Quantifying Maize Crop Evapotranspiration Using Eddy Covariance Flux Tower Weather Data

ABSTRACT

The study conducted at the Maize Research Centre, Agriculture Research Institute, Professor Jayashankar Telangana State Agricultural University (PJTSAU), Rajendranagar, Hyderabad, from November, 2022 to March, 2023 aimed to compute the crop evapotranspiration (ET_c) of maize crop under two different irrigation treatments using the weather data generated from the Eddy Covariance (EC) flux tower. The two treatments comprise of scheduling irrigation at certain Depletion of Available Soil Moisture (DASM) viz., T1: 20% DASM and T2: 40% DASM. The maize crop was sown and cultivated as per the recommended practices. The bio-physical parameters like plant height and LAI were recorded at 15 days interval. These parameters were statistically analysed by two sample T-test with equal variance. The plant height increased from 35 to 198 cm in 20% DASM and 36 to 180 cm in 40% DASM during the crop growth period (30 to 100 DAS). Similarly, LAI increased from 0.72 to 3.9 and 0.77 to 3.2 in 20 and 40 % DASM treatments till 90 DAS and later on decreased till harvest. The findings emphasize a positive influence of optimum moisture availability in the root zone on plant growth parameters. The amount of irrigation given was measured to compute ET_c using Soil Water Balance (SWB) method and the crop parameters like plant height, LAI, stomatal resistance values etc., were used for computing the Penman-Monteith equation using the weather parameters generated from the EC flux tower. Seasonal ETc estimated from the Soil Water Balance (SWB) method (340 & 280 mm) and FAO Penman-Monteith method (350 & 295 mm) in 20 and 40% DASM treatments showed a deviation of +10 and +15 mm, respectively. Furthermore, the study concludes that FAO Penman-Monteith can accurately estimate ET by using EC flux tower measured weather data, with minor

Keywords: Evapotranspiration; maize; eddy covariance; irrigation and DASM

1. INTRODUCTION

Maize is one of the most preferred and widely cultivated crops and has a great ability to adapt to various climate and soil environments [1]. It is the third most important cereal crop after rice and wheat, accounting for 10.8% (359.13 lakh tonnes) food grain production in India [2]. Globally, India ranks 4th and 6th in terms of acreage (3.96%) and production (2.13%) respectively, with 3.07 t/ha of productivity during 2021 [3]. It serves as a staple food and animal feed as well as a fundamental raw material for several industrial applications [4]. According a report [3], maize growth rate is projected to be 1.34% CAGR (Compound Annual Growth Rate), while the consumption rate would be slightly higher with 1.82 % CAGR during 2021-31. Furthermore, its demand as an animal feed will goes up to 54% from 51% by 2031. On the other hand, ever increasing population, over exploitation of ground water resources and climate changing scenario have increased the demand for fresh water resources in the country. Against this backdrop, adopting proper agronomic practices such as scheduling irrigation is essential as it may influence the plant physiological traits and yield [5]. Wise use of water with correct scheduling of irrigation is important in producing maximum yields [6]. In this context, deficit irrigation may be an option to meet the partial crop water requirements and allow plants to efficiently draw moisture from the soil [7].

In agricultural water management, understanding and accurately estimating evapotranspiration (ET), which is the combination of evaporation from the soil surface or water surface and transpiration from the vegetation [8] is crucial, as it plays a major role in the crop water requirement (CWR) of any crop [9]. However, estimating ET accurately remains a challenging task since, it is a complex process involving soil, water, land and vegetation. Several methods have been developed for ET estimation including simple Soil Water Balance method (SWB), Pan evaporation method, empirical methods (Penman-Monteith, Priestly-Taylor, Hargreaves–Samani, Thornthwaite, Blaney–Criddle), field-based measurements (Lysimeter, Bowen Ratio Energy Balance Systems (BREBS), Scintillometers, Eddy Covariance) and remote sensing models. Each method has their own advantages and limitations. Among all the methods, FAO Penman- Monteith method [10] is widely accepted and adopted by FAO [11]

The objective of this study is to estimate evapotranspiration of maize crop by FAO Penman-Monteith method using weather data measured from eddy covariance flux tower under two different irrigation regimes. It will compare these estimates with the traditional Soil Water Balance method and assess plant growth responses to deficit irrigation.

2. MATERIALS AND METHODS

A field experiment was conducted during *rabi*, 2022-23 at Maize Research Centre (MRC), Agriculture Research Institute (ARI), Professor Jayashankar Telangana State Agricultural University (PJTSAU), Rajendranagar, Hyderabad. The experimental field is situated within the fetch area (Fig.1) of Eddy Covariance flux tower, which is established at 17°19'34.15"N latitude and 78°23'44.67"E longitude at an elevation of 541 m above MSL. DHM-117, a medium duration maize hybrid, tolerant to lodging and moisture stress was sown in large plots with two different irrigation regimes i.e., Scheduling irrigation at certain Depletion of Available Soil Moisture (DASM) T1: at 20 % DASM and T2: at 40% DASM. The seeds were sown at a spacing of 60 cm x 20 cm on the side of ridges on 10th November, 2022. To maintain optimum plant population, gap filling was done at 15 DAS and thinning was done at 20 DAS. Remaining package of practices were adopted as per the recommendations of PJTSAU and additionally, various management practices were adopted to reduce runoff and seepage losses. Throughout the crop growth period, growth parameters like Plant height (cm), Leaf Area Index (LAI) were recorded and stomatal conductance ($1/r_l$) at tasselling stage was recorded with porometer. Gravimetric soil moisture content was estimated before and after the irrigation using equation (1) by recording fresh weight and oven dry weights of soil samples.

$$\text{Moisture content, } \theta_g\ (\%) = \frac{\text{Fresh weight} - \text{Oven dry weight}}{\text{Oven dry weightl}} \times 100 \qquad (1)$$

Irrigation was scheduled by adopting ridge and furrow method when available soil moisture is depleted by 20% and 40 % for T1 and T2 treatments, respectively.

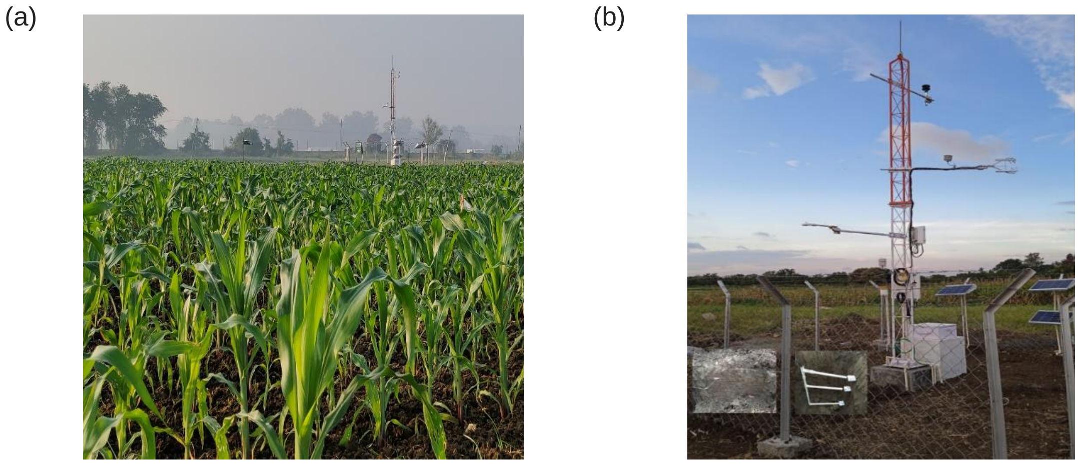


Fig. 1. Maize crop at knee-height stage (a) and EC flux tower (b) at MRC, ARI, PJTSAU, Hyderabad

Eddy covariance [12] is a widely used micro meteorological technique for measuring ET. It measures the vertical fluxes of water vapor and CO_2 between an ecosystem and the atmosphere. This method relies on the concept of eddies, circular air motions caused by temperature differences, possessing attributes such as mass, density, volume and velocity in three dimensions (3D). By utilizing an IRGASON sensor, which is a combination of a 3D sonic anemometer and infrared gas analyser, the eddies' characteristics in terms of velocity, density and gas concentration are measured. The statistical covariance of vertical velocity and gas concentration represents the flux of the given gas (water vapor, latent heat, sensible heat, CO_2).

The Eddy covariance flux tower is equipped with various other sensors and instruments, as detailed in the Table 1, which continuously measures the energy balance and weather parameters with fast sampling rate and high precision.

Table 1. Components of Eddy Covariance flux tower

S. No	Sensor/Instrument	Measurements
1	IRGASON sensor	• Sonic anemometer: 3D wind speed (cm), sonic temperatures (^oC) and wind direction. • Infrared gas analyzer: Density and concentration (mmol/mol) of CO_2, H_2O
2	Net radiometer	Net radiation along with incoming shortwave and outgoing longwave radiation (W/m^2)
3	Fine wire Thermocouple, ambient air temperature and Relative humidity sensor	Air temperature (^oC) and Relative humidity (%)
4	Soil moisture probes	Soil moisture (%v/v) and temperature (^oC) at 15, 35 and 45 cm depth
5	Soil heat flux plates	Soil heat flux (W/m^2) at 30 and 45 cm depth
6	Data logger	Integration of sensors and instruments, real time data recording, storage and transfer
7	Tipping bucket Rain gauge	Quantity (mm) and intensity of rainfall (mm/hr)
8	Solar panel and battery	Power supply

The collected data is processed in data logger and mean values are computed at every 30 min interval. These values were averaged to every day and used as crucial inputs, along with crop parameters like plant height, leaf area index (LAI) and bulk resistance, to be substituted into the FAO Penman-Monteith equation [10] (eq. 2) to obtain daily ET_c.

Despite the ability of the EC flux tower to measure ET_a, it provides a mean value for the fetch area. However, due to the existence of two irrigation treatments in the experiment, different ET_c values are possible. To capture these variations in ET_c between the treatments, the FAO Penman-Monteith method was employed for the study.

$$\lambda ET = \frac{\Delta(R_n - G) + \rho_a C_p \frac{(e_s - e_a)}{r_a}}{\Delta + \gamma\left[1 + \frac{r_s}{r_a}\right]} \qquad (2)$$

Where, R_n is net radiation (MJ/m^2/day),
G is soil heat flux (MJ/m^2/day),
ρ_a is atmospheric pressure (kpa),
C_p is specific heat of air at constant pressure (1.004×10^{-3} MJ/kg/^oC),
(e_s-e_a) is vapour pressure deficit (kpa),
Δ denotes slope of saturation vapour pressure curve vs temperature (kpa/^oC),
γ is psychrometric constant,
r_a and r_s are the surface and aerodynamic resistances (s/m) respectively,
λ is latent heat of vaporization (2.45 MJ/kg/^oC)
ET is evapotranspiration (mm/day)

Input parameters used for substitution in FAO Penman-Monteith equation are, weather parameters from EC flux tower such as, windspeed (u_6); height of wind speed (z_m= 6m) and relative humidity (z_h= 6m) measurements; air pressure (p_a); air temperature (T_a); vapour pressure deficit (e_s-e_a); net radiation (R_n); soil heat flux (G) and field observations includes, plant height (h); LAI; stomatal resistance (r_l). For computing surface (bulk) resistance (r_s) and aerodynamic resistance (r_a) the methodology outlined by [10] was followed. The other parameters like crop sowing, emergence of the seedlings, dates of scheduling irrigation the stage of physiological maturity were considered for ET_c computation

LAI and stomatal conductance played crucial roles as inputs in calculating surface resistance, whereas plant height (h), height of wind speed and RH measurements were critical inputs to determine aerodynamic resistance. The seasonal ET_c was calculated by summing the daily ET_c values obtained throughout the crop growth period. Subsequently, this seasonal ET_c was compared with the ET_C obtained by the SWB method for both treatments independently. ET_c by SWB method calculated as below in (eq. 3)

$$ET_c = (I + P + \Delta S) - DP \qquad (3)$$

Where, ET_c is crop evapotranspiration, I is irrigation water applied (mm), P is precipitation (mm), ΔS is changes in soil water storage in a given time Δt (days) in the root zone, DP is deep percolation losses beyond the root zone (mm)

Crop growth parameters were statistically analysed using two sample t-test with equal variances.

3. RESULTS AND DISCUSSION

3.1 Growth parameters

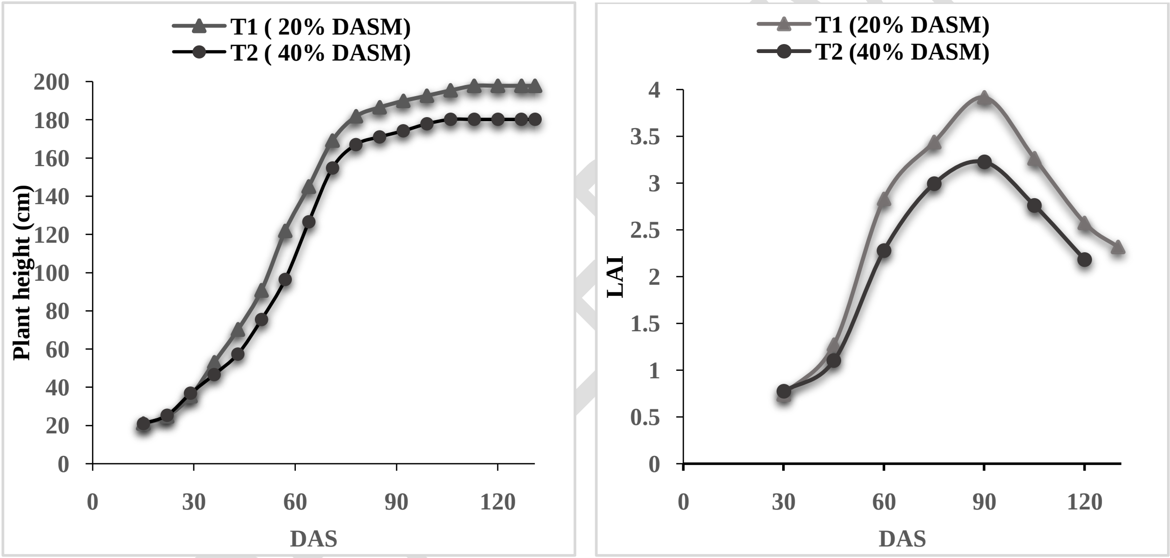
3.1.1 Plant height (cm)

Regardless of the treatments, the plant height shown a consistent increase from emergence to physiological maturity during the crop growth period with 21 cm (30 DAS) to 198 cm (110 DAS) in T1 treatment and 21 cm (30 DAS) to 180 cm (110 DAS) in T2 treatment as shown in Fig. 2(a). Notably, the plant height in T1 was relatively higher than in T2, as depicted in the Figure 2 (a). Statistically significant differences in plant height were observed only during the period of 45-60 DAS. An adequate amount of water applied at plant requirement promotes the plant's physiological parameters while the insufficient application, limits the plant growth. Similar results were reported by [13] and [14]. An increase in irrigation levels was found to be associated with an increase in plant height, as reported in various studies [15] and [16]. The increase in plant height observed in T1 can be attributed to enhanced moisture absorption and nutrient uptake by the plants [17], [18] and [19].

3.1.2 Leaf Area Index (LAI)

In both the treatments LAI exhibited an increase from emergence (8 DAS) to 90 DAS and later on, gradually decreased as depicted in the Fig. 2(b). These findings align with previous studies by [20],[21] and [22], which also observed similar trends. LAI observed was 0.73, 3.91, 2.31 in T1 and 0.77, 3.22 and 1.87 in T2 at 30, 90 and at harvest. T1 had a higher LAI compared to T2 during the crop growth period. Statistically significant differences between the treatments were observed from 60 DAS till harvest.

In T1, adoption of more frequent irrigation has played a crucial role in facilitating higher nutrient mobility and water uptake, which further supports cell division, elongation, turgidity and photosynthetic activity. Consequently, these favourable combinations of contributed significantly to higher LAI during 60 DAS to harvest, indicating improved canopy development. In contrast, the plants in T2 might have experienced water stress during their growth period due to limited moisture availability, hindering optimal cell expansion and overall growth. The water stress has negatively impacted plant physiological processes, leading to reduced canopy development and consequently, a lower LAI.



(a) (b)

Fig. 2. Plant height (a) and leaf area index (b) of maize crop as influenced by different irrigation treatments during rabi, 2022-23

3.1.3 Leaf stomatal resistance (r_l)

At tasselling stage, leaf stomatal conductance was measured using a porometer, revealing no significant difference between the two treatments (T1 and T2). For the initial and final stages, values were adopted from [23] for T1 and T2 respectively, corresponding to their respective irrigation conditions and then converted into resistance. The higher leaf stomatal resistance in the 40% DASM treatment may be attributed to its lower relative water content. As a C4 plant, the maize crop might have responded to limited water availability by adjusting their stomatal openings to reduce water loss through transpiration, thereby maintaining turgidity. In contrast, the lower stomatal resistance in the 20% DASM treatment may reflect a more efficient water use strategy, ensuring optimal physiological performance under favourable irrigation conditions.

3.2 Computation of Evapotranspiration

3.2.1 Soil Water Balance method

A total of 400 mm and 315.9 mm of irrigation water was applied. The deep percolation losses were found to be 60 and 40 mm for T1 and T2 treatments, respectively. T1 received 6 irrigations, while T2 received 5 irrigations during the crop growth period. By neglecting the runoff and seepage losses, evapotranspiration was found to be 340 mm and 280 mm in T1 and T2 treatments, respectively.

3.2.2 Penman-Monteith method

On substitution of plant parameters of given treatment along with weather parameters obtained from eddy covariance flux tower in equation (1), daily ET was obtained. Daily ET ranged from 0.44 to 5.65 mm/day and 0.42 to 4.89 mm/day in T1 and T2 treatments averaging at 2.6 and 2.19 mm/day respectively (Fig. 3). Furthermore, seasonal ET_c of T1 was recorded at 350 mm while T2 recorded a lower value of 295 mm. [24] reported a ET_c of 351.6 mm for entire growing season of maize crop using pan evaporation method at Hyderabad and similar findings were reported by [25] at Karnal.

The daily ET_c values consistently showed that T1 had a higher ET_c rate compared to T2, with an average difference of 0.41 mm/day. This discrepancy in daily ET_c was also evident in their cumulative seasonal ET_c, as T1 recorded 55 mm more ET_c than T2 during the entire crop growth period. At the initial stage, both treatments showed similar ET_c rates, as the treatments were not imposed until crop establishment. The peak ET_c occurred between 60-70 DAS in both treatments, with a slight decrease observed as the crops approached maturity.

As T1 received relatively more amount of irrigation water it has shown higher ET_c while, T2 might have adopted physiological changes to reduce transpiration due to the less availability of moisture in root zone and evaporation might also be less as the limited availability of water exerts a controlling influence on soil evaporation [10]. The variation in seasonal ET_c between the treatments can be attributed to variations in LAI, plant height and leaf stomatal resistance between the treatments, which are influenced by the availability of soil moisture

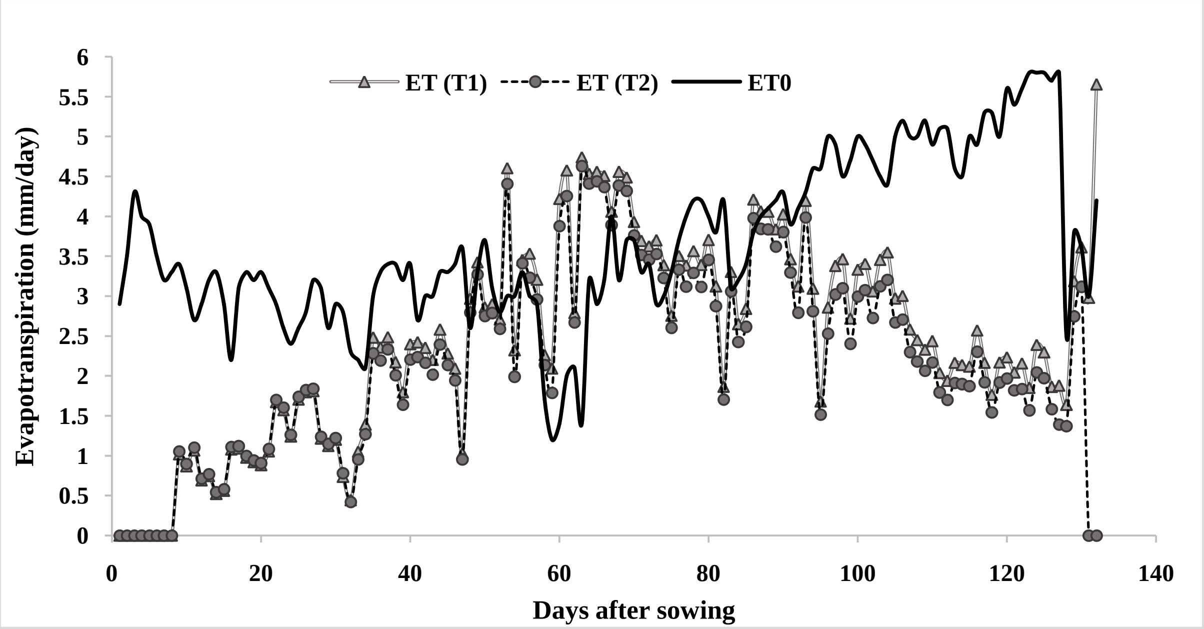


Fig. 3. Daily evapotranspiration of maize crop as influenced by irrigation during rabi, 2022-23

In the comparison of FAO Penman-Monteith method with the SWB method for T1 and T2 treatments, there was a deviation of +10 mm and +15 mm (Fig. 4), respectively. These deviations can be partly attributed to the high frequency (10 Hz) measurements obtained from EC flux sensors and instruments. The sensitive nature of these instruments allows them to capture even the minor variations, contributing to the observed differences between the two methods.

The FAO Penman-Monteith method using eddy covariance flux tower weather data as an input proved valuable in providing reliable ET estimates as it captured the difference in ET_c between two treatments. In terms of plant parameters, LAI, plant height and leaf stomatal resistance played a critical role in estimation of ET_c using the FAO Penman-Monteith equation, as variations in these parameters directly contributed to the observed differences in ET_c between the two treatments.

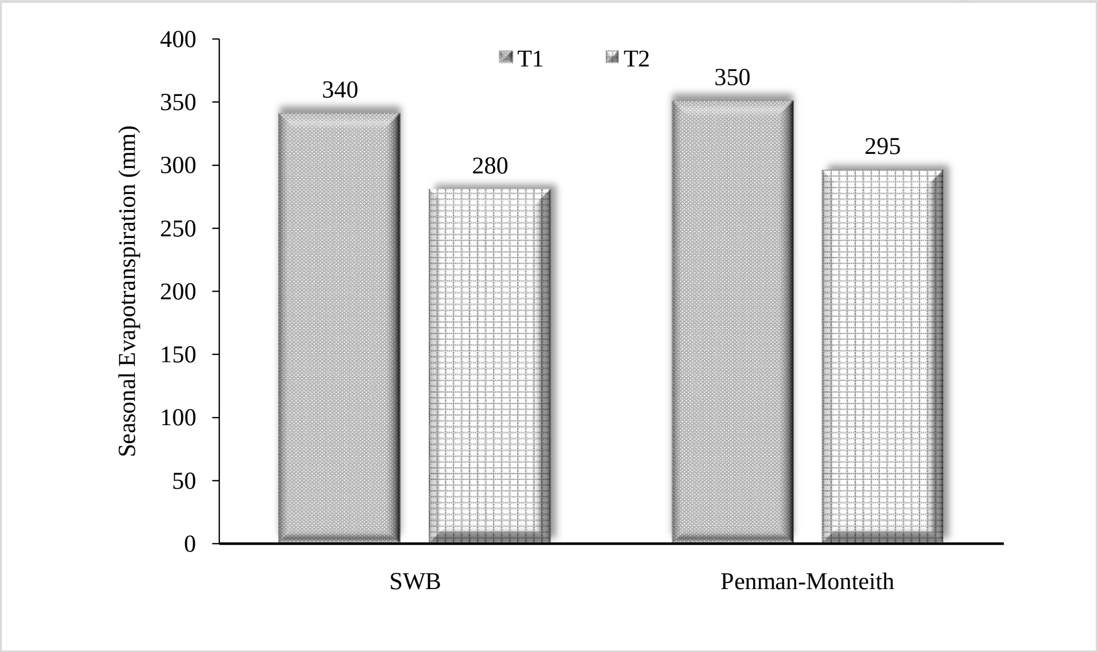


Fig. 4. Seasonal evapotranspiration (mm) of maize crop derived using two different methods

4. CONCLUSIONS

Adopting irrigation scheduling at 20% DASM is feasible for the maize crop, supported by the 10-20% increase in the plant growth parameters, such as plant height and LAI with the supply of 21% more irrigation water as compared to 40% DASM. Further, 20% DASM recorded a 17.6 and 15.7% more seasonal ET_C than 40% DASM in SWB and FAO Penman-Monteith methods respectively. However, the ET_c estimated by FAO Penman-Monteith metho showed a positive increase of 2% over SWB method.

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