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Effects of Different Soilless Media and Fertigation Schedules on the Yield and Quality of Greenhouse Tomato (*Lycopersicon esculentum*)

Adeline Anguah-Mante[1,2*], Raphael Adu-Gyamfi[3], Yayra K. Agbemabiese [1,2]

[1]*Department of Agricultural Engineering, University for Development Studies P.O Box TL 1882, Tamale, Ghana*

[2]*West African Center for Water, Irrigation and Sustainable Agriculture (WACWISA), University for Development Studies, P. O. Box TL 1882, Tamale, Ghana*

[3]*Department of Crop Science, Faculty of Agriculture, Food and Consumer Sciences, University for Development Studies P.O Box TL 1882, Tamale, Ghana*

**Corresponding Author's Email: gyanwaadeline@gmail.com*

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ABSTRACT

Soilless media are developed to address challenges like lack of fertile soil, controlling soil-borne diseases, and soil salinity. The use of drip fertigation and substrates in protected tomato cropping (Lycopersicon esculentum) has increased plant health and fruit quality, particularly in sustainable production methods. On the other hand, it is still unclear about tomato plants in terms of the relationship between fertigation frequency and substrate volume. This study evaluated the effects of drip fertigation frequencies and different soilless media on the fruit yield and quality of tomato plants grown in a greenhouse. The experiment utilized a split-plot design with fertigation frequency as the main plot and soilless media as the sub-plot. The fertigation which was a combination of the estimated crop water requirement and the calculated fertilizer rates were as follows: three times daily fertigation (40% deficit fertigation), four times daily fertigation (20% deficit fertigation) and full fertigation (100% fertigation) were applied to four soilless media: 100% cocopeat, 60% cocopeat + 40% Rice husk, 60% cocopeat + 40% Biochar, and 40% cocopeat + 40% Sawdust + 20% Sorghum haulm Biochar. The result of the study demonstrated that the interaction effect of the Five times daily fertigation (100% fertigation) with 60% Cocopeat + 40% Rice husk biochar exhibited superior yield performance in both wet (119.96 t/ha) and dry seasons (119.83 t/ha). Fruit yield increased with increasing irrigation frequency. On the average, 60% Cocopeat + 40% Rice husk biochar media was not significantly different from 100% cocopeat. The highest crop water productivity in both wet (16.51 t/mm) and the dry season (15.66 t/mm) was observed in 60% Cocopeat + 40% Rice husk biochar media. 100% cocopeat and cocopeat–rice husk mixtures consistently produced fruits with higher Total soluble solids and redness in both seasons. Technique for Order Preference by Similarity to Ideal Solution (TOPSIS) analysis revealed that 60% Cocopeat + 40% Rice-husk Biochar ranked first followed by 100% Cocopeat.

INTRODUCTION

The use of soilless media in greenhouse farming has drawn attention in agricultural research in recent years, especially in areas dealing with issues like low soil fertility, soil-borne disease, and high soil salinity. The development and investigation of diverse soilless media have resulted from the search for efficient and sustainable substitutes for conventional soil-based agriculture. Among the array of soilless media available, cocopeat has emerged as a preferred choice due to its desirable characteristics, including suitable pH, electrical conductivity, and bulk density (Karim *et al.,* 2020). The fibrous husk of coconuts (*Cocos nucifera*) is the source of cocopeat, which is a soilless media that has become increasingly popular because of its superior water retention, aeration, and sustainability qualities. It is an abundant source of lignocellulosic materials and a byproduct of the coconut industry. The ability of cocopeat to promote plant growth has been well investigated, and it is seen to be a more environmentally friendly option than peat moss, which is frequently connected to ecological issues (Chowdhury *et al*., 2019; Karim *et al*., 2020). However, the great water-holding capacity of cocopeat might hinder root zone aeration, which affects plant development and yield. Researchers have investigated the possibility of adding coarser materials to the medium to get over the drawback caused by the water retention characteristics of cocopeat. By increasing oxygen diffusion to the roots, this tactic seeks to increase aeration and encourage the best possible plant development (Hassan *et al*., 2018). Growing attention to sustainability in recent decades has prompted research into using organic materials as a soilless medium. Among others, sawdust, rice husk, and cocopeat have become more popular because of their favorable effects on plant development and their renewable nature (Ribeiro *et al*., 2021). It is essential to comprehend the complex relationship between aeration and water retention in soilless agriculture methods to maximize crop yields.

Crop water productivity, crop yield, and overall fruit quality are all impacted by efficient irrigation management, which is essential to greenhouse farming. To make sure that crops receive enough moisture at different phases of growth, accurate irrigation schedules must be established (Allen *et al*., 1998). Determining the ideal frequency of irrigation is essential for sustainable agricultural operations and resource optimization. Many important discoveries are shown by the literature that is now available on the usage of soilless media and irrigation frequency for tomato production in greenhouses. Both Pires *et al*. (2011) and Sezen *et al*. (2010) stress the value of high irrigation frequency in encouraging vegetative development and fruit yield; Pires *et al*. (2011) also draws attention to the possibility of calcium insufficiency in plants receiving less frequent irrigation. A crucial component of growing tomatoes in greenhouses is scheduling irrigation, which affects crop output, fruit quality, and crop water productivity. When growing tomatoes in a greenhouse, substrate selection has a big impact on drainage and water retention. To increase aeration and water-holding capacity, researchers have investigated changing the composition of the substrate. This has an impact on irrigation schedule (Liu *et al*., 2017). By optimizing irrigation techniques, greenhouse environments' particular obstacles are addressed, and tomatoes are guaranteed sufficient moisture at various growth stages. Understanding the water needs of greenhouse tomatoes is fundamental to developing effective irrigation schedules. Tomatoes exhibit varying water requirements at different growth stages, with the highest demand during periods of active vegetative growth, flowering, and fruit development (Albrizio *et al*., 2015). The difficulty is in supplying enough moisture without running the risk of soggy conditions, which can result in poor nutrient uptake and root infections (Abrisqueta *et al*., 2020). Because drip irrigation is precise and saves water, it has become the method of choice for growing tomatoes in greenhouses (Bittelli *et al*., 2018). Water can be applied directly to the root zone with drip systems, which minimizes water waste and lowers the chance of foliar diseases. Using drip systems to apply controlled-release fertilizers improves nutrient management even more. The primary objective of this study was to evaluate the impact of varying soilless media compositions, including cocopeat mixed with rice husk, biochar, and sawdust, on the yield and quality of greenhouse tomatoes. Additionally, the study sought to determine the optimal irrigation frequency that enhances crop productivity, and fruit quality in the semi-arid conditions of Ghana.

MATERIALS AND METHODS

Study Area

The experiments were conducted in a 480 m² (48 m × 10 m) Gothic-arch greenhouse with a north–south orientation, located in the West Gonja

Municipal District of the Savannah Region, Ghana. The geographic coordinates of the site are 9.1632442° N and –1.5099705° W. The greenhouse structure consists of galvanized poles with 50-mesh insect-proof netting on the sidewalls. The roof is covered with Solarig film, which blocks ultraviolet radiation, diffuses approximately 60% of incoming light, and incorporates an anti-drip feature that prevents water condensation on plant surfaces. The experiments were conducted in two seasons; the first from May to October 2023, and the second from October 2023 to March 2024. The Don F1 indeterminate tomato variety was used, and seedlings were transplanted after 21 days in the nursery. Irrigation water was supplied from a dugout well.

Experimental Design

A split-plot design with four replications was used (Figure 1). The main plot factor was fertigation frequency, and the subplot factor was the type of soilless medium. The soilless media treatments included; 60% cocopeat + 40% rice husk, 100% cocopeat, 60% cocopeat + 40% biochar, and 40% cocopeat + 40% sawdust + 20% sorghum-haulm biochar.

Fertigation involved applying both the estimated crop water requirement and calculated fertilizer rates. The fertigation treatments consisted of; W1: Three fertigations per day (40% deficit), W2: Four fertigations per day (20% deficit), and W3: Full fertigation (100%).

The irrigation schedules for each treatment were as; Three times daily: 06:00, 13:00, and 18:00, Four times daily: 06:00, 09:00, 13:00, and 18:00, and Five times daily: 06:00, 09:00, 13:00, 15:00, and 18:00. Off-take valves were installed to allow independent shutoff of each drip line.

Figure 1. Photographic view of the experimental set-up in the greenhouse

Cultural practices

During the trial period, pests and diseases were managed using pesticide sprayings in accordance with suggested protocols, old leaves, and weeds were removed. To guarantee the plant's upward growth during the late seedling stage, the tomato was hung from a small rope on a wire above the greenhouse. To maintain the growth of the main stem, the tomato side shoot branches were periodically removed.

Division of Tomato Growth Stages

The growth cycle was categorized into four (4) distinct phenological stages; initial, development, mid-season, and late season based on crop establishment, vegetative growth, flowering and fruiting, and maturation phases. The duration and corresponding calendar dates for each stage are presented in Tables 1 and 2.

Table 1. Division of Tomato Growth Period in a greenhouse for the wet season

Growth Stage	No. of Days	Duration
Initial	7	05/23/2023 to 05/29/2023
Development	49	05/30/2023 to 07/17/2023
Mid-Season	50	07/18/2023 to 09/05/2023
Late Season	14	09/06/2023 to 09/19/2023

Table 2. Division of Tomato Growth Period in a greenhouse for the dry season

Growth Stage	Stage Duration (days)	Duration
Initial	7	11/15/2023 to 11/21/2023
Development	49	11/22/2023 to 01/09/2024
Mid-Season	50	01/10/2024 to 02/28/2024
Late Season	7	03/01/2024 to 03/07/2024

Reference Evapotranspiration

Reference Evapotranspiration (ETo) was calculated using the Penman-Monteith Equation. Due to their relative closure, greenhouses have limited airflow. The reference crop evapotranspiration inside the greenhouse was determined using the Penman–Monteith equation, which was corrected for wind-related aerodynamic components, in order to prevent the effect of zero aerodynamics (Equation1).

$$ETo = \frac{0.408\Delta(Rn - G) + \gamma \frac{1694}{T+273} + 273(e_s - e_a)}{\Delta + 1.64\gamma} \quad \text{…Eqn 1}$$

Where; ETo is the Reference evaporation (mm/day), R_n = net radiation at the crop surface ($MJ/m^2/day$), G is the soil heat flux density ($MJ/m^2/day$), T is the air temperature at 2 meters (°C), e_s is the saturation vapor pressure (kPa), e_s is the actual vapor pressure (kPa), Δ is the slope of the saturation vapor pressure curve (kPa/°C), γ is the psychrometric constant ((kPa/°C).

Physical, Hydrological and Chemical Parameters of Soilless Media Treatment

Bulk Density

Core Sampling Method as proposed by Blake and Hartge (1986) was employed. A sample of known volume of soilless media is extracted, dried and weighed. The dry weight of the media was then divided by the cylinder volume providing an estimate of bulk density (Equation 2).

$$Bd = \frac{Mm}{Vm} \quad \text{…Eqn 2}$$

Where; Bd = Bulk density, Mm = mass of the oven dried media, Vm= volume of the media

Total Nitrogen

The method proposed by Kjeldahl (1883) was the technique used for measuring nitrogen content of the media. This method involves adding concentrated sulfuric acid and other chemicals such catalysts or digestion accelerators and potassium sulfate (K_2SO_4) which is a boiling point raising salt into a sample of media (digestion stage), adding absorbing solution, indicator solution and standard alkali (distillation stage), and finally distilling, collecting and measuring the released ammonia titrant (absorption and titration stage).

Total Phosphorus

Colorimetric method (Murphy and Riley, 1962) was used to determine the total phosphorus content of the media. ammonium molybdate solution was added to a solution of the media which was dissolved in concentrated H_2SO_4. A yellow crystalline precipitation of ammonium phospho-molybdate was produced. Phospho-molybdate reacts with amino-naphthol-sulphonic acid and produces a molybdenum complex which forms a blue- coloured solution. The intensity of the colour against known concentration was plotted on a graph paper to prepare a standard curve. The phosphorus concentration of the soilless media was estimated by comparing the intensity of the color with the standard curve.

Field Capacity

The saturation and drainage method as outlined by Hillel (1998) was used to determine the field capacity of the soilless media. After saturating the media, it was placed in the pressure plate apparatus and a suction of $-\frac{1}{3}$ atmosphere was applied and left to drain, when water was no longer draining from the media sample, the media moisture content was determined gravimetrically and equated to field capacity (Equation3).

$$F.C = \frac{Vw}{Vm} \, x \, 100 \text{.............................Eqn 3}$$

Where; FC = Field Capacity, Vw = volume of water held in the media after drainage, and Vm= volume of the media

Wilting Point

The wilting point of the soilless media was determined by using the pressure plate apparatus as suggested by Klute (1986). The pressure plate with the media samples were first saturated and then placed in the metallic chamber. The required pressure of -15 atmosphere was applied through a compressor. The applied pressure caused water in the media samples to drain from the outlet till equilibrium was achieved. After that, the media samples were taken out and oven- dried for determining the moisture content (Equation 4).

$$WP = \frac{Mw-Md}{Md} \, x \, 100 \text{........................Eqn 4}$$

Where; WP = wilting point, Mw = mass of wet media, and Md = mass of oven-dried media

Total Available Water

Total available water (TAW) is the total amount of water available to plants, estimated as the difference between water content at field capacity and permanent wilting point (Equation 5).

$$TAW = FC - WP \text{..........................Eqn 5}$$

Where; TAW= total available water, FC = field capacity, WP = wilting point

Available Carbon

Available carbon of the media was determined based on the Walkley and Black (1934) chromic acid wet oxidation method where oxidisable matter in the media was oxidised by 1 N $K_2Cr_2O_7$ solution. The reaction was aided by the heat generated when two volumes of H_2SO_4 was combined with one volume of the dichromate. The remaining dichromate was titrated with ferrous sulphate. The titre was inversely related to the amount of carbon present in the media sample.

Fertilizer Application

In this experiment, fertilizers soluble in water were utilized. A venturi injection device for fertigation was used. The fertilizers were formulated using a proportionate fertigation guideline by Peet and Welles (2005) for tomatoes during the course of the growth season. The fertilizers that were utilized during the growth season are magnesium sulphate ($MgSO_4$) [0-0-0-16-32.5], mono ammonium phosphate (MAP) [12-61-0], potassium nitrate (KNO_3) [13-0-46], and calcium nitrate ($CaNO_3$) [15.5-0-0 + 26.3]. The stock tank size was 25 liters and the injector ratio was 1:200. The fertigation per event was 0.2 L (200 mL). Up to one week before the final harvest, fertilizer was applied at the same concentration, and the EC value of the nutrient solution was maintained between 1.8 and 2.0 dS/m. For the duration of the tomato growing season, the pH of the solution was kept at 5-5.5.

Yield, Crop Water Productivity and Quality of Tomato

When the tomato plant was at the reddish fruit stage, eight plants from the rows in the center of the plot had their fruit weighed using an electronic weighing scale. Sorting and weighing were used to further divide them into marketable and unmarketable output. Fruits with fractures or blossom end rot were classified as unmarketable output. We assessed how yield, color, pH and total soluble solids (TSS) were affected by soilless media and irrigation frequency. The refractometer was used to determine the total soluble solids, and the colorimeter was used to determine the redness of the tomato, the pH of the tomato was determined using a pH meter. Equation 6 was used to calculate the CWP (kgm^{-3}) (Howell, 2006; Yang *et al.*, 2017):

$$CWP = \frac{Y\ x\ 100}{ETc} \text{.................................Eqn 6}$$

Where; CWP is the crop water productivity (t/mm), Y is the total fruit production (t ha^{-1}) and ETc is the total amount of water used (mm).

Comprehensive Analysis Based on TOPSIS

The ideal irrigation amount and ideal soilless media was determined by carefully analyzing and evaluating the experiment findings using the order preference by similarity to an Ideal Solution (TOPSIS) method (Luo *et al.*, 2018; Kuo, 2017). The yield, Brix, Redness and single fruit weights (SFW) were the parameters used for the soilless media comprehensive analysis whiles the yield, Brix, Redness and CWP were the criteria used for the comprehensive analysis of the Irrigation Frequency. Their criteria weights were calculated based on the Analytical Hierarchy Process (Saaty, 2008). The TOPSIS analysis procedure (Abdi *et al.*, 2010; Wang *et al.*, 2017) is presented in Equations 7 to 12.

Step 1: Building the initial evaluation parameter matrix

$$M = \begin{array}{c} \begin{matrix} C_1 & C_2 & C_3 \cdots & C_n \end{matrix} \\ \begin{bmatrix} b_1 & b_2 & b_3 & \cdots & b_{1n} \\ b_{11} & b_{12} & b_{13} & \cdots & b_{2n} \\ b_{21} & b_{22} & b_{23} & \cdots & b_{3n} \\ \vdots & \vdots & \vdots & \ddots & \vdots \\ b_{m1} & b_{m2} & b_{m3} & \cdots & b_{mn} \end{bmatrix} \begin{matrix} \\ A_1 \\ A_2 \\ A_3 \\ \\ \end{matrix} \end{array} \text{....Eqn 7}$$

Where; xij (i = 1, 2,..., n and j = 1, 2,..., m) is the j[th] measurement (water use efficiency, yield, or quality) after the i[th] treatment.

Step 2: Calculating normalized decision matrix ($\bar{x}_{iJ}$)

$$\bar{x}_{iJ} = \frac{x_{iJ}}{\sqrt{\sum_{J=1}^{n} x_{ij}^2}} \text{.................................Eqn 8}$$

Where; $\bar{x}_{iJ}$ is the normalized x_{iJ} , x_{iJ} is the performance value of alternative A_i for attributes C_j

Step 3*:* Calculating the weighted normalized matrix (V_{iJ})

$$V_{iJ} = \bar{x}_{iJ} * w_J \text{.................................Eqn 9}$$

Where; V_{ij} represents the weight of the attribute Cj

Step 4: Determine the Ideal Positive and the ideal negative (V_{ij}^{+}) and (V_{ij}^{-})

Where; V_{ij}^{+} is the maximum value of the weighted normalized value in each column and V_{ij}^{-} is the minimum value in each column.

Step 5: Calculate the Euclidian distance from the ideal best (S_i^{+}) and (S_i^{-})

$$PIS = S_i^{+} = \left[\sum_{J=1}^{m} \left(v_{iJ} - V_j^{+}\right)^2\right]^{0\cdot5} \text{........Eqn 10}$$

Where; PIS - Positive Ideal Separation

$$NIS = S_i^{-} = \left[\sum_{J=1}^{m} \left(v_{iJ} - V_j^{+}\right)^2\right]^{0\cdot5} \text{.....Eqn 11}$$

Where; NIS - Negative Ideal Separation

Step 6: Calculate the relative closeness to the ideal solution (C_i)

$$C_i = \frac{S\bar{\imath}}{S_i^{+} + S\bar{\imath}} \text{.................................Eqn 12}$$

Where; 0≤Ci≤1. The tomato offers the most overall benefit in terms of balancing yield, fruit quality, and water use efficiency when Ci is near to 1.

Step 6: Ranking of alternatives

Rank 1 is assigned to the option with the greatest or maximum value of priorities (Qi). In the same way, rank 2 corresponds to the second-highest Qi value. In a similar vein, a ranking of all the options is completed.

Data Analysis

Data on the yield and greenhouse environment were loaded into a Microsoft Excel spreadsheet and statistical analysis was performed. ANOVA was performed on the data using Split Plot Design model in GenStat. The relevance of the mean values was assessed through the application of Duncan's multiple range tests. The Comprehensive analysis based on TOPSIS was done using the Excel Software.

RESULTS AND DISCUSSION

Results

ETo Changes Throughout the Wet and Dry Season in the Greenhouse

Figure 2 and Figure 3 present the evolution of reference evapotranspiration (ETo) during the wet and dry seasons respectively. The ETo in the greenhouse varied within the range of 4.26 mm d^{-1} to 6.75 mm d^{-1} during the first growth season and for the second growth season, it varied within the range of 4.82 mm d^{-1} to 6.87 mm d^{-1}. The average ETo for the first growth season is 5.39 mm and that of the second growth period is 5.53 mm d^{-1}. The cumulative ETo for each season was 659.43 mm for the wet season and 612.57 mm d^{-1} for the dry season. The ETo in the wet season gradually decreased with time and the ETo for the dry season gradually increased with time.

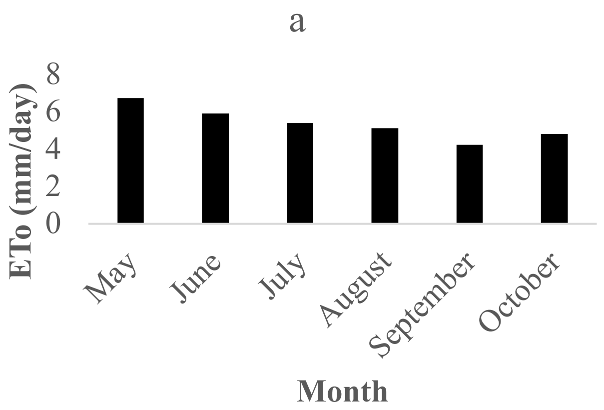

Figure 2. Reference crop's evapotranspiration (ETo) during the wet season

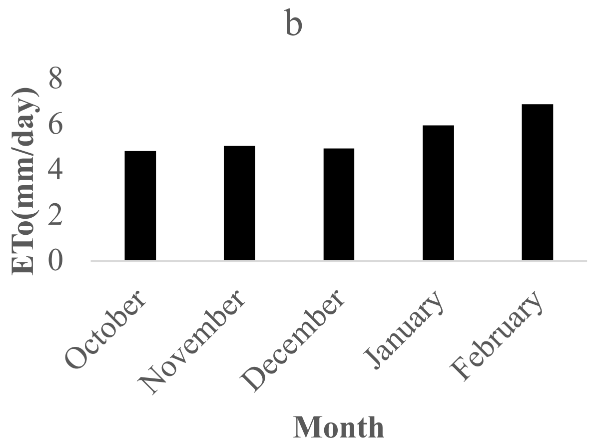

Figure 3. Reference crop's evapotranspiration (ETo) during the dry season

Physical, Hydrological and Chemical Parameters of Soilless Media Treatment

Table 3 presents selected physical, hydrological, and chemical properties of the four soilless media treatments used in the study.

Table 3. Some physical, hydrological and chemical properties of soilless media used

Physicochemical Property	G1	G2	G3	G4
FC (%)	51.48 ± 4.06 a	33.97 ± 7.57 b	22.27 ± 6.76 c	16.79 ± 2.18 d
WP (%)	27.83 ± 2.2 a	18.36 ± 7.98 b	12.04 ± 3.66 c	9.07 ± 1.18 d
TAW (%)	23.65 ± 1.87 a	15.61 ± 3.48 b	10.23 ± 3.11 c	7.71 ± 1.00 d
BD (g/ cm³)	0.3 ± 0.02 a	0.29 ± 0.03 a	0.19 ± 0.05 c	0.21 ± 0.03 b
pH	6.73 ± 0.03 d	7.37 ± 0.09 c	7.50 ± 0.15 b	7.87 ± 0.03 a
EC (mS/cm)	2.9 ± 0.09 a	1.4 ± 0.09 c	2.4 ± 0.09 b	1.3 ± 0.09 d
AC (%)	42.45 ± 0.28 b	46.76 ± 0.07 a	12.10 ± 0.00 c	42.49 ± 0.12 b
TN (%)	1.38 ± 0.01 c	0.59 ± 0.01 b	0.87 ± 0.02 a	0.38 ± 0.01 c
TP (%)	0.10 ± 0.00 c	0.08 ± 0.01 d	0.18 ± 0.00 b	0.43 ± 0.01 a

Note: G1, 100% cocopeat; G2, 60% cocopeat + 40% biochar; G3, 40% cocopeat + 40% sawdust + 20% sorghum haulm biochar; G4, 60% cocopeat + 40% rice husk; TAW, Total available water

Tomato Yield

The results of the wet season experiment revealed that the interaction between the frequency of fertigation and the media had significant effect (P=0.001) on fruit yield. Fruit yield increased with increasing fertigation frequency (Table 4). Within a fertigation frequency, it was observed that 60% Cocopeat + 40% Rice husk biochar produced nominally higher yield than the 100% Cocopeat treatment. The only exception was in the four times fertigation frequency where 100% cocopeat recorded nominally higher yield than the 60% Cocopeat + 40% Rice husk biochar. It emerged that 40% Cocopeat + 40% Sawdust + 20% Sorghum Haulm Biochar and 60% Cocopeat + 40% Rice husk did not give consistent yield across the different fertigation frequencies. At three times daily frequency the yield was not statistically different between the two treatments. At four times daily frequency, the treatment with 60% Cocopeat + 40% Rice husk yielded significantly higher than the treatment with 40% Cocopeat + 40% Sawdust + 20% Sorghum Haulm Biochar. However, when the fertigation frequency was increased to five the opposite happened with 40% Cocopeat + 40% Sawdust + 20% Sorghum Haulm Biochar outperforming 60% Cocopeat + 40% Rice husk (Table 4).

The result of the dry season experiment revealed that the interaction effect of the fertigation frequency and media on fruit yield was not significant (P = 0.503). However, the main effects of the fertigation frequency on fruit yield were highly significant (P = 0.001). The fruit yield increased with increasing frequency of fertigation (Figure 4). Similarly, different media composition had significant effect (P = 0.001) on the yield of greenhouse tomatoes. 60% Cocopeat + 40% Rice husk biochar had greater fruit yield than 100% Cocopeat though the difference was not significant (Figure 5). 40% Cocopeat + 40% Sawdust + 20% SWB was also not significantly different from 60% Cocopeat + 40% Rice husk in fruit yield (Figure 5).

Crop Water Productivity

The crop water productivity (CWP) in the wet season followed the fruit yield pattern. The productivity in four- and five-times fertigation were not different (Table 4). When irrigated five times, 60% Cocopeat +40% Rice husk biochar was the most productive in water use than the other media. The four times irrigation of 100% Cocopeat was better in productivity than the rest of the media. When the fertigation frequency was reduced to three the CWP of 100% Cocopeat was similar to that of 60% Cocopeat +40% Rice husk biochar. The inclusion of sawdust and sorghum haulm biochar did not lead to comparable productive use of water when compared with the use of uncharred rice husk (Table 4).

Table 5 summarizes the interaction effect of different soilless media and different fertigation frequency on the evapotranspiration (ETc) and crop water productivity (CWP) during the dry season. The results revealed that the ETc values remained consistent across all media at each frequency, but the CWP showed variation. Notably, for each fertigation frequency, the combination of 60% Cocopeat and 40% Rice husk biochar consistently resulted in the highest CWP, comparable to that of 100% Cocopeat. The CWP was highest at a frequency of five times daily, with 100% Cocopeat and 60% Cocopeat+ 40% Rice husk biochar having the highest CWP. In contrast, combinations that included sawdust and sorghum haulm biochar exhibited lower CWP across all irrigation schedules (Table 5).

Table 4. Effect of different soilless media on the yield, ETc, and CWP for the wet season trial

Fertigation frequency (daily)	Soilless media	Yield (t/ha)	ETc (mm)	CWP (kg m^{-3})
Thrice	100% Cocopeat	79.65d	485.7	16.40
	60% Cocopeat+40% Rice husk Biochar	80.19d	485.7	16.51
	40%Cocopeat+40%Sawdust+20% Sorghum Haulm Biochar	54.73f	485.7	11.27

	60% Cocopeat + 40% Rice husk	54.46f	485.7	11.21
Four times	100% Cocopeat	101.30c	647.6	15.64
	60% Cocopeat + 40% Rice husk Biochar	96.32c	647.6	14.87
	40% Cocopeat + 40% Sawdust + 20% Sorghum Haulm Biochar	61.26f	647.6	9.46
	60% Cocopeat + 40% Rice husk	72.41e	647.6	11.18
Five times	100% Cocopeat	110.84b	809.5	13.69
	60% Cocopeat + 40% Rice husk Biochar	119.96a	809.5	14.82
	40% Cocopeat + 40% Sawdust + 20% Sorghum Haulm Biochar	101.30c	809.5	12.51
	60% Cocopeat + 40% Rice husk	84.53d	809.5	10.44

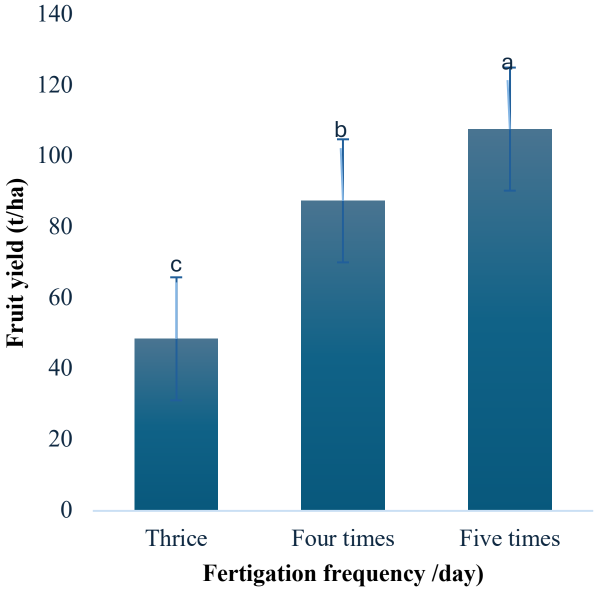

Figure 4. Influence of fertigation frequency on tomato fruit yield during the dry season. Error bars represent standard error of the mean

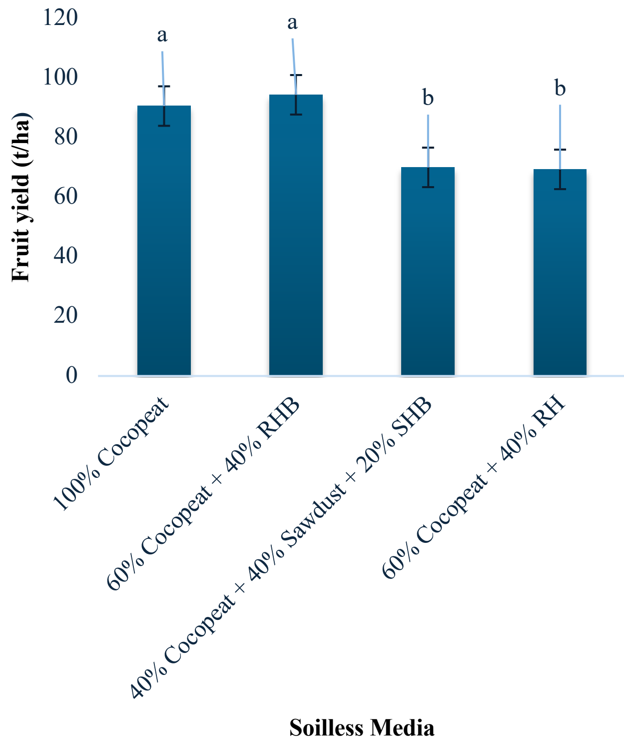

Figure 5. Influence of soilless medium on tomato fruit yield during the dry season. Error bars represent standard error of the mean. RHB = Rice husk Biochar, SHB = Sorghum Haulm Biochar, RH =Rice husk

Table 5. Effect of different soilless media on the ETc and CWP for the dry season

Fertigation Frequency (daily)	Soilless Media	ETc (mm)	CWP (Kg m^{-3})
Thrice	100% Cocopeat	459.18	12.68
	60% Cocopeat + 40% Rice husk Biochar	459.18	13.46
	40% Cocopeat + 40% Sawdust + 20% Sorghum Haulm Biochar	459.18	8.66
	60% Cocopeat + 40% Rice husk	459.18	7.52
	100% Cocopeat	612.24	15.37
	60% Cocopeat + 40% Rice husk Biochar	612.24	16.78

Four times	40% Cocopeat + 40% Sawdust + 20% Sorghum Haulm Biochar	612.24	12.06
	60% Cocopeat + 40% Rice husk	612.24	13.03
	100% Cocopeat	765.30	15.64
	60% Cocopeat + 40% Rice husk Biochar	765.30	15.66
Five times	40% Cocopeat + 40% Sawdust + 20% Sorghum Haulm Biochar	765.30	12.62
	60% Cocopeat + 40% Rice husk	765.30	12.26

Greenhouse Tomato Quality

The results indicate that the total soluble solids (°brix) were significantly (P < .001*)* influenced by the fertigation frequency. The brix level reduced as the fertigation frequency increased. This was seen in both the wet season trial (Table 6) and dry season trial (Table 7). Tomatoes grown on 60% Cocopeat + 40% Rice husk recorded higher brix values under all the fertigation frequencies in the wet season (Table 6). A similar Brix pattern was observed in the dry season trial. °Brix content of the fruits harvested in the dry season was relatively higher than that of the wet season The pH was in the acidic range for both seasons. The results indicate that the redness (a*) were significantly (P < .001*)* influenced by the fertigation frequency. The redness level reduced as the fertigation frequency increased. This was seen in both the wet season trial (Table 6) and dry season trial (Table 7).

Table 6. Interaction effect of fertigation frequency and soilless media on greenhouse tomato quality for the wet season

Fertigation frequency (Daily)	Soilless media	°Brix	pH	Redness (a*)
Thrice	100% Cocopeat	4.76d	5.2ab	33.96a
Thrice	60% Cocopeat + 40% Rice husk Biochar	4.83c	5.2ab	33.54d
Thrice	40% Cocopeat + 40% Sawdust + 20% Sorghum Haulm Biochar	4.21i	5.1bc	33.27f
Thrice	60% Cocopeat + 40% Rice husk	5.03a	5.3a	31.55d
Four times	100% Cocopeat	4.75d	5.1bc	34.19g
Four times	60% Cocopeat + 40% Rice husk Biochar	4.49fg	5.1bc	32.74b
Four times	40% Cocopeat + 40% Sawdust + 20% Sorghum Haulm Biochar	4.5f	5.0c	31.42e
Four times	60% Cocopeat + 40% Rice husk	4.97a	5.2ab	34.65c
Five times	100% Cocopeat	4.6be	5.0c	32.09h
Five times	60% Cocopeat + 40% Rice husk Biochar	4.23h	5.0c	31.89j
Five times	40% Cocopeat + 40% Sawdust + 20% Sorghum Haulm Biochar	4.59e	5.0c	32.44i
Five times	60% Cocopeat + 40% Rice husk	4.48e	5.0c	31.42e

Table 7. Interaction effect of fertigation frequency and soilless media on greenhouse tomato quality during the dry season

Fertigation Frequency (Daily)	Soilless Media	°Brix	pH	Redness (a*)
Thrice	100% Cocopeat	5.37a	5.2b	31.86g
Thrice	60% Cocopeat + 40% Rice husk Biochar	4.3k	5.2b	31.76h
Thrice	40% Cocopeat + 40% Sawdust + 20% Sorghum Haulm Biochar	4.97d	5.1c	33.02c

Thrice	60% Cocopeat + 40% Rice husk	5.0c	5.3a	32.48b
Four times	100% Cocopeat	4.64g	5.1c	31.58j
Four times	60% Cocopeat + 40% Rice husk Biochar	5.07b	5.1c	34.85a
Four times	40% Cocopeat + 40% Sawdust + 20% Sorghum Haulm Biochar	4.75f	5.0d	32.38f
Four times	60% Cocopeat + 40% Rice husk	4.93j	5.2b	32.54e
Five times	100% Cocopeat	4.48i	5.0d	31.86g
Five times	60% Cocopeat + 40% Rice husk Biochar	4.31	5.0d	31.62i
Five times	40% Cocopeat + 40% Sawdust + 20% Sorghum Haulm Biochar	4.58e	5.0d	31.32k
Five times	60% Cocopeat + 40% Rice husk	4.43j	5.0d	32.59d

Comprehensive evaluation using the TOPSIS methodology

Tables 8 and 9 summarize the comprehensive analysis using the TOPSIS method to assess the impacts of fertigation frequency and soilless media on tomato quality, yield, and crop water productivity (CWP) in the wet and dry season respectively. The media ranked better with increasing fertigation frequency. Notably, the treatment combination of 60% Cocopeat + 40% Rice husk biochar across the different fertigation frequencies consistently achieved higher rank over 100% Cocopeat in terms of yield, quality and CWP. Conversely, substituting raw rice husk for 40% of cocopeat resulted in lower rankings. In the second trial in the dry season, 100% cocopeat irrigated five times was the topmost treatment combination followed by 60% cocopeat+40% rice husk biochar. Subsequently, when the fertigation frequency was reduced to four and three times daily, 60% Cocopeat+40% rice husk biochar ranked higher than 100% Cocopeat and the other media (Table 8).

Table 8. Comprehensive analysis using TOPSIS to assess the impacts of fertigation frequency and soilless media on tomato quality, yield, and CWP for the wet season

Fertigation Frequency	Soilless Media	Yield	TSS	CWP	Redness	S_i^+	S_i^-	Ci	
Treatments		Normalized decision Matrix				Euclidian Distance		Relative Closeness	Rank
W1	G1	0.26	0.3	0.26	0.3	0.09	0.05	0.38	8
W1	G2	0.27	0.3	0.26	0.3	0.09	0.05	0.39	7
W1	G3	0.18	0.26	0.18	0.29	0.14	0	0.01	12
W1	G4	0.18	0.31	0.18	0.28	0.14	0.01	0.05	11
W2	G1	0.34	0.3	0.29	0.3	0.05	0.1	0.67	4
W2	G2	0.32	0.28	0.27	0.29	0.06	0.09	0.6	5
W2	G3	0.2	0.28	0.17	0.28	0.13	0.01	0.1	10
W2	G4	0.24	0.31	0.21	0.31	0.1	0.04	0.26	9
W3	G1	0.37	0.29	0.4	0.28	0.02	0.12	0.86	2
W3	G2	0.4	0.26	0.43	0.28	0.01	0.14	0.95	1
W3	G3	0.34	0.29	0.37	0.29	0.04	0.1	0.72	3
W3	G4	0.28	0.28	0.3	0.28	0.08	0.07	0.46	6
Weightage		0.1365	0.1967	0.0646	0.06038				

Note: G1, 100% cocopeat; G2, 60% cocopeat + 40% biochar; G3, 40% cocopeat + 40% sawdust + 20% sorghum haulm biochar; G4, 60% cocopeat + 40% Rice husk; W1, thrice daily; W2, four times daily; W3, five times daily; TSS, total soluble solids; CWP, crop water productivity; S_i^+*, Euclidean distance of ideal solutions;* S_i^-*, Euclidean distance of negative ideal solutions.*

Table 9. Comprehensive analysis using TOPSIS to assess the impacts of fertigation frequency and soilless media on tomato quality, yield, and CWP for the dry season

Treatments		Normalized Decision Matrix				Euclidian Distance		Relative Closeness	Rank
Fertigation Frequency	Soilless media	Yield	TSS	CWP	Redness	Si+	Si-	Ci	
W1	G1	0.12	0.04	0.05	0.02	0.13	0.05	0.29	10
W1	G2	0.13	0.04	0.05	0.02	0.12	0.06	0.33	9
W1	G3	0.08	0.04	0.03	0.02	0.17	0.01	0.06	11
W1	G4	0.07	0.04	0.03	0.02	0.18	0.01	0.04	12
W2	G1	0.19	0.04	0.06	0.02	0.05	0.13	0.71	5
W2	G2	0.21	0.04	0.07	0.02	0.04	0.15	0.81	3
W2	G3	0.15	0.04	0.05	0.02	0.1	0.08	0.46	8
W2	G4	0.16	0.04	0.05	0.02	0.08	0.1	0.54	7
W3	G1	0.24	0.04	0.07	0.02	0.01	0.18	0.98	2
W3	G2	0.24	0.04	0.07	0.02	0	0.18	0.96	1
W3	G3	0.2	0.04	0.06	0.02	0.05	0.13	0.73	4
W3	G4	0.19	0.04	0.06	0.02	0.06	0.12	0.69	6
Weightage		0.1365	0.1967	0.0646	0.06038				

Note: G1, 100% cocopeat; G2, 60% cocopeat + 40% Rice husk biochar; G3, 40% cocopeat + 40% sawdust + 20% sorghum haulm biochar; G4, 60% cocopeat + 40% Rice husk; W1, thrice daily; W2, four times daily; W3, five times daily; TSS, total soluble solids; CWP, crop water productivity; S_i^+*, Euclidean distance of ideal solutions;* S_i^-*, Euclidean distance of negative ideal solutions.*

Table 10 is the average ranking of the media across the fertigation frequencies in the two seasons. 60% Cocopeat+40% Rice husk biochar topped the treatments in terms of yield, quality and crop water productivity. 100% Cocopeat performed better than the two other treatments. Both trials show that the worst medium is when uncharred rice husk replaces part of the Cocopeat.

Table 10. Position ranking of the soilless media based on TOPSIS analysis

Soilless medium	**Average Rank in Trial 1**	**Average Rank in Trial 2**	**Average rank of the combined Trials**	**Position**
100% cocopeat	4.7	5.3	5.0	2nd
60% Cocopeat + 40% RHB	4.3	4.7	4.5	1st
40% Cocopeat + 40% Sawdust + 20% SHB	8.3	7.7	8.0	3rd
60% Cocopeat + 40% Rice husk	8.7	8.3	8.5	4th

Discussion

Tomato Yield

The study under consideration examined the effects of varying compositions of soilless medium and fertigation frequency on crop evapotranspiration (ETc), tomato fruit yield, and crop water productivity (CWP) in the wet and dry season of greenhouse tomato production. In the discussion below, we examine the trends that have been noticed, weigh the consequences for sustainable agriculture, and compare the findings with the body of current research.

The range of fruit mean yields recorded in the wet season trial was 54.46 to 119.96 t/ha and in the dry season yield reduced and the range was 34.54 to 119.73 t/ha. In the wet season fertigation frequency and media showed interaction. This interaction is explained by the yield across two media (60%Cocopeat+40% Rice husk biochar) and (100% Cocopeat). Yield was consistently higher in 60%Cocopeat+40% Rice husk biochar in three- and five-times fertigation frequency but in four times fertigation frequency 100% Cocopeat dominating in fruit yield. That between 40% Cocopeat + 40% Sawdust + 20% Sorghum haulm biochar and 60% Cocopeat + 40% Rice husk varied in four- and five-times fertigation frequency. In the wet season, every medium achieved its maximum at five times fertigation frequency. Higher yield was achieved on medium that has high available water capacity which was 100% Cocopeat. However, when 40% of the cocopeat was substituted for with Rice husk biochar, a coarser material that has properties that improves structure and capacity of medium to improve aeration (Rahmat, 2024), the growth and yield performance of the treatment (60%Cocopeat+40% Rice husk biochar) exceeded that of 100% Cocopeat. In three- and four-times fertigation frequency the yield from these two media were the same. In the dry season cropping where media and fertigation frequency interaction was absent the sterling performance of higher fertigation frequency and two media, 60%Cocopeat+40% Rice husk biochar and 100% Cocopeat, were prominent. Obtaining higher tomato fruit yield from higher fertigation frequency aligns with other studies emphasizing the role that sufficient supply of water plays in fostering the best possible crop growth and output (Yue *et al*., 2022). Liu *et al*. (2019) discovered that increasing fertigation frequency produced higher yields and increased water usage efficiency at an ideal frequency and volume. Li *et al*. (2021) found that optimal yield, water productivity, and fruit quality were achieved with a particular combination of irrigation frequency and nitrogen rate. Choi *et al*. (2022) emphasized the significance of appropriate irrigation management for the long-term growth of tomatoes, noting that increased irrigation volumes improve yields and stabilize nutrients and moisture better. The significance of drip irrigation and fertigation in augmenting tomato output was underscored by Sagar and Singh (2023), wherein certain approaches resulted in increased yields and net returns. Variations in water availability, root zone aeration, and nutrient uptake related to varying fertigation frequencies in the media may be the cause of the observed yield disparities (Jin *et al*., 2023).

The addition of Rice husk biochar to Cocopeat improved the resulting medium. Biochar improves a medium through its enhanced, hydrological, physical, chemical, and biological properties. Its nanoscale size increases the surface-to-volume ratio, leading to higher surface energy and adsorption potential. This results in improved cation exchange capacity (CEC), pH, organic matter content, and water holding capacity. Additionally, biochar enhances media structure, microbial activity, and gas exchange properties while reducing the mobility and bioavailability of soil pollutants. These characteristics make biochar an effective media conditioner for sustainable agriculture (Haile *et al*., 2024; Ramat, 2024). Biochar improves soil fertility by enhancing nutrient retention and reducing nutrient leaching. Its porous structure increases soil aeration and water retention, promoting better root growth (Haile *et al*., 2024; Pandian *et al*., 2024) From the foregoing discussion it is clear that addition of biochar improves medium structure and capacity however the biochar should be made from appropriate substrate. Adekiya *et al*. (2022) use biochar made from hardwood such as *Parkis biglosa*, *Khaya senegalensis, Prosopis africana* and *Terminalia glaucescens*. Its incorporation with Cocopeat at 50% or 30% did not match the use of 100%Cocopeat in yield and other parameters measured. There are potential environmental risks associated with its production and application, such as the release of greenhouse gases during production and possible soil acidification if not managed properly (Naseem *et al*., 2024). Therefore, careful consideration and management are essential to maximize the benefits of biochar while minimizing any adverse effects.

Crop evapotranspiration (ETc) and Crop water productivity (CWP)

Crop productivity is influenced by water availability, as seen by the positive association found between tomato fruit yield and crop evapotranspiration (ETc) levels. This result aligns with research emphasizing the role that a sufficient supply of water plays in fostering the best possible crop growth and output (Yue *et al*., 2022;Cui *et al*., 2022). Interestingly, the treatment with 100% cocopeat showed the highest ETc levels and the maximum water retention capacity, which resulted in higher tomato yields.

The CWP values in Table 4 and 5 reflect the productivity of water utilization in relation to tomato yield under different fertigation frequency and soilless media conditions. The order of CWP for soilless medium was in line with tomato fruit yield; the maximum productivity was shown by 60% Cocopeat + 40% Rice husk biochar which was followed by 100% cocopeat, 40% cocopeat + 40% sorghum haulm biochar, and finally 60% cocopeat + 40% rice husk (Table 4). Zhang *et al*. (2025) reported similar results, indicating that soilless media and irrigation frequency variations significantly influenced tomato evapotranspiration and yield. In particular, combinations of fertigation frequency and media composition resulted in higher CWP values, indicating a more productive use of water resources to achieve optimal crop yield; for example, tomatoes grown in soilless media with 100% cocopeat, fertigated four times daily, demonstrated higher CWP values compared to other treatments, highlighting the importance of water management practices in greenhouse tomato cultivation. Amankwaa-Yeboah *et al*. (2023) also report that combining deficit irrigation with nutrient amendments can maintain or improve nutrient productivity (kg yield per unit nutrient applied) and water productivity; this suggests that while the 3 times regime reduces absolute nutrient use, it may be more efficient in nutrient-use terms and could be advantageous where water or fertilizer supply is limiting or expensive. The variation in crop water productivity (CWP) between different soilless media compositions can be attributed to several factors related to the physical and chemical properties of the media such as water-holding capacity, aeration and drainage, etc.

Tomato Quality

°Brix values measure the sugar content of the fruit and in this study the combination of soilless media and fertigation frequency had a significant effect on greenhouse tomato sugar content. Varying soilless medium compositions showed varying effects on tomato quality measures when fertigation frequency varied. As the amount of water increased as a result of higher fertigation frequency, the total soluble solids in the tomato decreased progressively, in line with earlier studies (Liu *et al*., 2019; He *et al*., 2024). Higher °Brix values, indicating higher sugar content, were frequently observed in thrice daily fertigation, which may have contributed to tomatoes' heightened sweetness. It was also observed that media with lower hydrological properties, field water capacity, wilting point and total available water, in our study, 60% Cocopeat and 40% rice husk displayed higher °Brix values and this value generally increased with decreasing fertigation frequency. This phenomenon may be due to dilution effect. The sugars produced during photosynthesis get diluted in the fruit. Excess water can lead to waterlogged cells reducing the concentration of sugars and other solids in the fruit. Tomato plants under mild water stress as a physiological response produce more sugars and other compounds to cope with the stress resulting in sweeter fruits. Several studies have shown that moderate water and associated nutrient deficit can increase fruit soluble solids (TSS) and color intensity due to concentration effects and altered carbohydrate partitioning, even while reducing total marketable yield (Li *et al*., 2020; Zhang *et al*., 2025).

As shown in Tables 6 and 7, the interaction effect of soilless media and fertigation frequency also had an impact on the pH values of greenhouse tomatoes. As fertigation frequency increased, the pH, and redness both reduced though not significantly different. The pH was within 6 and 7 and a medium with lower hydrological properties tend to be less acidic and this favoured 60% Cocopeat and 40% rice husk.

Based on the result of the study, variations in redness values were observed, which suggests that the visual appearance of tomatoes is affected by the interaction effect between soilless media and irrigation frequency. As fertigation frequency increased, the pH, and redness both reduced though not significantly different. According to Hashem *et al*. (2022), The redness of tomatoes, generally evaluated by color indices, can be impacted by water stress and nutrient uptake. Frequent irrigation may lead to reduced stress, altering the synthesis of pigments like lycopene, which contributes to redness.

CONCLUSION

In conclusion, the results of this study emphasize the significance of soilless media and fertigation frequency in influencing tomato fruit yield, quality and crop water productivity. These findings contribute valuable insights to the optimization of soilless cultivation practices for sustainable and resource-efficient tomato production. The combination of 60% Cocopeat + 40% Rice Husk Biochar exhibited superior yield performance in both wet and dry seasons and achieved higher CWP. Tomatoes grown with 60% Cocopeat + 40% Rice Husk Biochar maintained higher °Brix levels, while pH and redness values were within acceptable ranges, showing consistency across fertigation frequencies. TOPSIS analysis confirmed 60% Cocopeat + 40% Rice Husk Biochar as the optimal combination for achieving high-quality tomatoes with satisfactory yields.

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CONFLICT OF INTEREST

The authors have declared no conflict of interest regarding the publication of the paper.

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