 Egypt. J. Soil Sci. **Vol. 65**, No. 2, pp: 1151 - 1165 (2025)

Egyptian Journal of Soil Science
http://ejss.journals.ekb.eg/

Adjusted Crop Coefficient for Wheat Using Energy Balance Systems in North Nile Delta of Egypt

Mohammed M. Saffan [a], **Abdelaziz A. Belal** [b], **Mohie Omar** [c] and **Alaa Mosad** [d*]

[a]*Soils and Water Department, Faculty of Agriculture, Kafrelsheikh University, 33516 Egypt*
[b]*National Authority for Remote Sensing and Space Sciences (NARSS), Al-Nozha Al-Gedida, Cairo, Egypt*
[c]*International Center of Agricultural Research in the Dry Areas (ICARDA), Egypt*
[d]*Soils, Water and Environment Research Institute, Agricultural Research Center, Egypt*

ACCURATE crop coefficient (K_c) is essential for optimizing irrigation water use as well as enlargement water productivity in agriculture. This study aims to update the K_c values for wheat in the North Nile Delta, Egypt, using an energy balance (EB) system powered by Campbell Scientific instrumentations. Field experiments were conducted during three consecutive wheat-growing seasons of 2022/23,2023/24 and 2024/25 at Sakha Agricultural Research Station, covering an area of 4.2 hectares. Actual evapotranspiration (ET_a) was measured using energy balance techniques, and K_c values were derived by comparing ET_a with reference evapotranspiration (ET_o) from FAO Penman Monteith approach. Results showed that FAO-56 K_c values tend to underestimate K_c during the initial (ini) and late-season (end) growth stages, while slightly overestimating mid-season K_c. The obtained K_c values for wheat were: 0.43–0.68 ($K_{c\ ini}$), 0.75–1.02 ($K_{c\ dev}$), 0.94–1.11 ($K_{c\ mid}$), and 0.4–0.64 ($K_{c\ end}$), differing from FAO-56 values. The findings suggest that local calibration of K_c is necessary for precise irrigation scheduling, enhancement water management efficiency, and consequently sustainable wheat production under water-scarce conditions.

Key words: Crop Coefficient, Energy Balance, Wheat, Evapotranspiration, Irrigation Scheduling, North Nile Delta, Water Use Efficiency.

1. Introduction

Wheat is a commonly grown crop, and its seeds are grains utilized globally as a primary food source. Out of the thousands of recognized wheat types, the most significant are common wheat (Triticum aestivum), durum wheat (T. durum), and club wheat (T. compactum). Wheat is grown as a cash crop due to its high yield per unit area, its ability to thrive in a temperate climate with a relatively short growing season, and its production of versatile, high-quality flour. Most of the wheat flour is utilized to produce items such as bread, pasta, cereal, pastries, cookies, crackers, muffins, tortillas and pitas. Wheat ranks as the second-highest produced cereal grain after maize, and its worldwide trade surpasses that of all other crops combined. For the 2023-24 marketing year, the worldwide wheat production reached 785 million tons. China, India, and Russia are the top three wheat producers globally, making up approximately 41% of the total wheat output in the world. The United States ranks as the fourth largest wheat producer globally. Nonetheless, if wheat production in the European Union were considered as one nation, it would surpass that of all countries except China (World Population Review, 2025).

Wheat is one of Egypt’s most important winter crops, cultivated broadly across both old and new lands. The total cultivation area is around 1.35 million hectare (ha), with the majority in the old lands of the Nile Valley and Delta, while newly reclaimed lands contribute a growing share to wheat production. In terms of productivity, wheat yields have shown steady improvements, with an average yield of about 6.55 to 7.13 tons per ha, depending on location and on-farm management practices. Egypt produces 9.44 million tons of wheat, covering

*Corresponding author e-mail: alaamosad993@yahoo.com
Received: 16/04/2025; Accepted: 22/05/2025
DOI: 10.21608/EJSS.2025.376115.2116

only 44.51 % of its 21.52 million-ton demand, leaving a 55.49 % import gap (12.08 million tons). The above stated was by Ministry of Agriculture and Land Reclamation, Economic Affairs Sector (2024).

Egypt's actual water demand is around 80 billion cubic meters per year. In contrast, the total available water resources in Egypt amount to approximately 59.25 billion cubic meters per year, creating a water insufficiency of 20.75 billion cubic meters annually due to the gap between increasing water demand and limited water resources (Central Agency for Public Mobilization and Statistics, 2024).

FAO (2023) stated that ET typically accounts for the largest portion of water loss from the system in agricultural and vegetated areas,which constitute the "consumptive" component of water use. Accurately measuring ET across space and time is crucial for effective water resource management. This includes monitoring water consumption across different land use types, regulating water allocation and transfers, optimizing irrigation at both farm and scheme levels, evaluating crop water productivity, predicting yields using models, assessing agricultural drought indices, and conducting water balance and accounting within hydrological systems.

Various methods and instruments have been developed over time to estimate evapotranspiration, which include soil moisture measurements for water depletion, weighing lysimeters, the Penman-Monteith equation, the Bowen ratio-energy balance method, the eddy covariance technique, and the Large Aperture Scintillometer (e.g., Howell et al., 1991; Baldocchi et al., 2001; Fisher et al., 2011; Liu et al., 2011).

ET can also be measured using EB methods, which rely on the EB equation at the crop surface to determine the energy consumed in water evaporation (latent heat, λE) and the energy used to heat the air (sensible heat, H). The ET rate from a cropped surface can be directly assessed using mass transfer or energy balance techniques. Additionally, it can be estimated through soil water balance studies conducted in cropped fields or lysimeters (Allen et al., 1998).

Crop ET is determined by multiplying ETo with K_c, a coefficient that represents the variation in ET between a cropped surface and a reference grass surface. This variation can be expressed using a single coefficient or divided into two distinct factors that separately account for the differences in evaporation and transpiration between the two surfaces. Doorenbos and Pruitt (1977) in FAO-24 and Allen et al. (1998) in FAO-56 proposed K_c values for various crops across different climatic conditions, which are widely used when local data is unavailable. However, local calibration of Kc is necessary to account for specific climatic conditions (Kashyap and Panda, 2001).

Allent et al., 1998 emphasized that the growth stage durations provided by (Doorenbos and Pruitt, 1977) are average estimates for the specified regions and periods and should be considered as examples. Whenever possible, local observations of plant development should be used to account for variations in crop variety, climate, and agricultural practices. In addition, tabulated crop coefficients (K_c) values provided by (Doorenbos and Kassam, 1979 for $K_{c\ ini}$), and (Doorenbos and Pruitt, 1977; Pruitt, 1986; Wright, 1981 &1982; Snyder et al., 1989) for K_c mid and K_c end, are for non-stressed, well-managed crops in subhumid climates (RHmin ≈ 45%, u_2 ≈ 2 m/s) intended for use with the FAO Penman-Monteith ET_o.

Thus, the main objective of Of the current research work is to update the K_c for wheat under the local conditions of the North Nile Delta region. This is achieved using a validated energy balance methodology, which addresses the limitations of the traditional crop coefficient approach by estimating ET_a independently of crop coefficient assumptions.

2. Materials and Methods

Materials and methodology of the research is described in figure (1), as follows:

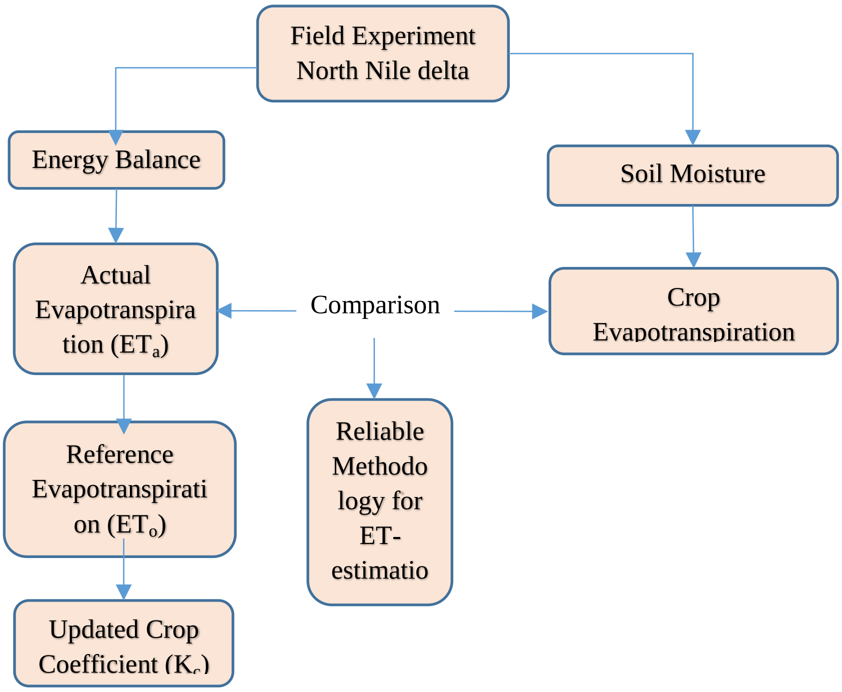

Fig. 1. Flowchart indicates objectives, materials and methods of the research.

2.1. Study area

A field experiment was conducted for three successive wheat seasons; 2021/2022, 2022/2023 and 2023/2024, at Sakha agricultural research station farm, Agricultural Research Center (ARC), North Nile Delta of Egypt (Figures 2 & 3). An area of 4.2 hectares, located at latitude: 31.096500, longitude: 30.922444. Soils are heavy clay (> 45% clay), salt affected due to shallow water table at about 95-100 cm. Salinity ranges from 1.93 – 3.5 ds/m. Hydrogen number ranges from (7.8-8.3). Apparent density is about 1.10-1.31 g cm-3 at the upper soil profile layers, and increases with depth. Hydrological soil parameters were estimated on volume basis, as shown in table (1).

Table 1. Some chemical and physical soil properties of the experimental site through growing seasons.

Soil depth (cm)	Field capacity (%)	Wilting point (%)	Bulk density (g cm-3)	Sand (%)	Silt (%)	Clay (%)	ECe (dS m^{-1})	pH
0-20	46.71	23.66	1.19	19.22	26.93	53.85	1.93	8.31
20-40	42.08	21.98	1.24	19.43	26.32	54.25	2.25	8.39
40-60	40.24	21.52	1.38	20.15	25.44	54.41	2.68	8.54
60-80	39.73	20.19	1.45	19.61	26.83	53.56	3.05	8.68

ECe (dS m-1): is hydraulic conductivity for the soil paste.

Fig. 2. Study area from Google Earth Explorer.

Fig. 3. Energy balance system at Sakha site.

2.2. Field experiment and measurements

2.2.1. Agronomic practices

A field experiment of wheat was carried out in three consequent winter seasons 2021/2022, 2022/2023, and 2023/2024, over an area of 4.2 ha. Ploughing was done twice perpendicularly in addition to land levelling. Traditional practices were done. As for fertilizers, 180 Nitrogen unit per ha, added as Urea (46.6 %) as three doses before irrigation events; 60 P_2O_5 unit per ha, added as mono calcium phosphate (15.5 %) during soil preparation; no other fertilizers depending on the stock in the soil. Seed rate was 144 kg/ha from bread wheat var. Ceds 14. Narrow and board weeds were controlled by herbicides at 27 days from planting. Planting dates for the three seasons were 15 Dec 2021, 25 Nov 2022, and 5 Dec 2023 respectively, whereas harvesting dates were 15 May 2022, 30 April 2023, and 14 May 2024 correspondingly. Four irrigation events in the three seasons through a border Irrigation system.

2.2.2. Actual Evapotranspiration

Allen et.al., (1998), and FAO (2023), stated four concepts in the energy exchange between the earth and the surrounding atmosphere as well as the underlying ground: The surface's net radiation (R_n) indicates the difference between the energy gained and that lost through radiation; the sensible heat flux (H) shows how much energy is lost or gained as a result of heat transfer to the atmosphere; the ground heat flux (G) shows how much energy is lost or gained through heat conduction through the surface layer's lower boundary; and the latent heat flux (λE) shows how much energy is lost or gained from the surface as a result of evaporation. Every term uses Watt per meter square (W m^{-2}), and the following equation shows that they are all in balance.

The calculation of ET using energy balance is based on the fundamental equation (1), where R_n equals the sum of λE, H and G.

$$R_n = \lambda E + H + G \quad \ldots\ldots\ldots\ldots\ldots \quad (1)$$

Manipulating the equation, it is possible to isolate λE as in eq (2). Therefore, if the terms R_n, G and H are known, it is possible to estimate λE and therefore the evaporated water from the crop.

$$\lambda E = Rn - (G + H) \quad \ldots\ldots\ldots\ldots\ldots\ldots \quad (2)$$

Energy Balance Instruments

Energy balance system is powered by Campbell Scientific (https://www.campbellsci.com/)

in Egypt, and involves a variety of sensors (figure 4), as follows:

Solar radiation sensors:

The CS320 is a digital thermopile pyranometer designed to measure broad-spectrum short-wave solar radiation accurately. It utilizes a blackbody thermopile detector combined with an acrylic diffuser, offering superior spectral response compared to silicon-cell pyranometers.

Wind Speed and Wind Direction Sensors

The CSAT3B is a three-dimensional sonic anemometer, designed to measure orthogonal wind components (u_x, u_y, u_z) and sonic temperature (T_s) at rates up to 100 Hz. It features an aerodynamic design with a 10 cm vertical measurement path and operates in a pulsed acoustic mode, ensuring high-precision measurements suitable for turbulence and eddy-covariance studies.

Soil Temperature Sensors

The TCAV-L is an averaging soil thermocouple probe designed to measure the average temperature of the top 6 to 8 cm of soil, primarily for energy-balance assessments in flux systems. It consists of four type E thermocouples connected in parallel within a 24 AWG wire. Each thermocouple pair can be installed at different depths, with the pairs spaced up to 1 meter apart.

Soil Heat Flux Sensors

The HFP01-L Soil Heat Flux Plate is designed to measure soil heat flux, commonly used in energy-balance or Bowen-ratio flux systems. It operates passively, utilizing a thermopile to detect temperature gradients across its plate, producing a voltage signal proportional to the heat flux of the surrounding medium.

Data Loggers

The CR1000Xe is a versatile measurement and control datalogger, built for reliability in remote and harsh environment. It operates within a standard temperature range of -40° to +70°C, extendable to -55° to +85°C. This low-power device supports both analog and digital sensors, which offer fast analog measurements exceeding 300 Hz with 24-bit ADC resolution.

Air Temperature and Relative Humidity Sensors

The HygroVue™10 is a digital sensor that measures both air temperature and relative humidity. It features a Swiss-made sensing element based on CMOSens® technology, ensuring accurate and stable measurements. The sensor outputs data via the SDI-12 protocol, facilitate easy integration with various data logging systems and minimizing errors associated with analog sensors.

Precipitation Sensors

The TE525MM-L is a tipping bucket rain gauge designed to measure rainfall in metric units, recording in 0.1 mm increments. It features a 24.5 cm (9.66 in.) diameter funnel, which constructed from anodized aluminium. The gauge operates effectively within a temperature range of 0° to 50°C. Each tip of the bucket corresponds to 4.73 ml of rainfall, with an accuracy of ±1% for rates up to 50 mm/h (2 in./h).

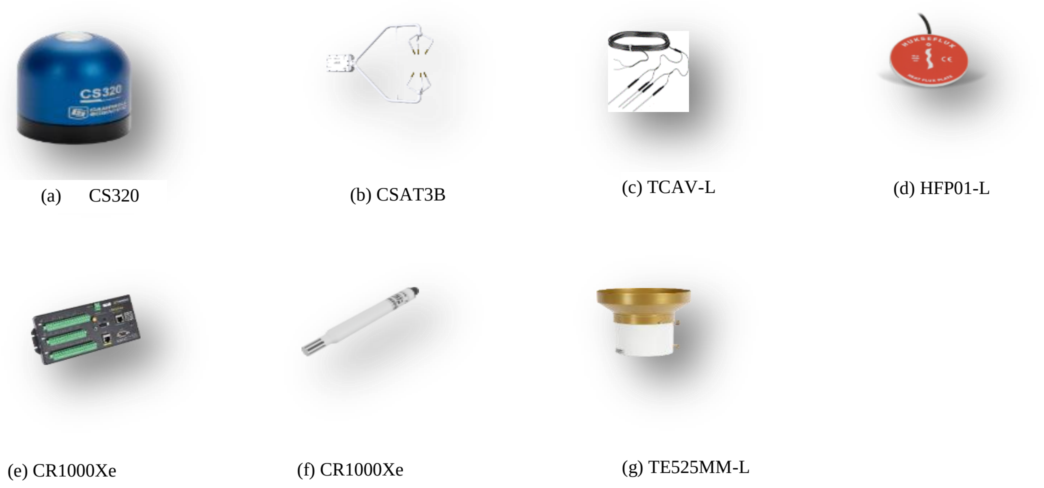

Fig. 4. Components of energy balance system powerd by Campbell Scientific.

2.2.3. Reference evapotranspiration

The Penman–Monteith equation was distinctive because it accounted for plant factors rather than relying solely on weather variables like radiation and temperature to estimate ET. However, its practical use was limited mainly to academic research due to the challenge of obtaining plant-specific parameters, particularly canopy resistance. To address this, Allen et al. (1998), in a collaboration between FAO and the International Commission on Irrigation and Drainage (ICID), simplified the equation by setting the canopy resistance (r_s) to a fixed seasonal average of 70 s m^{-1}. This adjustment resulted in the modified Penman–Monteith equation (equation 3).

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

Where

ETo: reference evapotranspiration [mm day^{-1}], Rn: net radiation at the crop surface [MJ m^{-2} day^{-1}], G: soil heat flux density [MJ m^{-2} day^{-1}], T: mean daily air temperature at 2 m height [C°], u2: wind speed at 2 m height [m s^{-1}], e_s: saturation vapour pressure [kPa], e_a: actual vapour pressure [kPa], (e_s-e_a): saturation vapour pressure deficit [kPa], Δ: slope vapour pressure curve [kPa $°C^{-1}$], γ: psychrometric constant [kPa $°C^{-1}$].

2.2.4. Crop evapotranspiration and crop coefficient

According to FAO paper no 56 (Allen et al., 1998) used the crop coefficient approach to calculate ET_c by multiplying ET_o by K_c:

$$ET_c = K_c\, ET_o \qquad \ldots\ldots\ldots\ldots\ldots\ldots (4)$$

where ET_c crop evapotranspiration [mm d^{-1}], K_c crop coefficient [dimensionless], ET_o reference crop evapotranspiration [mm d^{-1}].

3. Results

3.1. Evapotranspiration

The actual evapotranspiration estimated using the energy balance method (ETa_EB) consistently exceeded the estimated crop evapotranspiration using the FAO method (ET_c_FAO) across all three seasons. In the 2021/2022 season, ET_c_FAO was 358.28 mm, while ET_a_EB was slightly higher at 368.40 mm. This trend continued in 2022/2023, where both values arised significantly to 409.34 mm and 427.96 mm, respectively. However, in 2023/2024, both ET_c_FAO and ET_a_EB decreased to 341.18 mm and 364.51 mm, respectively. The highest ET values in both approaches were observed during the mid-season growth stage, whereas the lowest values occurred in the late-season growth stage. This was indicated by (tables 2, 3&4 – Figures 5, 6&7).

Table 2. average weekly weather, ET and K_c data over winter season (2021/2022).

To date	DOY	T_a_MAX	T_a_MIN	T_a_DEW	RH	WS	R	ET_a	ET_o	K_c
12/7/2021	341	23.97	14.85	10.63	62.05	2.63	0.10	0.68	2.21	0.31
12/14/2021	348	21.43	12.10	8.61	64.24	3.22	1.19	1.10	2.08	0.52
12/21/2021	355	22.13	10.75	10.61	76.51	2.41	1.05	0.93	1.97	0.47
12/28/2021	362	19.71	10.09	7.45	65.65	4.26	2.10	1.61	2.53	0.62
1/4/2022	4	17.98	9.03	6.97	69.93	3.56	2.23	1.62	1.91	0.85
1/11/2022	11	17.12	8.69	7.39	72.75	3.97	4.37	2.29	1.92	1.32
1/18/2022	18	19.11	11.15	9.71	76.12	2.64	2.26	1.83	1.53	1.16
1/25/2022	25	16.83	9.40	6.92	69.22	3.16	0.56	2.34	2.05	1.17
2/1/2022	32	19.27	8.15	8.19	75.94	2.14	0.02	2.33	2.15	1.09
2/8/2022	39	19.58	9.34	7.25	67.79	3.07	0.94	2.60	2.45	1.05
2/15/2022	46	19.70	9.07	8.47	73.27	2.55	0.16	2.38	2.27	1.11
2/22/2022	53	19.38	9.38	8.77	74.62	2.64	0.89	2.67	1.92	1.56
2/29/2022	60	21.39	9.40	8.70	70.92	2.37	1.36	3.13	2.66	1.22
3/7/2022	67	23.70	9.64	8.20	65.88	2.38	0.37	3.42	3.03	1.14
3/14/2022	74	23.68	11.53	11.30	76.50	3.65	9.68	3.12	2.92	1.06
3/21/2022	81	20.85	9.72	7.59	65.38	3.54	0.13	3.60	3.16	1.15
3/28/2022	88	24.60	10.20	9.53	67.82	2.76	0.10	3.44	3.70	0.94
4/4/2022	95	27.35	11.70	8.65	57.36	3.31	0.00	3.51	4.86	0.72
4/11/2022	102	23.38	12.38	9.72	65.19	2.87	0.02	2.36	3.95	0.60
4/18/2022	109	26.78	12.41	9.61	61.27	2.82	0.00	2.09	4.59	0.45
4/25/2022	116	28.75	14.12	11.56	63.13	3.25	14.28	1.70	4.80	0.35
5/2/2022	123	26.47	13.10	12.29	69.50	2.18	0.39	1.63	5.09	0.33
5/9/2022	130	28.45	13.93	12.21	64.36	3.35	0.01	1.08	6.03	0.21
5/13/2022	134	31.50	13.92	11.93	61.31	2.36	0.00	2.66	6.14	0.42

Table 3. average weekly weather, ET and K_c data during winter season (2022/2023).

To date	DOY	T_a_MAX	T_a_MIN	T_a_DEW	RH	WS	R	ET_a	ET_o	K_c
12/1/2022	336	22.21	13.23	10.56	67.49	1.89	1.30	1.46	2.71	0.56
12/8/2022	343	23.46	11.85	8.56	61.49	1.97	0.02	1.50	2.82	0.54
12/15/2022	350	22.58	11.20	7.91	61.71	2.58	0.20	1.72	2.28	0.76
12/22/2022	357	22.26	12.84	11.58	75.03	2.14	0.14	1.62	2.66	0.63
12/29/2022	364	22.87	12.44	10.58	70.88	2.41	0.00	1.87	2.29	0.78
1/5/2023	5	23.42	12.46	12.19	76.60	1.99	0.00	1.81	2.39	0.76
1/12/2023	12	25.86	12.55	11.77	72.86	1.87	0.02	1.78	3.09	0.59
1/19/2023	19	18.72	9.77	6.65	64.86	4.03	1.77	2.40	2.46	0.99
1/26/2023	26	19.71	8.20	6.34	66.34	2.33	0.10	2.92	3.30	0.91
2/2/2023	33	22.19	8.99	5.22	57.70	3.12	0.20	3.15	2.74	1.20
2/9/2023	40	24.47	11.31	8.60	66.36	2.25	0.30	2.90	3.12	0.93
2/16/2023	47	22.49	9.83	7.77	68.17	2.17	2.56	3.31	2.56	1.34
2/23/2023	54	16.78	8.77	6.62	70.77	3.08	3.63	3.11	3.01	1.05
3/2/2023	61	21.56	10.11	9.25	71.80	2.79	0.01	3.49	3.39	1.03
3/9/2023	68	22.60	9.27	7.99	68.33	2.59	0.72	4.09	4.13	1.06
3/16/2023	75	23.91	11.49	8.90	66.12	3.12	0.91	3.78	3.83	1.00
3/23/2023	82	24.67	12.16	10.68	66.19	2.73	17.37	3.78	3.58	1.07
3/30/2023	89	18.93	10.12	7.52	67.43	3.44	3.01	3.00	4.75	0.65
4/6/2023	96	24.58	9.22	8.37	65.31	2.65	2.74	3.57	5.19	0.70
4/13/2023	103	22.63	10.87	8.21	63.81	3.53	0.00	3.47	6.60	0.56
4/20/2023	110	32.06	13.57	10.31	55.26	2.84	0.05	3.05	6.15	0.51
4/27/2023	117	28.71	12.85	10.08	61.72	3.31	0.00	2.31	7.02	0.36
4/30/2023	120	36.43	14.38	10.39	53.04	2.91	0.00	2.40	7.41	0.31

Table 4. average weekly weather, ET and K_c data over winter season (2023/2024).

To date	DOY	T_a_MAX	T_a_MIN	T_a_DEW	RH	WS	R	ET_a	ET_o	K_c
12/11/2023	345	22.16	11.72	10.03	69.37	2.85	0.05	1.58	1.96	0.79
12/18/2023	352	20.10	12.11	10.70	75.46	2.82	1.25	1.24	1.75	0.71
12/25/2023	359	17.25	9.66	8.59	76.88	3.18	3.66	1.07	1.59	0.74
1/1/2024	1	18.36	9.65	8.89	76.45	2.47	1.63	0.84	1.67	0.52
1/8/2024	8	20.01	9.16	10.11	79.92	1.56	0.41	1.28	1.52	0.84
1/15/2024	15	17.76	7.34	5.01	65.64	3.86	1.36	1.23	2.23	0.57
1/22/2024	22	15.95	6.64	4.20	66.22	2.65	2.22	1.36	1.81	0.75
1/29/2024	29	14.26	6.82	5.81	76.81	3.05	5.45	1.04	1.53	0.71
2/5/2024	36	16.79	6.56	5.98	72.70	3.14	0.94	1.82	2.31	0.82
2/12/2024	43	18.98	7.89	6.98	71.53	2.79	0.18	2.02	2.43	0.86
2/19/2024	50	18.19	8.47	8.59	78.51	2.35	0.47	1.48	2.25	0.66
2/26/2024	57	20.55	8.99	7.82	68.84	2.55	0.58	2.56	2.67	1.04
3/5/2024	64	22.19	9.08	8.13	68.08	2.37	0.00	3.03	2.75	1.13
3/12/2024	71	19.80	9.68	7.86	70.11	3.45	2.00	3.08	3.06	1.02
3/19/2024	78	17.36	6.66	4.32	64.64	2.83	2.90	2.87	2.59	1.12
3/26/2024	85	17.47	7.56	5.55	68.48	3.39	3.98	2.65	2.80	0.96
4/2/2024	92	26.21	10.09	9.21	65.87	2.33	0.00	3.44	3.87	0.90
4/9/2024	99	31.08	13.15	10.59	59.27	3.17	0.00	4.27	5.16	0.85
4/16/2024	106	26.33	11.54	8.96	61.77	3.30	0.00	4.34	4.07	1.07
4/23/2024	113	28.57	13.28	10.37	60.80	3.20	0.00	3.88	4.67	0.86
4/30/2024	120	32.19	14.11	9.81	56.05	3.04	0.00	3.74	5.45	0.69
5/7/2024	127	28.58	15.20	11.12	59.29	3.71	0.00	2.04	5.14	0.40
5/14/2024	134	31.89	16.56	10.40	51.46	3.18	0.00	1.11	6.10	0.18

Where: T_a_MAX: Maximum temperature at 2 meters (C°), T_a_MIN: Minimum temperature at 2 meters (C°), T_a_DEW: Dew/Frost point temperature at 2 meters (C°), RH (%): Relative humidity at 2 meters (%), WS (m/s): Wind speed at 2 meters (m/s), DOY: Day of the year, and R: rainfall (mm).

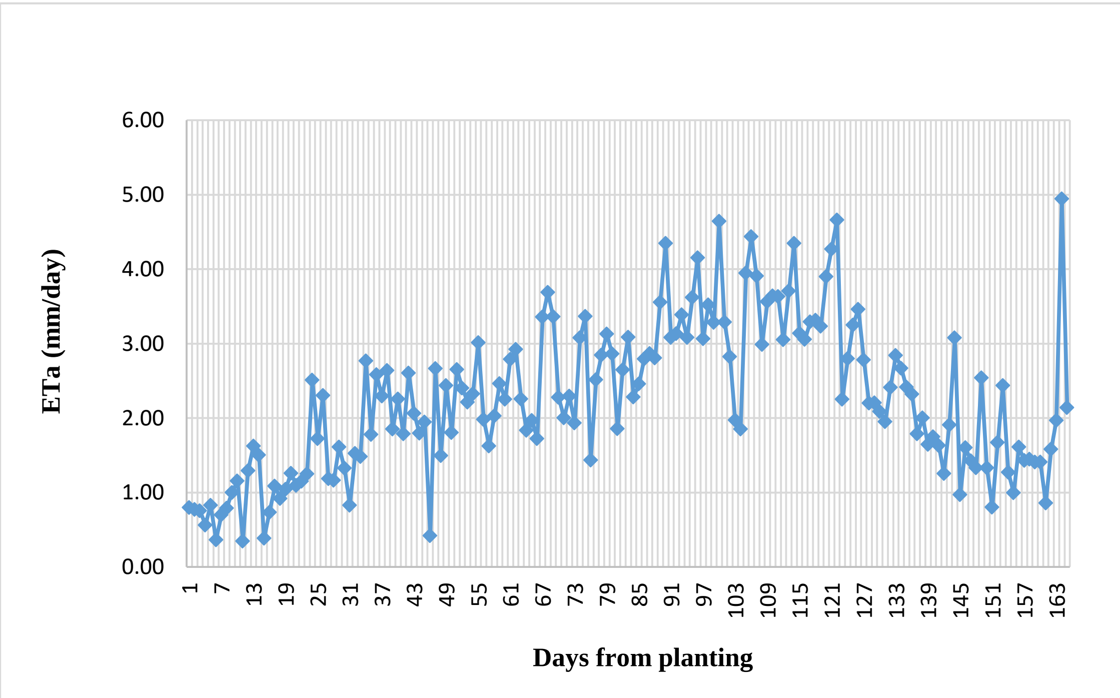

Fig. 5. actual evapotranspiration (ET_a) for season 2021/2022.

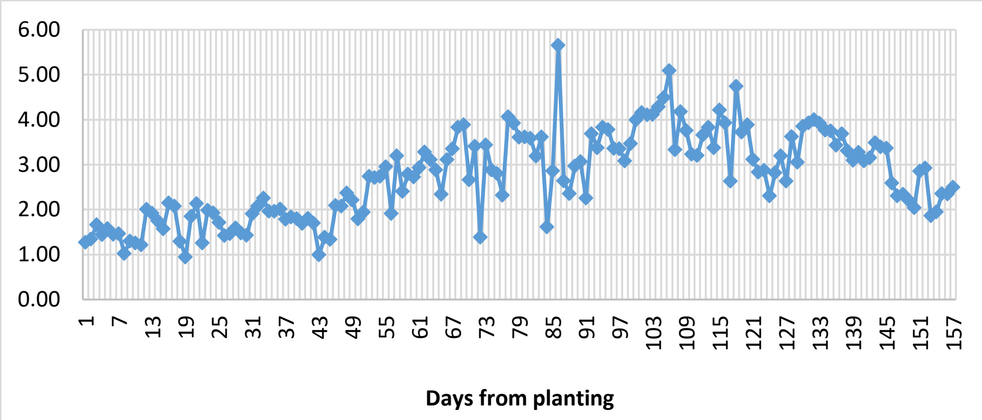

Fig. 6. actual evapotranspiration (ET_a) for season 2022/2023.

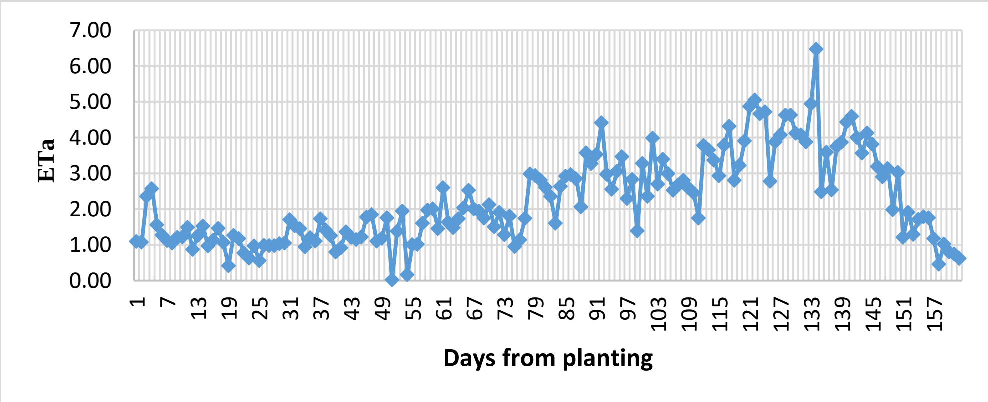

Fig. 7. actual evapotranspiration (ETa) for season 2023-2024.

3.2. Reference evapotranspiration (ET_o)

The reference evapotranspiration varied across the three growing seasons, reflecting differences in climatic conditions that influence water demand. The highest total ETo was recorded in the 2022/2023 season at 597.09 mm, followed by 475.93 mm in 2021/2022 and 472.85 mm in 2023/2024. The average daily ET_o was 3.76 mm/day in 2022/2023, the highest among the seasons, while the values in 2021/2022 and 2023/2024 were 2.99 mm/day and 2.97 mm/day, respectively. The daily peak ET_o reached 8.98 mm/day in 2022/2023, which was significantly higher compared to 6.20 mm/day in 2021/2022 and 7.39 mm/day in 2023/2024, indicating periods of extreme atmospheric demand. Conversely, the lowest recorded daily ETo values were 0.78 mm/day in 2021/2022, 1.00 mm/day in 2023/2024, and 1.73 mm/day in 2022/2023, showing seasonal variations in climatic patterns (tables 2, 3&4 – Figures 8, 9&10).

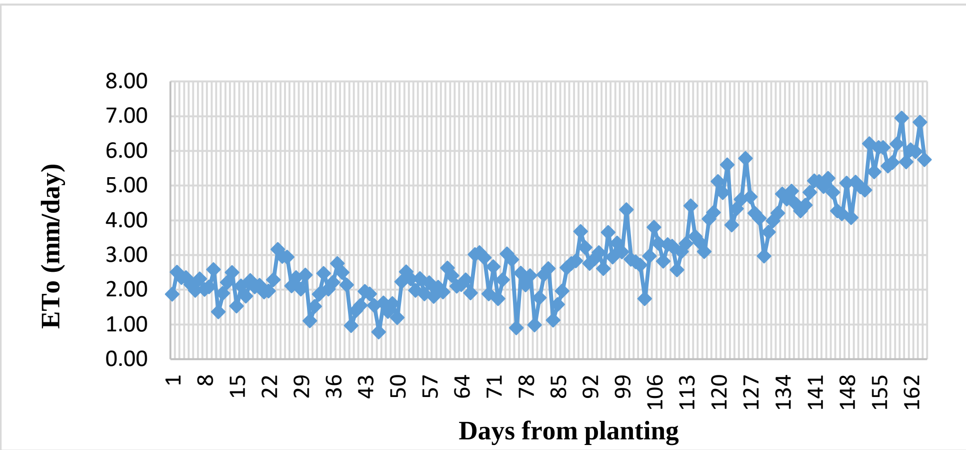

Fig. 8. Reference evapotranspiration (ET_o) for season 2021/2022.

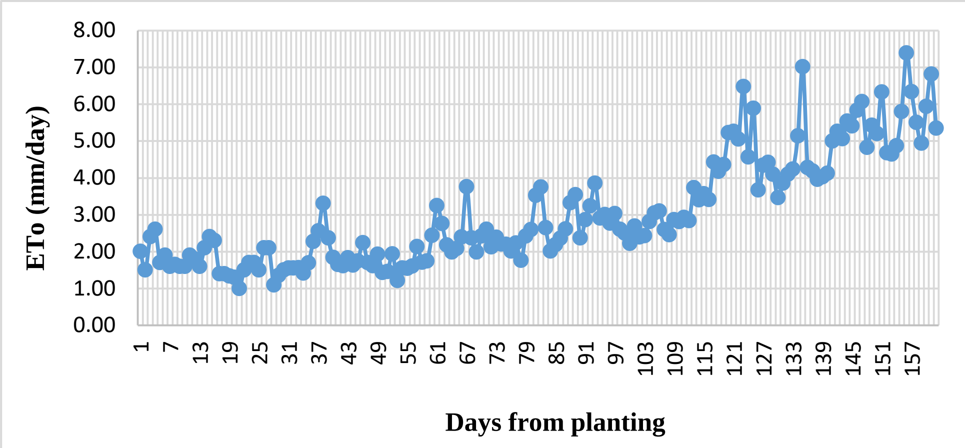

Fig. 9. Reference evapotranspiration (ET_o) for season 2022/2023.

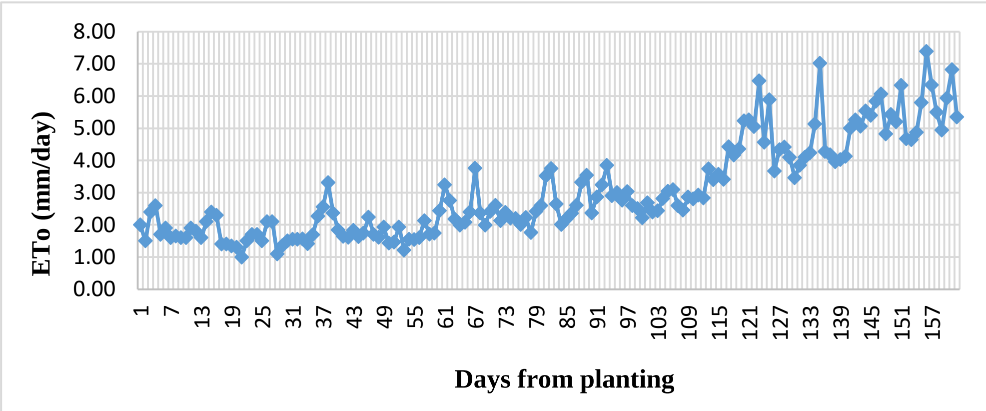

Fig. 10. Reference evapotranspiration (ET_o) for season 2023-2024.

3.3. Crop Coefficient (K_c)

The estimated crop coefficient (K_c) values using the energy balance method varied across three growing seasons, reflecting the influence of environmental conditions and management practices. These values were compared to FAO-56 reference K_c values to evaluate deviations. Table 5 presents the seasonal K_c values at different growth stages. In the initial stage ($K_{c\ ini}$), the EB-based K_c values ranged from 0.43 to 0.68, with the highest value observed in Season 3. In contrast, the FAO-56 reference K_c for this stage is 0.30. During the development stage ($K_{c\ dev}$), Kc values varied from 0.75 to 1.02, while FAO-56 specified a fixed value 0.73. For the mid-season stage ($K_{c\ mid}$), where peak evapotranspiration occurs, EB-derived values ranged from 0.94 to 1.11, compared to the FAO-56 reference of 1.15. In the late-season stage ($K_{c\ end}$), EB-based K_c values ranged from 0.40 to 0.64, whereas FAO-56 suggests a range of 0.25–0.40. This is indicated by (tables 2,3,4 &5 – Figures 11, 12&13).

Table 5. Crop coefficient in different growth stages between FAO and energy balance approaches.

Method	Kc ini	Kc dev	Kc mid	Kc end
EB - Season 1	0.43	1.02	1.11	0.40
EB - Season 2	0.62	0.77	1.04	0.51
EB - Season 3	0.68	0.75	0.94	0.64
FAO 56	0.30	0.73	1.15	0.25 -0.40

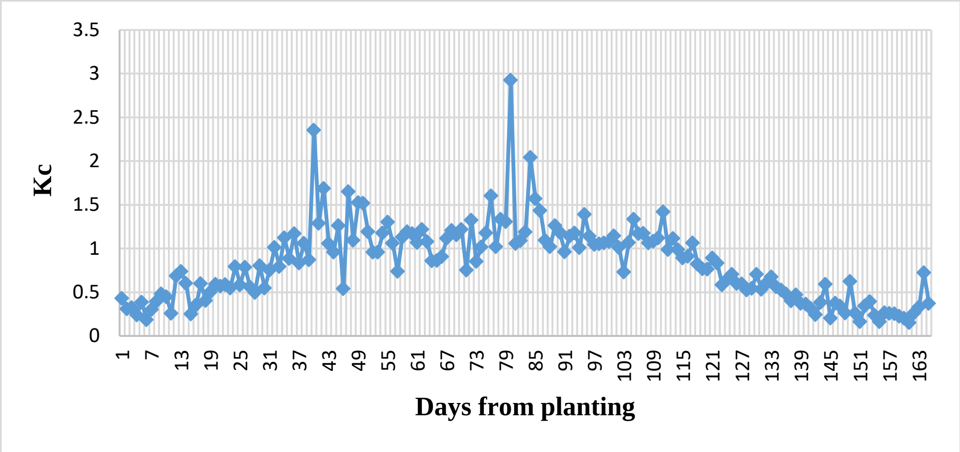

Fig. 11. Crop coefficient (K_c) for wheat during season 2021-2022.

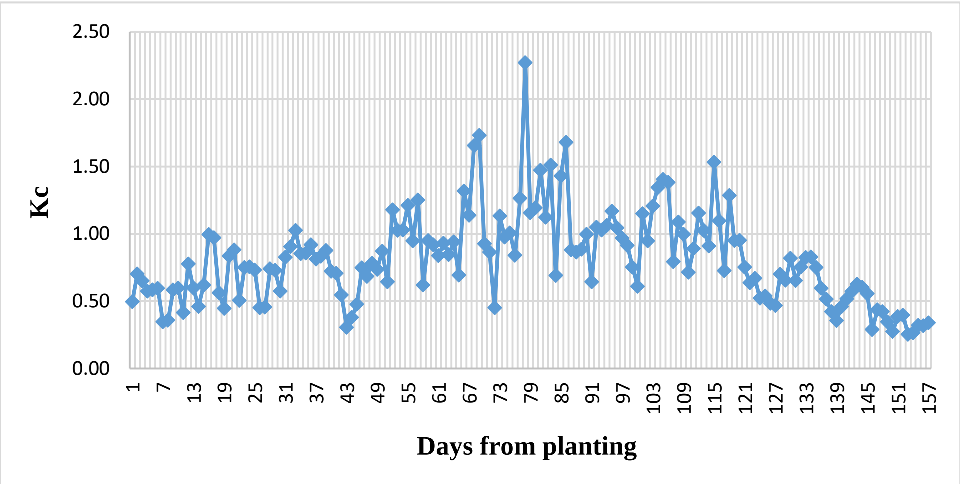

Fig. 12. Crop coefficient (Kc) for wheat during season 2022-2023.

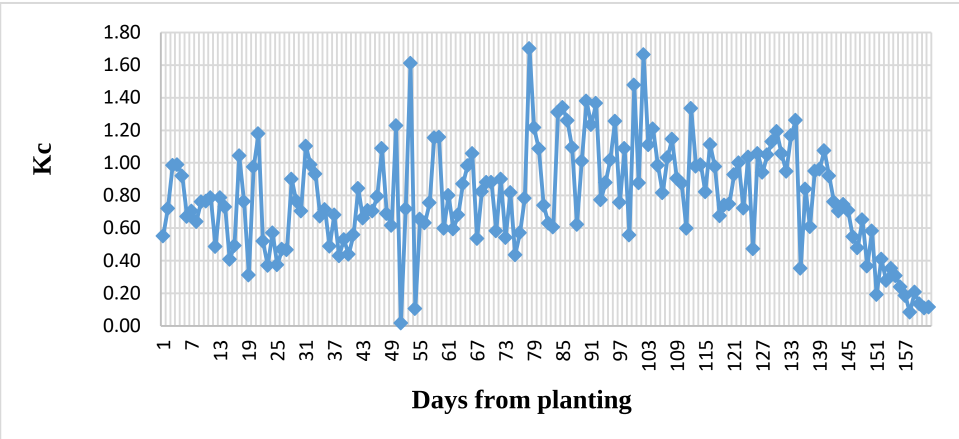

Fig. 13. Crop coefficient (K_c) for wheat during season 2023-2024.

3.4. Wheat-Soil-Water relatioships

Table (6) indicates that ET_a constitutes a large ratio of ET_o in the irrigated wheat area with more than 70 % in all three seasons. Data reveal an over-irrigation efficiency in 2021/2022 season and an inversely lower-irrigation efficiency in 2023/2024 season. Er_i ranged between 50-60 % indicating that more than 40 % of irrigation water was lost not only without any use by plants but also to decrease yield production. In addition, actual yield seem to be highly decreased than the potential wheat yield, namely the actual yield was 5.65, 5.29, and 5.58 ton/ ha for

2021/2022, 2022/2023, and 2023/2024 seasons, respectively. Low irrigation water use efficiency caused a low irrigation water productivity which ranged between 0.80 in 2022/2023 kg/m^3 season and 1.30 kg/m^3 in 2021/2022 season. Data announced an important declaration that applied irrigation water, which calculated using FAO-Kc and Allen et. al., 1998, was overestimated as compared to the traditional application. Values of applied irrigation were over-estimated by 22.91, 18.13, and 7.82 % for the successive three seasons according to FAO-Kc in relation to applied irrigation water by traditional application (Table 6).

Table 6. some parametrs relevant to evapotranspiration, irrigation efficiency, and productivity.

Season	ET_a (mm)	ET_o (mm)	ET_a/ET_o (%)	AW (mm)	AW_FAO	ER (mm)	CP (kg/ha)	Er_i (%)	WP (Kg/ m^3)
2021/2022	370.98	513.08	72.30	528.50	649.58	206.80	5652	58.39	1.3
2022/2023	427.96	582.57	73.40	642.85	759.43	171.73	5292	52.53	0.82
2023/2024	364.51	490.94	74.25	595.24	641.80	132.72	5580	50.07	1.13

Where, AW is applied water, ER is effective rainfall, CP is crop productivity, Er_i is irrigation water use efficiency, and WP is Irrigation Water Productivity.

4. Discussion

4.1. Evapotranspiration (ET_a & ET_c)

The observed discrepancy between ET_c_FAO and ET_a_EB suggests potential underestimation by the FAO method or overestimation by the energy balance approach. The consistently higher ET_a_EB values indicate that the FAO method may not fully represent actual field conditions, particularly in regions with complex climatic and soil-water relations. The significant increase in evapotranspiration in the 2022/2023 season suggests higher water demand or water consumption, which was attributed to climatic variations, increased crop growth, or changes in irrigation practices. Conversely, the decline in evapotranspiration in the 2023/2024 season reflects alterations in climate, crop conditions, or irrigation scheduling. The persistent gap between ET_c_FAO and ET_a_EB underscores the need for refining estimation methods to improve water management strategies and optimize irrigation efficiency. Moreover, over irrigation is the main challenge faces the agri-eco system, as farmers in Egypt used this bad culture since long ago, and it leads to increasing ET_a to higher extents. The findings indicate that FAO-56 Kc values tend to slightly underestimate Kc during the initial and late-season growth stages while slightly overestimating mid-season Kc, resulting more crop water requirements by 22.91, 18.13, and 7.82 % for 2021/2022, 2022/2023, and 2023/2024 seasons, respectively than the common practices. This is in an agreement with Ragab et al. (2017a, 2017b) who revealed that ETc values derived from the modified Penman–Monteith equation (Allen et al., 1998) were higher than the actual ET measured by eddy covariance and the scintillometer. On the other hand, there is a contrast findings. Shahrokhnia and Sepaskhah (2013) reported that the FAO methodology tends to underestimate the total ET of winter wheat and maize in semi-arid regions. This finding aligns with previous research by Malek and Sepaskhah (1982), Majnooni-Heris et al. (2007), Tyagi et al. (2000), and Kanemasu and Arkin (1974). Additionally, lysimeter measurements showed that the seasonal ETc for wheat was 6% higher than the ETc calculated using the FAO method (López-Urrea et al. 2009b).

4.2. Reference evapotranspiration

The variations in ET_o across the seasons emphasize the significant influence of temperature, wind speed, relative humidity, and solar radiation on evapotranspiration rates. The 2022/2023 season recorded the highest maximum temperature (40.53 C°) and higher average temperature (23.23 C°), coupled with relatively high wind speeds (6.55 m/s). These conditions likely contributed to increased atmospheric demand, leading to higher ET_o and greater irrigation requirements. Additionally, the warmer nights in this season, as indicated by the higher minimum temperature (12.04 C°), may have intensified cumulative evaporation, further stressing water resources.

In contrast, the 2021/2022 season exhibited lower maximum (33.45 C°) and minimum (15.03 C°) temperatures, which, despite slightly lower wind speeds (6.16 m/s), resulted in a relatively lower atmospheric demand. The average relative humidity in this season (68.66%) was slightly higher than in 2022/2023 (66.48%), suggesting slightly less arid conditions. The lower dew/frost point in 2021/2022 (9.05 C°) compared to 2022/2023 (8.94 C°) indicates variations in air moisture content, which may have contributed to differences in evaporation rates.

These seasonal differences emphasize the need for adaptive irrigation scheduling, as relying on fixed irrigation plans could lead to excessive water use in low-ET_o periods or crop water stress in high-ET_o seasons like 2022/2023. To improve water use efficiency, integrating real-time climate data with FAO Penman-Monteith calculations is essential for precision irrigation management. This approach ensures that irrigation applications match actual crop water requirements, reducing water waste and enhancing agricultural productivity under fluctuating climatic conditions.

4.3. Crop coefficient

The higher K_c values in the initial stage suggest increased evaporative losses from soil and early canopy expansion. The discrepancy with FAO-56 may be influenced by local climatic conditions, sowing dates, and soil moisture availability. The variation in K_c values during the development stage across seasons indicates differences in canopy expansion rates, influenced by climatic factors and irrigation scheduling. The slightly lower K_c in Season 3 may be due to delayed canopy closure or reduced transpiration efficiency. The mid-season K_c values derived from the EB method are slightly lower than FAO-56, suggesting a reduced peak water demand, possibly due to lower vapor pressure deficits or regional irrigation practices. However, the values remain close to FAO-56, confirming the high water requirements of wheat during this stage. The higher K_c values in the late-season stage suggest extended transpiration activity, actually due to higher residual soil moisture. This emphasizes the need for efficient late-season irrigation management to prevent excessive water application while ensuring proper grain filling.

Doorenbos and Pruitt (1977) emphasized the importance of locally determining crop coefficients, leading to numerous studies on ET_c and K_c estimation worldwide (Lopez-Urea et al., 2009a, b, c; Kang et al., 2003; Wang et al., 2007; Kjaersgaard et al., 2008). Some studies, such as those by Chen et al. (1995), Kang et al. (1992), and Li et al. (2008), reported higher measured crop coefficients than those provided by Allen et al. (1998) in FAO-56. Additionally, Er-Raki et al. (2007) highlighted the need for local calibration of the FAO-56 dual crop coefficient approach to improve wheat ET_c estimation accuracy. Ragab (2024) reported that eddy covariance was used to estimate actual ET_c with the crop coefficient calculated as the ratio of ET_c to ETo from the FAO-modified Penman–Monteith equation (Allen et al., 1998), finding that K_c values were, on average, 36% lower than FAO estimates, which suggests that using FAO K_c values may lead to an overestimation of the tomato crop's water requirements.

4.4. Crop water requirements

Data revealed previously that crop water requirements (ETc) which estimated according to FAO-56, was found to be higher than that found by traditional wheat cultivation in Egypt. The over-estimation of ET_c ranged from 7.82% in season 2023/2024 to 22.91% in season 2021/2022. As a consequent, irrigation use efficiency (Er_e) was decreased by 50 to 58%. This is mainly attributed to the vulgar privilage irrigation culture in Egypt depending on the recommended irrigation procedures by Ministry of Agriculture and Land Reclamation. Hence, it seems still a big gap between farmers and governmental sectors, reflecting a significant challenge towards a new scientific irrigation policy to increase water use efficiency. On the other hand, FAO method assumes general conditions for all regions and plant species and varieties which couldn't justify Egyptian cnditions and consequently an erroneous estimation for K_c and hence ET_c. It is also to note that ET_o calculated using the modified FAO Penman–Monteith equation lacks accuracy due to diurnal and seasonal variations in canopy resistance as well as inaccurate assumption by Allen et. al., (1998), leading to an overestimation of ET_o and subsequently ET_c (Han et al., 2022; Zheng et al.,2022; Hsieh et al., 2023; and Kashyap & Panda, 2001). Ragab (2024) highlighted that, on average, the actual ET measured using eddy covariance and scintillometers during two successive cropping seasons accounted only for 45% and 35% of the ET_o and ET_c estimated by the modified Penman–Monteith equation. Similarly, Paço et al. (2006) conducted ET measurements over a 3–4-year-old orchard using eddy covariance and found that the FAO-56 Penman–Monteith equation (Allen et al., 1998) overestimated ET_c when compared to eddy covariance measurements.

5. Conclusions

This study successfully monitored the crop coefficient (K_c) for wheat under common and traditional conditions in the North Nile Delta of Egypt, using an energy balance (EB) systems. The findings indicate that FAO-56 K_c values tend to slightly underestimate K_c during the initial and late-season growth stages while slightly overestimating mid-season K_c, resulting more crop water requirements than the common practices. The locally calibrated K_c values for wheat were determined to be: 0.43–0.68 ($K_{c\ ini}$), 0.75–1.02 ($K_{c\ dev}$), 0.94–1.11 ($K_{c\ mid}$), and 0.4–0.64 ($K_{c\ end}$), which not only differ from the standard FAO-56 values, but also represent the actual water requirements for wheat. These adopted locally calibrated K_c values can enlarge irrigation efficiency, reduce water wastage, and optimize wheat production under water-scarce conditions. Furthermore, the use of energy balance techniques in determining K_c can be extended to other crops, enabling better water resource management across Egypt. Future research should focus on scaling these findings using remote sensing and crop modeling to support large-scale implementation. Finally, agricultural extension and training programms have to be visualized to minimizethe gap between traditional water requirements and that resulted through several reform and developing procedures.

Declarations

Ethics approval and consent to participate

Consent for publication: The article contains no such material that may be unlawful, defamatory, or which would, if published, in any way whatsoever, violate the terms and conditions as laid down in the agreement.

Availability of data and material: applicable.

Competing interests: The authors declare that they have no conflict of interest in the

publication.

Funding: applicable.

Authors' contributions: Author Alaa Mosad carried out the research program and writing the manuscript under supervision and contribution of other authors. All authors read and agree for submission of manuscript to the journal. I did not have any scientific contribution from any scientific communities.

Acknowledgments: We acknowledge the International Center for the Agricultural Research in Dry Areas (ICARDA) for providing a doctoral scholarship through the project “Establishing and operating a regional network for field measurement of actual crop water consumption (evapotranspiration)” funded by Food and Agriculture Organization of the United Nations (FAO) and the Swedish International Development Cooperation Agency (Sida).

References

Allen, R.G., Pereira, L.S., Raes, D., & Smith, M. (1998). Crop evapotranspiration: Guidelines for computing crop water requirements. FAO Irrigation and Drainage Paper No. 56, FAO, Rome, Italy

Baldocchi, D., Falge, E., Gu, L.H., Olson, R.J., Hollinger, D., Running, S.W., Anthoni, P.M., Bernhofer, C., Davis, K., Evans, R., Fuentes, J., Goldstein, A., Katul, G., Law, B.E., Lee, X.H., Malhi, Y., Meyers, T., Munger, W., Oechel, W., Paw U, K.T., Pilegaard, K., Schmid, H.P., Valentini, R., Verma, S., Vesala, T., Wilson, K., & Wofsy, S.C. (2001). FLUXNET: A new tool to study the temporal and spatial variability of ecosystem-scale carbon dioxide, water vapor, and energy flux densities. Bulletin of the American Meteorological Society, 82(11), 2415-2434

Central Agency for Public Mobilization and Statistics. (2024). Annual Bulletin of Environment Statistics, Part Two: Environmental Quality & Energy 2022. Ref. No.: 71.22301.2022. Arab Republic of Egypt

Chen, Y.M., Guo, G.S., Wang, G.X., Kang, S.Z. (1995). Water requirements and irrigation for main crops in China. China Water Resources and Hydro-power Press, Beijing, 359 p

Doorenbo J., & Kassam, A.H. (1979). Yield response to water. FAO Irrigation and Drainage Paper No. 33, FAO, Rome, Italy

Doorenbos, J., & Pruitt, W.O. (1977). Crop water requirements. FAO Irrigation and Drainage Paper No. 24 (rev.), FAO, Rome, Italy

Er-Raki, S., Chehbouni, A., Guemouria, N., Duchemin, B., Ezzahar, J., Hadria, R. (2007). Combining FAO-56 model and ground-based remote sensing to estimate water consumptions of wheat crops in a semi-arid region. Agric Water Manag 87:41–54

FAO. (2023). Remote sensing determination of evapotranspiration – Algorithms, strengths, weaknesses, uncertainty and best fit-for-purpose. Cairo. https://doi.org/10.4060/cc8150en

Fisher, J.B., Whittaker, R.H., & Malhi, Y. (2011). ET Come Home: A critical evaluation of the use of evapotranspiration in geographical ecology. Global Ecology and Biogeography, 20, 1-18

Han, H., Feng, Q., Yu, T., Yang, X., Zhang, X. & Li, K. (2022) Characteristic of stomatal conductance and optimal stomatal behaviour in an arid oasis of Northwestern China. Sustainability, 14(2), 968. Available from: https://doi.org/10.3390/su14020968

Howell, T.A., Schneider, A.D., & Jensen, M.E. (1991). History of lysimeter design and use for evapotranspiration measurements. Proceedings of the International Symposium on Lysimetry, ASCE, Honolulu, Hawaii

Hsieh, C.-I., Huang, I.-H. & Lu, C.-T. (2023) Estimating canopy resistance using machine learning and analytical approaches. Watermark, 15(21), 3839. Available from: https://doi.org/10. 3390/w15213839

Kanemasu, E.T., Arkin, G.F. (1974). Radiant energy and light environment of crops. J Agric Meteorol 14:211–225.

Kang, S., Gu, B., Du, T., Zhang, J. (2003). Crop coefficient and ratio of transpiration to evapotranspiration of winter wheat and maize in a semi-humid region. Agric Water Manage 59:239–254

Kang, S.Z., He, Z.Z., Zhang, X. (1992). Crop water requirements and irrigation scheduling in Shaanxi province, China.

Kashyap, P.S. & Panda, R.K. (2001) Evaluation of evapotranspiration estimation methods and development of crop-coefficients for potato crop in a sub-humid region. Agricultural Water Management, 50(1), 9–25. Available from: https://doi.org/10.1016/ S0378-3774(01)00102-0

Kashyap, P.S., & Panda, R.K. (2001). Evaluation of evapotranspiration estimation methods and development of crop-coefficients for potato crop in a sub-humid region. Agricultural Water Management, 50(1), 9–25. https://doi.org/10.1016/S0378-3774(01)00102-0

Kjaersgaard, J.H., Plauborg, F., Mollerup, M., Petersen, C.T., Hansen, S. (2008). Crop coefficients for winter wheat in a sub-humid climate regime. Agric Water Manage 95:918–924

Li, S., Kang, S.H., Li, F., Zhang, L. (2008). Evapotranspiration and crop coefficient of spring maize with plastic mulch using eddy covariance in northwest China. Agric Water Manage 95:1214–1222

Liu, S.M., Xu, Z.W., Wang, W.Z., Jia, Z.Z., Zhu, M.J., Bai, J., & Wang, J.M. (2011). A comparison of eddy-covariance and large aperture scintillometer measurements with respect to the energy balance closure problem. Hydrology and Earth System Sciences, 15, 1291–1306

López-Urrea, R., de Santa, M., Olalla, F., Montoro, A., López-Fuster, P. (2009a). Single and dual crop coefficients and water requirements for onion (Allium cepa L.) under semiarid conditions. AgricWater Manag 96:1031–1036

López-Urrea, R., Montoro, A., González-Piqueras, J., López-Fuster, P., Fereres, E. (2009b). Water use of spring wheat to raise water productivity. Agric Water Manag 96:1305–1310

López-Urrea, R., Montoro, A., López-Fuster, P., Fereres, E. (2009c). Evapotranspiration and responses to irrigation of broccoli. Agric Water Manag 96:1155–1161

Majnooni-Heris, A., Zand-Parsa, S.H., Sepaskhah, A.R., Kamgar-Haghighi, A.A. (2007). Comparison of MSM model for prediction of potential evapotranspiration of maize with FAO methods. J Sci Tech Agric Nat Resour (Water Soil Sci) 11(41):29–42

Malek, A., Sepaskhah, A.R. (1981). Evaluation of advection in the Badjgah area. Iran J Agric Sci 1(1–4):29–44 (in Persian)

Ministry of Agriculture and Land Reclamation, Economic Affairs Sector. (2022). Bulletin of Agricultural Statistics: Part (1) Winter Crops, 2024/2022. Arab Republic of Egypt

Monteith, J.L. (1965). Evaporation and environment. Symposium of the Society for Experimental Biology, 19, 205–234. https://www.ncbi.nlm.nih.gov/pubmed/5321565

Paço, T.A., Ferreira, M.I. & Conceiç˜ao, N. (2006) Peach orchard evapotranspiration in a sandy soil: comparison between eddy covariance measurements and estimates by the FAO 56 approach. Agricultural Water Management, 85(3), 305–313. Available from: https://doi.org/10.1016/j.agwat.2006.05.014

Penman, H.L. (1948). Natural evaporation from open water, bare soil and grass. Proceedings of the Royal Society of London. Series A, Mathematical and Physical Sciences, 193, 120–145. https://doi.org/10.1098/rspa.1948.0037 - productivity. Agric Water Manag 96:1305–1310

Pruitt, W.O., & Swann, B.D. (1986). Evapotranspiration studies in N.S.W.: Daily vs. hourly meteorological data. Irrigation '86, Darling Downs Institute of Advanced Education, Toowoomba, Queensland, Australia, 29 p.

Ragab, R. (2024) Misconceptions and misunderstandings in agricultural water management: Time for revisiting, reflection and rethinking. Irrigation and Drainage, 1–23. Available from: https://doi.org/10. 1002/ird.2947

Ragab, R., Evans, J.G., Battilani, A., & Solimando, D. (2017a). Towards accurate estimation of crop water requirement without the crop coefficient Kc: new approach using modern technologies. Irrigation and Drainage, 66(4), 469–477. https://doi.org/10.1002/ird.2153

Ragab, R., Evans, J.G., Battilani, A., & Solimando, D. (2017b). The cosmic-ray soil moisture observation system (Cosmos) for estimating the crop water requirement: new approach. Irrigation and Drainage, 66(4), 456–468. https://doi.org/10.1002/ird.2152

Shahrokhnia, M.H., & Sepaskhah, A.R. (2013). Single and dual crop coefficients and crop evapotranspiration for wheat and maize in a semi-arid region. Theoretical and Applied Climatology, 113(1–2), 225–240. https://doi.org/10.1007/s00704-013-0848-6

Snyder, R.L., Lanini, B.J., Shaw, D.A., & Pruitt, W.O. (1989). Using reference evapotranspiration (ETo) and crop coefficients to estimate crop evapotranspiration (ETc) for agronomic crops, grasses, and vegETable crops. Cooperative Extension, University of California, Berkeley, CA, Leaflet No. 21427, 12 p

Tyagi, N.K., Sharma, D.K., Luthra, S.K. (2000). Evapotranspiration and crop coefficients of wheat and sorghum. J Irrig Drain Eng 126(4):215– 222

Wang, J., Sammis, T.W., Andales, A.A., Simmons, L.J., Gutschick, V.P., Miller, D.R. (2007). Crop coefficients of open-canopy pecan orchards. Agric Water Manag 88:253–262

World Population Review (2025). Wheat Production by Country. https://worldpopulationreview.com › country-rankings

Wright, J.L. (1981). Crop coefficients for estimates of daily crop evapotranspiration. Irrigation Scheduling for Water and Energy Conservation in the 80s, ASAE, Dec. 1981.