https://doi.org/10.17221/72/2025-SWR

Evapotranspiration and crop coefficient of drip irrigated walnut trees in semi-arid climatic conditions, Türkiye

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Citation: Erdem T., Göçmen E., Şener M., Coşkun Z., Yaşasın A.S., Önler B. (2026): Evapotranspiration and crop coefficient of drip irrigated walnut trees in semi-arid climatic conditions, Türkiye. Soil & Water Res., 21: 121–132.

Abstract: This study was conducted to find out the seasonal evapotranspiration (ET_c) and crop coefficient (K_c) for walnut trees (ages one to nine) that were grown with drip irrigation in Türkiye's semi-arid climate. Three different irrigation levels were applied at five-day intervals based on cumulative Class A pan evaporation using irrigation treatment coefficients (K_t = 0.75, 1.00, and 1.25) during the 2015, 2016, 2017, 2018, 2019, 2021, 2022, and 2023 growing seasons. The amount of irrigation water applied to the treatments varied from year to year according to the measured Class A pan evaporation amounts. The total amount of irrigation water applied to the treatment subjects varied between 371.7 mm and 619.6 mm as an average of eight years. Total ET_c of walnut trees varied over the years depending on the applied irrigation water and measured rainfall. The total evapotranspiration estimated from the I_2 treatment, representing the irrigation regime in which 100% of Class A pan evaporation was applied, fluctuated between 676.5 and 585.9 mm over the study years. The daily reference evapotranspiration (ET_0) values are calculated as between 1.85 and 7.07 mm/day. The K_c values for walnut trees were calculated as 0.55 for April, 0.71 for May, 1.02 for June, 1.07 for July, 1.01 for August, and 0.74 for September on average. The research revealed that seasonal evapotranspiration and plant coefficient values can assist in calculating the water requirements of walnut trees and improve water management in semi-arid regions.

Keywords: irrigation regimes; irrigation water use; precipitation; reference evapotranspiration

The increasing global scarcity of water is rendering agricultural production progressively more vulnerable, particularly in semi-arid and arid regions. Rising temperatures associated with climate change, irregularities in the spatial and temporal distribution of precipitation, and the increasing frequency of drought have made agricultural irrigation both indispensable and more complex to manage (Partigöç & Soğancı 2019; Deveci et al. 2025). Under these conditions, the efficient and sustainable use of limited water resources emerges as a fundamental requirement for the continuity of agricultural production and the conservation of natural resources.

One of the most critical variables in establishing a scientific basis for irrigation planning is crop evapotranspiration (ET_c), which represents the actual water consumption of plants. In practice, ET_c is most commonly estimated by multiplying reference evapotranspiration (ET_0) by the crop-specific coefficient (K_c). Therefore, K_c constitutes a key parameter in the

Supported by the Turkish Scientific and Technical Research Council (TUBITAK), Projects 114O532 and 120R072 and by the Tekirdağ Namık Kemal University Research Fund (TNKU-BAP), Project NKUBAP.03.YL.18.173.

https://doi.org/10.17221/72/2025-SWR

accurate determination of crop water requirements. However, K_c values vary significantly depending on crop species, growth stage, and climatic conditions. The direct application of generalised or average K_c values reported in the literature to different ecological conditions often leads to erroneous estimation of actual ET_c; this, in turn, results in insufficient or excessive irrigation practices, causing both yield losses and inefficient water use (Kadam et al. 2021). In this context, finding accurate ET_c and K_c values based on field measurements for different crop species and cultivation conditions forms the foundation of sustainable irrigation management.

In recent years, numerous studies have been conducted to determine ET_c and K_c across various crop species and ecological conditions (Jafari et al. 2021; Drechsler et al. 2022; Koç et al. 2022; Matsunaga et al. 2022; Pandey et al. 2023; Zhang et al. 2023; Baştuğ et al. 2024; Paredes et al. 2024; Pereira et al. 2024). However, a substantial proportion of these studies is based on short-term experiments, a single growth stage, or limited age ranges. Particularly in perennial fruit trees, canopy cover, root depth, and physiological characteristics change with plant age; accordingly, water consumption and K_c values acquire a dynamic structure. Indeed, studies on walnut (*Juglans regia* L.) indicate that crop water use varies over a wide range under different climatic and irrigation conditions. For example, under conditions in the United States, ET_c values for walnut have been reported to range between 1 100 and 1 200 mm, with monthly K_c values reaching up to 1.14 in mid-summer (Fulton et al. 2017). In contrast, studies conducted in China using under-tree micro-sprinkler irrigation have reported ET_c values in the range of 585.6–840.3 mm. In recent research carried out in high-density walnut orchards under semi-arid conditions in Argentina, ET_c values were found to vary between 656 and 709 mm (Calvo et al. 2022). These examples demonstrate that water consumption and Kc values in walnuts can differ markedly depending on climate, cultivation system, and plant developmental level; consequently, they clearly reveal the need for long-term field-based studies extending from the seedling stage to full maturity in order to reliably define ET_c and K_c in fruit trees.

Walnut (*Juglans regia* L.) is an important fruit species in many countries due to its economic value and widespread cultivation. Although studies determining ET_c and K_c values for walnut exist in different countries, these data are generally limited to specific regions and restricted time periods. In particular, for the Chandler cultivar, which has become widely adopted worldwide in recent years, ET_c and K_c studies based on long-term field measurements under semi-arid climatic conditions and modern irrigation systems are extremely limited in the literature.

Although Türkiye has significant potential for walnut cultivation, reliable ET_c and K_c data for walnut orchards grown under semi-arid climatic conditions are lacking. This deficiency makes it difficult for producers and practitioners to develop irrigation schedules on a scientific basis and often leads to intuitive practices.

The aim of this study is to determine seasonal ET_c values and monthly K_c based on field measurements conducted over eight vegetation periods, covering the developmental stages of Chandler walnut trees planted in 2015 in the Tekirdağ region with semi-arid climatic conditions, from 1 to 9 years of age. By revealing age- and season-dependent water consumption dynamics in walnut, the study seeks to provide a scientific basis for the development of more precise, reliable, and sustainable irrigation programs for walnut orchards in semi-arid regions.

MATERIAL AND METHODS

Experiment site and growth conditions. The research was conducted in Tekirdağ Province, located in northwestern Türkiye (40°59'N, 27°29'E), at the experimental fields of the Tekirdağ Viticulture Research Institute during the years 2015, 2016, 2017, 2018, 2019, 2021, 2022, and 2023. In 2020, no data could be collected due to the inability to carry out field studies and to perform regular measurements as a result of the COVID-19 pandemic; therefore, this year was excluded from the scope of the study. The region exhibits semi-arid climatic characteristics, with a long-term average annual precipitation of 580.8 mm, approximately 30% of which occurs between October and April. The distribution of monthly mean temperatures and total precipitation amounts for the April–October period in the study years is presented in Figure 1, indicating pronounced interannual variability in both temperature and precipitation among the experimental periods.

In the experimental area, Chandler walnut saplings were established in 2015 with a planting spacing of 8.0 × 8.0 m. The study was carried out over eight vegetation periods, covering the developmental stages of the trees from 1 to 9 years of age. The experiment was arranged according to a randomised complete

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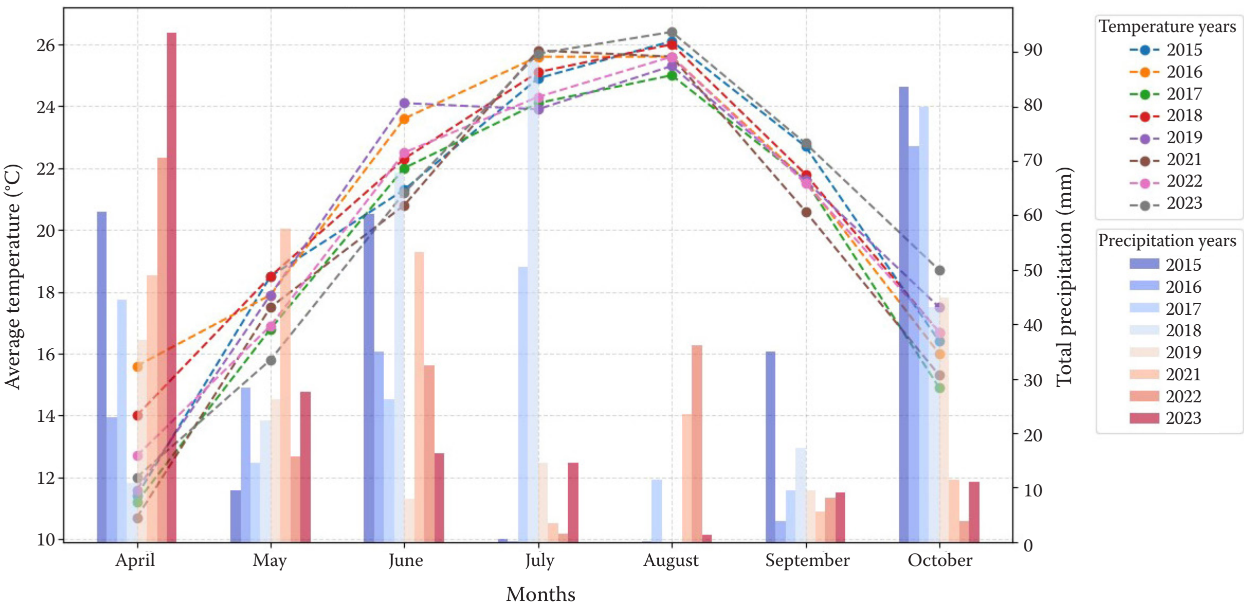

Figure 1. Average temperature and precipitation values for research years

block design with three irrigation treatments and three replications, resulting in a total of nine experimental plots; each plot measured 24.0 × 32.0 m (768 m^2) and consisted of 12 trees. During the irrigation season, weed control was performed when necessary, using mechanical methods both within and outside the plots. No permanent ground cover crop was maintained between tree rows, and the soil surface remained predominantly bare during the growing period.

Table 1 lists some physical and chemical properties of the irrigation-related experimental field soil. The soil texture is clay loam (CL) in the upper layers and clay (C) in the lower layers. The soil has no salinity or alkalinity problems. The available water-holding capacity within the soil profile at a depth of 0–120 cm is 162.36 mm. The irrigation water is classified as C2S1, with an electrical conductivity (EC) of 0.72 dS/m and a sodium adsorption ratio (SAR) of 0.9. Also, soil infiltration rate was measured as 12 mm/h.

Irrigation management and evapotranspiration measurements. Drip irrigation was employed in the experiment. Irrigation water was supplied from a reservoir located near the experimental area, and the system was equipped with a screen filter, a pressure regulator, and inlet–outlet manometers. The lateral lines were made of 16 mm polyethylene (PE) pipes, and each tree row was irrigated by two lateral lines. The spacing between emitters on the laterals was set at 50 cm.

In parallel with tree growth, the system was revised annually. Based on canopy width and arranged symmetrically for each tree, pressure-compensating on-line (top-inserted) emitters with a discharge rate of 4 L/h were used as follows: six emitters per tree during the first three years (2015, 2016, and 2017), eight emitters in the fourth and fifth years (2018 and 2019), twelve emitters in 2021, fourteen emitters in 2022, and sixteen emitters in 2023. This setup allowed the wetted area to grow along with the trees.

Table 1. Some soil properties of the experimental site

Soil depth (cm)	Texture class	Field capacity (m^3/m^3)	Wilting point (m^3/m^3)	Bulk density (g/cm^3)	Organic matter (%)	pH	EC (dS/m)
0–30	CL	0.388	0.267	1.49			
30–60	CL	0.450	0.311	1.58	0.86	7.62	0.60
60–90	C	0.511	0.370	1.61	1.12	7.77	0.61
90–120	C	0.477	0.334	1.58			

CL – clay loam; C – clay; EC – electrical conductivity

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Irrigation practices were based on evaporation data obtained from a Class A evaporation pan installed in the experimental area. Daily evaporation amounts were measured each day at 09:00; the water lost from the pan surface was replenished using a graduated measuring cylinder, and the daily evaporation value was thus determined. The irrigation interval was set at 5 days, taking into account the common practices of local farmers and the characteristics of walnut trees. Therefore, in calculating irrigation water amounts, the cumulative total of daily measurements over five days was used.

For each irrigation event, the amount of water to be applied was determined as 75%, 100%, and 125% of the five-day cumulative Class A pan evaporation (E_p) values and was calculated using the following equation (Equation 1) (Kanber et al. 2004):

$$I = E_p \times K_t \times P_w \quad (1)$$

where:
$I_{1,2,3}$ – the irrigation water amount applied to the experimental treatments (mm);
E_p – the five-day cumulative Class A pan evaporation (mm);
K_t – the irrigation treatment coefficient (0.75, 1.00, and 1.25);
P_w – the wetted area ratio (%).

The wetted area ratio (P_w) was determined before each growing season based on canopy width and was assumed to remain constant throughout the season.

Determination of soil moisture and evapotranspiration. Soil moisture measurements were conducted gravimetrically in order to determine the change in soil water content (ΔS), which is required for calculating crop water consumption using the soil water balance approach.

For this purpose, prior to each irrigation event, soil samples were collected from each plot within the 0–120 cm soil profile in 30 cm layers (0–30, 30–60, 60–90, and 90–120 cm), and soil moisture content was determined on a dry-weight basis.

According to FAO-56, crop evapotranspiration under standard conditions (ET_c) represents evapotranspiration from well-managed and disease-free crops grown under optimum soil water conditions (Allen et al. 1998). In the present study, fertilisation, disease control, and pruning practices were regularly carried out, and irrigation was carefully managed within the experimental treatments. Therefore, under these experimental conditions, the actual field evapotranspiration was assumed to be equal to ET_c.

Evapotranspiration (ET_c) was calculated using the soil water balance approach based on the effective root depth of the crop (Equation 2) (Walker & Skogerboe 1987; James 1988):

$$ET_c = I + P + C_p - D_p \pm R_f \pm \Delta S \quad (2)$$

where:
I – the applied irrigation water (mm);
P – the precipitation during the experimental period (mm);
C_p – the amount of water entering the root zone through capillary rise (mm);
D_p – the deep percolation loss occurring after irrigation and rainfall (mm);
R_f – the surface runoff entering or leaving the experimental plots (mm);
ΔS – the change in soil water content during the measurement period (mm).

Since the groundwater table in the research area is located well below the effective root zone of walnut trees, capillary rise from groundwater was assumed to be negligible ($C_p = 0$). As drip irrigation was applied in the experiment, surface runoff (R_f) was also considered negligible. Deep percolation losses (D_p) were evaluated based on soil moisture measurements taken at the 90–120 cm depth following irrigation and rainfall events. Since no significant increase in soil moisture was observed in this layer, deep percolation was considered negligible in the soil water balance calculations.

Reference evapotranspiration and crop coefficient calculations. The reference evapotranspiration (ET_0) was calculated using daily climatic data by means of the FAO-56 Penman–Monteith method revised by Allen et al. (1998) (Equation 3):

$$ET_0 = \frac{0.408\Delta(R_n - G) + \gamma \frac{900}{T + 273} u_2 (e_s - e_a)}{\Delta + \gamma(1 + 0.34u_2)} \quad (3)$$

where:
ET_0 – the reference evapotranspiration (mm/day);
Δ – the slope of vapour pressure curve (kPa/°C);
R_n – the net radiation at the crop surface (MJ/m^2/day);
G – the soil heat flux density (MJ/m^2/day);
γ – the psychrometric constant (kPa/°C);
T – the mean daily air temperature (°C);
u – the wind speed at 2 m height (m/s);

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e_s – the saturation vapour pressure (kPa);
e_a – the actual vapour pressure (kPa).

Crop coefficient (K_c) values were calculated for 10-day periods using the following equation (Equation 4) (Güngör & Yıldırım 1989; Allen et al. 1998):

$$K_c = \frac{\mathrm{ET_c}}{\mathrm{ET_o}} \tag{4}$$

RESULTS AND DISCUSSION

Walnut evapotranspiration (ET_c). The amounts of irrigation water applied to the walnut trees and the total crop evapotranspiration estimated from the soil water balance are presented in Table 2. In all study years, irrigation and measurements were generally carried out during the April–October period; the annual number of irrigations ranged from 13 to 23, with an average of 18. Precipitation during the measurement periods varied between 81.0 and 215.5 mm depending on the year. The applied irrigation water amounts differed among years based on open water surface evaporation. Over the years, the amounts of irrigation water applied ranged between 251.5 and 446.7 mm for treatment I_1, between 335.4 and 595.6 mm for treatment I_2, and between 419.2 and 744.5 mm for treatment I_3.

The total ET_c values of the walnut trees varied among years depending on the applied irrigation

Table 2. Amounts of irrigation water applied and estimated total evapotranspiration to walnut trees aged 1-9 years.

Year	Irrigation level	Measurement period	Rainfall (mm)	Number of irrigations	Total applied irrigation water (mm)	Estimated total evapotranspiration (mm/90 cm)
2015 (1 years old)	I_1	March 23 to October 5	209.0	23	446.7	732.8
	I_2				595.6	858.9
	I_3				744.5	978.9
2016 (2 years old)	I_1	April 1 to October 6	81.0	22	439.6	615.9
	I_2				585.9	757.5
	I_3				732.4	905.7
2017 (3 years old)	I_1	April 11 to October 12	215.5	19	333.3	593.8
	I_2				444.0	688.5
	I_3				555.2	793.8
2018 (4 years old)	I_1	April 12 to September 23	211.4	13	251.5	586.7
	I_2				335.4	676.5
	I_3				419.2	744.3
2019 (5 years old)	I_1	April 6 to September 26	110.0	18	361.5	575.9
	I_2				481.9	697.4
	I_3				602.4	809.9
2021 (7 years old)	I_1	April 4 to October 22	202.4	17	355.9	673.6
	I_2				474.5	782.5
	I_3				595.2	893.1
2022 (8 years old)	I_1	April 1 to October 22	168.5	17	338.2	601.7
	I_2				450.9	702.8
	I_3				563.7	791.1
2023 (9 years old)	I_1	April 6 to October 24	155.0	15	446.6	683.9
	I_2				595.4	825.1
	I_3				744.3	963.9
Average	I_1	April to October	169.10	18	371.7	633.0
	I_2				495.5	748.7
	I_3				619.6	860.1

I_1 – 75%; I_2 – 100%; I_3 – 125%

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Table 3. Reference evapotranspiration (ET_0) values calculated according to the Penman-Monteith method in the measurement years (mm/day)

Year	Month					
	April	May	June	July	August	September
2015	1.85–2.69	2.69–4.20	2.78–4.95	4.75–5.79	4.84–5.71	3.09–5.24
2016	3.10–3.28	3.14–3.57	3.64–6.07	5.33–6.47	5.54–6.32	4.37–4.55
2017	2.45–3.32	3.32–3.50	3.82–4.69	4.19–5.67	4.13–7.07	3.73–3.98
2018	2.74–2.82	3.68–4.74	3.76–4.91	4.92–5.47	4.39–6.60	3.50–3.57
2019	2.60–3.22	3.78–4.90	4.32–5.54	4.08–5.83	5.05–5.95	3.47–4.58
2021	2.44–3.00	4.08–4.45	4.33–5.39	6.10–6.15	4.76–5.57	3.03–4.36
2022	2.45–3.47	3.33–4.62	4.88–5.36	5.60–5.82	4.32–5.90	3.55–4.16
2023	2.06–2.88	3.20–3.51	4.34–5.22	5.77–6.10	5.16–5.34	2.72–4.78

level and precipitation amounts. In all treatments, the highest ET_c values were estimated in 2015, when the trees were one year old. As the trees developed, canopy cover increased; accordingly, annual ET_c values converged over the years and exhibited a more balanced pattern. The differences in ET_c estimated among irrigation levels were maintained in all years, indicating that evapotranspiration is sensitive to the amount of water applied. In treatment I_2, in which 100% of Class A pan evaporation was applied, total ET_c values ranged between 676.5 and 858.9 mm.

The ET_c values obtained in this study are generally consistent with those reported in the literature. Zhao et al. (2010) reported that seasonal ET_c values of 10-year-old walnut trees irrigated by micro-sprinkler systems under Chinese conditions ranged between 585.6 and 840.3 mm. In Argentina, the ET_c range reported for 7–8-year-old Chandler walnut trees is 656 to 709 mm (Calvo et al. 2022). In contrast, the ET_c values of 1 100–1 200 mm reported by Fulton et al. (2017) for the March–November period under U.S. conditions are higher than those obtained in the present study.

Reference evapotranspiration (ET_0). Reference evapotranspiration values calculated according to the climate data in the measurement periods for each research year according to the Penman-Monteith method are given in Table 3. Calculated daily reference evapotranspiration values varied between 1.85 and 7.07 mm/day. Reference evapotranspiration values were calculated to be higher in June-July and August months depending on climate data.

Walnut crop coefficient (K_c). The crop coefficient graphs obtained by ratioing the ten-day ET_c values between April and September to the ET_0 for three different irrigation applications (I_1, I_2 and I_3) in each research year are given in Figures 2–9. Among the

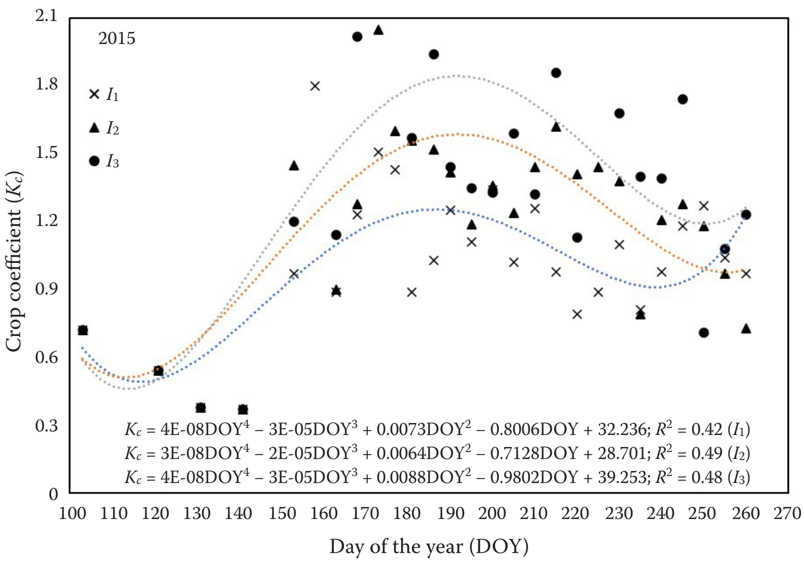

Figure 2. Plant coefficient curve for 2015 (1 years old)

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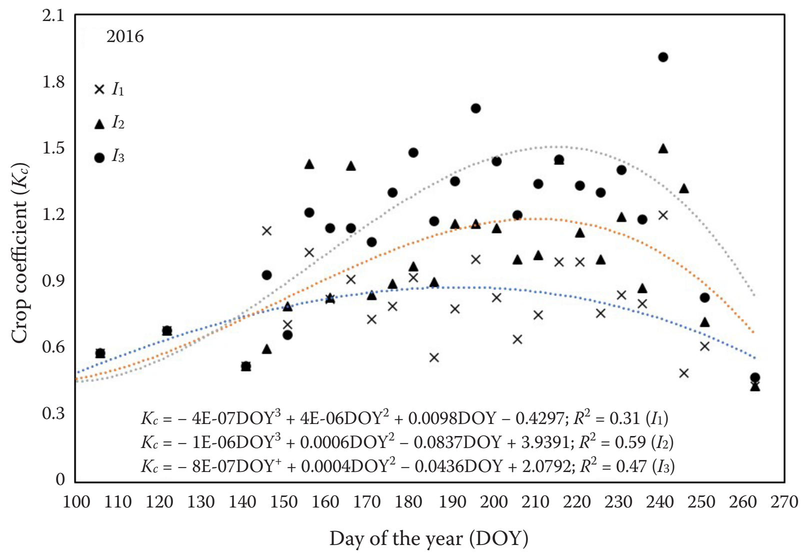

Figure 3. Plant coefficient curve for 2016 (2 years old)

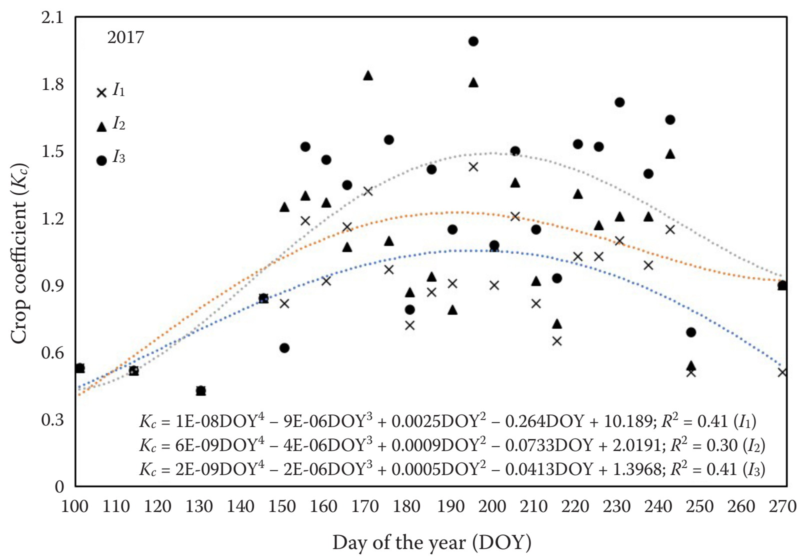

Figure 4. Plant coefficient curve for 2017 (3 years old)

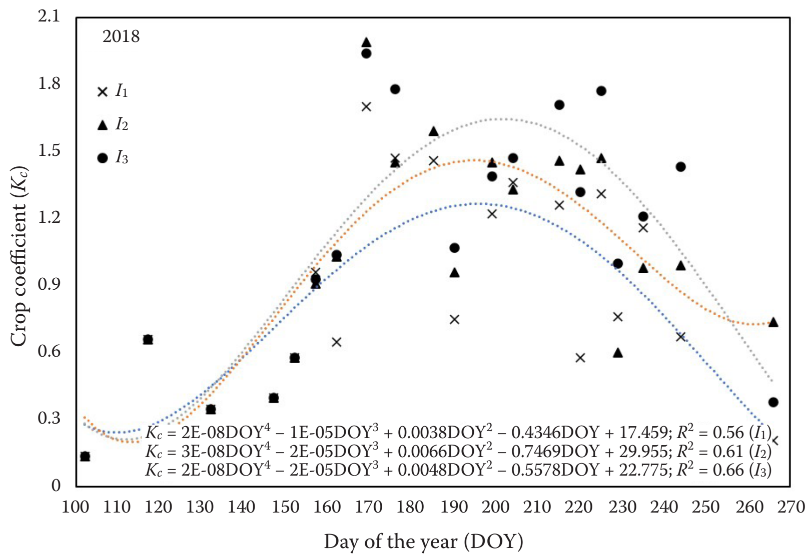

Figure 5. Plant coefficient curve for 2018 (4 years old)

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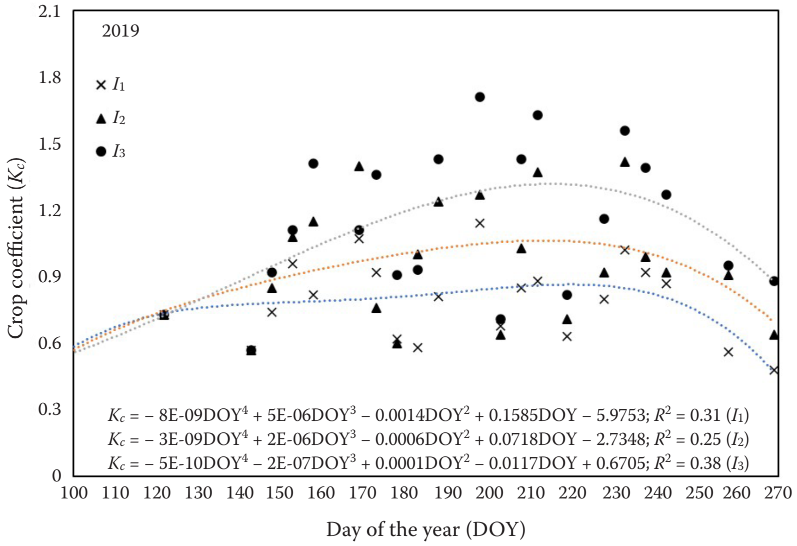

Figure 6. Plant coefficient curve for 2019 (5 years old)

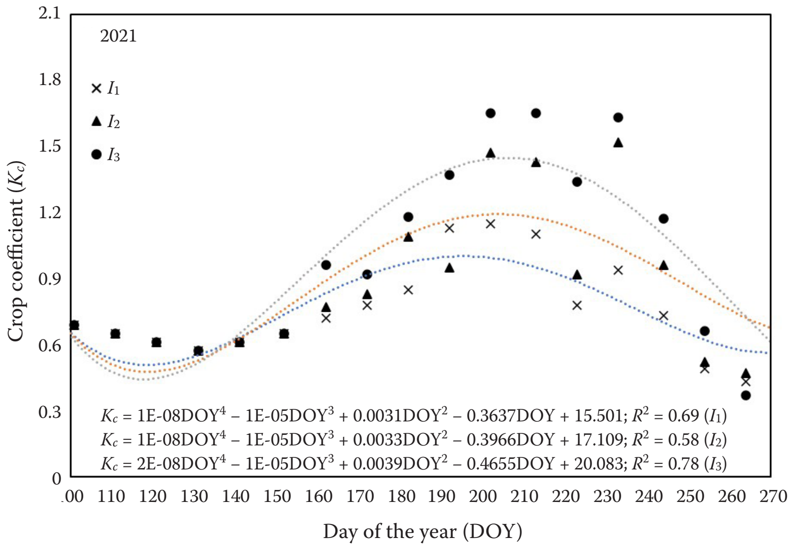

Figure 7. Plant coefficient curve for 2021 (7 years old)

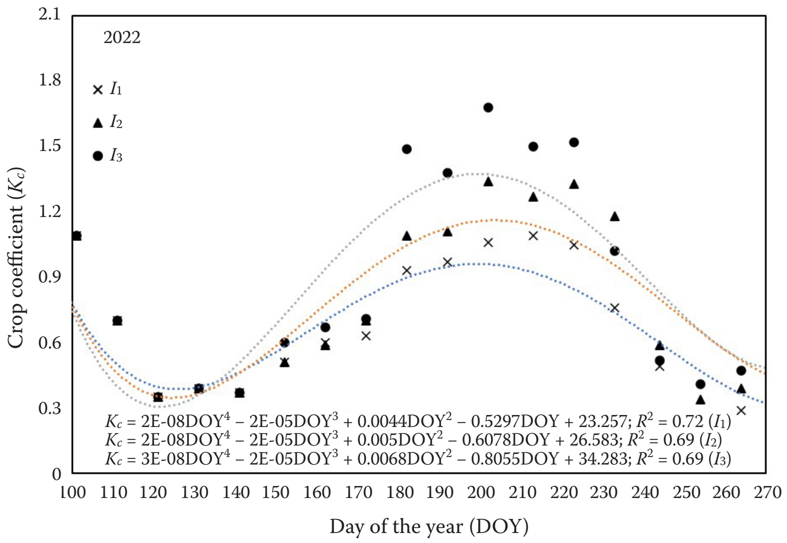

Figure 8. Plant coefficient curve for 2022 (8 years old)

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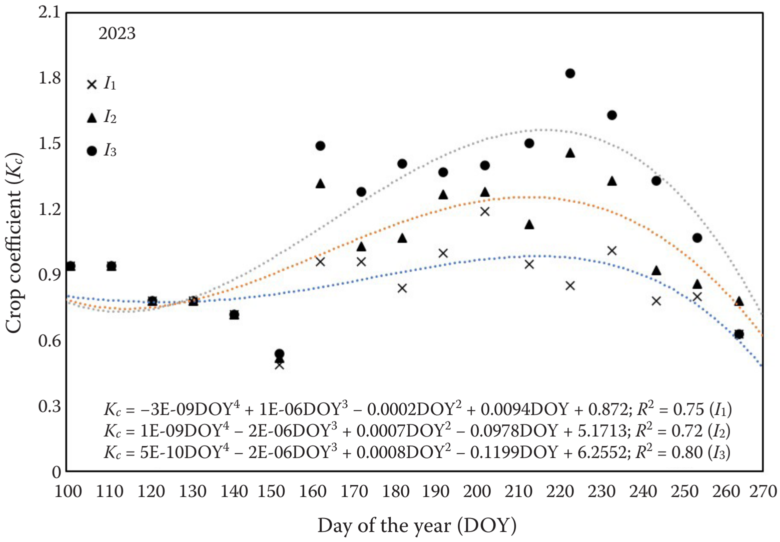

Figure 9. Plant coefficient curve for 2023 (9 years old)

Table 4. Monthly crop coefficients (K_c) for walnut trees in the measurement years

Year	Irrigation level	Month					
		April	May	June	July	August	September
2015 (1 years old)	I_1	0.72	0.43	1.25	1.17	0.93	1.12
	I_2	0.72	0.43	1.58	1.36	1.31	1.04
	I_3	0.72	0.43	1.83	1.50	1.60	1.19
2016 (2 years old)	I_1	0.47	0.76	0.87	0.76	0.93	0.51
	I_2	0.47	0.65	1.06	1.06	1.19	0.82
	I_3	0.47	0.70	1.23	1.36	1.43	1.15
2017 (3 years old)	I_1	0.53	0.70	1.05	1.02	0.99	0.51
	I_2	0.53	0.84	1.24	1.15	1.19	0.72
	I_3	0.53	0.63	1.47	1.38	1.46	0.80
2018 (4 years old)	I_1	0.40	0.44	1.20	1.20	0.96	0.21
	I_2	0.40	0.44	1.35	1.33	1.15	0.74
	I_3	0.40	0.44	1.42	1.51	1.41	0.38
2019 (5 years old)	I_1	0.55	0.68	0.88	0.82	0.85	0.52
	I_2	0.55	0.72	1.00	1.09	0.99	0.77
	I_3	0.55	0.74	1.18	1.31	1.20	0.92
2021 (7 years old)	I_1	0.69	0.59	0.72	1.04	0.94	0.55
	I_2	0.69	0.59	0.75	1.17	1.29	0.65
	I_3	0.69	0.59	0.84	1.40	1.54	0.73
2022 (8 years old)	I_1	0.88	0.37	0.58	0.99	0.97	0.34
	I_2	0.88	0.37	0.60	1.18	1.26	0.44
	I_3	0.83	0.37	0.66	1.52	1.35	0.47
2023 (9 years old)	I_1	0.85	0.76	0.80	1.01	0.94	0.74
	I_2	0.85	0.76	0.96	1.21	1.31	0.85
	I_3	0.85	0.76	1.10	1.39	1.65	1.01
Average	I_1	0.63	0.60	0.97	0.99	0.94	0.63
	I_2	0.63	0.60	1.15	1.19	1.19	0.77
	I_3	0.63	0.59	1.32	1.40	1.45	0.88

I_1 – 75%; I_2 – 100%; I_3 – 125%

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treatment subjects in all research years, the highest K_c values were obtained from subject I_3 where 125% of open water surface evaporation amounts were applied, while the lowest K_c values were obtained from I_1, where 100% of open water surface evaporation amounts were applied. As can be seen from the graphs, it is seen that the relationship between 10-day periods and the crop coefficient is generally polynomial at degree 4. It is seen that the determination coefficient (R^2) values of the resulting equations increase with the age of the walnut trees and varied between 0.72 and 0.80, especially in 2023, when walnut trees were 9 years old.

The K_c values between April and September, when ET_c measurements were carried out for three different treatment subjects in each research year, are given in Table 4. As can be seen from the table, while monthly K_c values were generally low in April and May, they started to increase in June, reached maximum values in July, and started to decrease after August. Among the treatment subjects in all research years, the highest monthly K_c values were obtained from subject I_3 where 125% of open water surface evaporation amounts were applied, while the lowest monthly K_c values were obtained from I_1, where 100% of open water surface evaporation amounts were applied. Figure 5 presents the graph based on the monthly K_c coefficient averages from the 9-year research period. Between April and September, monthly K_c values varied between 0.60 and 0.93 in the I_1 where 75% of the open water surface evaporation amount was applied, 0.60 and 1.19 in the I_2, where 100% was applied, and 0.59 and 1.40 in the I_3, where 125% was applied.

Figure 10 presents the K_c curve of 1–9-year-old walnut trees derived from the research. When the eight years in which the research was conducted are evaluated together, considering the average of all treatment subjects; the K_c values for walnut trees were calculated as 0.55 for April, 0.71 for May, 1.02 for June, 1.07 for July, 1.01 for August, and 0.74 for September. It was determined that the values obtained because of the research were in parallel with the studies obtained at the international studies. Goldhamer (1998) determined that the monthly K_c values of walnut trees in California, USA, were 0.12 in March, 0.53–0.68 in April, 0.79–0.86 in May, 0.93–1.00 in June, 1.14 in July and August, 0.97–1.08 in September, 0.51–0.88 in October, and 0.28 in November. According to Fulton et al. (2017), their study in California from 2011 to 2016 found that the K_c values changed every month from April to November, averaging between 0.14 and 1.04. The highest vegetation coefficient values were found in June and July.

CONCLUSION

In this study, ET_c and K_c values were determined for Chandler walnut trees grown under semi-arid climatic conditions, based on field measurements conducted over eight vegetation periods covering the developmental stages from 1 to 9 years of age. The results indicated that seasonal ET_c values for the April–September period ranged, on a multi-year average basis, between 633.0 and 860.1 mm, depending on the applied irrigation level. The corresponding monthly K_c values for the same period were calculated as 0.55 for April, 0.71 for May, 1.02

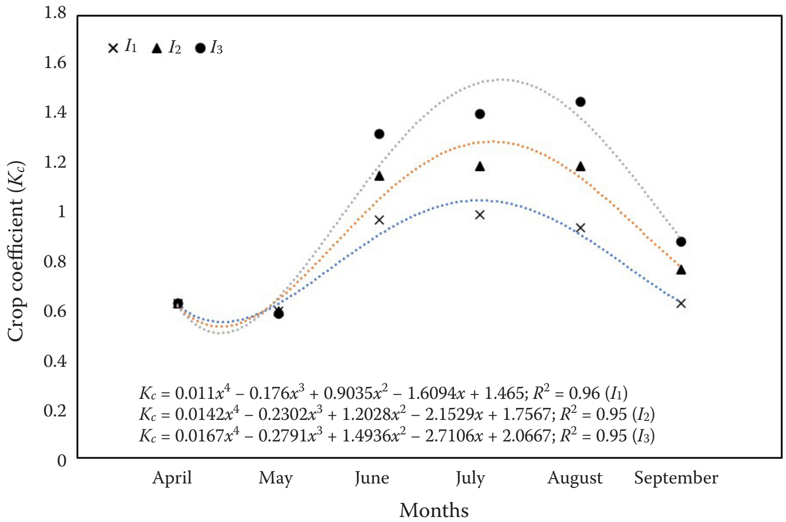

Figure 10. Monthly crop coefficient (K_c) for walnut trees

https://doi.org/10.17221/72/2025-SWR

for June, 1.07 for July, 1.01 for August, and 0.74 for September.

The findings demonstrate that crop water consumption and crop coefficient in walnut are sensitive not only to climatic conditions but also to the developmental stage of the trees and the amount of irrigation water applied. This indicates that the direct use of fixed K_c values recommended for mature and fully developed walnut trees, particularly during the early years after planting (young trees), may lead to inaccurate determination of irrigation water amounts. In perennial fruit trees, changes in canopy cover and root development with age substantially affect water consumption dynamics.

This study provides an original reference by presenting ET_c and K_c values for Chandler walnut trees under semi-arid conditions derived from long-term field measurements. The age- and month-specific K_c values obtained will enable the development of more precise and sustainable irrigation programs in walnut cultivation, contributing to the efficient use of water resources and to the reduction of yield losses associated with over- or under-irrigation. In this context, it is recommended that walnut producers use K_c values specific to tree age and growth stage, rather than relying on a single average K_c value, in irrigation scheduling.

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Received: June 16, 2025
Accepted: March 16, 2026
Published online March 27, 2026