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Application of Drainage-Type Mini-Lysimeters for Evaluating Evapotranspiration, Crop Coefficients, and Water Use Efficiency in Wheat (Triticum aestivum L.)

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Abstract

For water conservation and good agricultural management, especially in a semi-arid climate zone, it is important to accurately estimate how much water crops use. While large lysimeters are often expensive and difficult to handle, mini-lysimeters provide a cost-effective and practical alternative. The current study evaluates the performance of mini-lysimeters in determining crop evapotranspiration (ETc), water use efficiency (WUE), and establishing crop coefficients (Kc) for different wheat growth stages from November 2022 to May 2023. The experimental design contains three soil water depletion (SWD) treatments: T1; 25% SWD, T2; 50% SWD, and T3; 75% SWD, with four replicates using mini-lysimeters. The findings indicate that the daily actual evapotranspiration (ETa) of wheat ranged from 0.23 to 10.3 mm, while the seasonal ET fluctuated annually, spanning from 634 to 698 mm. However, among all soil water depletion treatments T2 has shown significant ($P < 0.05$) effects on wheat growth parameters, including the maximum plant height, highest spike length, numbers of tillers and the total weight of 86.8 cm, 10 cm, 137 cm, and 0.59 kg, respectively. The highest WUE was observed in T1, as it produced a relatively good yield with less water, making it the most water-efficient treatment. In contrast, T3 showed the lowest WUE due to excessive water application without proportional yield benefits. These findings suggest that a 50% SWD treatment is optimal for wheat cultivation in arid and semi-arid regions.

Keywords: Mini-lysimeter, Evapotranspiration, Crop Coefficients, Water use efficiency, Soil Water depletion, Wheat (*Triticum aestivum* L.)

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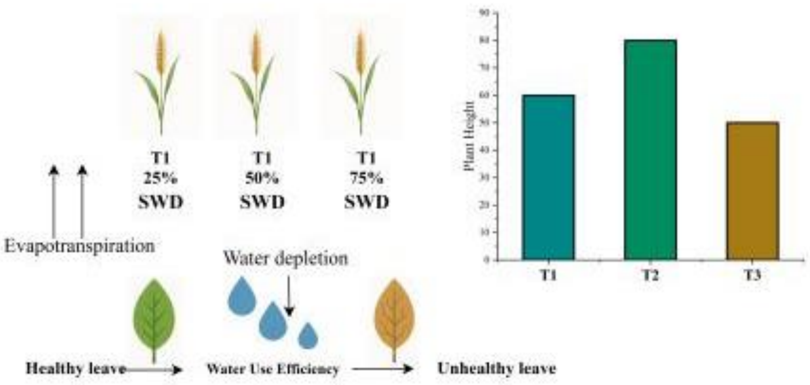
Graphical abstract



1. Introduction

Water is one of the most valuable natural resources, but it is limited in arid and semi-arid zones. Water is becoming a limiting factor for crop production in many parts of the world, particularly in developing countries like India, Pakistan, Sudan, Ethiopia and Nigeria (López-Urrea *et al.*, 2021). Pakistan has the major canal irrigation system, but due to insufficient maintenance, its efficiency is in continuous decline (Allen *et al.*, 2011). Crops need water throughout their growing period, but each crop has a different requirement due to crop type and climatic conditions (Solangi *et al.*, 2024). Approximately 99% of the water absorbed by plants is lost to the atmosphere through transpiration, a key component of evapotranspiration (ETc), while only about 1% is retained for photosynthesis and growth (Sánchez *et al.*, 2015). Standard crop evapotranspiration (ETc) is an essential factor in agro-ecosystems, and it plays an important role in irrigation design and its management (Martínez-Romero *et al.*, 2019). Therefore, it is important to identify the water requirements and crop coefficients for irrigation scheduling, water requirements for crop and agricultural water management. There are two different methods commonly used for calculating crop evapotranspiration (ETc) rate, such as direct and indirect methods. In the direct method, ETc is directly determined by eddy covariance systems, Bowen Ratio and lysimeters. While in the indirect method ETc is determined by the reference crop evapotranspiration (ETo) and crop coefficient (Kc) (Hussain *et al.*, 2023). The Standard crop evapotranspiration (ETc) amount is defined as the loss of water through transpiration of plant vegetative surfaces and water evaporation from the soil surface, which has the potential benefit of managing proper irrigation planning (Allen, Pruitt, *et al.*, 2005). A researcher in 1989 by Allen was first found that standard crop evapotranspiration related to the ET_0, using a conversion factor known as the crop coefficient (Kc). The Food and Agricultural Organization (FAO) recommended the Penman-Monteith reference evapotranspiration method, as described by (Allen *et al.*, 1998), widely used to estimate crop water use and irrigation scheduling. It is necessary to understand sustainable environmental and water management practices, crop water consumption requires data on specific water loss through standard evapotranspiration (Allen, Clemmens, *et al.*, 2005). Estimation of ETc typically employs two-step approaches, with a general agreement between the estimated ETc values and those derived from the lysimeter-measurements (Soler-Méndez *et al.*, 2021). However, irrigation scheduling plays a vital role in the whole plant's life cycle, from seed germination to the plant maturation stage (Piccinni *et al.*, 2009). Irrigation water scheduling is applied to crop water needs, reducing the risk of under- or over-watering (Negash *et al.*, 2023).

Wheat (*Triticum aestivum* L.) is one of the essential cereal diets all over the world including in Pakistan and is mainly grown in cold climatic conditions (Arzani & Ashraf, 2017). It contributes 2.8% to Pakistan's GDP and 13.1% to the economic value added in agriculture. Wheat crops usually require five times irrigation throughout their growth period (sowing to maturity). The water requirements of the wheat crop vary between 180 and 420 mm, but it depends on various conditions. A previous study reported that soil water stress in the soil reduces wheat yield by about 3.3 to 7 tonnes per hectare from spike emergence to maturity stages (López-Urrea *et al.*, 2024). During crop growth stages, maintaining a suitable water requirement could improve crop quality and production, promoting root growth (Rahmati *et al.*, 2018).

There are several studies that focus on the Kc of various crops (Hong *et al.*, 2017). A previous study used drainage lysimeters and neutron probe observations to determine the soil water coefficient and compared the Kc values in plastic mulch conditions and without plastic mulch (Ai *et al.*, 2018). While in another study drainage lysimeters used to calculate Kc for mustard and performed the water bank with watermark sensors in his study (Shankar *et al.*, 2012). Further, Bezerra, *et al.*, (Bezerra *et al.*, 2012) calculated Kc for cotton crops using ETc data obtained from weighing lysimeters. In the north of China's semi-arid climate, researchers irrigated winter wheat and maize using the dual culture Kc method, and after two years of farming, they confirmed a higher Kc in the full bloom and mature stages ranging close to 1.1 and 1.0 mm, respectively (Rajput *et al.*, 2024). Furthermore, weighing lysimeters (WL) have been widely applied to quantify crop water use in several field crops, including spring wheat, canola, and cowpea (Cavalcante Junior 2016; López-Urrea, R. et al 2020). Similarly, lysimeter-based experiments have been conducted by different researchers to determine actual evapotranspiration (ETa) in paddy rice cultivation systems (Kumari, A *et al.*, 2022). Another earlier study demonstrated the single Kc and basal crop coefficients for vegetables and field crops, updating the FAO56 publication (Pereira *et al.*, 2021). This study highlighted the need for accurate ETc investigation to derive new (updated) crop coefficients as provided by the measurement of the lysimeter. This study determines crop Kc in two different soils, such as can residue mulch and bare soil, and finds that growing crops in bare soil raises more Kc compared to mulch soil.

This is most likely because the organic mulch can control surface evaporation (Gupta *et al.*, 2018; Paredes *et al.*, 2017). Recently, increasing food demand and decreasing freshwater availability provide sufficient opportunity to determine the minimum water application amount required for maximum yield. Also, numerous researchers have utilized mini-sized, cheaper, removable weighing lysimeters for various crops. Accurate monitoring of crop evapotranspiration (ETc) and crop coefficient (Kc) is essential for efficient irrigation scheduling and sustainable water resource management, mainly in semi-arid regions where water scarcity is a major constraint. Howvere, wheat (*Triticum aestivum L.*) is a major cereal crop, limited information is available on ETc and Kc values for the locally cultivated variety TJ-83 under semi-arid climatic conditions using small-sized drainage-type lysimeters. Keeping this in mind, the current study conducted a mini-lysimetric experiment on evapotranspiration measurement and developed a crop coefficient curve under different soil water depletion treatments for wheat crops. The main objectives of the study are (1) to determine the crop evapotranspiration (ETc) rate and crop coefficient (Kc) curve for wheat crops. (2) to evaluate the growth parameters of wheat crops including plant height, spike length, number of tillers per lysimeter and grain yield. (3) Further, this study also examines water use efficiency (WUE) under various soil water levels.

Table.1. Presented the initial soil physic-chemical soil properties

Treatment	BD (g/cm^3)	FC (%, v/v)	pH	EC (dS/m)	Sand (%)	Silt (%)	Clay(%)
T1	1.45	26.5	7.6	1.84	27.9	58.06	14.1
T2	1.48	28.4	7.9	1.80	27.0	52.2	15.3
T3	1.46	27.6	7.8	1.82	26.5	58.1	15.4

Note: BD (bulk density) FC (field capacity), pH (soil pH), EC (electrical conductivity).

2. Materials and methods

2.1. Study area and soil determination

A mini-lysimeter experiment was conducted at the Drainage and Reclamation Institute of Pakistan (DRIP), Tandojam, within the coordinates of 25°42′34′′ N and 68°54′08′′ E in Sindh Province, from October 2021 to March 2022, utilizing mini-lysimetric to examine the ETc and Kc for the wheat crop shown in **Figure 1**. We collected soil samples from each lysimeter before sowing and after harvest at the two different depths: 0-15 and 15-30. After that, all samples were manually mixed and prepared to examine the soil basic characteristics (**Table 1**). Water content of soil samples was determined by using an oven-dryer at 110 ºC for 24 hours (Bouyoucos, 1927) and the suggested procedure using the Bouyoucos hydrometer method was used to determine the soil textural classes. Soil electrical conductivity (EC) and the soil pH were examined using an EC meter (SensoDirect Con 100) and a pH meter (SensoDirect pH 110), respectively. The bulk density was measured by the cutting-ring method (Zhou *et al.*, 2015). Both surface water and ground water were available for the irrigation purposes, but surface water was used. Also, we analyzed chemical properties of water, which are shown in **Figure 2**.

2.2. Experimental conditions

The mini-lysimetric experiment is further divided into 12 sub-lysimeters, arranged in two main rows, with six lysimeters in each row. Each sub-lysimeter, 45 cm diameter was covered with a reinforced cement concrete (RCC) pipe having a 120 cm depth. Place the pipes on a cement concrete slab. Two main rows were chosen for the lysimeter, and six lysimeters were settled in each row. Each lysimeter has a perforated, electrified iron pipe with a diameter of 1.25 cm at its bottom to collect the drainage water (**Figure 3**). Fertilizers such as nitrogen (N), phosphorus (P), and potassium (K) were applied at the recommended rates of 120 kg N, 60 kg P_2O_5, and 60 kg K_2O (Laghari *et al.*, 2010). Urea, di-ammonium phosphate (DAP), and sulphate of potash (SOP) fertilizer sources were used for N, P, and K. A full dose of P and K was applied, with the small portion of N applied as the basal dose. The remaining nitrogen was applied in three equal separations at the 2nd, 3rd, and 4th irrigation stages. The TJ-83 wheat variety was used in this experiment, and seeds were collected from the DRIP institute in Tando Jam city. The seeds were manually sown at a rate of 125kgha^{-1} in October 2021.

2.3. Experimental setup

During the entire experimental condition, a buffer zone was provided around the lysimeter setup to prevent any external factors from influencing the results. This buffer zone ensured that the collected data reflected only the conditions within the lysimeter. This setup provides a more accurate analysis of the soil and water interactions. Wheat crop was planted in a furrow pattern, and canal water was used for irrigation scheduling, matching the requirements of the lysimeter experiment. Three replicates were used for each treatment in pattern of complete randomized design (CRD). The irrigation treatments contain soil water depletion levels as follows: T1 (25%), T2 (50%), and T3 (75%). We determined the soil water storage for each treatment and then calculated the required water depth. A previously described formula was used to examine the soil water depth shown in equation 1 (Holmes *et al.*, 2008).

$$D = \frac{(F \cdot C - M \cdot C)}{100} \times B \times d \quad (1)$$

Where: D represents water depth in cm, F.C shows soil field capacity (%), M.C = water content one day before applying water (%), B presents dry bulk density, d = root depth of the crop at the time of irrigation (cm).

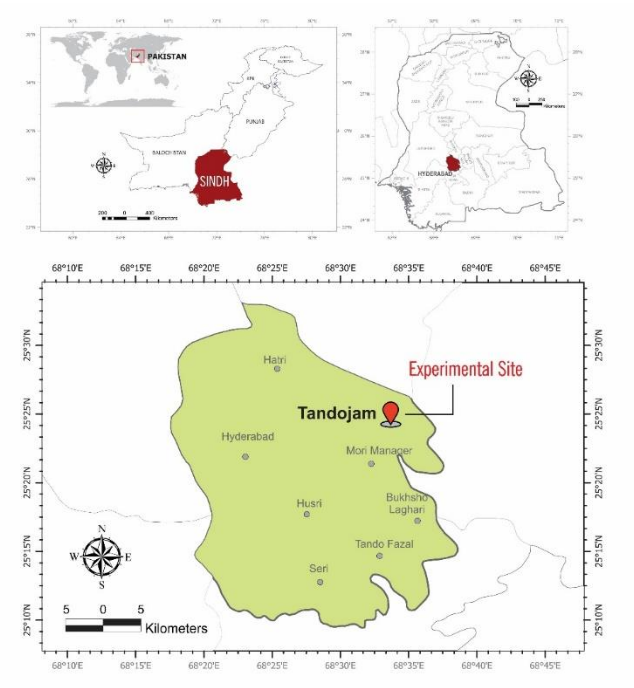


Figure 1. Location map of study area.

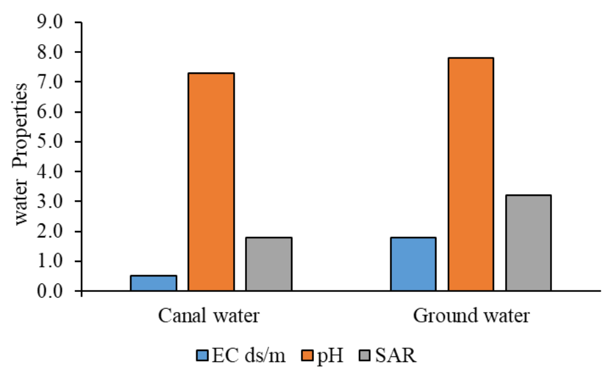


Figure 2. Illustrates the initial canal and ground water properties.

2.4. *Meteorological data collection*

Drainage and reclamation Institute of Pakistan (DRIP) Tando Jam established a meteorological observatory in 1985 at its own campus. Different gadgets are installed for observation, such as a humidity meter, digital temperature, rain gauge, wind vane, three cup anemometer, class A pan evaporation tank and Campbell stocks sunshine recorder. These gadgets provide daily basis data required for ETo measurements. Those data are relative humidity, minimum and maximum temperature (°C), sunshine (hours), wind speed (km/day), wind direction, rainfall (mm), and evaporation rate (mm/day). Current study calculated evapotranspiration (ET_o) by the Modified Penman Method (MPM). To calculate ET_o, the following Equation was used for the MPM method (Doorenbos & Pruitt, 1977).

$$ETo = W \cdot Rn + (1 - W) - f(U) - (ea - ed) \quad (2)$$

where ET_o = reference evapotranspiration (mm/day), W = temperature – related weighting factor, Rn = net radiation in equivalent evaporation (mm/day), f (U) = wind – related function, ea - ed = difference between the saturation vapor pressure at mean air temperature and mean actual vapor pressure (m bar). These parameters were further computed using the relations given by (Doorenbos & Pruitt, 1977).

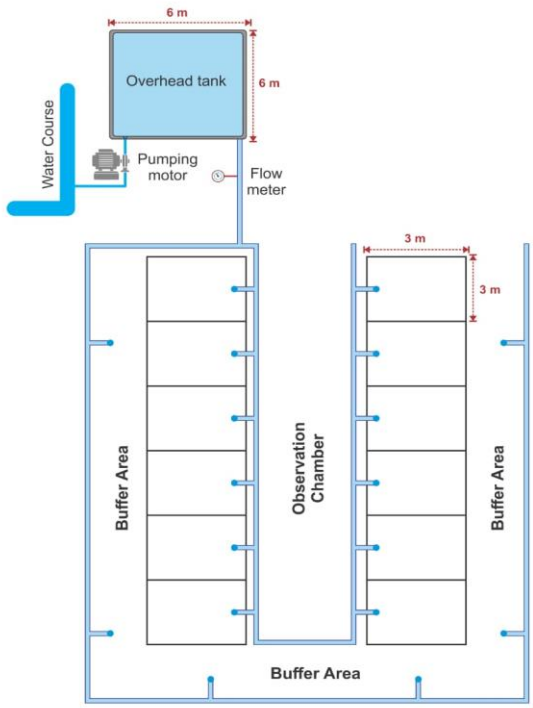


Figure 3. The Experimental setup showed the arrangement of mini-lysimeters, space between lysimeters rows

2.5. *Crop coefficient (Kc)*

The crop coefficient values were calculated to observe the effects of crop characteristics on crop water requirements, as crop coefficient values vary from day to day. The growing period was divided into four growth stages: initial, development, mid, and late to determine crop coefficients. We calculated the crop coefficient values using the following equation (3) (Allen *et al.*, 1998). The curves were developed according to the standard methods.

$$Kc=\frac{ETc}{ETo} \quad (3)$$

where Kc = crop coefficient, ET = crop water requirement (mm day^{-1}) and ET0 = reference evapotranspiration (mm day^{-1}).

2.6. Statistical analysis

A one-way ANOVA on the SPSS Statistics version 20.0 (Corp., Armonk, NY, USA) was used to determine the SWD treatment differences using Tukey's multiple variable tests at $P < 0.05$. The growth parameter figures were prepared by Origin Pro. 9.0 (Northampton, MA, USA).

Table 2. Monthly average maximum and minimum reference evapotranspiration (ET_0), daily actual evaporation (ETa) temperature ◦C (T), relative humidity (RH%), wind speed (WS), and precipitation (P) at the experimental site in 2021- 22 during wheat growing seasons.

Months-Year	Daily Reference ETo (mm)	Daily actual (ETa) (mm)	Max.T (◦C),	Min. T(◦C),	Max. RH (%)	Min. RH (%)	WS (Knot/hr)	P (mm)
Novmber-2021	3.17	3.3	29.39	14.16	82.42	43.84	0.81	0
December-21	2.7	3.4	25.35	11.07	89.4	56.81	1.8	0
January-22	2.16	2.7	25.81	9.84	93.3	49.29	0.89	0
February -22	3.33	3.02	26.16	12.39	39.71	44.52	1.08	0
March-22	5.32	5.31	37.03	19.27	92.60	49.00	1.58	2.5
April-22	6.52	8.73	40.40	23.87	85.40	53.87	2.76	0.0
May-22	7.05	9.96	42.19	27.40	87.65	58.06	3.73	0.0

3. Results

3.1. Meteorological Conditions

The meteorological station of the experimental field measured daily evapotranspiration, temperature (T), wind speeds (WS), relative humidity (RH), precipitation (P), and sunshine hours (SH) from November 2021 to May 2022 (**Table 2**). For the entire experimental period, the field meteorological station recorded a total Potential Evapotranspiration (ETP) of 118.2 mm, with the lowest being 82.2 mm. The month of May recorded the highest average daily ETo and ETc measuring 7.1 mm and 9.96 mm, respectively. In December, the ET0 was lower by 2.6 mm. However, the monthly highest average temperature ranged between 27.3 and 42.2 ◦C and the wind speed between 3.37 and 0.81 knots/hr. Throughout the entire study period, November recorded the lowest average RH (%) value at 43.8%, while February recorded the highest mean at 92.3%. The month of March recorded 2.5 mm of precipitation throughout the entire experimental period.

3.2. Wheat growth parameters

Soil water depletion (SWD) treatments significantly ($P < 0.05$) affect the wheat growth parameters such as plant height, spike length, number of tillers per lysimeter, and total weight (test weight) per tiller in treatments as presented in **Figure 4**. Maximum plant height was 86.8 cm in T2, while the minimum plant height was noted at 71.4 cm in T3. This value was in between T2. However, the higher spike length of 10 cm was noted when the plant was irrigated at a 50% depletion level (T2) treatment. The T3 treatment produced the smallest spike length, measuring 9.1 cm. The average number of tillers per lysimeter ranged between 100 and 137 under all treatments. T2 recorded the highest number of tillers as 137, while T3 recorded the lowest number as 100. Compared to other depletion treatments, the plants irrigated in the 50% water depletion range produced a greater test weight of 0.59 kg per tiller. Despite verifying the lowest test weight of wheat 0.32 kg/lysimeters in the 75% water depletion treatment (**Figure 4**).

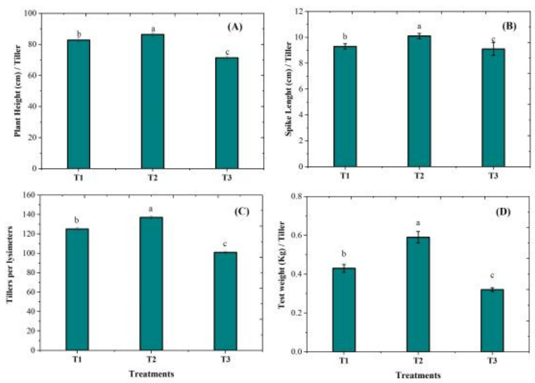


Figure 4. Effects of different soil water depletion treatments on plant height, spike length, numbers of tiller per lysimeter and test weight. Note: T1; 25% T2; 50% and T3; 75% SWD treatments, average ± SE ($n = 4$), different letters, indicate significant differences according to Tukey's multiple variable tests at $P < 0.05$ level.

3.3. Biomass yield and grain yield.

The SWD applications affected the biomass yield and grain yield (kg/ lysimeter) of the wheat crop, as shown in **Figure 5**. The higher wheat biomass yield was seen in T2 treatment by 0.376 (kg/L) among all treatments. The lowest biomass yield was recorded at 0.220 kg/lysimeter on T3 treatment. In the T2 treatment, the grain yield increased by 0.186 kg/lysimeter, whereas the T3 treatment recorded a lower grain yield of 0.119 kg/lysimeter.

Table 3. Irrigation scheduling and water use efficiency (WUE) of wheat crop throughout the season.

Irrigation water depth (mm)	WUE (mm)	
T1	264.5	21.25
T2	332	20.5
T3	451.4	9.6
Total	1047.9	51.3

Note: *T1 (15%), T2 (50%), and T3 (75%) soil moisture depletion treatments*

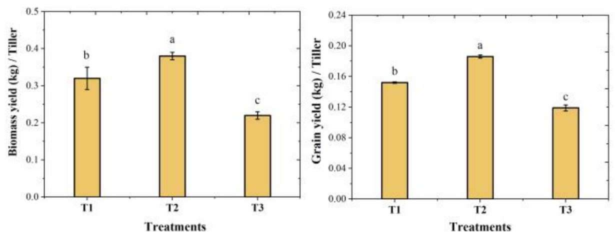


Figure 5. Influence of different SWD treatments on fresh biomass yield, and grain yield kg/lysimetric. Note: T1; 25% T2; 50% and T3; 75% SWD treatments, average ± SE (*n* = 4), small letters within the same column, indicate significant differences according to Tukey's multiple variable tests at *P* < 0.05 range.

3.4. Irrigation scheduling and water use efficiency

Table 3 presents the average irrigation levels applied during different growth stages of each treatment. The wheat crop's WUE varied across different moisture depletion levels. The total water applied under T1 was 264.5 mm, under T2 was 332 mm, and under T3 was 451.4 mm. The highest WUE was observed in T1, as it produced a relatively good yield with less water, making it the most water-efficient treatment. In contrast, T3 showed the lowest WUE due to excessive water application without proportional yield benefits.

3.5. Crop coefficient (Kc) curve

The Kc ranges significantly depend on wheat growth stages (initial, mature, mid, and later stages) and SWD applications (**Figure 6**). The results indicated that the values at the initial stage were 0.51, 0.64, and 0.87 for T1, T2, and T3, respectively. The T3 (SWD 75%) treatment showed a significant drop in Kc during the development stage, indicating that reduced water availability impacted the efficiency of water use in crops at this depletion level. The Kc values at the mid-stage decreased in the following orders: T1, T2, and T3, by 0.43, 0.55, and 0.74, respectively. These results demonstrated that adequate water usage efficiency (SWD 50%) could potentially support better growth during this critical stage. The values for late stages were 0.27, 0.34, and 0.47 under T1, T2, and T3, respectively. However, the overall seasonal crop coefficient under TI, T2, and T3 is 0.45, 0.57, and 0.77, respectively.

4. Discussion

The current study practices mini-lysimeters to investigate the ETa, Kc, and growth parameters of wheat crops under different soil water depletions. Lysimeters are widely used to assess ETc and developed crop coefficients. However, traditionally large size lysimeters are often expensive, challenging to install, time-consuming and difficult to manage (Ruth *et al.*, 2018).

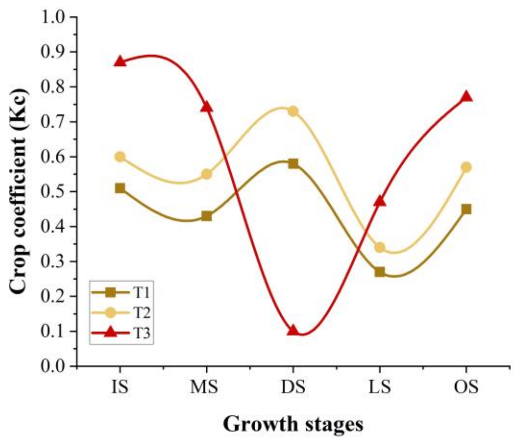


Figure 6. Crop coefficient curve for different growth stages of wheat crop IS (initial stage), DS (development stage), MS (mature stage), LS (late stage).

Recently, mini-lysimeters, which are small pieces of structural equipment, have become more popular because they are cheaper and easier to use for keeping track of soil water balance. They could be a good replacement for large weighing lysimeters (Nicolás-Cuevas *et al.*, 2020). In this study, the daily ETc of wheat varied from 2.07 mm to 9.96 mm, while reference of the ETo reached from 634.2 mm to 697.7 mm, respectively. These findings are consistent with previous studies that were conducted in China utilized weighing lysimeters to measure ETc and evaluate models. Previous study showed influencing daily ETc, with radiation accounting for up to 88% of the changes in evapotranspiration, which emphasized the role of solar radiation (Yang & Lei, 2022). In early growth stages of the plant the evaporation shows the major loss of water through the evapotranspiration of the crop, despite regular irrigation intervals. By crop development, the soil cover by the plant leaves greatly decreased the direct evaporation of the soil, and the crop physiology became more descriptive in the evapotranspiration (Sánchez *et al.*, 2015). Additionally, an earlier study demonstrated that soil water evaporation accounts for 29 % of ETc during wheat crop cultivation (Khan *et al.*, 2020).

The researchers advised exercising caution when investigating data on soil water evaporation from small lysimeters. Plant roots and small-lysimeters soil no longer lose water, so it's possible to overestimate the amount of water evaporation. Because covered soil can be used as a tool to minimize water loss through evaporation (Gul *et al.*, 2023). However, wheat growth parameters are significantly different between treatment for soil moisture depletion. In this study, 50% soil moisture depletion increased greater biomass, grain yield, and plant height, compared to other SWD treatments. The previous study revealed similarities, showing that decrease in the essential amount of irrigation water under a sprinkler irrigation system could reduce wheat grain by 7% (Teshome *et al.*, 2023). In contrast, another study described that nearly 50% of water stress could significantly enhance matter production and yield of wheat crops (Thapa *et al.*, 2023). Measuring soil moisture and water storage changes is critical for estimating crop water availability and developing management methods that maximize the use of environmental resources. This monitoring allows for the determination of the water balance and the avoidance of water losses due to drainage. Crop coefficient (Kc) is an essential factor required to plan irrigation schedules and estimate crop water use (Alcaras *et al.*, 2016).

Modern advances in computer vision have verified strong potential for early pest detection in coffee plantations, with Hybrid Vision Graph Neural Networks (HV-GNN) attaining a detection accuracy of 93.66% on annotated coffee plant pictures. This methodology enables automated and precise recognition of major pests such as Coffee Berry Borer and Leaf Miners, proving proactive pest organization and enhanced crop productivity (Maruthai et al 2025). Current improvements in hybrid vision graph neural networks have shown strong potential for experimental pest discovery in coffee plantations, achieving over 93% detection accuracy using labeled field datasets (Maruthai et al 2025). Such intelligent vision-based systems assist precise identification of multiple insect infestations, supporting timely intervention and sustainable crop protection strategies (Rekha R Nair et al 2025; Venkatraman M et al 2023). Blockchain-integrated monitoring frameworks enhanced with IPFS have demonstrated high scalability and consistency for continuous crop inspection, achieving 98% accurateness while confirming assured and confidential data conduction. Such devolved systems support real-time decision-making in plant and water management by developing data integrity, cost-efficiency, and transparency in accuracy agriculture (Vinayagam et al 2025; Sivasubramanian et al 2025).This study evaluates the Kc value for the wheat crop, and the results indicate that suitable water usage efficiency SWD in 50% at the mid-stage could potentially support better growth during this critical stage. The Kc values, described as ETc/ETo, signify crop characteristics. Irrigation systems, crop species, and ecological conditions affect it, but it varies little with climate change (Gao *et al.*, 2021). Wheat irrigation requirements were estimated using two methods: locally developed crop coefficients (Kc) and FAO-recommended Kc values follow by (Gul *et al.*, 2024) With the locally developed Kc, requirements ranged from 758.4 to 848.3 mm, with an average of 800.2 mm. Using FAO Kc values, estimates ranged from 835.5 to 935.6 mm, averaging 912.2 mm (Djaman *et al.*, 2018). Different studies demonstrated the Kc values for wheat crops with various irrigation methods in different areas. According to these reports, winter wheat monocultures in Northern China have Kc values ranging from 0.26 to 0.80, 0.91 to 1.44, and 0.27 to 0.98 at the early, mid, and late growth stages, respectively. The Kc values for the mid- season first declined and then progressively increased between February to May the year of 2022–2023. Furthermore, research was also conducted for the wheat crop and measured the Kc values from 0.54 at the early growth stage to 1.15 at the mid-season stage (Ko *et al.*, 2009). The Kc curve of this study presents the modification at the vegetation stage and shows the effects of ETc during plant development and maturation. Therefore, it reached its highest and relatively remained constant at the mid-season stage, and values of Kc decreased quickly during the late-season stage. Recently, innovative technologies and strategies, including machine learning and remote sensing models, were utilised to estimate the ETo (Deng *et al.*, 2024) . Research carried out in northern China, characterized by a semi-arid climate with dry, cold winters and hot, humid summers, evaluated the dual crop coefficient (Kc) method for wheat (irrigated in winter) and corn. The study recorded maximum basal crop coefficient (Kcb) and soil evaporation coefficient (Kc) values of approximately 1.1 and 1.0, respectively, during the flowering and maturation stages over two cultivation years (Wang *et al.*, 2012). As the crop matures, leaf canopy cover increases, reducing direct soil evaporation and making the crop more dominant in the evapotranspiration process. Another study in China, which focused on determining the Kc for drip-irrigated wheat crop, found that Kc values of 0.25, 1.06, and 0.34 during the initial, mid, and final growth stages, respectively (Irmak *et al.*, 2015). Total crop evapotranspiration over three cultivation years ranged from 393 to 449 mm. Recently, innovative technologies and strategies, including machine learning and remote sensing models, were utilised to estimate the ETo (Kumar *et al.*, 2024). Future research further needs to use these advanced methods and compare the scope of applicability of different methods in our study area.

5. Conclusion

This study uses mini-lysimeters to highlight the critical role of wheat growth parameters from November 2021 to May 2022. The T2 (50% SWD) promoted maximum wheat growth parameters, such as fresh biomass plant height and spike length. The T3 (75% SWD), which effectively supports optimal crop development, produced the lowest values across all growth parameters, suggesting that excessive moisture depletion can significantly delay wheat growth and development. However, T1 (15% SWD) has supported water effectively; it may not provide sufficient moisture for optimal wheat growth. The 50% (T2) SWD treatment yielded better wheat growth parameters, as evidenced by improved crop parameters like plant height, spike length, and biomass. On the other hand, the 75% (T3) SWD produced the lowest values across all parameters, indicating that excessive moisture depletion can delay wheat development. These findings suggest that precise irrigation management, particularly with a 50% moisture depletion threshold, can optimize wheat production and improve water conservation in semi-arid regions. The study also highlights the importance of continuously monitoring meteorological variables to enhance irrigation strategies and crop productivity in water-limited environments. Adopting this strategy could enhance both water use efficiency and wheat productivity. Future studies should investigate the long-term performance of drainage-type mini-lysimeters across different wheat cultivars, soil textures, and climatic zones to validate the broader applicability of the 50% SWD threshold. Additionally, integrating lysimeter-based measurements with remote sensing techniques and climate variability analyses could further improve evapotranspiration estimation, dynamic crop coefficient development, and precision irrigation management strategies.

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Data Availability Statement

The raw data can be obtained upon reasonable request.

Competing interests

The authors stated that they had no conflict of interest.

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