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Estimation of Actual Evapotranspiration and Crop Coefficient of Transplanted Puddled Rice Using a Modified Non-Weighing Paddy Lysimeter

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Abstract: Lysimetric and eddy covariance techniques are commonly used to directly estimate actual crop evapotranspiration (ET_a). However, these technologies are costly, laborious, and require skills which make in situ ET estimation difficult, particularly in developing countries. With this in mind, an attempt was made to determine ET_a and stagewise crop coefficient (K_c) values of transplanted puddled rice using a modified non-weighing paddy lysimeter. The results were compared to indirect methods, viz., FAO Penman–Monteith and pan evaporation. Daily ET_a ranged from 1.9 to 8.2 mmday^{-1}, with a mean of 4.02 ± 1.35 mmday^{-1}, and their comparison showed that the FAO Penman–Monteith equation performed well for the coefficient of determination (R^2 of 0.63), root mean squared error (RMSE = 0.80), and mean absolute percentage error (MAPE = 13.6 %), and was highly correlated with ET_a throughout the crop season. However, the pan evaporation approach was underestimated (R^2 of 0.24; RMSE = 0.98; MAPE = 22.13%) due to a consistent pan coefficient value (0.71), vegetation role and measurement errors. In addition, actual K_c values were obtained as 1.13 ± 0.13, 1.27 ± 0.2, 1.23 ± 0.16, and 0.93 ± 0.18 for the initial, crop development, mid-season, and end-season stages, respectively. These estimated crop coefficient values were higher than FAO K_c values. Statistical analysis results revealed that the overall stagewise-derived average K_c values were in line with FAO values, but different from the derived pan K_c values, although found insignificant at a 5% significance level. In addition, water productivity and agro-meteorological indices were derived to evaluate the cultivar performance in this experiment. Therefore, such a methodology may be used in the absence of weighing lysimeter-derived K_c values. The derived regional K_c values can be applied to improve irrigation scheduling under similar agro-climatic conditions.

Keywords: crop growth stages; reference evapotranspiration; pan evaporation; irrigation scheduling; crop evapotranspiration

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1. Introduction

Water is one of the most critical natural resources for almost all living organisms existing on the blue planet, and is needed for socio-economic development activities [1–3]. Freshwater resources are dynamically fluctuating globally owing to global warming, climate change and unsustainable anthropogenic actions [4]. Freshwater scarcity is a major challenge in today's world, and it has been projected to worsen by 2050 when the world population may reach between 9.4 and 10.2 billion [1]. Worldwide, agriculture water use currently accounts for 70% of the total water resource availability, and is mostly used for irrigation [5]. India accounts

for about 17% of the world's population and has 4% of the world's freshwater resources [2]. Water resources in India are highly unevenly distributed at spatial and temporal scales [6]. The dynamic distribution of water resources must be managed efficiently to achieve the sustainable overall development of the nation.

The most important cropping systems followed under rainfed medium land situations are rice–fallow, rice–wheat, rice–winter maize, rice–gram, rice–winter vegetables, etc., with approximately 135% cropping intensity [7]. The rice–wheat cropping system is mainly followed in the Indo-Gangetic plains (IGPs), the heartland of the green revolution which covers about 13.5 million hectares and contributes significantly to India's food security [7]. In India, approximately 85% of the upland rice (*Oryza sativa* L.) areas are located in the states of Assam, Bihar, Jharkhand, Odisha, West Bengal, the eastern parts of Madhya Pradesh, and Uttar Pradesh [8]. Furthermore, there has also been a substantial amount of yield variability in these regions, which is threatening IGP agriculture sustainability. Except for Punjab and Haryana states in the Trans-Gangetic plains, middle and lower IGPs such as Bihar, Uttar Pradesh, and West Bengal still have low productivity for rice–wheat cropping patterns [8]. The lack of irrigation facilities, high crop water requirements, the declining water table, high pumping expenses, labor-intensive production, lack of reliable on-farm gadgets, and erratic rainfall all contribute to lower crop productivity in these regions.

Due to current water shortages, particularly in IGPs, water-saving is difficult for rice production. Major crops such as rice require significantly more water than other cereal crops, i.e., 1 kg of rice production needs 3000–5000 L of water [9–11]. Similarly, more than 75% of worldwide rice is grown in nurseries before being transplanted into puddled fields [12]. Rice production using the traditional method is seen as resource-intensive regarding water, energy, and money [13]. Various researchers have reported that puddling and conventional rice farming require massive amounts of water (>2000 mm) to harvest a single rice crop [7,9,12,14]. Around 50–80% of the applied water is lost in deep percolation, seepage, and evaporation [15–18]. Therefore, estimating actual crop evapotranspiration (ET_a) and developing stagewise crop coefficient (K_c) values for transplanted puddled rice based on local climatic conditions and existing crop management practices would be helpful in the efficient irrigation scheduling, planning, and design of irrigation systems to obtain higher crop water productivity [7,19–21]. Among various methods, the FAO Penman–Monteith method was found to have the lowest overestimation error (1%) and is widely known as the best approach for estimating reference evapotranspiration [22,23].

Crop evapotranspiration is highly sensitive to K_c values [20,22,24–26]. Stagewise K_c values vary depending on local field management approaches, canopy cover, variety, weather variations, etc. Various studies have been carried out to estimate ET_a and derive stagewise K_c values of various crops in different agro-climatic regions worldwide [20,24,26–29]. Multiple methods, such as lysimetric studies, field water balance, modeling, eddy covariance (EC) techniques, etc., can be used for actual evapotranspiration estimation [30–35]. In addition to these techniques, soil water balance based on TDR for barley [17], neutron probes for quinoa [36], gravimetric approaches for amaranth grain [37], EC and remote sensing approaches [38], and EC and modelling approaches (SIMDualKc) in wheat [39] have also been used. However, most research has concentrated on ET_a measurements using non-weighing and weighing lysimeters in various crops [19,40–43]. The lysimeter provides a precise and continuous field measurement of ET_a. However, it is expensive, complicated and should only be used by skilled personnel. For various crops, drainage lysimeters (non-weighing) have been used to estimate ET_a in dry beans along with a soil water balance based on neutron probes [44], and in green gram along with capacitance probes [45]. Moreover, weighing lysimeters (WL) has been used in spring wheat [46], canola [47], and cowpea [48]. In addition, various researchers have also completed lysimetric studies to estimate the ET_a in paddy crop [18,28,29,49] and developed stagewise crop coefficients (K_c) varied from 0.61 to 1.15, 0.97 to 1.44, 1.14 to 1.59, and 0.9 to 1.02 for the initial, crop development, mid-season, and late season stages, respectively, in different agro-climatic zones [16,23,27,28,42,50,51]. However, a few researchers used a locally constructed paddy lysimeter to quantify ET_a which is simple in design, inexpensive,

and provides satisfactory results [52,53]. Time-averaged crop coefficient values for low land paddy in the Senegal river valley were 1.01, 1.31, and 1.12 during the crop development, mid-season, and late-season stages, respectively, and actual crop evapotranspiration was 841.5 and 855.4 mm in 2014 and 2015, respectively [29]. Doorenbos and Pruitt [54] proposed K_c values for various crops cultivated in diverse agro-climatic regions.

Furthermore, previous studies showed that there is no database of crop coefficients for different crops in diverse agro-climatic regions of the MIGP. Therefore, FAO K_c values are commonly utilized for irrigation scheduling in different crops. FAO-56, on the other hand, is recommended for developing in situ stagewise K_c values for various crops for precise irrigation scheduling at the regional scale [20,30]. Therefore, the present investigation was conducted with two specific objectives, i.e., (1) to estimate ET_a and develop stagewise K_c values of transplanted puddled rice using modified non-weighing paddy lysimeter, and (2), to compare ET_a and K_c values with indirect methods such as Penman–Monteith and pan evaporation to improve in situ water productivity. In addition, water productivity and agrometeorological indices were also computed for drought-tolerant rice cultivar, viz., Swarn Shreya. The developed knowledge of rice ET_a and K_c values may aid in improving water use efficiency in similar agro-climatic regions by reducing the water wastage attributed to deep percolation and runoff produced in the vicinity of over irrigation due to the inadequacy of efficient irrigation scheduling information.

2. Materials and Methods

2.1. Site Description, Climate, and Soil

A field experiment was carried out at the ICAR Research Complex for Eastern Region (ICAR-RCER), Patna, Bihar (25° 35′30″ N, 85° 05′03″ E and 52 m above mean sea level), which is located in the sub-tropical humid climatic region of the Middle Indo-Gangetic Plains (MIGP) (Figure 1). The Indo-Gangetic Plains have been divided into four parts which include Upper Indo-Gangetic Plains (UIGP), Trans-Indo-Gangetic Plains (TIGP), MIGP, and Lower Indo-Gangetic Plains (LIGP), as displayed in Figure 1.

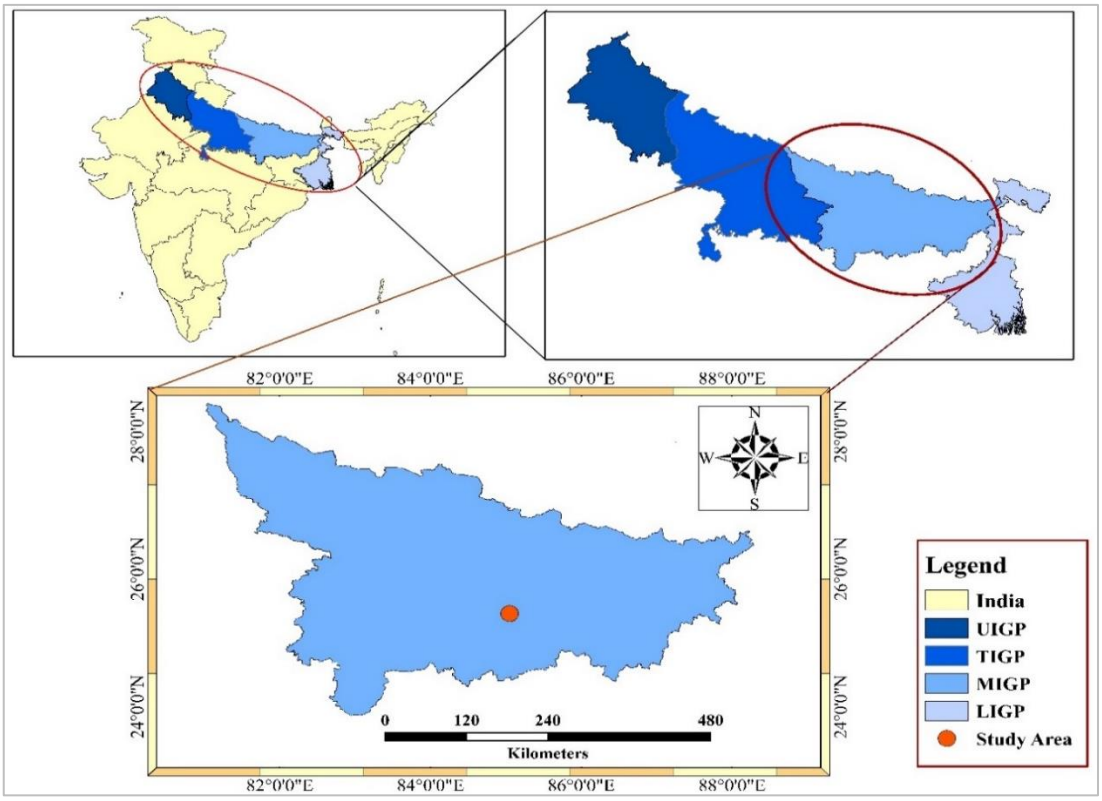

Figure 1. Location map of the experimental site.

Daily weather data were collected from ICAR-RCER, an agro-meteorological observatory, and their variation throughout the cropping season was depicted in Table 1.

Table 1. Weekly average variability of weather parameters during crop season (after transplanting).

Weeks	Weather Parameters						
	Minimum Temp. (°C)	Maximum Temp. (°C)	Relative Humidity (%)	Wind Speed (km/h)	Sunshine Hours	Pan Evaporation (mm)	Weekly Total Rainfall (mm)
1	26.8	32.8	78.0	7.3	2.3	4.3	67.4
2	27.3	33.3	77.0	2.8	1.8	4.2	70.6
3	26.9	32.6	81.6	4.4	2.8	4.5	25.4
4	26.9	34.1	74.9	6.4	5.1	4.7	59.4
5	26.4	31.8	83.7	4.6	0.7	4.0	74.4
6	26.9	34.1	76.4	3.5	4.3	4.7	10.4
7	26.7	33.7	74.4	7.1	6.5	4.7	54.3
8	25.8	31.5	83.4	8.4	2.0	3.2	55.0
9	26.8	33.4	75.6	5.4	5.7	4.6	12.1
10	25.3	30.8	79.9	9.2	2.8	3.9	34.4
11	24.5	32.8	79.0	1.9	5.1	4.6	0.4
12	25.4	33.8	74.4	3.5	4.2	4.4	1.2
13	23.3	31.2	76.7	5.0	4.9	4.2	27.2
14	22.4	30.4	77.0	2.6	0.6	3.8	0.0

The region receives an annual mean precipitation of about 1213 mm. Soil samples were also collected using a core sampler, and soil physical properties were determined using the standard methods presented in Table 2. Paddy seedlings were transplanted on 26 July and harvested on 25 October 2021. All the recommended fertilizer doses, irrigation, and agronomical practices were followed across the entire field and within lysimeters to ensure uniform growth and check the oasis effect on crop ET.

Table 2. Soil physical properties of the experimental plot.

Parameters	Values	Methods Employed for Estimation
Particle size distribution (%)		Hydrometer method [55]
Sand	54	
Silt	28	
Clay	18	
Soil texture	Sandy loam	
Hydraulic conductivity (cm/h)	1.55	Klute and Dirksen method [56]
Bulk density (g/cm3)	1.52	Core sampler [57]
pH (1:1 soil: water)	7.87	Elico pH meter [58]
Organic content (%)	0.51	Walkley and Black method [59]
Field capacity (%)	18.42	Pressure plate apparatus [60]
Permanent wilting point (%)	8.42	

2.2. Estimation of Actual Crop Evapotranspiration Using Paddy Lysimeter

Actual evapotranspiration was determined using a modified paddy non-weighing lysimeter based on the water budget equation expressed in Equation (1).

$$\sum \text{Inflow} - \sum \text{Outflow} = \pm \Delta \text{Storage} \quad (1)$$

where $\sum Inflow = I + P$; $\sum Outflow = ET_a + R + DP$; $\Delta Storage = \Delta$S within the root zone; *I is irrigation; P is rainfall; DP is percolation beyond the root zone; R is runoff; and ΔS is the change in soil moisture storage in the root zone.

Both I and P were directly measured. To measure ET_a, a paddy lysimeter with slight modifications (outlet at recommended bund height for this region) was used in which three drums (namely, A, B, and C) with a diameter of 50 cm and height of 128.75 cm were buried in a rice field with roughly a fourth of their height above ground level (Figure 2). Drum A had a closed bottom, while Drum B and C had open bottoms. The outlet pipe was installed at bund height (25 cm) in container C for precise runoff estimation.

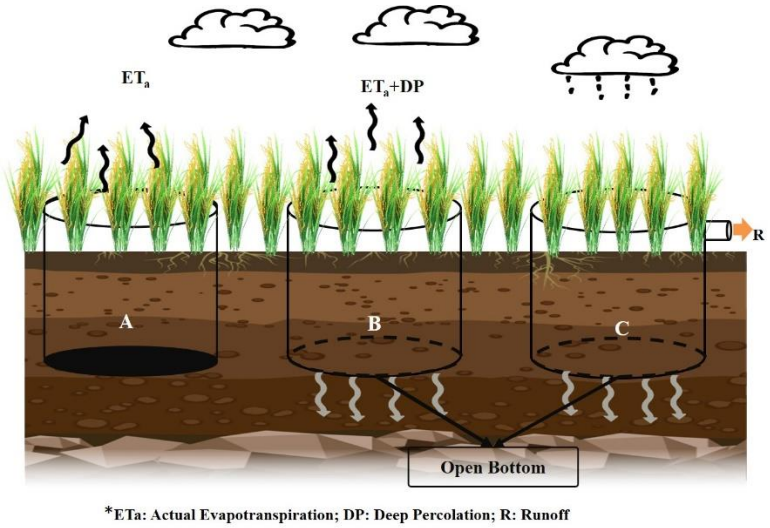

Figure 2. Water balance components in modified non-weighing paddy lysimeter.

In this experiment, the modified paddy lysimeter was a low-cost volumetric-type set of three drums used to measure ET_a and soil water balance components. The major modifications include setting the outlet at the recommended bund height (25 cm) of these regions to estimate runoff from the field. Twenty-seven-day-old seedlings of the rice cultivar Swarn Shreya were transplanted using a standard agronomic package of practices inside the drums. The entire area of outside drums was also transplanted with the same rice variety. The water level inside the drums was maintained at the same level as it was in the cropped field. The difference in water level over two successive days in drum A represents actual evapotranspiration. In contrast, percolation loss is defined as the daily difference in water levels between drums A and B. The plots were bunded (25 cm) and there was no overflow from drum C throughout the season, resulting in no runoff from the paddy field.

2.3. Estimation of Reference Evapotranspiration

Reference evapotranspiration (ET_0) from 2017 to 2021 was computed using daily weather data collected from a local agro-meteorological observatory using FAO Penman–Monteith and US Class A pan evaporimeter techniques.

2.3.1. FAO Penman–Monteith Equation

Daily observations of air temperature (maximum and minimum), relative humidity, daily solar hours, and wind speed were considered for determining ET_0 using FAO's CROPWAT 8.0 software [20,24]. For estimating reference evapotranspiration (ET_0), the Penman–Monteith equation was used as follows:

$$ET_0 = \frac{0.408\Delta(R_n - G) + \gamma \frac{900}{T+273} u_2 (e_s - e_a)}{\Delta + \gamma(1 + 0.34u_2)} \quad (2)$$

where ET_0 = a reference evapotranspiration (mm day^{-1}), u_2 = a wind speed at 2 m height (m s^{-1}), R_n = a net radiation at crop surface (MJ m^{-2} day^{-1}), G = a soil heat flux density (MJ m^{-2} day^{-1}) Tmean = a mean daily air temperature at 2 m height (°C), γ = a psychrometric constant (kPa $°C^{-1}$), Δ = a slope of vapor pressure curve (kPa $°C^{-1}$), and $e_s - e_a$ = a saturation vapor pressure deficit (kPa).

2.3.2. Pan Evaporation Approach

The pan evaporation method is a physical approach that may be applied worldwide without requiring parameter adjustments. In this method, the Class A evaporation pan from the US Weather Bureau, having a circular cross-section with a diameter of 120.7 cm and a depth of 25 cm, is widely used to monitor daily evaporation losses. The relationship between reference evapotranspiration and pan evaporation is expressed in Equation (3)

$$ET_0 = K_P \times E_{pan} \quad (3)$$

where ET_0 = a reference evapotranspiration (mm day^{-1}), K_P = a pan coefficient (0.71), and E_{pan} = a daily pan evaporation (mm day^{-1}).

2.4. Estimation of Stagewise Crop Coefficient

The impacts of actual crop evapotranspiration and soil evaporation are integrated into the single crop coefficient approach. In order to estimate stage–K_c, daily reference evapotranspiration was estimated using CROPWAT 8.0 software, and modified paddy lysimeter was used to estimate actual daily evapotranspiration by observing the daily water level change in these three drums. Then, the crop coefficient was determined as the ratio of actual evapotranspiration to reference evapotranspiration, as given by Equation (4)

$$K_c = \frac{ET_a}{ET_0} \quad (4)$$

where ET_a = an actual crop evapotranspiration (mm^{-1}) and ET_0 = a reference crop evapotranspiration (mm^{-1}).

Pan–crop coefficient was estimated by the ratio of actual evapotranspiration to reference evapotranspiration based on the pan evaporation approach.

2.5. Statistical Analysis

Various statistical performance parameters such as mean absolute percentage error (MAPE), root mean square error (RMSE) and coefficient of determination (R^2) were calculated for error analysis (Equations (5)–(7)).

$$MAPE = \frac{1}{n}\sum_{i=1}^{n}|(O_i - P_i)/O_i| \quad (5)$$

$$RMSE = \sqrt{\frac{\sum_i^n (P_i - O_i)^2}{n}} \quad (6)$$

$$R^2 = 1 - \frac{\sum_i^n (P_i - O_i)^2}{\sum_i^n (P_i - \overline{O})^2} \quad (7)$$

where P_i, O_i and $\overline{O}$ are the observed, estimated, and mean estimated values, respectively. Then, the significant test between the measured and estimated K_c values was performed using the non-parametric Mann–Whitney U test. The flowchart of the whole methodology was presented in Figure 3.

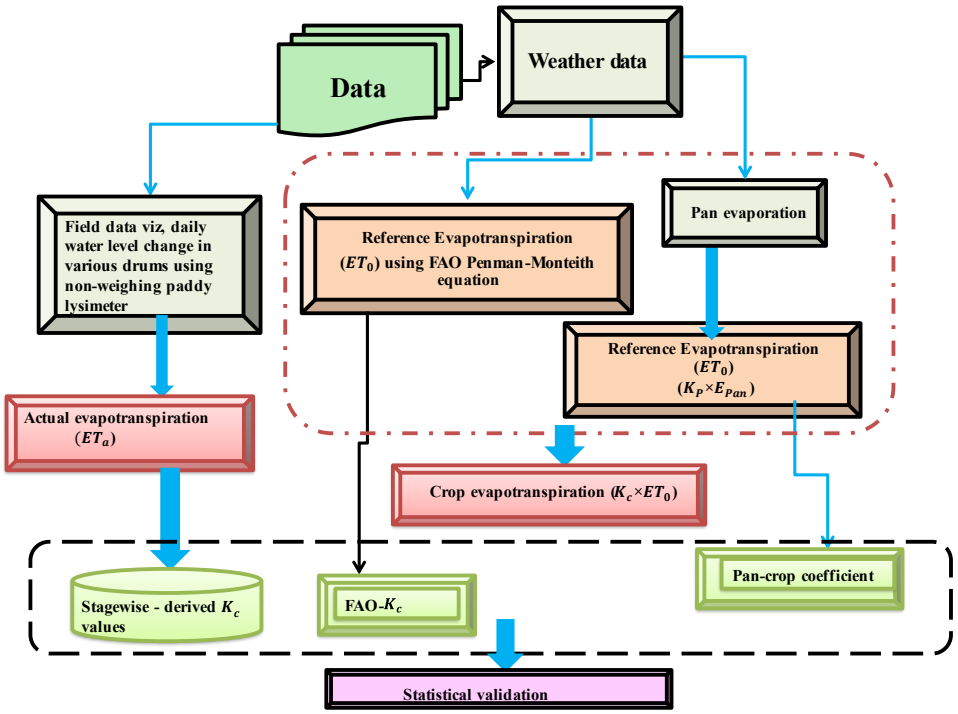

Figure 3. Methodology of ET_a and stagewise K_c estimation using modified non-weighing paddy lysimeter.

2.6. Water Productivity and Agro-Meteorological Indices

In this study, two different approaches were used to estimate water productivity: crop water productivity (CWP) and total water productivity (TWP). Crop water productivity was determined by dividing the marketable grain yield by the water used to meet crop evapotranspiration. Then CWP of the rice cultivar (Swarn Shreya) was estimated by the following equation:

$$\text{CWP } (\text{kg ha}^{-1}\text{mm}^{-1}) = \frac{\text{Grain Yield } \left(\text{kg ha}^{-1}\right)}{\text{Actual Crop Evapotranspiration } (\text{mm})} \quad (8)$$

Irrigation water use efficiency (IWUE), or total water productivity(TWP), originated from drought resistance and tolerance ideas [61]. In crop production, IWUEis defined as the crop yield ratio to the water applied in the field [62].

$$\text{IWUE} = \frac{\text{Crop Yield } \left(\text{kg ha}^{-1}\right)}{\text{Water used to produce yield} \left(\text{m}^3\text{ha}^{-1}\right)} \quad (9)$$

The daily meteorological data were used to calculate agro-meteorological indices, viz., growing degree days (GDD), heliothermal units (HTU), photothermal units (PTU), heat use efficiency (HUE), and heliothermal use efficiency (HTUE) (Equations (10)–(14), respectively). Daily GDD was calculated using a base temperature of 10 °C. The daily mean temperature above the base temperature, expressed in degree days, was added to calculate cumulative growing degree days.

Growing degree days (GDD) is calculated as:

$$\text{GDD} = \sum \frac{\text{T}_{\text{max}} + \text{T}_{\text{min}}}{2} - \text{Tb} \quad (10)$$

where T_{max}—daily maximum temperature (°C), T_{min}—daily minimum temperature (°C), and T_b—minimum threshold/base temperature (°C).

Heliothermal units (HTU): the product of the growing degree day and the corresponding bright sunshine hours has been termed heliothermal units (HTU).

$$\text{HTU} = \sum \text{GDD} \times \text{actual bright sunshine hours (n)} \quad (11)$$

Photothermal units (PTU): the product of the growing degree day and the corresponding maximum possible sunshine hours has been termed photothermal units (PTU).

$$\text{PTU} = \sum \text{GDD} \times \text{N} \quad (12)$$

N—maximum possible sunshine hours.

Heat use efficiency (HUE): heat use efficiency is also represented by thermal time use efficiency (TTUE), which indicates the amount of dry matter produced per unit of growing degree days or thermal time, expressed in $g/m^2/^\circ$ day. This was computed by using the following formula:

$$\text{HUE} = \frac{\text{Total dry matter}}{\sum \text{GDD}} \quad (13)$$

Heliothermal use efficiency (HTUE): heliothermal use efficiency was calculated by dividing the total dry matter recorded on respective days by the accumulated heliothermal units, and is expressed as kg ha^{-1} °C Day h.

HTUE was calculated as

$$\text{HTUE} = \frac{\text{Total dry matter}}{\sum \text{HTU}} \quad (14)$$

3. Results

3.1. Variation in Reference Evapotranspiration, Water Balance Components and Actual Crop Evapotranspiration

Daily mean ET_0-PM varied from 1.72 to 5.67 mm day^{-1} with a mean value of 3.39 (±0.95) mm day^{-1}, while the corresponding daily ET_0-Pan ranged between 1.56 and 3.98 mm day^{-1} with an average value of 3.06 ± 0.52 mm day^{-1} throughout the crop season. However, stagewise ET_0-PM revealed 3.42 ± 0.73 mm day^{-1}, 3.56 ± 0.94 mm day^{-1}, 3.40 ± 1.03 mm day^{-1}, and 2.77 ± 0.55 mm day^{-1} during the initial, crop development, mid-season and late-season stages, respectively. Daily mean ET_0-Pan findings showed their values to be 2.99 ± 0.66 mm day^{-1}, 3.16 ± 0.47 mm day^{-1}, 3.02 ± 0.56 mm day^{-1}, and 2.97 ± 0.29 mm day^{-1} during the initial, crop development, mid-season and end/late-season stages, respectively. In addition, the daily variations in ET_0-PM and ET_0-Pan throughout the last five years (2017–2021) of the crop period were shown in Figure 4. The results showed that their values ranged between 2.69 and 4.92 mm day^{-1}, with an average value of 3.59 ± 0.56 mm day^{-1} for ET_0-PM and 2.03 to 3.78 mm day^{-1} with an average of 2.78 ± 0.33 mm day^{-1} for ET_0-Pan.

The overall relationship between ET_0-PM and ET_0-Pan presented in Figure 5 showed a poor relationship, with R^2 = 0.27 (RMSE:0.28, MAPE:8.34%) in the MIGP region. Throughout the crop period, lower reference evapotranspiration had been reported compared to ET_0-PM, suggesting the development of local revised pan coefficient values in these regions.

During the cropping season, ET_a using a modified paddy lysimeter varied from 1.9 to 8.2 mm day^{-1}, with a mean value of 4.02 ± 1.35 mm day^{-1}, and reported a total of 369.4 mm, accounting for 49.77% of the total water applied after transplanting. On the other hand, the percolation beyond the crop root zone was 262.48 mm, or around 35.36% of the total water applied, and the rest (14.87%) was stored within the root zone of the crop (Figure 6). A total of 111.09 mm evapotranspiration was estimated during the nursery. In addition to this, the stagewise-measured daily average ET_a was 3.86 ± 0.95 mm day^{-1}, 4.51 ± 1.41 mm day^{-1}, 4.05 ± 1.28 mm day^{-1}, and 2.52 ± 0.51 mm day^{-1} during the initial, crop development, mid-season, and late-season stages, respectively (Table 3).

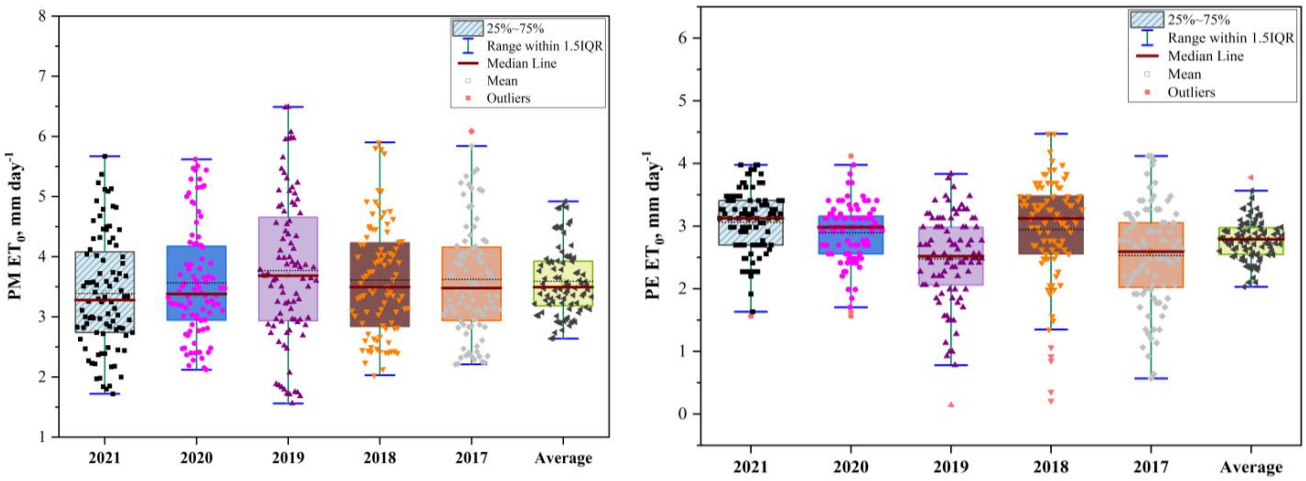

Figure 4. Daily variation in ET_0-PM and ET_0-Pan from 2017 to 2021 during crop period.

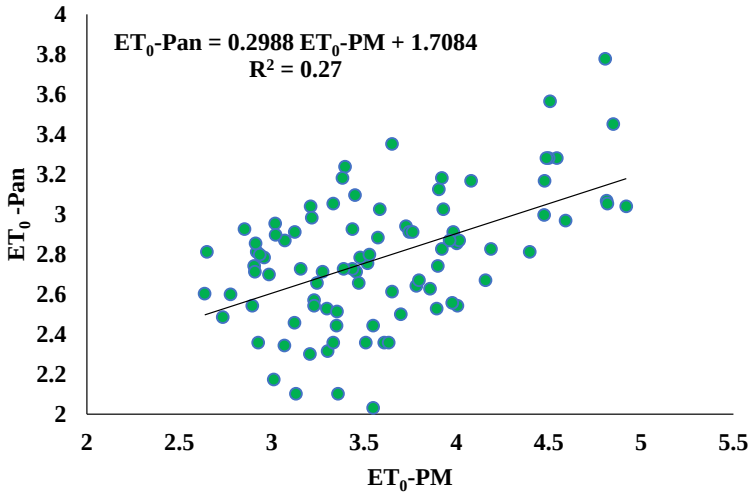

Figure 5. Relationship between ET_0-PM and ET_0-Pan (mm day^{-1}) for the last five years (2017–2021).

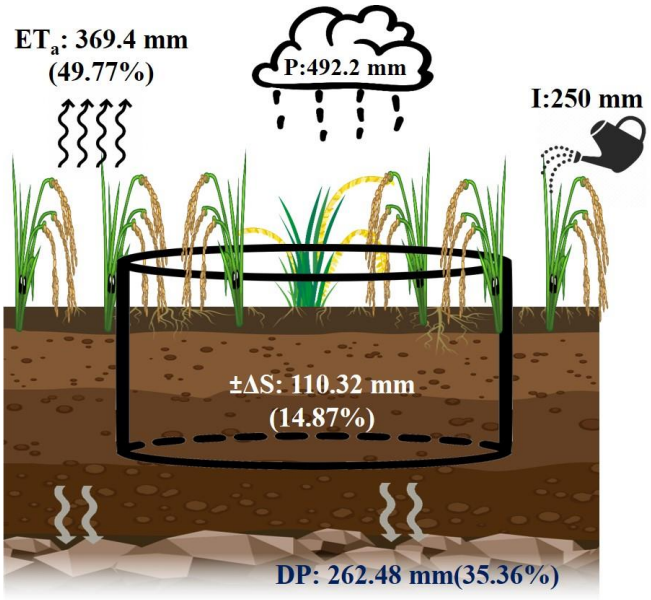

Figure 6. Water balance estimation in modified paddy lysimeter.

Table 3. Stagewise variation in crop evapotranspiration throughout cropping season.

Crop Growth Stages	ET_c-PM (mm Day^{-1})	ET_c-Pan (mm Day^{-1})	ET_a (mm Day^{-1})
Initial	3.59 ± 0.77	3.15 ± 0.69	3.86 ± 0.95
Crop development	4.05 ± 1.16	3.59 ± 0.60	4.51 ± 1.41
Mid-season	4.07 ± 1.26	3.61 ± 0.67	4.05 ± 1.28
End season	2.50 ± 0.50	2.67 ± 0.26	2.52 ± 0.51
Overall	3.84 ± 1.21	3.45 ± 0.69	4.02 ± 1.35

Note: All values are given in mean ± standard deviation (SD).

3.2. Comparation of Actual Evapotranspiration with FAO-PMand Pan Evaporation-Derived Evapotranpiration during Crop Period

During the crop growing season, FAO-PM derived evapotranspiration (ET_c-PM) varied from 1.55 to 6.8 mm/day with a mean value of 3.84 ± 1.21 mm day^{-1}, while the corresponding daily pan-derived evapotranspiration (ET_c-Pan) varied from 1.87 to 4.77 mm day^{-1} with a mean value of 3.45 ± 0.69 mm day^{-1}. Similarly, daily ET_a loss during the crop growing season varied from 1.9 to 8.2 mm/day, with a mean value of 4.02 ± 1.35 mm day^{-1} (Table 3). Overall, the variations in stagewise-estimated crop evapotranspiration using Penman–Monteith, the pan evaporation approach, and measured daily mean ET_a were shown in Figure 7.

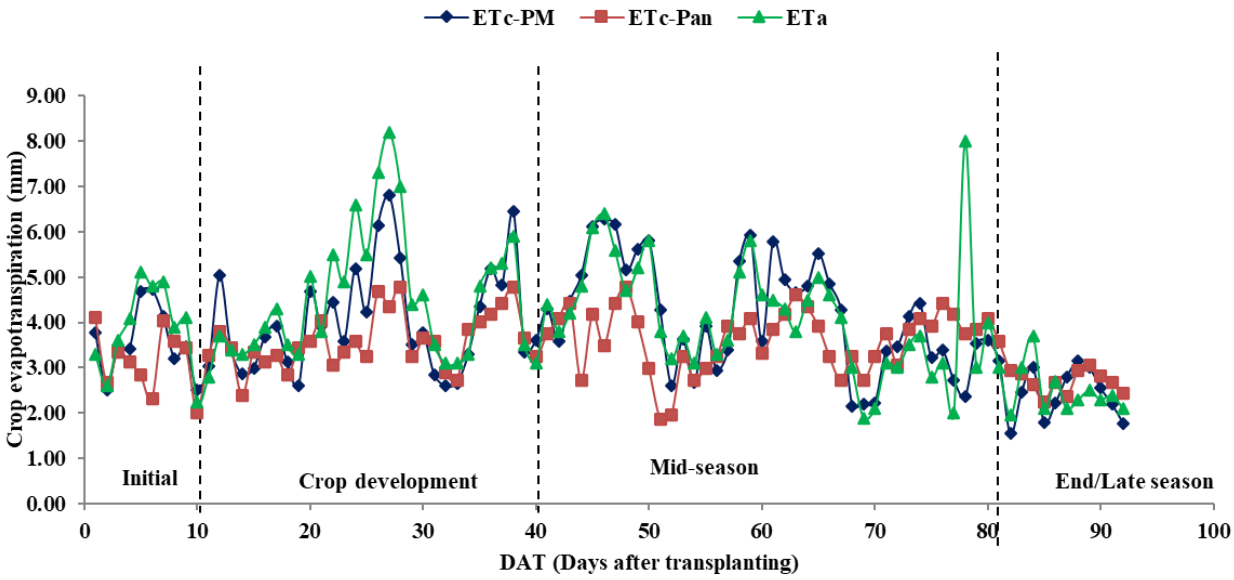

Figure 7. Crop stagewise variation in actual, FAO-PM and pan-derived evapotranspiration (mm day^{-1}).

Multiple regression analysis results showed that, overall, pan evapotranspiration underestimated the crop evapotranspiration in all four crop growth stages (R^2 = 0.24; RMSE = 0.96; and MAPE = 22.3%), whereas the Penman–Monteith equation performed well (R^2 = 0.63; RMSE = 0.64; and MAPE = 13.6%), as shown in Figure 8.

However, crop evapotranspiration using the Penman–Monteith equation was highly correlated with measured ET_a in the initial (R^2 = 0.80; RMSE = 0.49; MAPE = 10.76%) and crop development stages (R^2 = 0.79; RMSE = 0.79; MAPE = 13.69%); conversely, in the mid-season and end-season stages, R^2 varied to 0.47 (with RMSE = 1.01 and MAPE = 12.76%) and R^2 = 0.15(with RMSE = 0.53 and MAPE= 19.42 %), respectively. Similarly, stagewise crop evapotranspiration based on the pan evaporation approach was found to poorly correlate with ET_a in the initial (R^2 = 0.08; RMSE = 1.19; MAPE = 20.70%), mid-season (R^2 = 0.06; RMSE = 1.36; MAPE =26.15 %) and end-season stages (R^2 = 0.09; RMSE = 0.50; MAPE =15.32%), while the opposite stronger correlation was found for the crop development stage (R^2 = 0.43; RMSE = 1.43; MAPE =19.86% (Figure 9)).

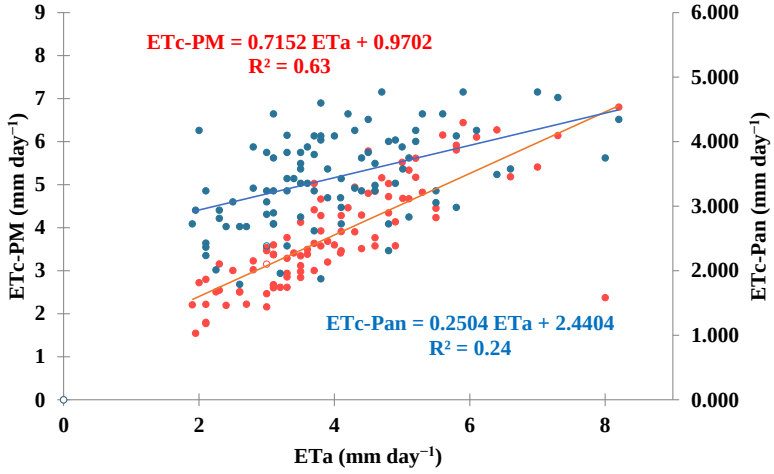

Figure 8. Multiple linear regression analysis of actual, FAO-PM and pan evaporation (mm day^{-1}) during crop period.

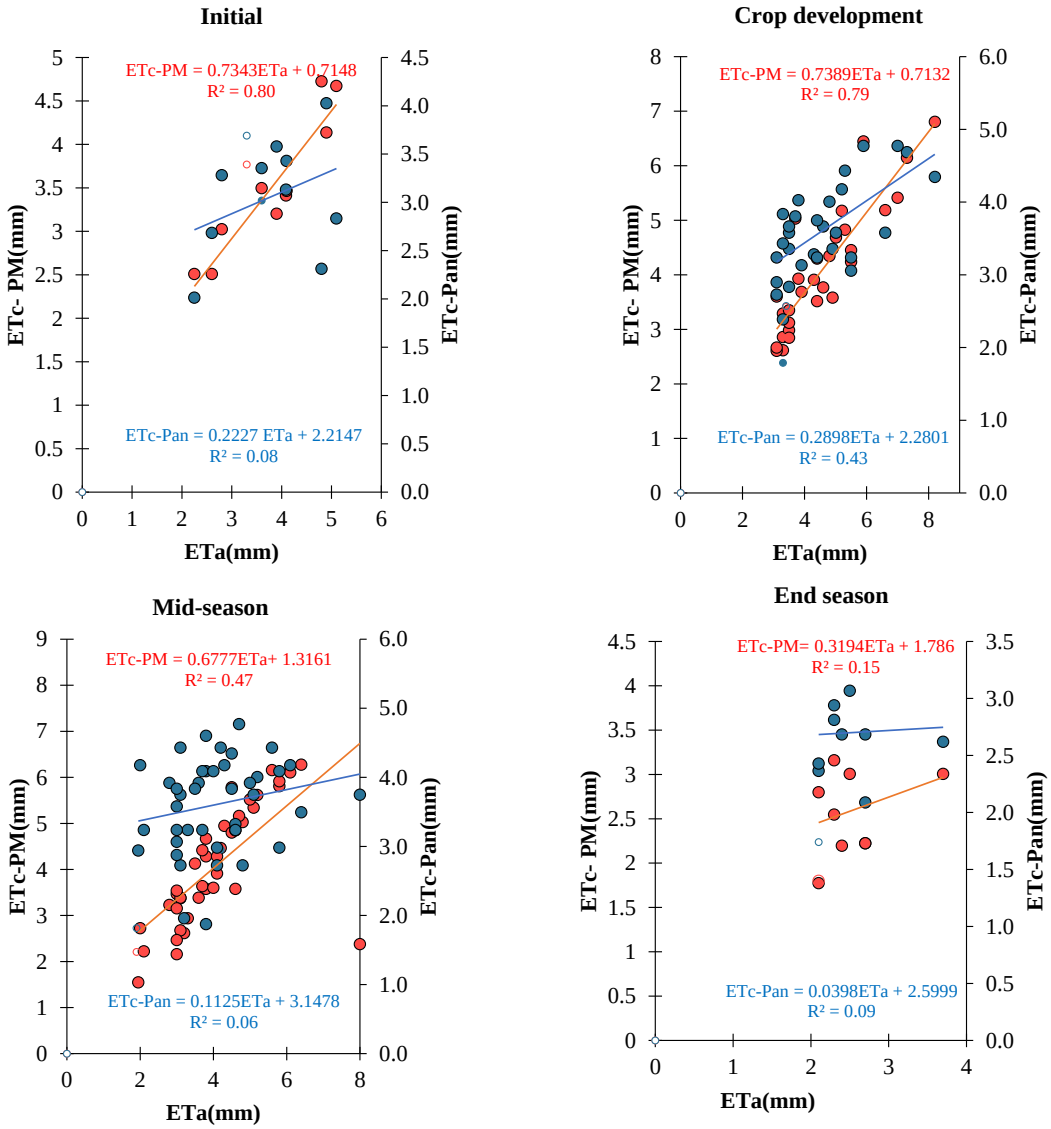

Figure 9. Stagewise multiple linear regression analysis of actual, FAO PM and pan evaporation crop evapotranspiration.

3.3. Comparison of Stagewise Actual K_c vs. Single FAO-56 K_c Values and Derived Pan–Crop Coefficient Values

At the regional scale, actual crop coefficient values were estimated to be 1.13 ± 0.13, 1.27 ± 0.2, 1.23 ± 0.16, and 0.93 ± 0.18 for the initial, crop development, mid-season and late-season stages, respectively. The derived crop coefficient values were 7.62%, 5.83%, 2.5%, and 3.33%, higher during the initial, crop development, mid-season and end/late season stages than the FAO K_c values for the MIGP region, while the pan–crop coefficient values estimated were 1.33 ± 0.41, 1.42 ± 0.36, 1.38 ± 0.48, and 0.85 ± 0.16, i.e., 26.67%, 18.33%, and 15% higher and 5.5% lower for the initial, crop development, mid-season and late-season stages respectively in comparison to the FAO K_c values. Overall, the stagewise variation in measured K_c compared to the FAO-56 K_c values and Pan- K_c values depicted in Figure 10. However, the non-parametric Mann–Whitney U test was performed to compare the association between these stagewise- derived averaged actual K_c values with FAO-56 K_c values and pan–crop coefficient values. The results showed that, at different crop growth stages, the actual average K_c values were in line with FAO values but slightly deviated from the pan-coefficient values, though were non-significant at the 5% level of significance (Figure 11). Overall, the coefficients of determination (R^2) between the derived average stagewise K_c vs. single FAO-56 K_c values and derived pan–crop coefficient values were shown in Table 4.

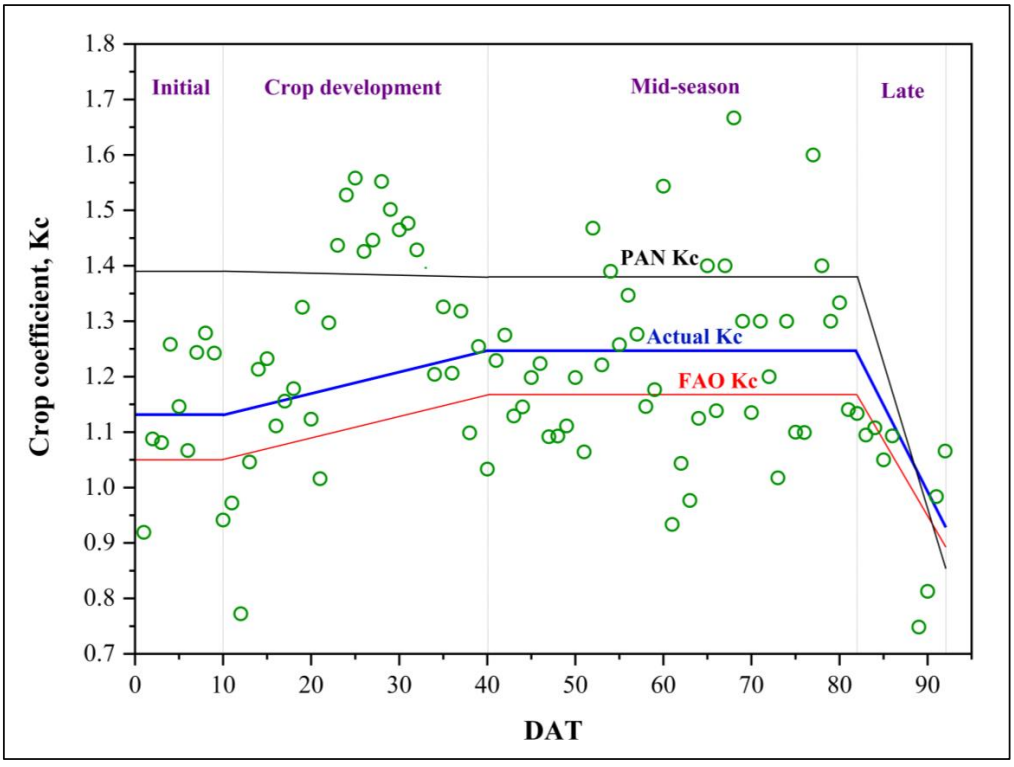

Figure 10. Stagewise variation in actual K_c values, FAO-56 K_c values, and pan–crop coefficient values during DAT (days after transplanting).

Table 4. Correlation coefficient (r) between measured average actual K_c, FAO-56 K_c and pan K_c values.

Variables	K_c-Actual	K_c-Pan	FAO-K_c
K_c-actual		0.933	0.972
K_c-Pan	0.933		0.852
FAO-K_c	0.972	0.852	

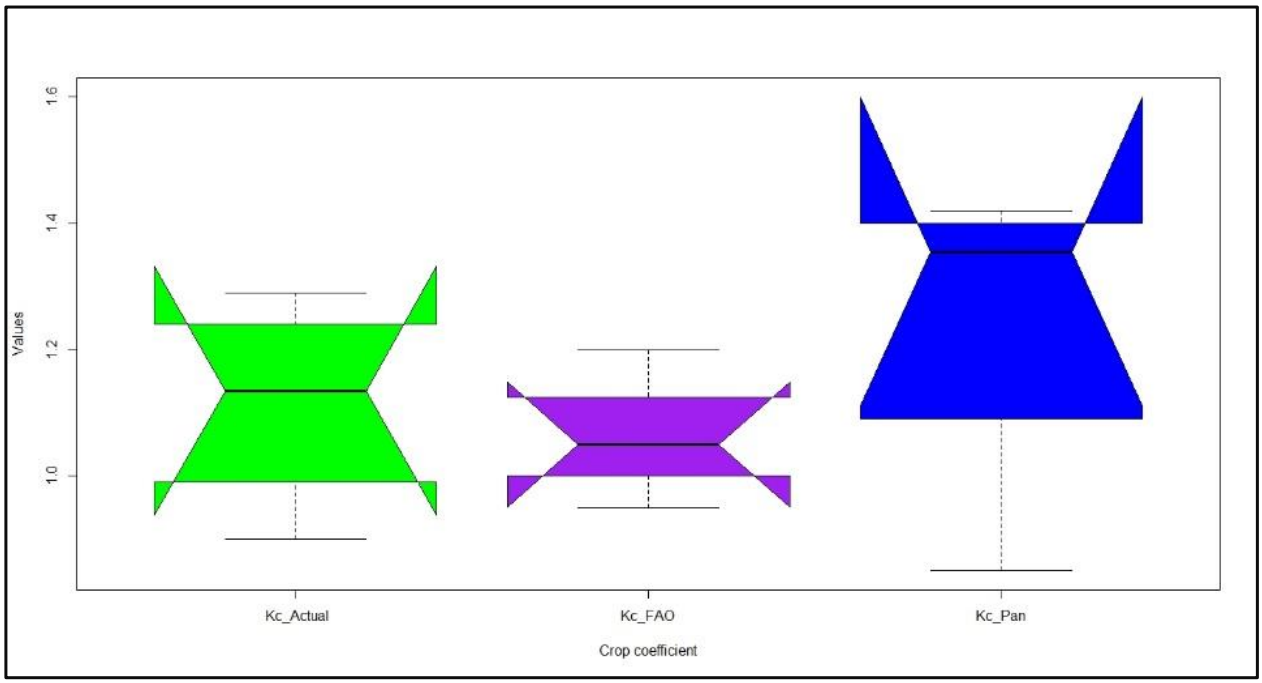

Figure 11. Variation in actual stagewise K_c vs. FAO-56 K_c and pan–crop coefficient values (at 5 % level of significance).

However, based on the average ET_0-PM and ET_0-Pan estimated from 2017 to 2021 in reference to the actual measured crop evapotranspiration during 2021, the average actual K_c values were calculated to be 1.08 ± 0.29, 1.14 ± 0.33, 1.18 ± 0.37, and 0.84 ± 0.09, while the corresponding average K_c-Pan values were 1.42 ± 0.35, 1.57 ± 049, 1.52 ± 053, and 0.90 ± 1.67 during the initial, crop development, mid-season and end/late-season stages, respectively.

3.4. Influence of Weather Variables on Reference and Actual Evapotranspiration

From the correlation matrix involving weather variables and evapotranspiration, it was confirmed that ET_0-PM was positively and significantly influenced by solar radiation, sunshine hours, Tmax, and wind speed and negatively affected by RH_{mean}, whereas in the case of ET_0-Pan, pan evaporation, Tmax and solar radiation were the dominant factors that affected it positively and RH_{mean} had a negative effect. More or less similar trends were also seen in ET_a as well, where Tmax, sunshine hours, and solar radiation were the main determinants (Figure 12).

3.5. Water Productivity and Agro-Meteorological Indices

The grain yield was measured to be 0.548 kg/m^2. Irrigation water use efficiency (IWUE) was estimated to be 0.74 kg/m^3, whereas crop water productivity (CWP) was 1.14 kg/m^3**.** Agrometeorological indices, viz., accumulated GDD (°C days), HTU (°C days h), PTU (°C days day $^{-1}$), and RTD during different phenophases, as well as HUE (kg ha^{-1} °C Day), HTUE (kg ha^{-1} °C Day h) and PTUE (kg ha^{-1} °C Day hrs) for grain and dry matter production under different phenophases, were calculated and presented in Tables 5 and 6. The results showed that the accumulated GDD, HTU, PTU and RTD values of the rice cultivar (Swarn Shreya) were estimated to be 2321 °C days, 8138 °C days hr, 25,995 °C days day $^{-1}$, and 26.3 °C, respectively, throughout the crop period (transplanting to harvesting). However, HUE, HTUE and PTUE were estimated to be 2.40 kg ha^{-1} °C day, 0.62 kg ha^{-1} °C day h, and 0.21 kg ha^{-1} °C day h, respectively, which will help in studying the crop response to ambient temperature at different phenological stages.

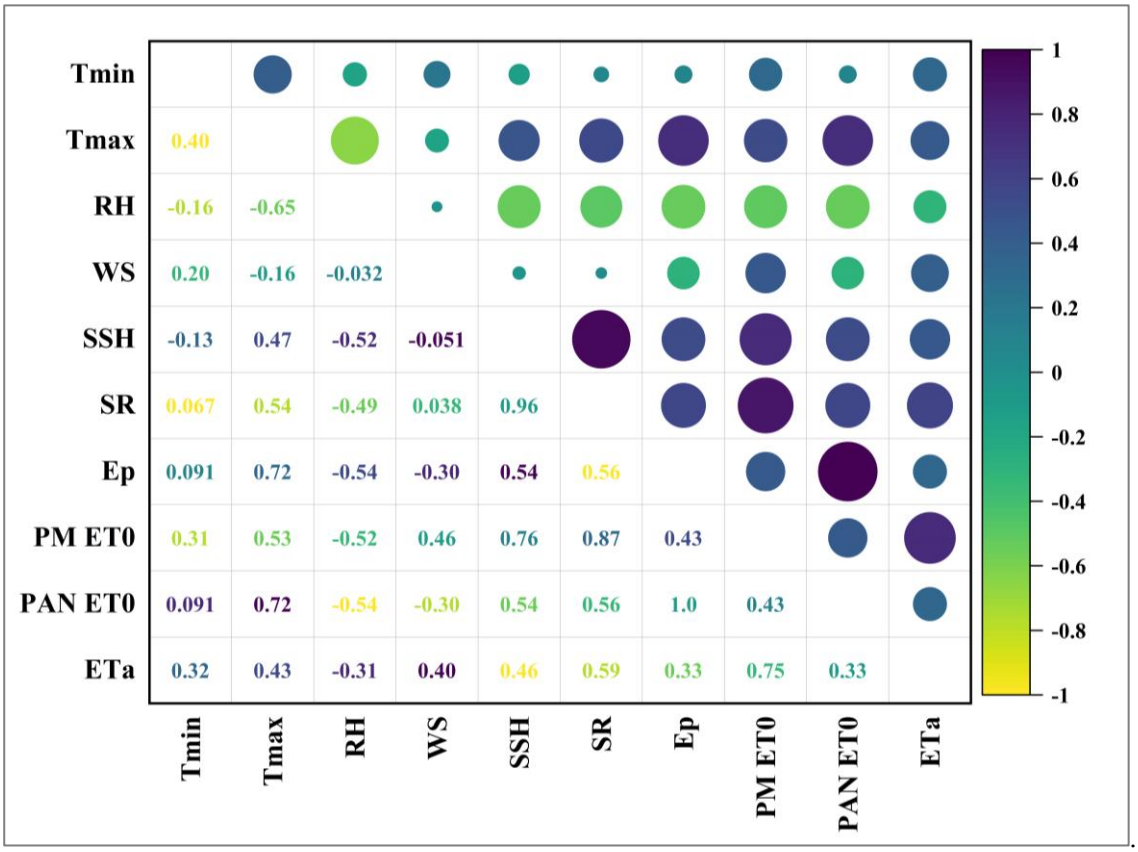

Figure 12. Correlation plot between weather variables and evapotranspiration (ET_0-PM, ET_0-Pan and ET_a).

Table 5. Accumulated GDD (°C days), HTU (°C days hr), PTU (°C days day $^{-1}$), and RTD (°C) during different phenophases of rice cultivar.

Agrometeorological Indices	Tillering	Panicle Initiation	Flowering	Physiological Maturity	Harvesting
GDD	698	1117	1748	2024	2321
HTU	1881	3287	5679	6975	8138
PTU	9200	13,929	21063	23.94	25,995
RTD	17.9	19.10	20.8	23.7	26.3

Note: GDD: growing degree days; HTU: heliothermal unit; PTU: photothermal unit; RTD: relative temperature disparity.

Table 6. HUE (kg ha^{-1} °C Day), HTUE (kg ha^{-1} °C Day hrs), and PTUE (kg ha^{-1} °C Day h) of rice for grain and dry matter production under different phenophases.

Agrometeorological Indices	Grain Yield	Dry Biomass
HUE	2.40	8.50
HTUE	0.62	2.41
PTUE	0.21	0.75

Note: HUE (kg ha^{-1} °C day), HTUE (kg ha^{-1} °C day h), and PTUE (kg ha^{-1} °C day h) of rice for grain and dry matter production under different phenophases.

4. Discussion

4.1. Variation in Reference Evapotranspiration, Water Balance Components, and Actual Evapotranspiration

Overall, a poor relationship was found between the FAO-PM and pan evaporation approaches for estimating reference evapotranspiration, with R^2 = 0.27, RMSE = 0.28, and MAPE = 8.34% for the last five years (2017–2021). The reason behind the lower reference

evapotranspiration in the case of the pan approach in comparison to ET_0-PM is mainly due to a constant pan coefficient (0.71) that needs to be revised at the local scale to imitate the evaporation from the free water surface. This resulted in the underestimation of vegetation role as well as human errors. Similarly, Chatterjee et al. [30] conducted research in Cuttack, Odisha, and part of Eastern India, and reported a poor relationship between FAO-modified PM and Epan-derived ET_0, with R^2 varying from 0.16 to 0.24, which is in close agreement with our findings. The decrease in Epan could be due to a phenomenon known as the "Pan Evaporation Paradox" [63,64]. However, previous studies also revealed that ET_a can exceed Epan for short periods of time (e.g., at different stages of plant growth) when there is a lot of advected heat and a drop in the diurnal temperature range [63,65–69]. Daily ET_a used 369.4 mm of water, accounting for 49.77% of the total water applied after transplanting to the harvesting stage. Likewise, Dash et al. [70] reported that around half of the water applied in irrigated puddled rice fields is used in the form of evapotranspiration. However, daily ET_a using a modified paddy lysimeter varied from 1.9 to 8.2 mm/day, with a mean value of 4.02 ± 1.35 mm day^{-1}. This variation is mainly due to various biophysical parameters such as vegetation type and density, growth phase, stomatal conductance, weather variations, local field management practices, etc. [34]. Several researchers have indicated that daily mean ET_a rates of rice in the Asian continent ranged from 4 to 7 mm per day [30,71], which is in line with the ET_a values obtained in our study. However, overall, daily measured ET_a increased erratically with the increase in days after transplanting (DAT), reached peak value at the crop development to mid-season stages, mainly due to a larger leaf area index leading to maximum transpiration losses, and eventually decreased at the end-season stage due to leaf senescence [16,18].

ET_a estimation using a modified lysimeter, however, had its own limitations. For example, because the drums were installed about 36 cm above the ground, the microclimate (Tmin slightly increased and Tmax slightly decreased by about 0.1–0.3 °C compared to the open field, while relative humidity varied by 1–2%) within the drum differed from the entire field and affected ET_a estimation, but only up to 15–20 days after transplanting. After that, plant height increased and came outside the drum. Therefore, the microclimate did not have too much affected ET_a estimation. However, the exposed rim of modified lysimeter also caused local advection, but did not significantly affect the ET_a estimation. Similarly, research on the potential impacts of advection on flooded rice has not revealed any substantial advection implications [72]. The FAO-recommended Penman–Monteith method is considered to be the best method for ET_0 estimation due to the fact that it considers all the weather parameters which influence ET_0 [20].

4.2. Comparison of Crop Evapotranspiration and Stagewise Crop Coefficients

Based on the results, overall ET_a measured using a modified paddy lysimeter showed a close association with FAO PM-derived evapotranspiration (R^2: 0.63). However, the ET_0-Pan approach underestimated (R^2: 0.24) in these regions. Maina et al. [73] also reported FAO-PM as a better approach than the pan approach due to its good approximation of trustworthy lysimeter readings. In these areas, there has been a documented underestimation of the pan method. The main cause is the constant pan coefficient, which should be updated for these regions [74–76]. Similarly, the bulk of the estimated pan coefficients, according to Sabziparvar et al. [77], were not statistically used in the pan ET_0 conversion technique. As a result, for each climate, a good model for calculating the pan coefficient is required [78]. However, the overall actual evapotranspiration estimated using the FAO-PM and pan approaches increased significantly as the phenological phases of growth progressed, peaked at mid-season, and subsequently declined at maturity during the crop growing season, similar to previous Indian and international studies [42,79,80]. Tyagi et al. [18] also reported similar results to those obtained in our study. These variations are mainly due to changes in ET_a because of weather conditions, crop type and variety, crop growth stages, and local management practices in these areas [33,72]. Rice crop coefficient values for the initial, crop development, mid-season and late-season stages were calculated

as 1.13 ± 0.13, 1.27 ± 0.2, 1.23 ± 0.16, and 0.93 ± 0.18, respectively, and results showed that the overall average crop coefficient values at different stages showed at par with the FAO K_c values, but slightly deviated with pan–crop coefficient values. Statistically, these variations were insignificant (at a 5% level of significance). Higher crop coefficient values had been observed, except for end/late-season stage, mainly due to the stagnation of water during the crop season. Depending on the irrigation method, the K_c in the initial stage, with the exception of permanent flooding, declined in comparison to the FAO 56 K_c value [81]. Various findings also reported that stagewise crop coefficients for rice varied from 0.61 to 1.15, 0.97 to 1.44, 1.14 to 1.59, and 0.9 to 1.02, in the initial, crop development, mid-season, and late-season stages, respectively, using a lysimetric and other water balance approaches which were consistent with our findings [14,18,24,26,27,50,51]. Many distinct crop varieties and diverse water management practices, ranging from deep water to floating up to aerobic sprinkler settings, have been observed to cause a significant difference in the paddy crop coefficient [82]. In addition, higher pan–crop coefficient values were found owing to the constant and fixed pan coefficient value (0.71), resulting in significant ET_0 estimation errors which need to be revised in these locations, and this approach also underestimated the vegetation contribution [77,81,83]. Undertaking studies to revise the pan coefficient values locally considering the influence of weather parameters on pan evaporation in different climatic conditions is recommended.

4.3. Influence of Weather Variables on Reference and Actual Evapotranspiration

From the results, it was concluded that solar radiation, sunshine hours, Tmax, and wind speed positively affected evapotranspiration, whereas RHmean negatively affected evapotranspiration (ET_0-PM, ET_0-Pan and ET_a). Similar patterns of influence of these weather variables on evapotranspiration estimation were also reported in semi-arid IGPs [84]. Additionally, a significant factor influencing the weekly fluctuation in ET_a was reported as net solar radiation variation ($r \geq 0.87$) in IGPs by [7]. Chatterjee et al. [30] also reported a strong positive relationship between ET_a and Tmean, as well as solar radiation in Eastern India. These variables mainly affected the sensible heat flux from soil to canopy and substantially affected their estimations during crop season.

4.4. Assessment of Water Productivity (WP) and Agro-Meteorological Indices

The results revealed that the IWUEand CWPof rice were 0.74 and 1.14 kg/m^3, respectively. This figure fits within the range of the internationally recorded WP of rice (0.6–1.6 kg/m^3) [85]. Similarly, the crop water productivity ranged between 0.9 and 1.54 kg/m^3, while total WP was varied from 0.68 to 0.98 kg/m^3 for different rice varieties [85]. Rice water productivity ranged from 0.6 to 1.5 kg/m^3, which supports our findings according to Mboyerwa et al. [86]. These variations are mainly due to climate, soil type, soil structure, crop type, variety, duration, irrigation methods, fertilizer applications, etc. Agrometeorological indices showed that temperature affects crop growth and yield. These indices also varied due to different transplanting dates and varieties [84]. In the present study, various agrometeorological indices for the rice cultivar Swarna Shreya had been calculated and their variations showed the pattern of biomass accumulation at different phenological stages, which ultimately affect crop productivity. This type of study helps in understanding crop response to temperature variation for future yield forecasting in these regions under climate change scenarios.

5. Conclusions

Agriculture water management is aided by accurate ET quantification and crop coefficient computation during different crop growth stages. In this study, the stagewise average daily crop evapotranspiration rates (mm day^{-1}) were estimated as 3.86 ± 0.95, 4.51 ± 1.41, 4.05 ± 1.28, and 2.52 ± 0.51, and their corresponding K_c values were 1.13 ± 0.13, 1.27 ± 0.2, 1.23 ± 0.16, and 0.93 ± 0.18 for the initial, crop development, mid-season and late-season stages, respectively. The derived average crop coefficient values were reported

7.62%, 5.83%, 2.5%, and 3.33%, higher during the initial, crop development, mid-season, and end-season stages compared to FAO K_c values. However, the average pan–crop coefficients estimated as 1.33 ± 0.41, 1.42 ± 0.36, 1.38 ± 0.48, and 0.85 ± 0.16 were 26.67%, 18.33%, and 15% higher and 5.5% lower than the initial, crop development, mid-season and late-season stages, respectively, in comparison to FAO K_c values. Overall, the results showed good agreement (R^2 = 0.63) between ET_a and FAO-PM-calculated ETc. Conversely, the pan evaporation approach underestimated the crop evapotranspiration compared to ET_a, which suggests revising the pan coefficient values for the study region will achieve better accuracy. Thus, we recommend revising the pan coefficient values considering the influence of weather parameters. The IWUEand CWP for rice were estimated as 0.74 and 1.14 kg/m^3, respectively. Similarly, agrometeorological indices were also estimated for Swarna Shreya to help in forecasting the occurrence of different phenophases in similar agro-climatic regions. Therefore, this type of methodology could also be used in other edaphoclimatic and data-scarce regions where lysimeters are unavailable to estimate actual evapotranspiration in paddy areas. In addition, the derived stagewise K_c values at the regional scale may help in efficient irrigation planning for similar agro-climatic conditions. Overall, K_c and ET_a values may be beneficial to improve irrigation scheduling in water-intensive rice crop.

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