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Quantifying the Direct Relationship between Solar Radiation and Lysimeter-Measured Evapotranspiration of Cherry Tomato under Tropical Greenhouse Conditions

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Abstract. *Despite advances in greenhouse technology, few studies have quantified the direct relationship between solar radiation and lysimeter-measured crop evapotranspiration (ETc) in cherry tomato under tropical greenhouse conditions. This study aimed to fill this gap by determining ETc of cherry tomato (Solanum lycopersicum* var. *cerasiforme) using a weighing lysimeter (5 min intervals, November 28, 2023 to January 6, 2024) and analysing its relationship with solar radiation under different sky conditions. The experiment was conducted in a greenhouse containing 32 plants arranged in two planting beds and irrigated with a drip system. All environmental and crop parameters were monitored through sensors integrated into a digital dashboard. Daily solar radiation ranged from 4.7 to 13.6 MJ m^{-2} d^{-1} (mean 9.0 MJ m^{-2} d^{-1}), whereas ETc ranged from 2.03 to 3.19 mm day^{-1} (mean 2.60 mm day^{-1}). A significant positive correlation was found ($r = 0.717$, $R^2 = 0.514$, $p < 0.001$), yielding the overall regression ETc = 0.069 × Rad + 2.004. A critical threshold of 8 MJ m^{-2} d^{-1} was identified: under sunny conditions (Rad ≥8), ETc = 0.074 × Rad + 2.000 ($R^2 = 0.446$, $p < 0.001$); under cloudy conditions (Rad <8), the near-zero slope (0.009, $R^2 = 0.314$) supported using mean ETc = 2.41 mm day^{-1}. Diurnal analysis revealed a 30–45 min ETc lag on sunny days, informing optimal irrigation timing (before 11:00–12:00). Water use efficiency was 33% higher on cloudy days (0.364 vs. 0.273 mm MJ^{-1} m^2). These empirical models can be directly embedded into automated irrigation systems, supporting precision irrigation practices in greenhouse cherry tomato cultivation under tropical conditions. Future research should focus on integrating VPD and physiological crop parameters to further improve ETc prediction accuracy under low-light conditions.*

Keywords: *drip irrigation; evapotranspiration; lysimeter; solar radiation; greenhouse.*

Type of the Paper: Regular Article.

1. Introduction

Cherry tomato 'Golden Sweet' *(Solanum lycopersicum var. cerasiforme)* is an annual fruit vegetable increasingly consumed fresh as a table fruit and salad ingredient, as well as processed into canned products, juice and sauce. The growing demand has led to rising consumption in Indonesia. According to the Agricultural Data and Information Centre, average household consumption of tomato in 2019 was 2.192 kg/capita/year and was projected to increase to 3.093 kg/capita/year in 2020 [1]. Cherry tomatoes are commonly available in supermarkets and restaurants, but remain less accessible in traditional markets, presenting both challenges and opportunities for farmers to expand cultivated area, productivity and fruit quality.

To achieve improved yield and quality, cultivation techniques such as greenhouse farming

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are essential. Controlled greenhouse systems are effective in enhancing cherry tomato production and quality by providing optimal microclimate conditions, reducing pest and disease incidence, and enabling year-round production with efficient water use [2]. In greenhouse environments, cherry tomato yield has been reported to reach approximately 2.26 kg per plant, with the total weight of the first fruit truss reaching a maximum of 148.2 g [3]. Greenhouse tomato cultivation is commonly combined with hydroponic systems, which provide nutrients directly to plant roots.

In hydroponic drip irrigation, knowledge of plant water requirements across growth stages is crucial for achieving irrigation efficiency. Crop water demand is primarily determined by evapotranspiration (ET), which is driven by atmospheric energy balance, where solar radiation is recognised as the most significant energy source for the vaporisation of water [4,5]. Solar radiation directly affects stomatal conductance [6], which regulates water and gas exchange with the external environment [7]. Increased solar radiation results in higher evapotranspiration [8]. Whereas evapotranspiration estimation for tomato has been successfully applied in open-field conditions using atmometers [9] and a non-weighing lysimeter [10], such tools are less applicable inside greenhouses. Thus, accurate tools are required to predict ET and ensure irrigation meets crop requirements under controlled environments.

Several methods have been used to determine crop evapotranspiration (ETc), ranging from empirical equations to direct measurements using lysimeters. Lysimeters are considered the most reliable tools for estimating ETc because they directly measure water loss under controlled conditions [8–11]. For greenhouse crops such as tomato, lysimeter studies have provided valuable insights into crop coefficients, water use patterns, and the interaction between plant physiology and environmental drivers [12–14]. Shin et al. [13] demonstrated that accumulated radiation can be used to predict transpiration in paprika under soilless culture. In particular, solar radiation is recognised as one of the most influential climatic factors affecting ETc, given its direct role in driving transpiration and crop energy balance [15,16]. Recent advances in modelling and sensor technology have enhanced evapotranspiration estimation in greenhouses, including modified Priestley–Taylor [14,17], simplified Penman-Monteith formulation [18], dual crop coefficient models [15], lysimeter-based evaluations [11–13,16], and machine learning approaches [19,20]. These tools have improved predictive accuracy and irrigation efficiency in temperate production systems.

Despite these advances, few studies have quantified the direct quantitative relationship between solar radiation and lysimeter-measured ETc in cherry tomato under tropical greenhouse conditions. Therefore, this study aims to fill this gap by determining ETc using a weighing lysimeter and analysing its relationship with solar radiation under different sky conditions. The findings are expected to provide empirical models that can be applied in automated irrigation systems, supporting precision irrigation practices in greenhouse tomato cultivation.

2. Materials and Methods

2.1. Experimental Site and Crop Management

This experiment was conducted from October 2023 to January 2024 in a piggyback-type greenhouse (9.4 m × 6.4 m) located at the Integrated Field Laboratory, Faculty of Agriculture, Universitas Lampung, in collaboration with the Telecommunication Laboratory, Faculty of Engineering, Universitas Lampung. The planting system used two cherry tomato beds (1 m × 4 m × 0.2 m) placed on cultivation tables inside the greenhouse (Fig. 1b). Each bed was equipped with two lateral drip irrigation lines, with one emitter per plant (Fig. 1a).

The instruments employed in this study included:

a) Cherry tomato cultivation tools: buckets, ruler, knife, scissors, perforated trays, water hose, plastic mulch, plant stakes, light steel frame, soldering tooland measuring cylinder.
b) Drip irrigation system components: two water drums, a pump, pressure regulator valve (PRV), two screen filters, PVC pipes (19 mm and 13 mm), four water flow meters, drip tape with 50 cm spacing, connectors and end-line plugs, planter bagsand fittings.
c) Electronic weighing balance system: load cell sensors, jumper cables, and plastic containers.
d) Greenhouse environmental monitoring equipment: TDS meter, pH sensor, soil moisture sensor, DS18B20 temperature sensor, BME280 sensor, Raspberry Pi 4, anemometer, wind vane, infrared sensor, pyranometer, ESP32 microcontroller, Wi-Fi module, jumper cables, power terminal and control panel box. The greenhouse was equipped with a comprehensive monitoring system to maintain optimal growth conditions. A pH sensor was utilised to ensure nutrient solution stability (ranged 5.5 – 6.5), and other parameters such as wind speed and soil moisture were monitored as control variables to ensure a stable greenhouse environment during the integration period.

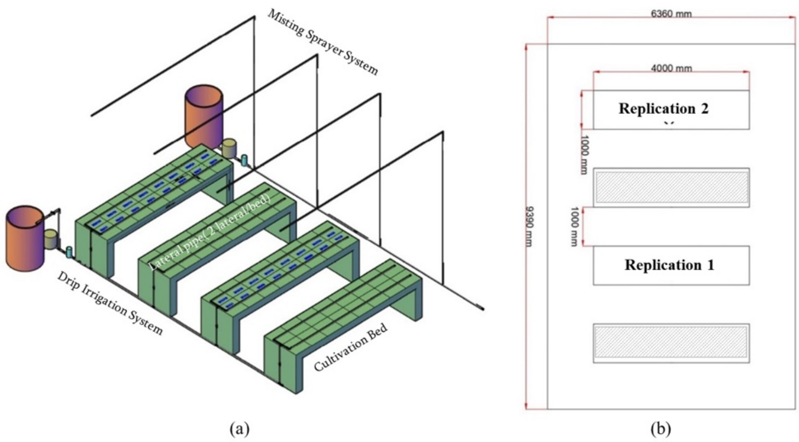

Fig. 1. (a) Layout of the drip irrigation system and misting nozzle; (b) planting bed in the greenhouse.

The materials used included Golden Sweet cherry tomato seeds, rice husk charcoal, cocopeat, rockwool, AB-mix nutrient solution and fungicide. Although the greenhouse contained four beds, this experiment utilised two identical beds to serve as replicates. Each bed was filled with a consistent mixture of cocopeat and rice husk charcoal (1:1 ratio) and managed under the same irrigation protocol to ensure the reproducibility of the data. The total number of experimental plants was 32.

2.2. Reference Evapotranspiration (ETo) and Crop Evapotranspiration (ETc) Measurement

The measured parameters included reference evapotranspiration (ETo), crop evapotranspiration (ETc), and solar radiation (Rad). ETo was estimated from climatic data (temperature, humidity, wind speed and sunshine duration) using the Makkink radiation method [21] as shown in Eqs. (1) and (2):

$$ET_o = \mathrm{c} \times \mathrm{W} \times \mathrm{Rs} \quad (1)$$

$$\mathrm{Rs} = (0.25 + 0.5\,\mathrm{n/N}) \times \mathrm{Rad} \quad (2)$$

where *ETo* is the reference evapotranspiration (mm day^{-1}), *Rs* is solar radiation expressed as evaporation equivalent (mm day^{-1}), *W* is a weighing factor dependent on temperature and altitude, *c* is an adjustment factor dependent on average humidity and daytime wind speed, *Rad* is extraterrestrial radiation, and *n/N* is the ratio of actual sunshine hours to maximum possible sunshine hours.

Crop evapotranspiration (ETc) was determined using the gravimetric method with a custom-built weighing lysimeter system. The lysimeter consists of a high-precision load cell integrated with a digital data logger, which continuously monitors the weight of the pot system. This setup captures the cumulative weight loss resulting from the combination of plant transpiration and substrate evaporation. To ensure accuracy, irrigation events were excluded from the weight loss calculation. The actual ETc was determined using a weighting lysimeter based on Eq. (3):

$$\mathrm{ETc} = [(W_{(\mathrm{i}-1)} - \mathrm{W}_i)/\rho]/\mathrm{A} \quad (3)$$

where *ETc* is evapotranspiration (cm), W_i is planter bag weight on day *i* (g), $W_{(i-1)}$ is planter bag weight on day *(i-1)* (g), *ρ* is the density of water (g cm^{-3}) and *A* is the surface area of the planting container (cm^2). Measurements were recorded continuously at 5 min intervals and processed for daily ETc values.

2.3. Solar Radiation Measurement and Processing

To analyse the influence of solar energy, the instantaneous solar irradiance (W m^{-2}) recorded every 5 minutes was integrated over a 24 h period to obtain the daily solar radiation, SR (MJ m^{-2} d^{-1}), following Eq. (4).

$$SR = \sum\left(\frac{I \times \Delta t}{10^6}\right) \quad (4)$$

where *SR* is the daily solar radiation (MJ m^{-2} d^{-1}), *I* is the instantaneous irradiance (W m^{-2}), and *Δt* is the sampling interval in seconds (300 seconds for a 5 min interval). These cumulative daily radiation data was then used for all regression analyses and correlations with the daily ETc measurements.

Finally, to standardise the results according to FAO-56 guidelines, the volumetric ETc data initially recorded in grams per plant (g $plant^{-1}$) were converted into depth units (mm day^{-1}). This conversion was performed based on the plant population density of 4 plants per m^2 of bed within the greenhouse. Since 1 mm of water depth is equivalent to 1 litre per square meter, the daily ETc in mm was calculated by multiplying the average water consumption per plant (converted to litres) by the number of plants per unit area. All subsequent analyses, including regression models with solar radiation, were conducted using these standardised units.

2.4. Classification of Light Conditions (Cloudy vs. Sunny)

To evaluate the differential response of cherry tomato evapotranspiration to solar radiation under varying light availability, daily solar radiation (SR, MJ m^{-2} d^{-1}) was used to classify prevailing weather conditions. Based on the distribution of observed solar radiation data (range: 4.7 – 13.6 MJ m^{-2} d^{-1}) and previous literature on greenhouse light requirements for tomato crops [22–24], a threshold of 8 MJ m^{-2} d^{-1} was established to separate cloudy and sunny conditions. Days with solar radiation below 8 MJ m^{-2} d^{-1} were classified as cloudy conditions (light-limited), whereas days with solar radiation equal to or exceeding 8 MJ m^{-2} d^{-1} were classified as sunny conditions (light-abundant).

2.5. Water Use Eficiency Calculation (ETc/Rad Ratio)

To assess the efficiency of crop water use relative to available solar energy, the evapotranspiration-to-radiation ratio (ETc/Rad) was calculated for each day. This metric represents the amount of water transpired per unit of incident solar radiation and serves as an indicator of crop water use efficiency under different light conditions.

For each experimental day i, the *ETc/Rad ratio* (mm MJ^{-1} m^2) was computed as Eq.(5) and the *mean ETc/Rad ratio* for each light condition (cloudy, sunny, and overall) was then calculated as the arithmetic mean of the individual daily ratios as Eq. (6):

$$\frac{ETc}{Rad} = \frac{ETc_i}{SR_i} \quad (5)$$

$$Mean\ \frac{ETc}{Rad} = \frac{1}{n} \times \sum_{i=1}^{n}\left(\frac{ETc_i}{SR_i}\right) \quad (6)$$

where ETc_i is the daily crop evapotranspiration (mm day^{-1}), SR_i is the daily solar radiation (MJ m^{-2} d^{-1}), n is number of the day for each light condition (cloudy, sunny, and overall). This metric differs from the regression slope (ΔETc/ΔSR) in that it represents the average water use efficiency across the entire radiation range, rather than the marginal increase in ETc per unit increase in radiation. The relationship between these two metrics is mathematically expressed as Eq. (7):

$$\frac{ETc}{Rad} = Slope + \left(\frac{Intercept}{SR}\right) \quad (7)$$

where *Slope* and *Intercept* are derived from the linear regression ETc = Slope × SR + Intercept. This formulation demonstrates that ETc/Rad is expected to be higher under low radiation conditions when the intercept (baseline ETc from non-radiative sources) contributes proportionally more to total ETc.

2.6. *Statistical* Analysis

To quantify the relationship between solar radiation and crop evapotranspiration under different light conditions, linear regression analysis was performed separately for cloudy days (SR < 8 MJ m^{-2} d^{-1}), sunny days (SR ≥ 8 MJ m^{-2} d^{-1}), and for all days combined (overall). The regression model took the form shown in Eq. (8):

$$ETc = \beta_0 + \beta_1 \times SR \quad (8)$$

where β_1 is the slope (mm MJ^{-1} m^2) representing the marginal increase in ETc per unit increase in solar radiation, and β_0 is the intercept (mm day^{-1}) representing baseline ETc in the absence of radiation.

The following statistical parameters were calculated for each condition: (a) coefficient of determination (R^2): proportion of ETc variation explained by radiation.; (b) Pearson correlation coefficient (r): strength and direction of the linear relationship; and (c) Significance F (p-value): probability that the observed relationship occurred by chance.

The water use efficiency ratio (ETc/Rad) was compared between cloudy and sunny conditions using an independent t-test (α = 0.05) to determine whether the observed differences were statistically significant. All statistical analyses were performed using Microsoft Excel with the Analysis ToolPak add-in.

3. Results and Discussion

3.1. Solar Radiation

Solar radiation was measured to evaluate the greenhouse microclimate affecting cherry tomato growth and transpiration. Radiation data were recorded automatically using a pyranometer. Peak radiation ranged from 253 to 993 W m^{-2}, with a mean of 655.2 ± 216.9 W m^{-2}. Accumulated daily radiation ranged from 4.7 to 13.6 MJ m^{-2} d^{-1}, with a mean of 9.0 ± 2.0 MJ m^{-2} d^{-1} (Fig. 2). These values indicate that solar radiation inside the greenhouse was sufficient to support photosynthesis and evapotranspiration. The optimum solar radiation required for tomato during fruit ripening is approximately 282 ± 42 W m^{-2} (equivalent to a PAR value of 592 ± 89 μmol m^{-2} s^{-1}) [25]. Although solar radiation effectively drives plant growth and yield, part of it is reflected or transmitted through the canopy, which is influenced by leaf area, plant architecture and atmospheric conditions [26].

Several notable patterns emerged when comparing peak and accumulated radiation. On December 8, the highest peak radiation of the study (993 W m^{-2}) was recorded, yet accumulated radiation on this day was only 10.0 MJ m^{-2} d^{-1}. Conversely, on December 20, a moderate peak of 673 W m^{-2} coincided with the highest accumulated radiation (13.6 MJ m^{-2} d^{-1}). This contrast suggests that total daily energy input depends not only on peak intensity but also on the duration of high radiation periods. Both peak and accumulated radiation showed a general decline from late November to early December, reaching minimum values on December 4 (peak: 320 W m^{-2}; accumulated: 4.7 MJ m^{-2} d^{-1}). A recovery occurred in mid-December, with sustained high values from December 19 to December 24. During this sunny period, peak radiation consistently exceeded 650 W m^{-2}, and accumulated radiation remained above 11 MJ m^{-2} d^{-1} for five consecutive days. Another notable sunny period occurred on January 5, with peak radiation of 843 W m^{-2} and accumulated radiation of 13.1 MJ m^{-2} d^{-1}.

Visual inspection of Fig. 2 reveals that accumulated radiation increased more rapidly once peak radiation exceeded approximately 500–600 W m^{-2}. Days with peak radiation below 450 W m^{-2} (e.g., December 1, 4, 5, 27 and 29) consistently resulted in accumulated radiation below 8 MJ m^{-2} d^{-1}, suggesting a threshold peak intensity required for meaningful daily energy accumulation. This pattern supports the use of peak radiation as a practical indicator for classifying daily light conditions in greenhouse management. From a crop physiology perspective, the distinction between peak and accumulated radiation is critical. Tomato photosynthesis and transpiration respond to both light intensity and duration. Whereas peak radiation determines maximum photosynthetic rate during optimal conditions, accumulated radiation better represents total daily carbon gain and water use [27]. The observation that December 8 achieved the highest peak (993 W m^{-2}) but only moderate accumulation (10.0 MJ m^{-2} d^{-1}) suggests that the intense radiation occurred over a short duration, possibly due to intermittent cloud cover or low solar angle. In contrast, the sustained moderate radiation on December 20 (peak: 673 W m^{-2}, accumulated: 13.6 MJ m^{-2} d^{-1}) likely provided more favourable conditions for crop growth and transpiration.

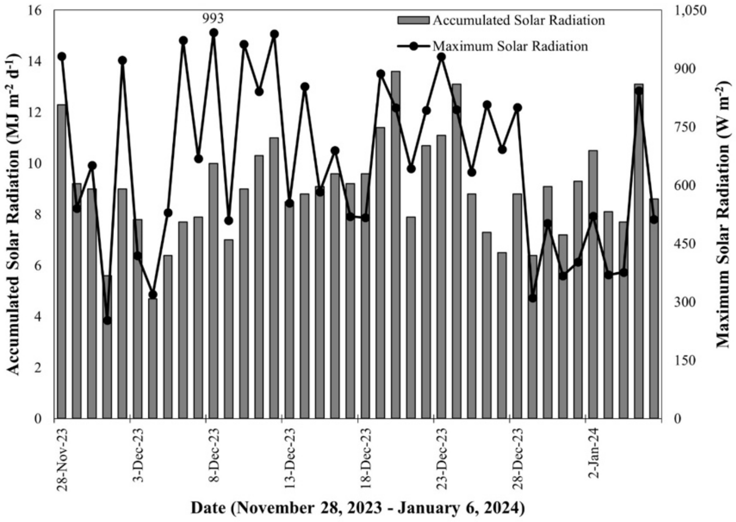

Fig. 2. Daily maximum (peak) solar radiation (W m^{-2}, line and symbols) and accumulated solar radiation (MJ m^{-2} d^{-1}, bars) inside the cherry tomato canopy from November 28, 2023 to January 6, 2024. Bars represent total daily solar energy input, whereas the line indicates instantaneous peak intensity.

3.2. Reference and Crop Evapotranspiration

Reference evapotranspiration (ETo) calculated using the Makkink radiation method remained remarkably stable throughout the 40-day study period (8.52 ± 0.16 mm day^{-1}) as shown in Fig. 3. The relatively high ETo values were influenced by strong solar radiation, which elevated greenhouse air temperature to 43 °C with 41% relative humidity. Such conditions are not optimal for cherry tomato growth, as the recommended ranges are 24–28 °C and 60–80 % relative humidity [25,28,29]. ETo consistently exceeded ETc by a factor of approximately 3.3 (ETo ≈ 8.5 mm day^{-1}, ETc ≈ 2.6 mm day^{-1}), yielding a mean crop coefficient (Kc = ETc/ETo) of 0.306. This value is substantially lower than field-grown tomatoes (Kc = 0.7-1.2) but consistent with greenhouse production, where low wind speed (0.1 - 1.1 m s^{-1}) and moderate vapour pressure deficit (VPD ranged 1.84 – 2.67 kPa) reduce aerodynamic water loss [30]. The low wind speeds observed in this study (mean ± SD: 0.48 ± 0.34 m s^{-1}) indicate minimal advective energy transfer, whereas the VPD range (mean: 2.14 ± 0.23 kPa) reflects the humid greenhouse microclimate that suppresses transpiration compared to open field conditions. This suggests that natural ventilation in the piggyback greenhouse was insufficient, and mechanical cooling strategies such as exhaust fans were needed.

Crop evapotranspiration (ETc) values obtained from lysimeter measurements varied substantially from 2.03 to 3.19 mm day^{-1} (mean 2.60 ± 0.19 mm day^{-1}), demonstrating that actual crop water use is highly responsive to radiation fluctuations even when reference ET remains constant. These values align with the general ETc range for mature tomato crops (2.3–4.4 mm day^{-1}) [31], indicating that plant water requirements were adequately met under the applied irrigation regime.

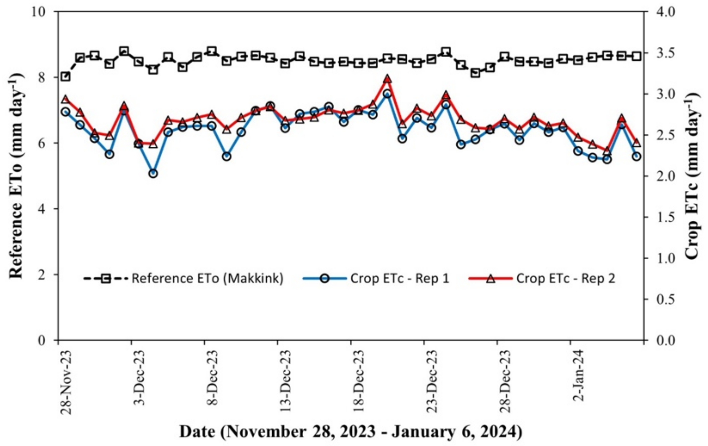

Fig. 3. Reference evapotranspiration (ETo, Makkink method) and crop evapotranspiration (ETc) of cherry tomato in greenhouse from November 28, 2023 to January 6, 2024. Dashed line with squares represents ETo; solid lines with circles (Rep 1) and triangles (Rep 2) represent ETc.

3.3. Relationship between ETc and Solar Radiation

Cherry tomato evapotranspiration (ETc) closely tracked solar radiation dynamics, with both replications showing similar temporal patterns (Fig. 4). ETc ranged from 2.03 to 3.00 mm day^{-1} for Replication 1 and from 2.31 to 3.19 mm day^{-1} for Replication 2. The highest ETc values (3.00–3.19 mm day^{-1}) occurred on December 20, coinciding with the peak solar radiation event (13.6 MJ m^{-2} d^{-1}). Conversely, the lowest ETc values (2.03–2.39 mm day^{-1}) were recorded on December 4, when solar radiation was at its minimum (4.7 MJ m^{-2} d^{-1}).

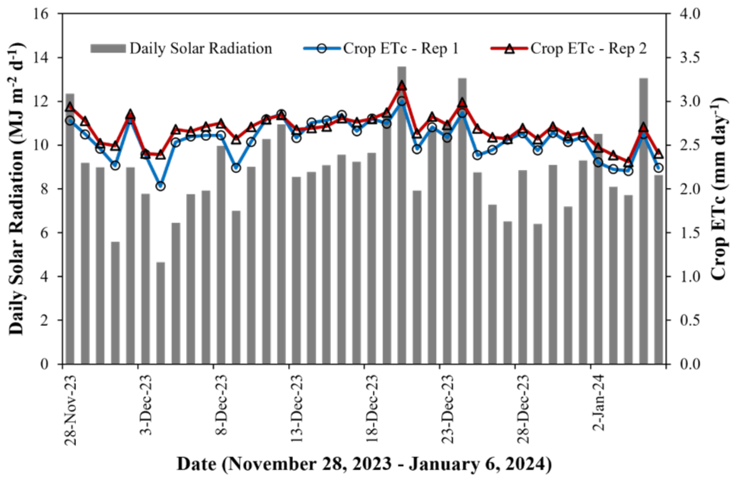

Fig. 4. Relationship between daily solar radiation and cherry tomato evapotranspiration (ETc) inside greenhouse canopy. Time series showing daily solar radiation (bars, left axis) and crop ETc for two replications (lines, right axis) from November 28, 2023 to January 6, 2024.

The ETc values observed in this study fall within the range reported for greenhouse tomato production under similar climatic conditions. Qiu et al. [32] reported ETc values of 2.5-4.0 mm day^{-1} for solar greenhouse-grown tomatoes in northwest China, whereas Orgaz et al. [33] found ETc ranging from 1.5 to 3.5 mm day^{-1} in unheated plastic greenhouses in Spain. The slightly lower values in our study may be attributed to the smaller leaf area index of cherry tomato compared to standard tomato varieties or the use of the Makkink method for reference ETo calculation. The strong radiation-ETc coupling observed here supports the use of radiation-based ETc models for irrigation scheduling in greenhouse cherry tomato production.

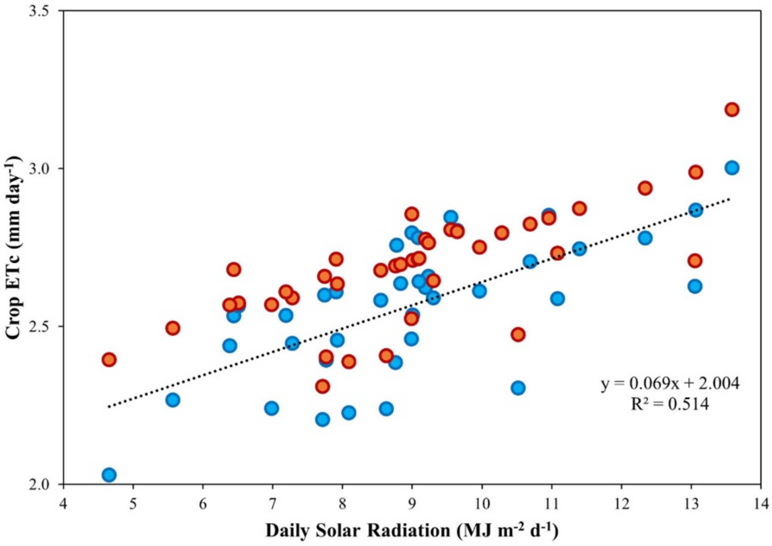

Fig. 5. Correlation between daily solar radiation and cherry tomato evapotranspiration (ETc). Blue circles (●) represent Replication 1 (n = 40); Red circles (●) represent Replication 2 (n = 40). The dashed black line shows the combined linear regression (ETc = 0.069 × Radiation + 2.004, $R^2 = 0.514$, n = 80, $p < 0.001$).

The close tracking of cherry tomato evapotranspiration (ETc) with solar radiation observed in this study is consistent with the fundamental biophysical principle that net radiation provides the energy for latent heat flux (evapotranspiration) [30,34]. Under greenhouse conditions where advective energy is minimal due to low wind speeds (0.1-1.1 m s^{-1}), radiation becomes the predominant driver of crop water use [23,34]. Fig. 5 revealed a significant positive correlation between daily solar radiation and cherry tomato evapotranspiration (r = 0.717, $R^2 = 0.514$, $p < 0.001$). The regression equation ETc = 0.069 × Rad + 2.004 indicates that each 1 MJ m^{-2} d^{-1} increase in solar radiation results in a 0.069 mm day^{-1} increase in ETc. The positive intercept (2.004 mm day^{-1}) represents the theoretical baseline ETc in the absence of solar radiation, which is contributed by non-radiative energy sources including sensible heat transfer from warm air, longwave radiation exchange, and residual stomatal transpiration driven by VPD [30]. The R^2=0.514 indicates that approximately 51% of ETc variation is explained by solar radiation alone, with the remaining 49% attributed to other factors including vapour pressure deficit (VPD), air temperature and plant physiological responses [23]. This finding aligns with Gong et al. [35], who reported that solar radiation is the single most important environmental factor controlling greenhouse tomato evapotranspiration.

Linear regression analysis revealed fundamentally different ETc responses to solar radiation under cloudy and sunny conditions (Table 1). Under cloudy conditions (<8 MJ m^{-2} d^{-1}), the near-zero slope (0.009 mm MJ^{-1} m^2, $R^2 = 0.314$, p = 0.0465) indicates that cherry tomato evapotranspiration is essentially insensitive to radiation fluctuations within this low-light range, remaining relatively constant at 2.0-2.6 mm day^{-1} (mean ± SD: 2.41 ± 0.18 mm day^{-1}). This suggests that on cloudy days, stomatal aperture is already maximised to capture limited light, decoupling ETc from radiation availability.

Table 1. ETc values based on cloudy and sunny weather conditions.

Condition	n	Equation	R^2	r	p-value	ETc/Rad (mm MJ^{-1} m^2)
Cloudy (<8)	13	ETc = 0.009 × Rad + 1.723	0.314	0.560	0.0465	0.364
Sunny (≥8)	27	ETc = 0.074 × Rad + 2.000	0.446	0.668	0.000139	0.273
Overall	40	ETc = 0.069 × Rad + 2.004	0.514	0.717	0.00000019	0.302

In contrast, under sunny conditions (≥8 MJ m^{-2} d^{-1}), a strong positive relationship was observed (slope = 0.074 mm MJ^{-1} m^2, R^2 = 0.446, $p < 0.001$), demonstrating that ETc increases significantly with radiation when light is abundant. This indicates that on sunny days, transpiration is energy-limited and responds directly to available radiation.

Water use efficiency (ETc/Rad) was 33% higher on cloudy days (0.364 mm MJ^{-1} m^2) compared to sunny days (0.273 mm MJ^{-1} m^2), reflecting the combined effects of lower vapour pressure deficit and more open stomata under low-light conditions. The overall regression combining all data yielded ETc = 0.069 × Rad + 2.004 (R^2 = 0.514, r = 0.717, $p < 0.001$, n = 40).

The near-zero slope on cloudy days (0.009 mm MJ^{-1} m^2) represents a novel finding for cherry tomato physiology. This plateau in ETc response suggests that below 8 MJ m^{-2} d^{-1}, radiation ceases to be the dominant control on transpiration, with vapour pressure deficit (VPD) and stomatal behaviour taking precedence. The 33% higher water use efficiency on cloudy days (0.364 vs. 0.273 mm MJ^{-1} m^2) indicates that cherry tomatoes adapt to light limitation by maximising water use per unit of available energy, likely through more open stomata and reduced cuticular resistance. These findings have practical implications for greenhouse irrigation: on cloudy days, ETc is relatively stable and predictable (≈2.4 mm day^{-1}) regardless of minor radiation fluctuations, whereas on sunny days, ETc should be estimated dynamically based on radiation forecasts.

3.4. Implications for Irrigation and Greenhouse Climate Management

These findings demonstrate that solar radiation is a reliable predictor of ETc in greenhouse-grown cherry tomato, with the relationship varying significantly between light conditions as illustrated by the diurnal time course patterns (Fig.6). Under sunny conditions (December 24, 2023; solar radiation ≥8 MJ m^{-2} d^{-1}), the bell-shaped diurnal pattern of ETc closely followed radiation but exhibited a 30–45 min time lag, peaking at 0.257 mm per 15 min (≈1.03 mm h^{-1}). This lag, clearly visible in Fig. 6a, indicates that stomatal opening requires time to respond to increasing morning radiation. Therefore, the regression equation ETc = 0.074 × Rad + 2.000 (R^2 = 0.446, $p < 0.001$) is recommended for daily ETc prediction under sunny conditions, with irrigation preferably scheduled before the peak transpiration period (11:00-12:00) to avoid water deficit.

Under cloudy conditions (<8 MJ m^{-2} d^{-1}) as shown in Fig. 6b, both radiation and ETc werelower with minimal time lag, as radiation never exceeded 0.282 MJ per 15 min (≈1.13 MJ m^{-2} h^{-1}). This indicates that radiation has minimal influence on ETc. Crop ETc peaked at only 0.060 mm per 15 min (≈0.24 mm h^{-1}). The near-zero slope (0.009) in the daily analysis reflects this diurnal pattern, where stomata remained in a relatively constant, partially open state throughout the day due to light limitation. Consequently, for cloudy days, the mean ETc value of 2.41 ± 0.18 mm day^{-1} is recommended for practical irrigation scheduling, as shown by the stable ETc range in Fig. 6b.

Sensor recording intervals of 1–15 minutes (validated by our 5 min measurements in (Fig. 6) are appropriate for capturing ETc dynamics and enabling precision irrigation automation. The diurnal patterns also revealed that on sunny days, ETc remained elevated in the afternoon (14:00–16:00) despite decreasing radiation (Fig. 6a), suggesting a hysteresis effect whereby afternoon transpiration exceeds morning transpiration at equivalent radiation levels due to higher leaf temperature and VPD.

Greenhouse climate management should maintain VPD within the optimal range (2.0–3.0 kPa) using ventilation, cooling pads or misting, as our measured VPD (1.84–2.67 kPa, mean 2.14 kPa) contributed to the strong ETc-radiation coupling observed under sunny conditions. However, the diurnal patterns in Fig. 6 also indicate that under cloudy conditions, VPD may become a relatively more important driver of ETc when radiation is limiting.

Whereas our correlation analysis suggested that VPD may influence ETc under cloudy conditions, further research is needed to develop a comprehensive VPD-based ETc prediction model for low-light conditions. Future studies should also investigate the combined effects of wind speed (measured range: 0.1–1.1m s^{-1}), VPD and physiological crop conditions (e.g., stomatal conductance, leaf area indexand plant water status) on ETc dynamics. Furthermore, the hysteresis phenomenon observed in Fig. 6a (afternoon ETc > morning ETc at same radiation), which may be explained by diurnal VPD pattern and leaf temperature dynamics.

Such integrated models would enable more accurate ETc prediction across all light conditions and improve irrigation efficiency in greenhouse cherry tomato production. Overall, this study provides an empirical basis for integrating light condition-specific, radiation-based ETc models into precision irrigation systems, whereas the diurnal patterns in Fig. 6 highlight key physiological responses (time lag, hysteresis, and threshold behaviour) that warrant further investigation.

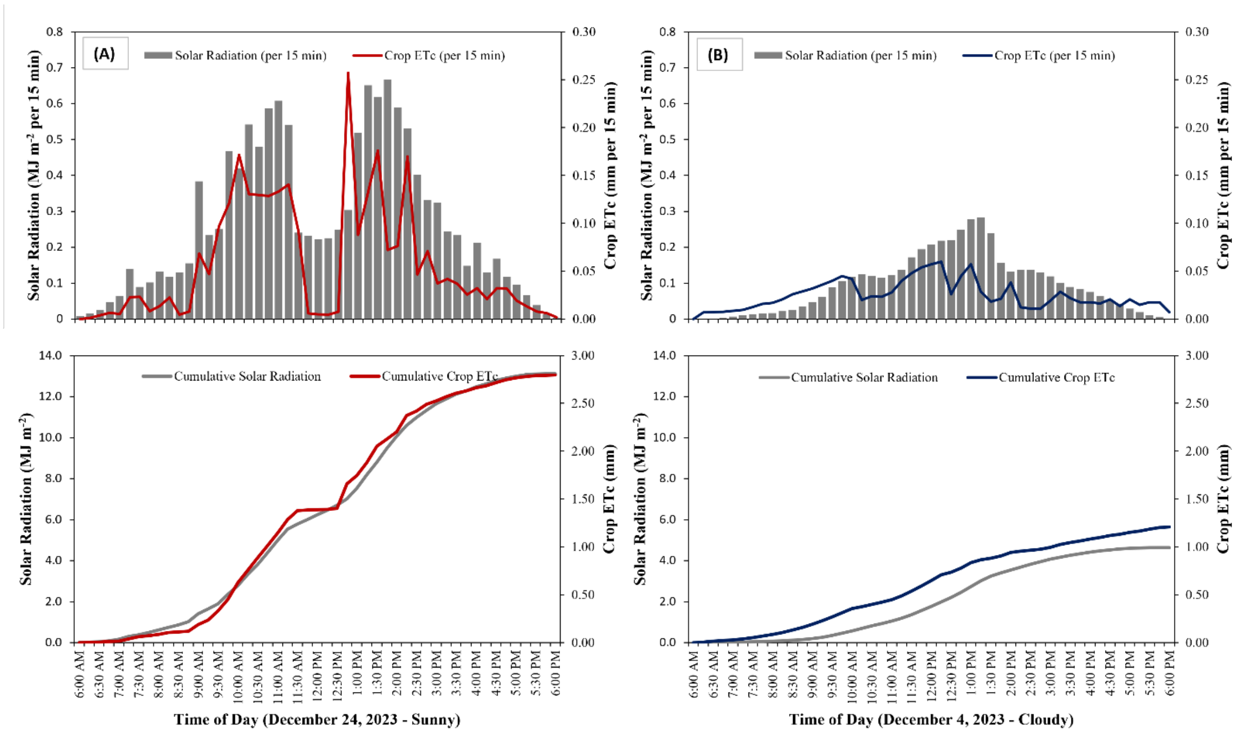

Fig. 6. Diurnal time course comparison of solar radiation (bars, left axis) and cherry tomato evapotranspiration (solid lines, right axis) between a sunny day (December 24, 2023, red solid line) and a cloudy day (December 4, 2023, blue solid lines).

4. Conclusions

This study successfully addressed the identified research gap by quantifying the direct quantitative relationship between solar radiation and lysimeter-measured ETc in cherry tomato under tropical greenhouse conditions. Using a high-precision weighing lysimeter with 5 min recording intervals over 40 days (November 28, 2023 to January 6, 2024), we demonstrated that solar radiation is a reliable predictor of ETc in greenhouse-grown cherry tomato, with the relationship varying significantly between light conditions. The overall regression equation $ETc = 0.069 \times Rad + 2.004$ ($r = 0.717$, $R^2 = 0.514$, $p < 0.001$) provides a quantitative basis for radiation-based ETc estimation. Importantly, a critical threshold of 8 MJ m^{-2} d^{-1} was identified, separating distinct ETc response patterns: under sunny conditions (Rad ≥8), the strong relationship $ETc = 0.074 \times Rad + 2.000$ ($R^2 = 0.446$, $p < 0.001$) is recommended, whereas under cloudy conditions (Rad <8), the near-zero slope (0.009) indicates minimal radiation influence, supporting the use of mean ETc = 2.41 ± 0.18 mm day^{-1}.

These empirical models can be directly embedded into automated irrigation systems using the proposed decision rule with sensor recording intervals of 1–15 minutes recommended for capturing diurnal dynamics. Thus, this study provides the quantitative empirical basis needed to support precision irrigation practices in greenhouse cherry tomato cultivation under tropical conditions, enabling real-time water supply adjustment based on solar radiation measurements whilst identifying cloudy vs. sunny conditions as a critical operational distinction.

Abbreviations

ETo	Reference evapotranspiration
ETc	Crop evapotranspiration
Rad	Solar radiation

Data availability statement

Data will be shared upon request by the readers

Authors' Contributions

Ahmad Tusi: All activity include conceptualization, data curation, formal analysis, funding acquisition, investigation, methodology, project administration, software supervision, validation, visualization, writing – original draft, writing – review and editing. **Fitrasia Aura Ramadanti:** data curation, project administration, visualization, formal analysis, investigation, and writing – original draft. **Melvi:** conceptualization, resources, project administration, supervision, funding acquisition, and software. **Oktafri:** formal analysis, writing: review and editing.

Declaration of Competing Interest

The authors of this manuscript declare no conflict of interest or competing interest.

Declaration of Use of AI in the Writing Process

Nothing to disclose

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