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Determining evapotranspiration of Faba bean and Chickpea using the soil water balance method under field conditions in the Gezira Scheme, Sudan

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Abstract

Water scarcity is a major constraint to agricultural productivity in Sudan, making the accurate estimation of crop water requirements (CWRs) essential for efficient irrigation management. This study quantified crop evapotranspiration (ET_c) and developed growth-stage-specific crop coefficients (K_c) for faba bean (*Vicia faba* L.) and chickpea (*Cicer arietinum* L.) under field conditions in the Gezira Scheme, Sudan. ET_c was determined using the soil water balance method with gravimetric soil moisture measurements across four phenological stages: initial, development, mid-season, and late season, while reference evapotranspiration (ET_o) was computed using the FAO Penman–Monteith approach in CROPWAT. The average seasonal ET_c was 435 mm for faba bean and 380 mm for chickpea, with maximum daily values observed during the mid-season stage. Stage-specific K_c values were 0.31, 0.85, 1.07, and 0.55 for faba bean, and 0.28, 0.71, 1.04, and 0.30 for chickpea, respectively. These locally derived coefficients reflect the combined effects of Vertisols hydrology and semi-arid climatic conditions on crop water use. The findings provide reliable, site-specific parameters for improving irrigation scheduling and enhancing water-use efficiency in the Gezira Scheme, thereby supporting sustainable legume production in Sudan.

Keywords ET_c, K_c, Faba bean, Chickpea, Soil water balance, Gezira scheme

1 Introduction

Water scarcity has become one of the most pressing challenges to sustainable development in the 21st century. As of 2023, over two billion people live in countries experiencing high levels of water stress, with agriculture accounting for nearly 70% of global freshwater withdrawals [11]. Global water scarcity entails both quantitative insufficiency and qualitative degradation of freshwater resources, constraining water availability for agricultural, industrial, and domestic uses [20]. It is commonly classified as either physical, where natural supplies are insufficient, or economic, where access is restricted by



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weak governance, institutional limitations, or inadequate infrastructure [7]. The interaction between these two forms of scarcity has profound implications for global food production, particularly in regions where irrigated agriculture underpins food security.

Sudan has historically exemplified economic water scarcity, in which the substantial water resources of the Nile have been underutilized due to limited investment, poor infrastructure, and suboptimal management of hydraulic systems [27]. However, recent hydro-political developments—including the secession of South Sudan in 2011 and ongoing internal instability—have compounded this situation, leading to a convergence of economic scarcity with intensifying physical water stress. Consequently, irrigation water availability, rather than arable land, has become the primary factor constraining agricultural production. This shift poses a direct threat to national food and protein security and emphasizes the urgent need to enhance water productivity at both farm and system levels.

In this constrained water environment, identifying and promoting water-efficient, high-value crops constitutes a critical adaptation strategy. Legumes, particularly faba bean (*Vicia faba* L.) and chickpea (*Cicer arietinum* L.), hold strategic importance due to their high protein content (25–30%), capacity for biological nitrogen fixation, and relatively high water-use efficiency compared with cereals [19, 22, 22]. These crops play a key role in improving soil fertility and contributing to sustainable intensification—enhancing productivity while conserving water and maintaining soil health. In Sudan, faba bean and chickpea are vital components of the winter cropping system, making substantial contributions to national nutrition. Between 2013 and 2022, faba bean was cultivated on an average of 50,000 hectares and chickpea on 10,000 hectares, with average yields of 3.8 t ha⁻¹ and 3.2 t ha⁻¹, respectively [11].

The Gezira Scheme, located in central Sudan, remains the principal production zone for these crops and one of the largest irrigation initiatives in the world. The scheme's foundation lies in the heavy montmorillonitic Gezira clay (Vertisol), characterized by pronounced shrink–swell behavior. This soil forms deep cracks upon drying—promoting rapid initial infiltration but high evaporative losses—and exhibits extremely low permeability when wet [13]. This distinctive hydrological regime makes the precise determination of crop water requirements (CWR) critical for sustainable management. Given that the Gezira Scheme consumes roughly one-third of Sudan's Nile water quota [1], even small inaccuracies in estimating CWR can translate into substantial volumes of wasted water.

Despite the critical importance of irrigation water, inefficient water management continues to constrain legume productivity in Sudan. Many farmers rely on fixed irrigation schedules or visual crop indicators rather than scientific methods of irrigation scheduling, resulting in both over-irrigation and water stress [10]. The first step toward overcoming this challenge is the accurate determination of crop water requirements, which are governed primarily by crop evapotranspiration (ET_c). Precise estimation of ET_c ensures that irrigation applications match actual crop demand, minimizing water losses and preventing yield reductions due to moisture stress [4]. ET_c represents the water lost through evapotranspiration by a healthy, well-managed crop under optimal conditions and is a central parameter in irrigation design and scheduling.

Several approaches exist for estimating ET_c. Direct measurement using lysimeters remains the most accurate method but is costly and technically demanding, limiting

its use to specialized research facilities [15]. Soil water balance methods, which integrate precipitation, irrigation, and changes in soil moisture storage, provide a practical and reliable alternative under real field conditions. More commonly, ET_c is estimated from meteorological data using the relationship $ET_c = ET_o \times K_c$, where ET is the reference evapotranspiration and K_c is the crop coefficient [9]. The FAO Penman–Monteith method is internationally recognized as the standard approach for ET_o estimation [25], while the K_c -based approach offers an optimal balance between simplicity and empirical reliability [4]. The K_c value depends on crop type, growth stage, season length, climatic conditions, and soil characteristics. Accurate determination of K_c allows ET_c values to be extrapolated across diverse climatic regions by combining local ET with the crop-specific coefficient.

Existing research demonstrates substantial variability in ET_c and K_c values for faba bean and chickpea, reflecting the strong influence of local agro-climatic and soil conditions. For example, while FAO-56 guidelines suggest a mid-season K_c of 1.05–1.15 for faba bean, a study at Hudeiba, Sudan, reported a higher value of 1.22 [3]. This discrepancy emphasizes the site-specific nature of crop water use, indicating that K_c values developed elsewhere cannot be directly applied to the unique hydrological and agro-ecological conditions of the Gezira Scheme. Consequently, the lack of localized ET_c and K_c data represents a significant knowledge gap, limiting the potential for precise irrigation planning and efficient water allocation.

Accordingly, the present study aims to:

1. Quantify the seasonal and average daily crop water requirements (ET_c) of faba bean and chickpea; and.
2. Establish growth-stage-specific crop coefficients (K_c) for the four phenological stages initial, development, mid, and late under field conditions of the Gezira Scheme, Sudan.

Given the limited availability of lysimetric facilities, the soil water balance method was adopted as a practical and reliable approach for ET_c estimation under actual management practices. The resulting locally derived ET_c and K_c values will provide a scientific basis for evidence-based irrigation scheduling, enabling water managers and farmers in the Gezira Scheme to apply the right amount of water at the right time. This will contribute to the sustainable and water-efficient intensification of legume production in Sudan.

2 Materials and methods

2.1 Experimental site

Field experiments were conducted during the winter seasons of 2021/2022 and 2022/2023 at the Gezira Research Station Farm, Wad Medani, Sudan (14°23' N, 33°29' E; 405 m a.s.l.). The site is located within the semi-arid central Gezira Scheme. The soils are heavy cracking clays (Vertisols) characterized by very low permeability, with a field capacity (FC) of 43% (v/v) and a permanent wilting point (PWP) of 23% (v/v) [1, 1]. The winter season in central Sudan extends from early November to late March. No rain-fall occurred during either experimental season; therefore, irrigation was the sole water input. Figures 1 and 2 show the study area location and the experimental field layout, respectively.

Schematic layout of experimental plots showing faba bean and chickpea plots. The Wad Medani Meteorological Station is located 1 km from the experimental site.

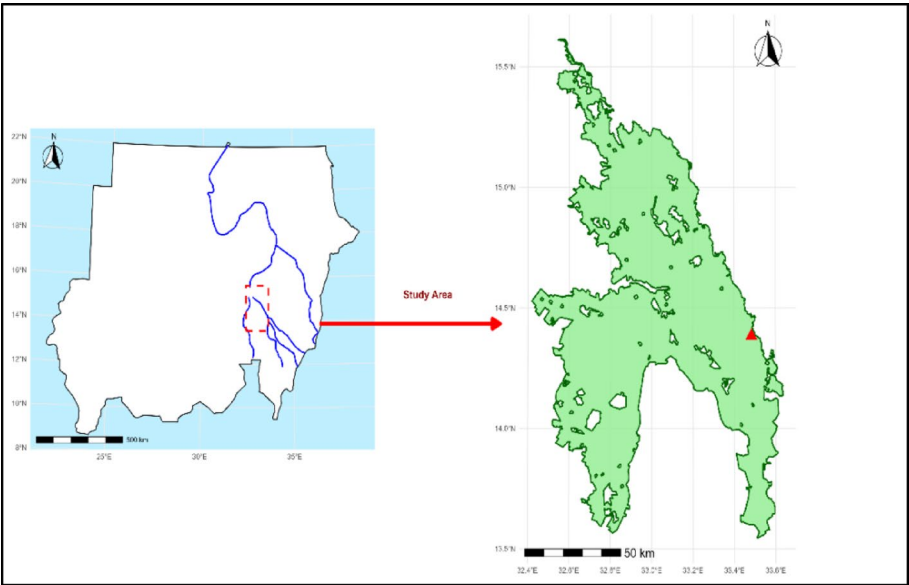


Fig. 1 Location of the Study Area, indicated by a red triangle

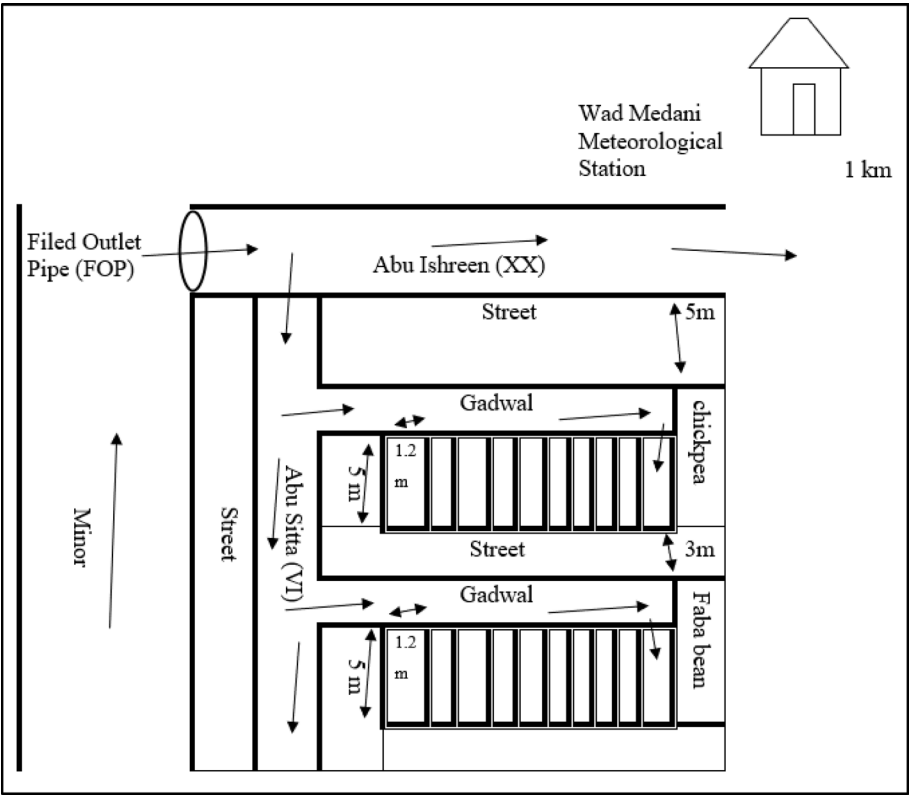


Fig. 2 Experimental Field Layout

2.2 Plant materials and experimental layout

Two winter legumes were studied: faba bean (*Vicia faba* L., Ed-Damer variety) and chickpea (*Cicer arietinum* L., Hawata variety). These cultivars were released by Hudeiba Research Station (ARC) and certified by the National Variety Release Committee. Identity verification was conducted by the first author. The study was designed as an

Table 1 Sowing and harvesting dates for Faba bean and Chickpea

Crop	Season	Sowing date	Harvesting date
Faba bean	2021/2022	18-Nov-21	2-Mar-22
Faba bean	2022/2023	10-Nov-22	22-Feb-23
Chickpea	2021/2022	19-Nov-21	26-Feb-22
Chickpea	2022/2023	10-Nov-22	17-Feb-23

Table 2 Duration of growth stages (Days) for Faba bean and Chickpea

Stage	Description	Faba bean	Chickpea
Initial	Sowing to 10% ground cover	20	20
Crop development	10% to 70% ground cover	26	22
Mid-season	Flowering and yield formation	37	35
Late season	Ripening to harvest	22	23
Total	—	105	100

observational field experiment to calibrate crop evapotranspiration (ET_c) and crop coefficient (K_c) under typical Gezira management. Each crop occupied a single non-replicated plot (60 m²) per season. A single large plot per crop was selected to represent field-scale irrigation practice in the Gezira Scheme; therefore, the study provides baseline, location-specific ET_c and K_c data rather than treatment comparisons. Land was prepared by disc plowing, harrowing, and leveling. Raised beds measured 1.2 m (center-to-center) × 10 raised beds × 5.0 m each. Seeds were sown manually during the second week of November in each season (Table 1) at a density of 33 seeds m⁻² with 0.10 m intra-row spacing. Phosphorus fertilizer was applied at 43 kg P₂O₅ ha⁻¹ as di-ammonium phosphate (DAP) at sowing, and nitrogen at 43 kg N ha⁻¹ as urea before the second irrigation. Weeds were removed manually. Irrigation was applied from the Gezira Canal at 7–10 day intervals according to local practice.

2.3 Crop growth stages

Crop ground cover was estimated visually every 10 days following the FAO (1998) visual guide for estimating canopy cover. The growing period was divided into four stages following [9]: Initial, Development, Mid-season, and Late season. Stage durations (days after sowing, DAS) are reported in Table 2.

2.4 Weather data and reference evapotranspiration (ET_o)

Daily weather data, including maximum and minimum temperature, relative humidity, sunshine duration, and wind speed at 2 m height, were obtained from the Wad Medani Meteorological Station, located 1 km from the experimental site. Reference evapotranspiration (ET_o) was estimated using the FAO Penman–Monteith method, implemented in FAO CROPWAT 8.0 [4]. Daily ET_o values computed by CROPWAT were averaged over each irrigation interval (7–10 days) to match the temporal resolution of the measured crop evapotranspiration (ET_c). For presentation of seasonal trends, decadal (10-day) averages derived from daily values are reported.

2.5 Measurement of crop evapotranspiration (ET_c)

Crop evapotranspiration (ET_c) for the interval between consecutive irrigations was determined using a soil water balance approach:

$$ET_c = I + P \pm \Delta S - D - R.$$

Where: I = irrigation depth (mm), P = precipitation (mm), ΔS = change in soil water storage in the root zone (mm), D = deep drainage (mm), R = surface runoff (mm). Under Gezira conditions, $P = 0$ (winter is rainless), $D = 0$ (heavy Vertisols), and $R = 0$ (nearly level topography). No other water was applied between post- and pre-irrigation sampling; thus, the balance simplifies to:

No other external water input or output occurred during the sampling interval (Δt) between the post-irrigation measurement and the pre-irrigation measurement. Therefore, ET_c is solely accounted for by the change in soil water storage:

$$ET_c = -\Delta S.$$

Soil moisture sampling: At each measurement event, one auger sample was collected from each of ten raised beds per plot at depths of 0–20, 20–40, and 40–60 cm (0–60 cm active root zone). Samples were taken adjacent to plants, and sampling positions were shifted along the beds on subsequent events to avoid root damage.

Gravimetric water content (θ_g) was determined by oven-drying samples at 105 °C for 24 h. The volumetric water content (θ_v) was then calculated using BD values derived from empirically developed BD–gravimetric moisture content (θ_g) relationships for the local Vertisols [13].

$$0\text{--}20\text{ cm: } BD = -0.00003(\theta_g)^2 - 0.0019(\theta_g) + 1.274.$$

$$20\text{--}40\text{ cm: } BD = -0.00003(\theta_g)^2 - 0.0019(\theta_g) + 1.274.$$

$$40\text{--}60\text{ cm: } BD = -0.00005(\theta_g)^2 - 0.0027(\theta_g) + 1.386.$$

Change in soil water storage for the 0–60 cm profile was calculated as:

$$\Delta S = [\sum (\theta_{v1} - \theta_{v2})_i \times d_i]$$

Where:

θ_{v1} = Volumetric moisture content in layer i after irrigation.

θ_{v2} = Volumetric moisture content in layer i before the next irrigation.

d_i = Thickness of layer i (200 mm for each of the three layers).

Interval ET_c (mm) was converted to daily ET_c (mm day^{-1}) by dividing by the interval length Δt (days):

$$ET_{c\text{ daily}} = ET_{c\text{ interval}} / \Delta t = -\Delta S / \Delta t.$$

2.6 Measurement of irrigation water applied (I)

Irrigation water volume for each event was measured in the field using a current meter in the supply canal and then converted to applied depth (mm) over the plot area:

$$I = A \times V \times T.$$

where I = applied water (m^3), A = canal cross-sectional area (m^2), V = flow velocity (m s^{-1}) and T = irrigation duration (s). Applied depth (mm) was obtained by dividing volume by plot area.

2.7 Crop coefficient (K_c) determination

Interval-based K_c values were calculated as:

$$K_c = ET_c / ET_o.$$

Where ET_c and ET_o are in mm day^{-1} and correspond to the same measurement interval (ET_o averaged over the interval using CROPWAT). K_c values were computed for each 7–10 day interval, plotted against days after sowing (DAS), and smoothed to derive continuous seasonal K_c curves. Stage-wise mean K_c values were obtained by averaging

interval Kc values within each defined growth stage (initial, development, mid-season, late).

2.8 Statistical analysis

Graphical analyses and regression modelling were performed using Microsoft Excel (Version 2021) and R Statistical Software (Version 4.5.1; R Core Team, 2024). Linear and quadratic regressions were applied to examine relationships between ETc and key drivers, including ET₀, T_{max}, sunshine duration, and irrigation volume. Goodness-of-fit was reported as the coefficient of determination (R^2), and significance was considered at $p < 0.05$ where applicable.

Because the experiment employed single, non-replicated plots per crop (observational calibration study), formal inferential statistics comparing treatments or seasons (e.g., ANOVA) and measures of between-plot variance were not applicable.

3 Results

3.1 Climatic conditions during the study period

Daily meteorological observations from the Wad Medani station during 2021/2022 and 2022/2023 reflected semi-arid winter conditions with no rainfall. Decadal averages (10-day means) were computed from daily records to illustrate seasonal trends. Minimum air temperatures ranged from 13 to 23 °C, while maximum temperatures varied from 33 °C to >40 °C toward the late season. Relative humidity ranged between 18 and 49% across seasons. Sunshine duration averaged 10 h day⁻¹ across most decadal periods. Reference evapotranspiration (ET₀, calculated using CROPWAT) increased toward late season, reaching values coinciding with the late grain-filling stage of both crops (Fig. 3; Table 3).

3.2 Relationship between etc and Climatic drivers

Interval ETc values (converted to a daily basis) were regressed against ET₀, maximum temperature (T_{max}), and sunshine duration. For faba bean, ETc increased with ET₀ (slope = 1.226; $R^2 = 0.214$) but showed a moderate negative relationship with T_{max} (slope = -0.357; $R^2 = 0.235$), consistent with stomatal limitations under high

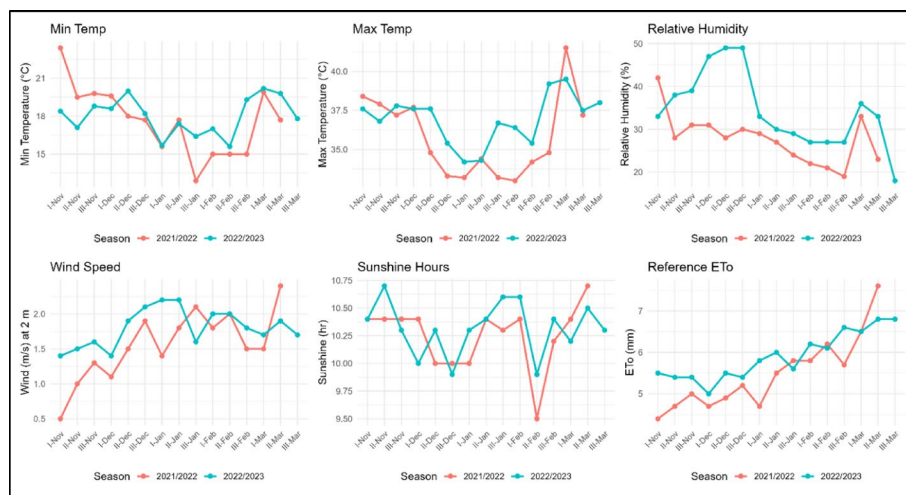


Fig. 3 Seasonal trends of meteorological parameters and ET₀ during the 2021/2022 and 2022/2023 winter seasons

Table 3 Decadal mean meteorological parameters (minimum and maximum temperature, relative humidity, wind speed, sunshine hours, and ETo) for 2021/2022 and 2022/2023 (Wad Medani meteorological Station)

Month	Min Temp (oC)	Max Temp (oC)	RH (%)	Wind (m s ⁻¹) 2 m height	Sunshine (hr)	ETo (mm day ⁻¹)
2021/2022						
I-Nov	23.4	38.4	42	0.5	10.4	4.4
II-Nov	19.5	37.9	28	1.0	10.4	4.7
III-Nov	19.8	37.2	31	1.3	10.4	5.0
I-Dec	19.6	37.7	31	1.1	10.4	4.7
II-Dec	18.0	34.8	28	1.5	10.0	4.9
III-Dec	17.7	33.3	30	1.9	10.0	5.2
I-Jan	15.6	33.2	29	1.4	10.0	4.7
II-Jan	17.7	34.4	27	1.8	10.4	5.5
III-Jan	12.9	33.2	24	2.1	10.3	5.8
I-Feb	15.0	33.0	22	1.8	10.4	5.8
II-Feb	15.0	34.2	21	2.0	9.5	6.2
III-Feb	15.0	34.8	19	1.5	10.2	5.7
I-Mar	19.9	41.5	33	1.5	10.4	6.5
II-Mar	17.7	37.2	23	2.4	10.7	7.6
2022/2023						
I-Nov	18.4	37.6	33	1.4	10.4	5.5
II-Nov	17.1	36.8	38	1.5	10.7	5.4
III-Nov	18.8	37.8	39	1.6	10.3	5.4
I-Dec	18.6	37.6	47	1.4	10.0	5.0
II-Dec	20.0	37.6	49	1.9	10.3	5.5
III-Dec	18.2	35.4	49	2.1	9.9	5.4
I-Jan	15.7	34.2	33	2.2	10.3	5.8
II-Jan	17.4	34.3	30	2.2	10.4	6.0
III-Jan	16.4	36.7	29	1.6	10.6	5.6
I-Feb	17.0	36.4	27	2.0	10.6	6.2
II-Feb	15.6	35.4	27	2.0	9.9	6.1
III-Feb	19.3	39.2	27	1.8	10.4	6.6
I-Mar	20.2	39.5	36	1.7	10.2	6.5
II-Mar	19.8	37.5	33	1.9	10.5	6.8
III-Mar	17.8	38.0	18	1.7	10.3	6.8

temperatures. Sunshine duration showed a weak negative association (slope = -0.713 ; $R^2 = 0.030$).

For chickpea, ETc responses were weaker: ETc vs. ETo (slope = 1.031 ; $R^2 = 0.119$), Tmax effect was negligible (slope = -0.083 ; $R^2 = 0.008$), and a larger negative slope was observed for sunshine (slope = -1.538 ; $R^2 = 0.130$) (Fig. 4; Table 4).

3.3 Temporal variations in ETc, applied irrigation, and statistical relationship

ETc was low during the initial stage (0–20 DAS) for both crops, ranging 1.5 – 2.3 mm day⁻¹ for faba bean and 1.2 – 1.8 mm day⁻¹ for chickpea, and increased during the development and mid-season stages, peaking during flowering and pod formation. Peak average daily ETc during mid-season reached approximately 6 – 7 mm day⁻¹ for faba bean and 5 – 6 mm day⁻¹ for chickpea.

Irrigation applications, applied at 7–10 day intervals, are overlaid on the ETc time series (Figs. 5 and 6). The sharp ETc peaks immediately following irrigation events highlight the dominance of soil evaporation E on the heavy Vertisols when the surface is wet.

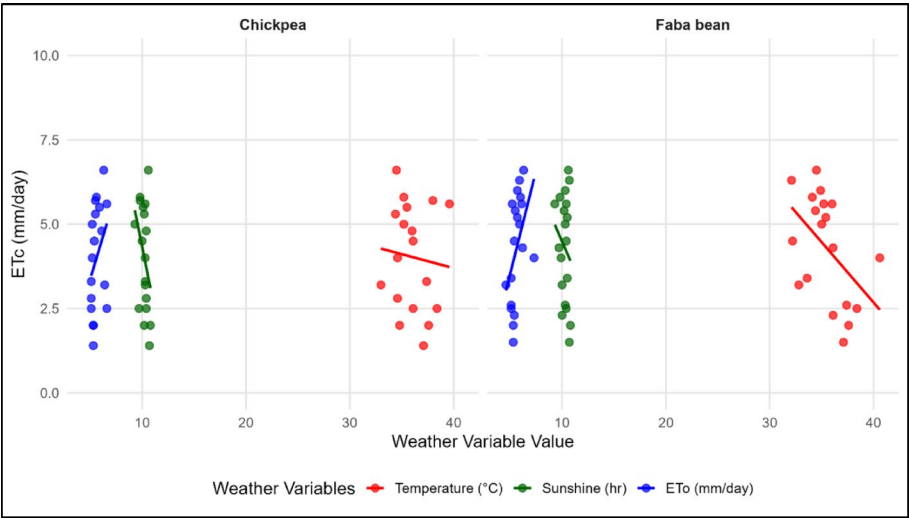


Fig. 4 Relationships between ETc and selected weather variables (ETo, Tmax, sunshine duration) for faba bean and chickpea (interval-based data)

Table 4 Simple linear regression equations and R² values for etc vs. ETo, Tmax, and sunshine duration (faba bean and chickpea)

Relationship	Crop	Simple regression equation	Simple R ²
ETc vs. ETo	Faba bean	$ETc = -2.607 + 1.226 \times ETo \text{ (mm/day)}$	0.214
	Chickpea	$ETc = -1.783 + 1.031 \times ETo \text{ (mm/day)}$	0.119
ETc vs. Tmax (°C)	Faba bean	$ETc = 16.974 - 0.357 \times Tmax$	0.235
	Chickpea	$ETc = 7.01 - 0.083 \times Tmax$	0.008
ETc vs. Sunshine (hr)	Faba bean	$ETc = 11.612 - 0.713 \times Sunshine$	0.030
	Chickpea	$ETc = 19.717 - 1.538 \times Sunshine$	0.130

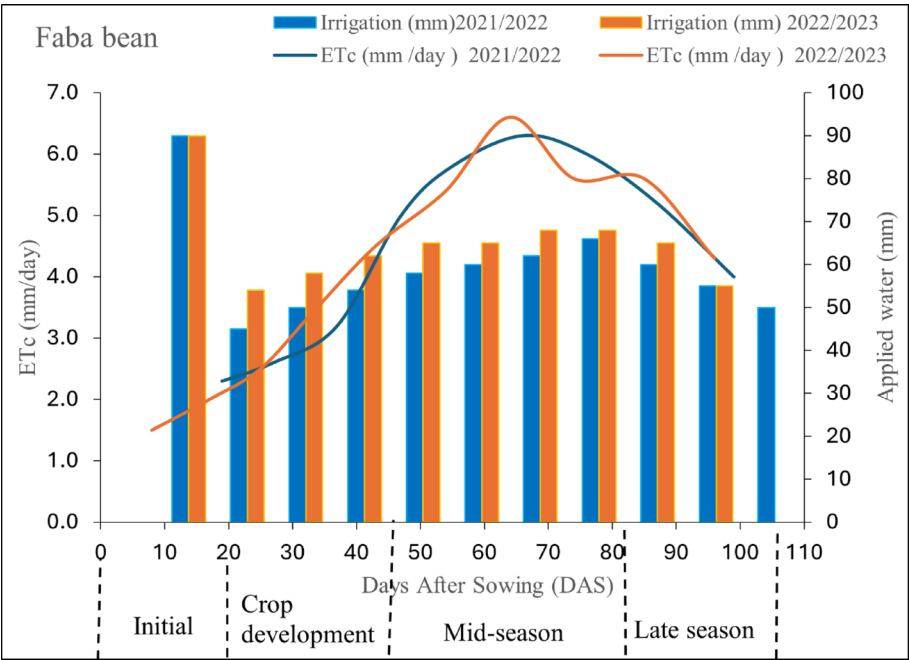


Fig. 5 Seasonal ETc and applied irrigation water for faba bean (2021/2022 and 2022/2023). Growth stages are indicated by vertical dashed lines; irrigation events are marked

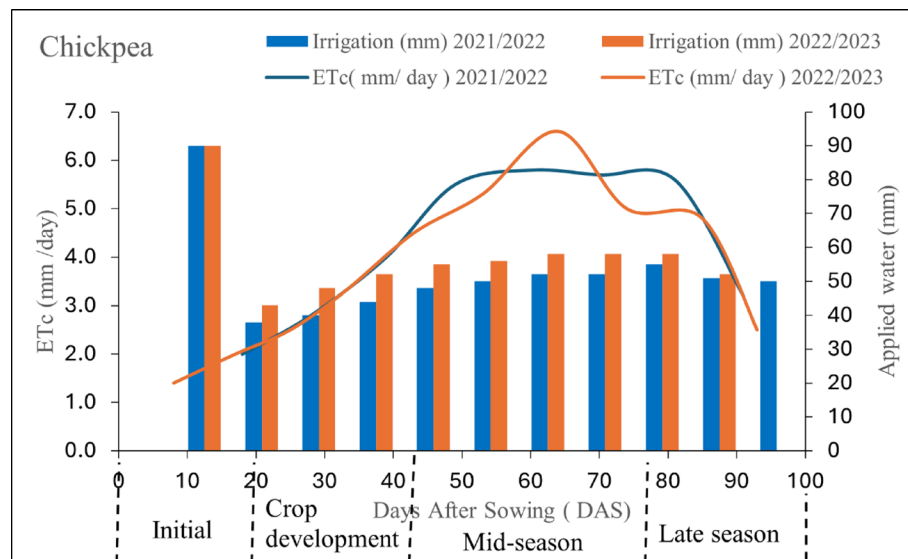


Fig. 6 Seasonal ETc and applied irrigation water for chickpea (2021/2022 and 2022/2023). Growth stages are indicated by vertical dashed lines; irrigation events are marked

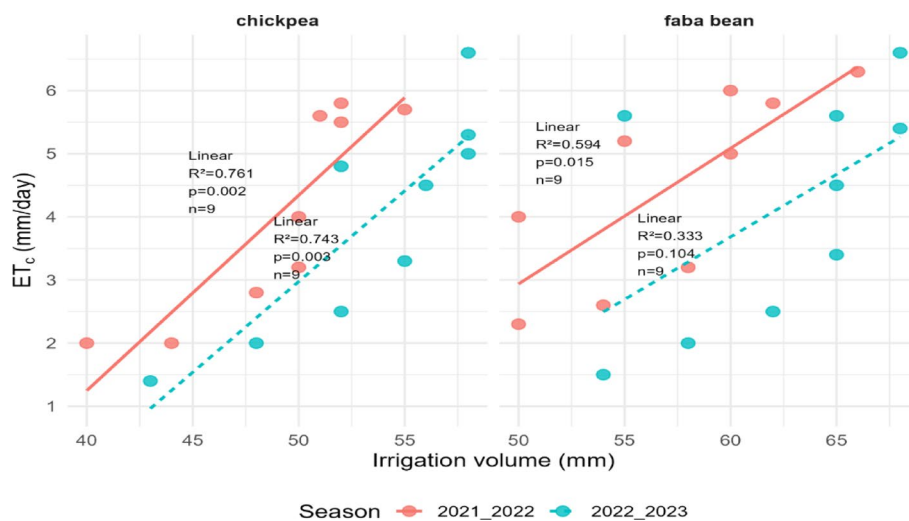


Fig. 7 Linear regressions of ETc on applied irrigation volume for faba bean and chickpea (each season)

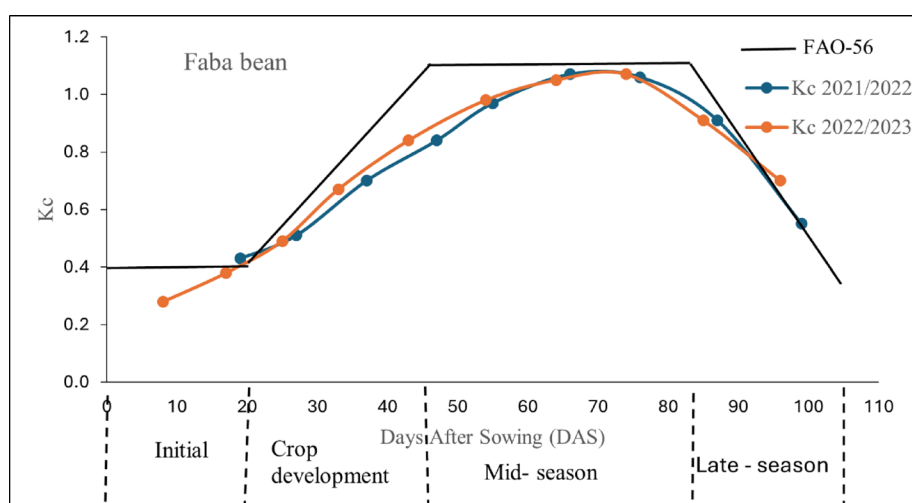
Linear and quadratic regressions between applied irrigation depth and ETc were fitted for both seasons, with the linear models presented in Fig. 7. The strong statistical relationship between interval ETc and the applied irrigation depth confirms that water availability is a major factor driving measured water loss in this system (Fig. 7) and the quadratic models in Fig. 8.

Chickpea showed a consistent linear relationship across both seasons (2021/2022: $R^2 = 0.761$, $p = 0.002$; 2022/2023: $R^2 = 0.743$, $p = 0.003$). The Faba bean relationship was moderate in 2021/2022 ($R^2 = 0.594$, $p = 0.015$) but a weaker relationship in 2022/2023 ($R^2 = 0.333$, $p = 0.094$), demonstrating crop-specific responses to local management and soil conditions.

Investigation into potential non-linear responses utilized quadratic regression. For chickpea, while quadratic fits produced nominally higher R^2 values, the quadratic terms

Table 5 Stage-wise partitioning of seasonal etc for Faba bean and Chickpea (total mm and % of seasonal etc)

Crop	Growth Stage	Duration (Days)	Total Water Use (mm)	% of Seasonal ETc
Faba Bean	Initial	20	32.2	7.4%
	Development	26	85.3	19.6%
	Mid-Season	37	223.1	51.3%
	Late Season	22	94.4	21.7%
	Total Season	105	435.0	100%
Chickpea	Initial	20	28.9	7.6%
	Development	22	67.7	17.8%
	Mid-Season	35	194.7	51.2%
	Late Season	23	78.7	20.7%
	Total Season	100	380.0	100%

**Fig. 9** Seasonal Kc curve for faba bean (observed interval values and FAO-style segmented fit)

were consistently found to be statistically non-significant ($p > 0.05$). Similarly, for faba bean, a quadratic fit for 2022/2023 produced a high $R^2 = 0.947$, but the quadratic term was also not significant ($p > 0.05$), indicating caution in interpreting non-linearity. Based on these findings, the linear model provides the most statistically robust and scientifically parsimonious explanation for the effect of applied irrigation depth on ETc under these field conditions.

3.4 Cumulative etc and stage-wise partitioning

Seasonal ETc was partitioned into four growth stages. For both crops, the mid-season accounted for the largest share of seasonal water use (51%). Stage-wise totals, averaged over the two seasons, are presented in Table 5.

3.5 Crop coefficient (Kc) determination and FAO comparison

Interval-based Kc values ($Kc = ETc/ETo$) were computed and smoothed to derive seasonal curves (Figs. 9, 10). Stage-wise mean Kc values are summarized in Table 6.

Applying FAO-56 Kc to the local ETo would overestimate seasonal ETc by 12.1% for faba bean (+52.5 mm) and ~2.7% for chickpea (+10.3 mm) (Table 7). These deviations

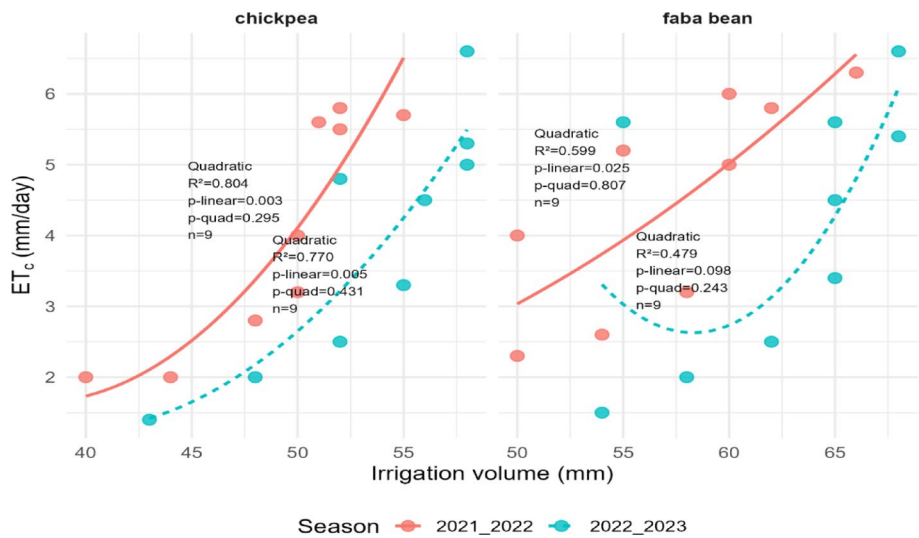


Fig. 8 Quadratic regressions of ET_c on applied irrigation volume for faba bean and chickpea (each season)

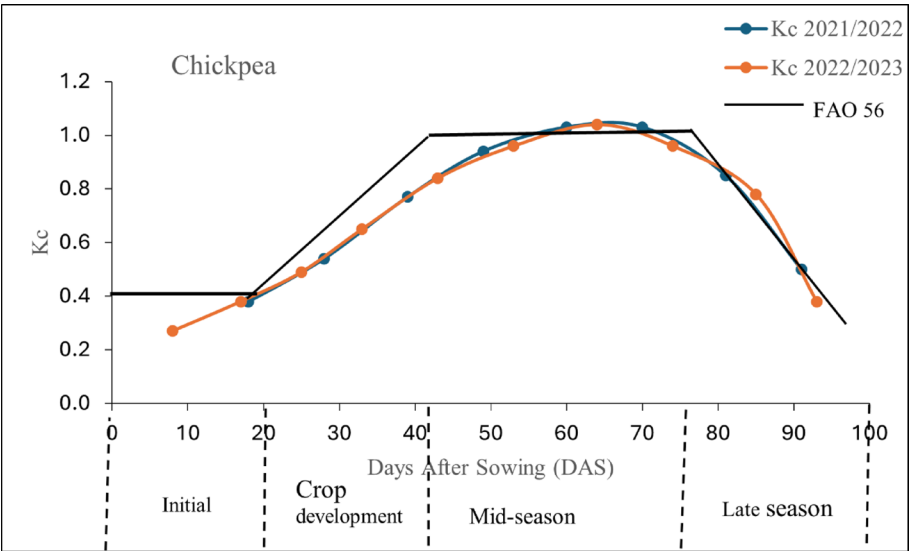


Fig. 10 Seasonal K_c curve for chickpea (observed interval values and FAO-style segmented fit)

Table 6 Stage-specific K_c values (current study vs. FAO-56 defaults)

Crop	K _c Stage	Current study (Gezira)	FAO-56 default	Difference (Local – FAO)
Faba bean	Initial	0.31	0.40	−0.09
	Mid	1.07	1.15	−0.08
	Late	0.55	0.35	+ 0.20
Chickpea	Initial	0.28	0.40	−0.12
	Mid	1.04	1.00	+ 0.04
	Late	0.30	0.35	−0.05

Table 7 Impact of using FAO-56 Kc versus locally derived Kc on seasonal etc

Crop	Scenario	Total ETc (mm)	Difference from local ETc (mm)	Overestimation (%)
Faba bean	FAO-56 Kc	487.5	+ 52.5	+ 12.1
	Local Kc	435.0	-	-
Chickpea	FAO-56 Kc	390.3	+ 10.3	+ 2.7
	Local Kc	380.0	-	-

Table 8 Grain yield of Faba bean and Chickpea (kg ha⁻¹) over two growing seasons

Crop	2021/2022	2022/2023
Faba bean	1552.5	1423.9
Chickpea	1980.3	1815.5

highlight the benefits of local Kc calibration for irrigation scheduling in the Gezira Scheme.

3.6 Crop yield

Grain yields (kg ha⁻¹) for each season are presented in Table 8. Faba bean yielded 1,552.5 (2021/2022) and 1,423.9 (2022/2023) kg ha⁻¹, while chickpea yielded 1,980.3 (2021/2022) and 1,815.5 (2022/2023) kg ha⁻¹. Because the experimental design used single non-replicated plots per crop, yield differences are reported descriptively without inferential statistical testing.

4 Discussion

This study demonstrates that effective irrigation management for faba bean and chickpea in the Gezira Scheme requires crop coefficients (Kc) calibrated for local conditions. The interaction of heavy Vertisols with a semi-arid climate renders standard FAO-56 Kc values inadequate, often leading to inefficient water use. Semi-arid winter conditions during the study, characterized by wide diurnal temperature fluctuations and high atmospheric demand, defined a narrow optimal window for crop growth. Maximum temperatures exceeding 40 °C in March represented a critical risk period, as temperatures above 35 °C are known to cause floral abortion and yield reduction in faba bean [24, 29]. High reference evapotranspiration (ET_o) values of 5.7–6.6 mm day⁻¹ observed in February, coinciding with the late grain-filling stage, highlight the need for careful terminal water stress management [4, 26].

Regression analyses revealed distinct water-use strategies between the two crops. Faba bean's ETc showed a strong positive relationship with ET_o ($R^2 = 0.214$, slope = 1.226), but a significant negative correlation with high maximum temperatures ($R^2 = 0.235$, slope = -0.357), indicating that atmospheric demand drives water use while heat stress impairs physiological function and reduces transpiration efficiency. In contrast, chickpea's ETc was weakly correlated with ET_o ($R^2 = 0.119$) and T_{max} ($R^2 = 0.008$), confirming its conservative water-use strategy and drought avoidance mechanisms, such as early stomatal closure [21]. These findings suggest that ET_o-based irrigation scheduling is appropriate for faba bean, whereas soil moisture-based scheduling is more suitable for chickpea under high-temperature conditions.

Seasonal ETc patterns followed expectations for cool-season legumes in semi-arid regions, increasing from 1 to 2 mm day⁻¹ during the initial stage to a peak during flowering and pod formation, before declining toward maturity [16]. Faba bean consistently

exhibited higher ET_c , peaking at 6–7 mm day⁻¹, due to its denser canopy, longer growing period, and deeper root system [29]. Chickpea, with its smaller leaf area and greater drought tolerance [5], showed a lower peak ET_c of 5–6 mm day⁻¹. The mid-season stage accounted for 51% of seasonal ET_c for both crops, emphasizing the importance of sufficient irrigation during flowering and pod formation [8].

A principal finding is the significant deviation of local K_c values from FAO-56 defaults. Initial crop coefficients ($K_{c, ini}$ = 0.30) were 25% lower than FAO-56 (0.40), likely due to the self-mulching Vertisols surface, which reduces soil evaporation after irrigation. Mid-season K_c values were largely consistent with FAO-56 benchmarks, but late-season K_c , particularly for faba bean (0.55 vs. FAO-56 0.35), was substantially higher, reflecting delayed senescence and prolonged transpiration during pod filling. Applying default FAO-56 values would likely overestimate water requirements, increasing the risk of water stress management errors.

The adoption of locally calibrated K_c values allows more precise irrigation scheduling, potentially reducing seasonal water use by 12.1% for faba bean and 2.7% for chickpea without yield penalty. This has significant implications for the Gezira Scheme, where irrigation efficiency is critical for sustainable Nile water allocation. Optimized scheduling can also reduce early-season waterlogging and nutrient leaching, while preserving late-season yield potential [6].

This study provides field-based evidence that site-specific K_c calibration is essential for sustainable water management in large irrigation schemes. Future research should explore dynamic dual K_c models to separate soil evaporation and crop transpiration under variable Vertisol wetting cycles [23] and evaluate deficit irrigation strategies and crop rotations to enhance water productivity under climate variability.

5 Conclusions and recommendations

5.1 Summary of key findings

This study quantified crop evapotranspiration (ET_c) and established locally calibrated, growth-stage-specific crop coefficients (K_c) for faba bean (*Vicia faba* L.) and chickpea (*Cicer arietinum* L.) under irrigated Vertisols conditions in the Gezira Scheme, Sudan. Using the soil water balance approach, seasonal ET_c averaged 435 mm for faba bean and 380 mm for chickpea across two winter seasons. Stage-specific K_c values were 0.31 (initial), 1.07 (mid-season), and 0.55 (late-season) for faba bean, and 0.28, 1.04, and 0.30 for chickpea, respectively.

Faba bean exhibited higher ET_c due to its denser canopy, longer duration, and deeper rooting, whereas chickpea displayed a conservative water-use pattern, consistent with its drought-avoidance mechanisms. Substantial deviations from FAO-56 standard K_c values were observed, particularly during the initial and late growth stages, highlighting the importance of site-specific calibration.

5.2 Practical implications for irrigation management

The locally derived K_c values provide a robust basis for stage-specific irrigation scheduling in the Gezira Scheme, improving irrigation efficiency and optimizing Nile water allocation. Adoption of these coefficients could reduce seasonal irrigation water use by 12% for faba bean and 3% for chickpea without compromising yields.

These findings reinforce the value of locally validated crop coefficients in large-scale canal irrigation systems, where uniform scheduling can lead to both over- and under-irrigation. The results can guide the Gezira Board and Agricultural Research Corporation in implementing precise, crop- and stage-specific water management under semi-arid conditions.

5.3 Limitations and future research directions

This study used an observational design with single large plots per crop, aimed at establishing baseline ETc and Kc values rather than statistical comparisons. While this captured realistic field-scale water-use dynamics, future studies should include replicated trials across multiple soil types, planting dates, and management practices to validate spatial and temporal variability.

Further research should focus on:

- *Integration of derived Kc values into dual crop coefficient ($K_{cb} + K_e$) models* to account for soil evaporation under variable Vertisol wetting cycles.
- *Deficit irrigation and automated irrigation studies* to assess crop resilience under controlled water stress.
- *Climate change adaptation modeling* evaluating water-use responses under projected warming scenarios in central Sudan.

These results provide the first calibrated baseline for ETc and Kc dynamics under Gezira conditions, supporting improved irrigation scheduling and long-term sustainability of irrigated legume production in Sudan's semi-arid environment.

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Author contributions

Maie Kabbashi Alla Jabow Mahmoud : designed the study, conducted fieldwork, analyzed the data, and wrote the main manuscript Mahasin Ali Mohamed: contributed to the experimental design, validated the data, and revised the manuscript. Mohie El Din Mohamed Omar: supervised the methodology, contributed to interpretation of the results, and reviewed the manuscript.

Data availability

All data generated or analysed during this study are included in this published article.

Declarations

Ethics approval and consent to participate

Not applicable.

Consent for publication

Not applicable.

Competing interests

The authors declare no competing interests.

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