions, such as warming temperatures, could enhance biological processes that produce CO_2. The increase suggests that while the environment experienced a period of low emissions in May, some of the factors contributing to CO_2 levels began to rise again in June.

Growth Variables of Pepper

The number of leaves and canopy structure in habanero pepper under different treatments exhibit clear differences across the irrigation and water levels (Figure 8a). The number of leaves

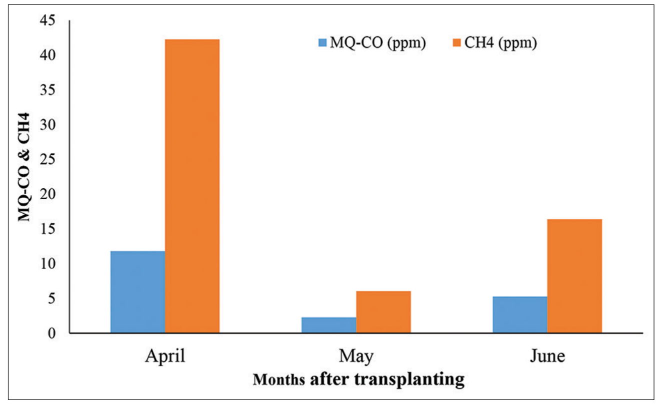

Figure 7: Monthly trend of CO_2 and methane within the greenhouse during pepper growth

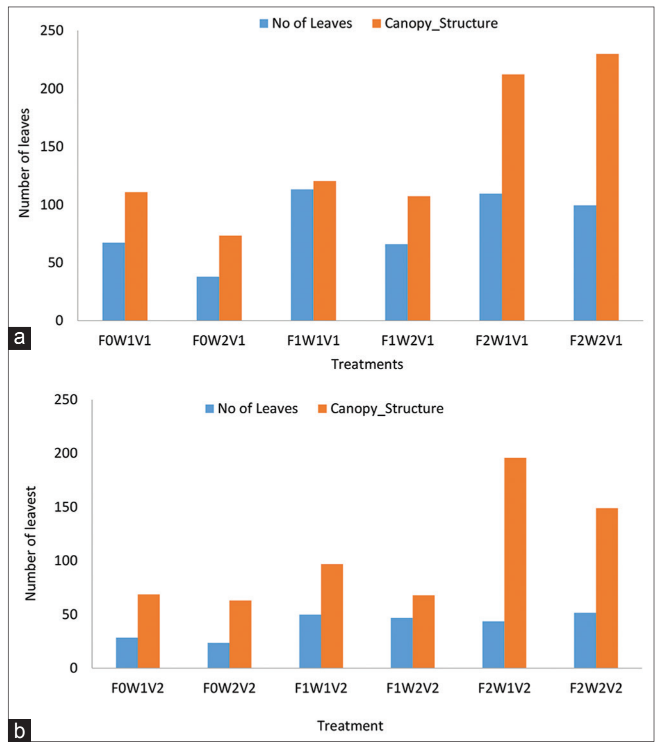

Figure 8: a) Effect of fertigation on leaf development of Habanero pepper and b) Effect of fertigation on leaf development of bell pepper

ranged from 38 for No fertilizer + 100% Fc (F_0W_2) to a high of 113 for 100 kg N/ha and 100% FC (F_1W_1) treatment. This suggests that a moderate level of irrigation (F_1) combined with higher water application (W_1) is most conducive to leaf development. The second-highest number of leaves (110) was observed in the F_2W_1 (100 kg N/ha + 70% Fc) treatment, indicating that increased irrigation (F_2) with moderate water application (W_1) also supports healthy leaf growth. The lowest number of leaves, recorded in the F_0W_2 (No fertilizer + 100% Fc) treatment, highlights the negative impact of minimal irrigation and lower water availability on leaf production in Habanero pepper. With respect to canopy structure, the treatment F_2W_2 (100 kg N/ha + 100% Fc) produced the most extensive canopy (229.875), followed by F_2W_1 (100 kg N/ha + 70% Fc) (212.25). These results suggest that higher irrigation levels (F_2), particularly when combined with increased water supply (W_2), significantly enhance canopy spread. Conversely, the smallest canopy structure was seen in the F_0W_2 (No fertilizer + 100% Fc) treatment (73.375), reinforcing the observation that insufficient water and irrigation hinder canopy development. Overall, Habanero pepper responded best to higher irrigation and fertilizer treatments particularly in treatments with F_1 or F_2, as both leaf number and canopy structure were maximised under these conditions.

The response of bell pepper to fertigation is similar to observations for habanero pepper. However, leaf development and canopy structure were not as vigorous compared to habanero pepper (Figure 8b). The number of leaves ranged from 23.5 in the F_0W_2 (No fertilizer + 100% Fc) treatment to 51.5 in the F_2W_2 (100 kg N/ha + 100% Fc) treatment. The highest number of leaves in F_2W_2 (100 kg N/ha + 100% Fc) followed by the F_1W_1 treatment, where 49.75 leaves were recorded, indicating that moderate irrigation paired with higher water levels can also boost leaf growth. The lowest number of leaves, found in F_0W_2 (No fertilizer + 100% Fc), underscores that limited irrigation and water supply severely constrain leaf development. Canopy structure in bell pepper followed a similar trend, with the largest canopy (195.875) observed under the F_2W_1 (100 kg N/ha + 70% Fc) treatment, followed by the F_2W_2 (100 kg N/ha + 100% Fc) treatment (149). These findings suggest that increased irrigation levels (F_2) are crucial for enhancing canopy development. The smallest canopy structure was recorded under F_0W_2 (No fertilizer + 100% Fc) (63), further illustrating the detrimental effects of low water and irrigation levels on canopy growth. Bell pepper performed best in terms of both leaf production and canopy spread under optimum levels of irrigation and fertilizer application.

The tallest habanero plants (49.1 cm) were produced under 100 kg N/ha + 70% Fc treatment which was significantly different from other irrigation-fertilizer rate combinations. In contrast, the shortest plants (35.5 cm) were found under no fertilizer combined with irrigation at 100% Fc) treatment. The treatments No fertilizer + 70% Fc and 60 kg N/ha + 70% Fc produced relatively tall plants (45.72 and 45.55 cm respectively) which were not significantly different. Height of bell pepper plants was somewhat different, 60 kg N/ha + 70% Fc treatment produced the tallest plants (43.36 cm) followed by 100 kg N/ha + 70% Fc treatment (43.4 cm) Shortest plants were found for No fertilizer combined with 100 and 70% Fc irrigation.

Both habanero and bell pepper plants exhibited significant differences in height based on the irrigation and water treatments applied. The F_2W_1 (100 kg N/ha + 70% Fc) treatment was optimal for Habanero growth, whereas 60 kg N/ha + 70% Fc irrigation was optimum for bell peppers.

Fruit Yield and Yield Components of Pepper

The results showed distinct patterns in fruit production by habanero and bell pepper. Habanero produced highest number of fruits for F_2W_2 (100 kg N/ha + 100% Fc) treatment, with an average of 9.27 fruits per plant. This result suggests that the combination of the highest fertilizer level (F_2) and the second water level (W_2) was most favourable for fruit production in Habanero. Conversely, the lowest fruit count was recorded in the F_1W_2 (60 kg N/ha + 100% Fc) treatment, with an average of 5.15 fruits. The other fertigation treatments (F_0W_1, F_1W_1, F_2W_1) were moderate in fruit production, ranging between 6.08 and 6.60 fruits per plant, the results indicate that higher fertilizer levels (I_2) paired with either water level can lead to improved fruit production, as seen in F_2W_2 (100 kg N/ha + 100% Fc) and F_2W_1 (100 kg N/ha + 70% Fc). Bell pepper (V_2) had highest number of fruits under the F_1W_2 (60 kg N/ha + 100% Fc) treatment, with an average of 1.13 fruits per plant. This was followed by the F_2W_2 (100 kg N/ha + 100% Fc) treatment, which yielded 1.04 fruits. The lowest fruit count was observed in the F_2W_1 treatment, with only 0.58 fruits per plant, indicating that the highest fertilizer level paired with the first water level (W_1) was not favourable for fruit production in Bell pepper. The F_0W_1 (No fertilizer + 70% Fc) treatment produced 0.88 fruits per plant, while F_0W_2 (No fertilizer + 100% Fc) resulted in 0.96 fruits, suggesting that lower irrigation (F_0) did not necessarily lead to poor fruit production, as moderate fruit counts were observed under these conditions (Tables 5, 6 & 7).

Table 5: Effect of fertigation regime on height (cm) of pepper plants

Treatments	Habanero (V_1)	Bell pepper (V_2)
F_0W_1 (No fertilizer+70% Fc)	45.72^{bc}	36.31a
F_0W_2 (No fertilizer+100% Fc)	35.51^{a}	37.11^{a}
F_1W_1 (60 kg N/ha+70% Fc)	45.55^{bc}	43.36^{b}
F_1W_2 (60 kg N/ha+100% Fc)	37.78^{a}	40.10^{ab}
F_2W_1 (100 kg N/ha+70% Fc)	49.09^{c}	40.96^{ab}
F_2W_2 (100 kg N/ha+100% Fc)	41.30^{ab}	39.54^{ab}

Values within a column with different letters are statistically significant at P<0.05

Table 6: Effect of fertigation regime on fruit yields of peppers

Treatments	Habanero (V_1)	Bell pepper (V_2)
F_0W_1 (No fertilizer+70% Fc)	75.29	99.94
F_0W_2 (No fertilizer+100% Fc)	44.88	65.81
F_1W_1 (60 kg N/ha+70% Fc)	53.25	106.35
F_1W_2 (60 kg N/ha+100% Fc)	50.63	59.90
F_2W_1 (100 kg N/ha+70% Fc)	51.67	65.67
F_2W_2 (100 kg N/ha+100% Fc)	72.69	77.10

Values within a column with different letters are statistically significant at P<0.05

Table 7: Effect of fertigation regime on the number of fruits of pepper

Treatments	Habanero (V_1)	Bell pepper (V_2)
F_0W_1 (No fertilizer+70% Fc)	6.60	0.88
F_0W_2 (No fertilizer+100% Fc)	5.21	0.96
F_1W_1 (60 kg N/ha+70% Fc)	6.08	0.73
F_1W_2 (60 kg N/ha+100% Fc)	5.15	1.13
F_2W_1 (100 kg N/ha+70% Fc)	6.23	0.58
F_2W_2 (100 kg N/ha+100% Fc)	9.27	1.04

Values within a column with different letters are statistically significant at P<0.05

Fruit weight

Habanero produced heaviest fruits under No fertilizer + 70% Fc treatment, with an average weight of 75.29 g followed closely by 100 kg N/ha + 100% Fc (F_2W_2) treatment, which produced fruit weight of 72.69 g. Despite these higher values, no significant difference were observed among treatments F_1W_1 (60 kg N/ha + 70% Fc) (53.25 g), F_1W_2 (60 kg N/ha + 100% Fc) (50.63 g), and F_2W_1 (100 kg N/ha + 70% Fc) (51.67 g). The lowest fruit weight (44.9 g) was recorded in the F_0W_2 treatment. The lack of significant differences suggests that the fruit weight of Habanero was relatively unaffected by fertigation levels, all treatments produced comparable fruit weights. Bell pepper produced heaviest fruits under the F_1W_1 (60 kg N/ha + 70% Fc) treatment, with an average weight of 106.35 g. This was followed by the F_0W_1 (No fertilizer + 70% Fc) treatment, which produced fruit weight of 99.94 g. The lowest fruit weights were recorded in the F_1W_2 (59.90 g) and F_2W_1 (100 kg N/ha + 70% Fc) (65.67 g) treatments, indicating that, while there are some variations in the recorded values, these differences were not statistically meaningful. The F_2W_2 (100 kg N/ha + 100% Fc) treatment resulted in a fruit weight of 77.10 g, which was also not significantly different from the other treatments.

Association of Some Weather Variables, Yield and Water Use of Pepper

The relationships range from linear, power and logarithm functions (Table 8) while the correlation coefficients (R^2) differed ranging from very high (very strong), high (strong) and low (weak) relationships. The results showed that weather variables were negatively and positively correlated with pepper yield parameters. The correlation among weather and pepper variables and weather variables range from strong to very weak and the associations were most times negative the correlation coefficients (R^2) varied from -0.2 to -0.5 and +0.6 to 0.9. There were strong positive correlations between air temperature (T), maximum temperature (Tmax), and growing degree days (GDD). GDD is a measure of heat accumulation during plant growth stages. Conversely, fruit weight and water use efficiency (WUE) show negative correlations with several temperature-related variables. Specifically, both fruit weight and WUE are negatively correlated with Tmax and GDD. Humidity also demonstrated a negative correlation with Tmax and GDD, which suggests that higher humidity might alleviate some of the stress associated with extreme temperatures.

Machine Learning Algorithm as Control System for Greenhouse Practice

Gradient Boosting was used to develop machine learning algorithm for the control system. Gradient Boosting is an ensemble learning technique that enhances predictive performance through the sequential addition of weak learners, typically decision trees. By iteratively refining predictions based on the errors of preceding models, Gradient Boosting effectively captures complex patterns in data, making it particularly well-suited for applications in control systems. The performance of the Gradient Boosting model in predicting the yield of greenhouse-grown pepper was evaluated using two key metrics: Mean Absolute Error (MAE) and Root Mean Squared Error (RMSE). The obtained values were MAE=18.34 and RMSE=24.01 for Habanero pepper (V_1) while MAE=26.24 and RMSE=32.03 for Bell pepper (V_2). These metrics provide insights into the accuracy and reliability of the model's predictions, highlighting its potential effectiveness in the context of the study's objectives. The MAE of 18.34 indicates that, on average, the model's predictions differ from the actual pepper yields by about 18.34. This error suggests that while the model is capturing the general trend of yield variations under the fertigation regimes, some discrepancies between predicted and observed yields remain. The lower the MAE, the closer the model's predictions are to the actual values, implying better performance. Although a MAE of 18.34 is reasonably acceptable in agricultural settings. The RMSE value of 24.01 and 32.03 for V_1 and V_2 respectively provides an additional layer of insight, capturing both the magnitude and the variance of prediction errors. RMSE, being more sensitive to larger errors than MAE, underscores the occasional presence of more significant deviations in the model's predictions (Figure 9a & b).

DISCUSSION

Impact of Fertigation on Soil Physical and Chemical Properties

Fertigation regimes affected soil physical and chemical properties, including temperature, electrical conductivity (EC), and moisture contents. Fertigation produced significant differences in soil temperature under Habanero but not for Bell pepper. Lower soil temperatures were observed No fertilizer and 70% Fc irrigation (F_0W_2) treatment (F_0W_2 for Habanero), suggesting that targeted deficit irrigation can help regulate the root zone temperature, which is beneficial for plant growth. Similar findings were reported by Pramanik *et al.* (2021),

Table 8: Correlation of weather variables with yield and WUE of pepper

	T (°C)	Humidity	Tmax (°C)	Tmin (°C)	GDD	Fruit weight	WUE
T (°C)	1						
Humidity	-0.53524	1					
Tmax (°C)	0.634599	-0.61831	1				
Tmin (°C)	0.737614	-0.03179	0.12554	1			
GDD	0.902767	-0.47416	0.810621	0.682704	1		
Fruit weight	-0.16943	-0.16818	-0.02223	-0.32096	-0.20582	1	
WUE	-0.16943	-0.16818	-0.02223	-0.32096	-0.20582	1	1

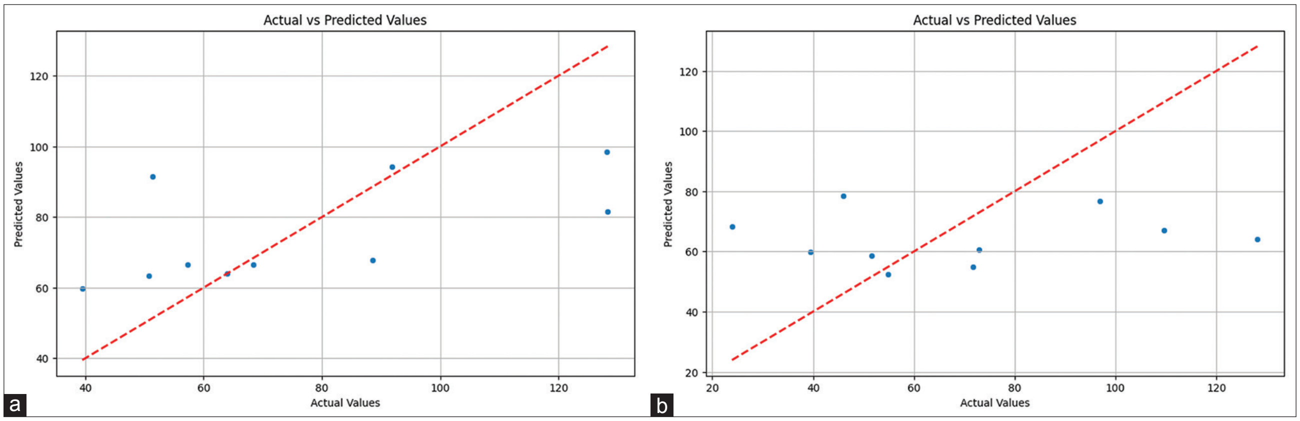

Figure 9: a) Actual yield vs Predicted yield of Habanero pepper and b) Gradient Boosting for Bell pepper

who noted that greenhouse-grown Capsicum experienced less temperature stress compared to open-field cultivation due to the protective effect of the greenhouse structure. Stable temperatures facilitated root function and nutrient uptake, aligning with the present study's findings. Fertigation practices can increase soil salinity, potentially impacting crop performance. High soil salinity is known to impair plant growth and yield, as observed in open-field cultivation where salinity is often uncontrolled (Zörb *et al.*, 2019). However, greenhouse systems with precise irrigation management can mitigate these effects by maintaining favourable soil moisture conditions, as evidenced in previous studies where controlled fertigation reduced EC levels and improved crop productivity (Dorai *et al.*, 2001; Zörb *et al.*, 2019).

Effect of Fertigation on Growth and Yield of Pepper

The result of the study showed that varying irrigation and fertilizer regimes significantly influenced the growth parameters of both Habanero (V_1) and Bell pepper (V_2). For Habanero, tallest plant were observed under the F_2W_1 (100 kg N/ha + 70% Fc) treatment (49.09 cm), indicating that increased fertilizer rate with moderate water levels provided optimal conditions for growth of pepper. In contrast, Bell pepper achieved the tallest plants under the F_1W_1 (60 kg N/ha + 70% Fc) treatment (43.36 cm), suggesting that moderate irrigation was most effective for delivery of irrigation water and fertilizer. These findings align with previous research, which has shown that controlled irrigation and fertigation within greenhouse can lead to substantial improvements in plant growth compared to open-field cultivation. For instance, An *et al.* (2020) observed that automated sensor-based irrigation significantly enhanced plant height and overall growth of pepper by maintaining optimal soil moisture and nutrient levels. This study demonstrated that fertigation positively impacted fruit yield, with the F_2W_2 (100 kg N/ha + 100% Fc) treatment producing the highest number of fruits for Habanero (9.27 fruits per plant). This result highlights the importance of precise irrigation strategies in maximizing yield. This is supported by previous studies showing that regulated fertigation systems can improve water use efficiency and nutrient uptake, leading to higher yields (Li *et al.*, 2021). It is consistent with other findings Ningoji *et al.* (2024), reported that smart fertigation in greenhouse environments enhanced Capsicum yield by ensuring timely nutrient delivery, contrasting with the lower and more variable yields observed under field conditions.

Methane and carbon dioxide gases within greenhouse during pepper growth: This level of methane can be linked to factors such as agricultural activities nearby (livestock husbandry) or anaerobic decomposition of organic matter in soils or from organic waste materials. It is possible that the high concentration of methane was a result of the breakdown of organic waste or seasonal factors that intensified emissions. The high methane level could also be related to stagnant atmospheric conditions that limited the dispersion of the gas, leading to its accumulation in the environment. It is possible that the high concentration of methane was a result of the breakdown of organic waste or seasonal factors that intensified emissions. The high methane level could also be related to stagnant atmospheric conditions that limited the dispersion of the gas, leading to its accumulation in the environment.

Association of Weather Variables with Pepper Yield and Water Use

The correlation matrix of the relationships among weather variables and pepper yield parameters and water use showed that suggests as temperatures rise, there is a corresponding increase in GDD, which is crucial for assessing plant growth and development. GDD is a measure of heat accumulation during plant growth stages, indicating that warmer conditions may facilitate quicker growth. However, this positive relationship raises concerns about the potential for heat stress, which could adversely affect plant health if temperatures exceed optimal levels. Conversely, fruit weight and water use efficiency (WUE) show negative correlations with several temperature-related variables. Specifically, both fruit weight and WUE are negatively correlated with Tmax and GDD. This suggest that as temperatures and heat accumulation increase, fruit weight may decline. This could be indicative of physiological stress on the plants, where excessive heat may impede fruit development or reduce overall yield. The negative correlation of between temperature-related variables and pepper WUE further implies that higher temperatures could lead to increased evapotranspiration, potentially exacerbating water stress conditions for the plants. Humidity demonstrates negative correlation with Tmax and GDD, which suggests that higher humidity levels might alleviate some of the stress associated with extreme temperatures. Increased humidity could help maintain plant turgor pressure and reduce transpiration rates, thus supporting better growth outcomes in warmer conditions.

Performance of Gradient Boosting Model for Predicting Yield of Greenhouse –Grown Pepper

The ability of Gradient Boosting model to predict pepper yield performance under greenhouse-condition was established using key metrics, Mean Absolute Error (MAE) and Root Mean Squared Error (RMSE), results indicate that while the model effectively captures general yield trends, some discrepancies between predicted and actual values persist. Despite this, the level of prediction error is considered reasonably acceptable in agricultural contexts, where such variability is often anticipated. When comparing these results to previous studies, it becomes clear that the Gradient Boosting model's performance aligns with findings from other agricultural yield prediction models. For example, Mancer *et al.* (2024) utilized Gradient Boosting to predict tomato yields in greenhouse environments, achieving MAE values within a similar range. Aworka *et al.* (2022), who found that machine learning models like Gradient Boosting and Random Forest consistently outperformed traditional statistical methods like linear regression for agricultural yield prediction. Fan *et al.* (2018), who used Random Forest models for similar purposes, suggests that other ensemble models may sometimes produce lower RMSE values. the reports of other studies indicates that machine learning models, especially Gradient Boosting, offer reliable predictive power for crops like Capsicum when grown in controlled environments. The model's ability to account for various factors, such as irrigation levels and fertilizer regimes, makes it suitable for applications in precision agriculture, where accurate yield prediction is crucial for decision-making and management efficiency. In addition to yield prediction, the integration of date from sensor networks with machine learning algorithms offers opportunity for improvements in real-time decision-making for greenhouse practice. The studies of Li *et al.* (2021) highlighted the importance of automated systems in improving resource efficiency in greenhouse environments, particularly by reducing water and nutrient wastage. By using machine learning to interpret data from these networks, the current study demonstrates how predictive models can enhance greenhouse productivity by providing actionable insights such as to growers.

CONCLUSIONS

The effects of fertigation regime on the growth and yield of greenhouse-grown peppers was evaluated. A mobile weather station equipped with sensors was deployed for collection of data on microclimatic variables as well and methane (CH_4) and carbon dioxide (CO_2) gases within and outside the greenhouse. The data obtained was deployed in a machine learning algorithm (Gradient Boosting model) using non-linear relationships among variables (irrigation and fertilizer rates, soil properties and pepper growth variables) to predict pepper yield under greenhouse condition. The results showed that habanero performed best with F_2W_1 (100 kg N/ha + 70% Fc), while bell pepper benefited from moderate irrigation F_1W_1 (60 kg N/ha + 70% Fc). The finding confirms the critical role of regulated fertigation for optimizing pepper growth and yield in the greenhouse. The soil, plant, and weather (microclimate) variables responded to fertigation regimes and impacted the growth and yield of pepper under greenhouse condition. These interactions are relevant for optimizing productivity and resource use for greenhouse-grown pepper. The performance of Gradient Boosting model, a machine learning algorithm, to predict pepper performance in the greenhouse was evaluated. Results demonstrated that the model is a valuable tool for predicting yield and enhancing decision making and resource efficiency of greenhouse vegetable production.

The integration of technologies such as sensor networks and machine learning will advance development of smart environment control system, improve decision making, productivity, resource use and sustainability of greenhouse management. This study has advanced knowledge by providing insights into the optimization of fertigation regimes for improved pepper productivity while findings will be useful in the development of management guidelines for greenhouse vegetable cultivation and enhanced data-driven decisions and efficiency of greenhouse practice.

REFERENCES

Acedo Jr, A. L., & Buntong, B. (2021). *Tropical Greenhouse Production of Vegetables*. Phnom Penh, Cambodia: Abt Associates, Feed the Future Cambodia Harvest II.

An, S. K., Lee, H. B., Kim, J., & Kim, K. S. (2020). Efficient water management for cymbidium grown in coir dust using a soil moisture sensor-based automated irrigation system. *Agronomy, 11*(1), 41. https://doi.org/10.3390/agronomy11010041

Aworka, R., Cedric, L. S., Adoni, W. Y. H., Zoueu, J. T., Mutombo, F. K., Kimpolo, C. L. M., & Krichen, M. (2022). Agricultural decision system based on advanced machine learning models for yield prediction: Case of East African countries. *Smart Agricultural Technology, 2*, 100048. https://doi.org/10.1016/j.atech.2022.100048

Dorai, M., Papadopoulos, A. P., & Gosselin, A. (2001). Influence of electric conductivity management on greenhouse tomato yield and fruit quality. *Agronomie, 21*(4), 367-383. https://doi.org/10.1051/agro:2001130

Fan, J., Yue, W., Wu, L., Zhang, F., Cai, H., Wang, X., Lu, X., & Xiang, Y. (2018). Evaluation of SVM, ELM and four tree-based ensemble models for predicting daily reference evapotranspiration using limited meteorological data in different climates of China. *Agricultural and Forest Meteorology, 263*, 225-241. https://doi.org/10.1016/j.agrformet.2018.08.019

González-Chavira, M. M., Herrera-Hernández, M. G., Guzmán-Maldonado, H., & Pons-Hernández, J. L. (2018). Controlled water deficit as abiotic stress factor for enhancing the phytochemical content and adding-value of crops. *Scientia Horticulturae, 234*, 354-360. https://doi.org/10.1016/j.scienta.2018.02.049

Li, H., Guo, Y., Zhao, H., Wang, Y., & Chow, D. (2021). Towards automated greenhouse: A state of the art review on greenhouse monitoring methods and technologies based on internet of things. *Computers and Electronics in Agriculture, 191*, 106558. https://doi.org/10.1016/j.compag.2021.106558

Mancer, M., Terrissa, L. S., & Ayad, S. (2024). Machine Learning-Based Prediction of Tomato Yield in Greenhouse Environments. International

Conference on Emerging Intelligent Systems for Sustainable Development (ICEIS 2024) (pp. 117-128). Atlantis Press.

Ningoji, S. N., Thimmegowda, M. N., Mudalagiriyappa, Vasanthi, B. G., Shivaramu, H. S., & Hegde, M. (2024). Effect of automated sensor-driven irrigation and fertigation on green pepper (*Capsicum annuum* L.) growth, phenology, quality and production. *Scientia Horticulturae, 334*, 113306. https://doi.org/10.1016/j.scienta.2024.113306

Oh, S.-Y., & Koh, S. C. (2019). Fruit development and quality of hot pepper (*Capsicum annuum* L.) under various temperature regimes. *Horticultural Science and Technology, 37*(3), 313-321. https://doi.org/10.7235/HORT.20190032

Pramanik, K., Mohapatra, P. P., Jena, C., & Behera, A. (2021). Performance of capsicum under protected cultivation. In *Food and Agriculture* (pp. 15-34) Tamil Nadu, India: ESN Publications.

Rouphael, Y., Cardarelli, M., Colla, G., & Rea, E. (2010). Yield, mineral composition, water relations, and water use efficiency of grafted mini-watermelon plants under deficit irrigation. *HortScience, 43*(3), 730-736. https://doi.org/10.21273/HORTSCI.43.3.730

Saliu, F., & Deari, H. (2023). Precision Agriculture: A Transformative Approach in Improving Crop Production. *International Journal of Research and Advances in Agricultural Science, 2*(3), 14-33.

Savic, D., & Ilin, Z. M. (2022). Advantages of Growing Vegetable Crops in Modern Greenhouses. In E. Yildirim & M. Ekinci (Eds.), *Vegetable Crops - Health Benefits and Cultivation* London, UK: IntechOpen Limited. https://doi.org/10.5772/intechopen.101469

Wang, X., Liu, B., Wu, G., Sun, Y., Guo, X., Jin, Z., Xu, W., Zhao, Y., Zhang, F., Zou, C., & Chen, X. (2018). Environmental costs and mitigation potential in plastic-greenhouse pepper production system in China: A life cycle assessment. *Agricultural Systems, 167*, 186-194. https://doi.org/10.1016/j.agsy.2018.09.013

Zörb, C., Geilfus, C.-M., & Dietz, K.-J. (2019). Salinity and crop yield. *Plant Biology, 21*(S1), 31-38. https://doi.org/10.1111/plb.12884

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