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ORIGINAL ARTICLE

Application of regression modeling for the prediction of field crop coefficients in a humid sub-tropical agro-climate: a study in Hamirpur district of Himachal Pradesh (India)

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Abstract

Prediction of crop coefficients is important to establish optimized irrigation water scheduling and management practices. In the present study, regression modeling was utilized to predict the field crop coefficients of crops grown in the humid sub-tropical agro-climate of Hamirpur (Himachal Pradesh, India). Field experiments were conducted on seven crops categorized as Cereals (Wheat and Maize), Oilseed (Indian mustard), Vegetable (Potato), Fodder crop (Sorghum), Green manure crop (Guar), and Legumes (Pea). The crop coefficients were determined using a modification and field-based approach. In the modification approach, FAO-recommended standard crop coefficients were modified using the crop coefficient modification procedure given in FAO-56. In the field-based approach, crop coefficients were obtained as the ratio of field crop evapotranspiration to the reference evapotranspiration. FAO modified crop coefficients presented satisfactory performance with the field crop coefficients (squared error = 0.0009–0.0225; R^2 = 0.80–0.89; bias error = − 0.09–0.15). New crop coefficients were developed by performing regression modeling between the FAO modified and field-based crop coefficients. Furthermore, new crop evapotranspiration values were obtained using new crop coefficients, which presented a strong and reliable agreement with the field crop evapotranspiration values, i.e., they exhibited small bias error = 10–24 mm, and high R^2 = 0.90–0.93. The developed regression equations can be employed as useful tools for predicting field crop coefficients from the FAO-56 modified crop coefficients, subsequently resulting in the precise estimation of the crop evapotranspiration.

Keywords Crop coefficient · Lysimeter · Evapotranspiration · Water balance · Regression

List of symbols

R_{n}	Net radiation at 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)
$(\mathrm{e_s{-}e_a})$	Saturation vapor pressure deficit (kPa)
Δ	Slope of vapor pressure curve (kPa $°\mathrm{C}^{-1}$)
γ	Psychrometric constant (kPa $°\mathrm{C}^{-1}$)
I	Average infiltration depth (mm)
$K_{\mathrm{c\ ini\ (FAO)}}$	FAO-recommended $K_{\mathrm{c\ ini}}$ value
$K_{\mathrm{c\ ini\ (heavy\ wetting)}}$	$K_{\mathrm{C\ ini}}$ derived from the FAO-curve corresponding to the heavy wetting
$K_{\mathrm{c\ ini\ (light\ wetting)}}$	$K_{\mathrm{C\ ini}}$ derived from FAO-curve corresponding to light wetting for the corresponding parameters
$K_{\mathrm{c\ mid/end(FAO)}}$	FAO-recommended K_{c} value
$\mathrm{RH_{min}}$	Mean value for daily minimum relative humidity (%) ($20\% < \mathrm{RH_{min}} < 80\%$)
u_2	Mean value for daily wind speed at 2 m height ($\mathrm{m\ s^{-1}}$) ($1\ \mathrm{m\ s^{-1}} < u_2 < 6\ \mathrm{m\ s^{-1}}$)

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Introduction

Efficient irrigation water management strategies are vital for enhancing crop productivity with sufficient availability and minimum wastage of water. For optimizing irrigation water requirements, in situ measurements of reference evapotranspiration (ET_0), crop evapotranspiration (ET_c), and crop coefficient (K_c) are essential, especially for regions with limited water resources. ET_0 is “the evapotranspiration from disease-free, well-fertilized crops, grown in large fields, under optimum soil water conditions, and achieving full production under the given climatic conditions” (Nandagiri and Kovoor 2006). Various studies have proved that FAO-56 Penman–Monteith (PM) method is the most reliable method for precise estimation of ET_0 and evaluation of other empirical models (Lima et al. 2013; Pandey et al. 2014; Pereira et al. 2015), but FAO-56 PM requires all the variables that regulate energy exchange and corresponds latent heat flux. Due to this, various investigators felt the need to develop models to determine ET_0 based on limited climatic parameters available for the particular agro-climate. Tyagi et al. (2019) utilized the DSSAT model to explore the trend of ET_0 in eastern Uttar Pradesh having sub-humid climate and found a decreasing trend of ET_0 during 1978–2003 and projected an increase during the 2040s for crops like wheat and rice. Laqui et al. (2019) developed ANN models for estimation of ET_0 at Peruvian highlands using meteorological parameters as input parameters. Yirga et al. (2019) devised a model employing multiple linear regression which can be used to predict ET_0 in the Megecha catchment. Mohsin and Lone (2020) developed regression models for the prediction of monthly ET_0 using monthly weather data for three stations in the Kashmir Valley having temperate agro-climate. Kumar et al. (2020) investigated the impact of constrained meteorological data on evapotranspiration-based numerical modeling. However, the ET_0 determined by the researchers using various techniques was not implemented in estimating ET_c values for specific crops.

ET_c is an important agro-meteorological parameter that assesses loss of moisture from the soil–plant system and is considered a critical component of water balance (Uniyal et al. 2019). Several investigators have used historical data for modeling ET_c (Valipour et al. 2017). The field measured $ET_{c\text{-field}}$ provides an accurate assessment of crop water productivity (Nhamo et al. 2020), but its measurement involves the use of specific instruments and precise observation of various physical parameters of the soil water balance using Lysimeter. It is important to determine accurate ET_c using the appropriate method for the study region. However, due to tediousness and instrumentation constraints, the measurement of ET_c is not feasible (Minacapilli et al. 2009). Therefore, ET_c is generally determined as “the product of K_c for the crop growth stage and the corresponding ET_0”. The K_c value represents crop-specific water use, thus, correct values of K_c are important for the accurate estimation of irrigation requirements and can lead to adequate water savings. The K_c value for a crop varies throughout the entire crop period and is not only crop development stage-dependent but also the climatic conditions. The stage-wise K_c for various crops necessitates local calibration of K_c under given climatic conditions and crop canopy. In the absence of localized K_c values, K_c for different growth stages, as recommended by FAO, are widely utilized to determine ET_c. However, field observed stage-specific K_c ($K_{c\ \text{field}}$) value for any agro-climate, i.e., the ratio of measured ET_c and computed ET_0, provides its accurate estimation.

Jamshidi et al. (2020) stated that there were inconsistencies in reported K_c values of various studies because of the unpredictability and complexity of climatic factors, irrigation management, crop physical and biological features. Mobe et al. (2020) estimated K_c using detailed observation of evapotranspiration, transpiration, soil attributes, weather, and tree physiological variables and concluded that the necessity for a method to derive precise K_c utilizing readily accessible information is essential for accurate water resources management. Allen et al. (1998) recommended that the K_c values should be obtained empirically for each crop based on lysimetric data and local meteorological parameters. However, only a few studies have been reported on ET_c for field crops due to the complexity involved in the estimation technique and its necessity for soil parameters and daily meteorological data (Poddar et al. 2018). The K_c values attained through lysimeter-based experiments have not been enhanced for different crops under semi-arid climatic conditions in South Asian countries (Benli et al. 2006). Various researchers globally reported that for precise estimation of ET_c, determining accurate K_c for local climatic conditions is an important task (Montazar et al. 2016). Numerous studies were performed for calibration of the K_c for various crops in several agro-climates (Poddar et al. 2020).

The above-cited literature emphasizes the need for the determination of K_c values for different crops in various agro-climates. However, due to inherent inconsistencies in K_c values, a field study for local calibration of K_c values is needed. Hence, the present study is undertaken to estimate $K_{c\ \text{field}}$ from FAO-56 modified K_c ($K_{c\ \text{FAO-M}}$) using regression modeling for seven crops grown in a humid subtropical agro-climate. The specific objectives are to:

(a) Determine field K_c ($K_{c\ \text{field}}$) from actual ET_c and ET_0
(b) Obtain $K_{c\ \text{FAO-M}}$ for local agro-climate using the FAO-56 modification procedure

(c) Develop new K_c ($K_{c\text{-new}}$) through regression modeling between modified and field K_c and
(d) Compare and evaluate the $K_{c\ \mathrm{new}}$ based ET_c with actual ET_c.

Materials and methods

Study area

The field crop experiments were performed at Hamirpur (Himachal Pradesh, India). The experimental station is located at 31° 42′ 40.8″ N latitude and 76° 31′ 33.3″ E longitude, and the average elevation is 895 m above mean sea level. The geographical outline of the study location is shown in Fig. 1. The climate of the study is categorized as humid sub-tropical (Kumari et al. 2021). The meteorological data for the study period were obtained from an Automatic Weather Station (AWS) located at the National Institute of Technology Hamirpur, as shown in Fig. 2. The precipitation recorded using a digital rain gauge is presented in Fig. 3. Daily actual evaporation was observed from the ISI standard Pan (Modified class A) at 09:00 A.M. Indian Standard Time. The daily climatic data (relative humidity, maximum temperature, average temperature, minimum temperature, solar radiation, and wind speed) is given in Fig. 4. The soil is sandy loam in texture with sand, silt, and clay content of 54.98%, 23.83%, and 21.19%, respectively. The field crop experiments were executed according to the prevailing agricultural practices in the study area.

Crop details

Seven crops, i.e., Wheat, Indian mustard, Potato, Maize, Sorghum, Guar, and Pea were grown in the experimental station and the lysimeters. The details of the crop duration, growth stages, and irrigation days for Maize, Pea, Wheat,

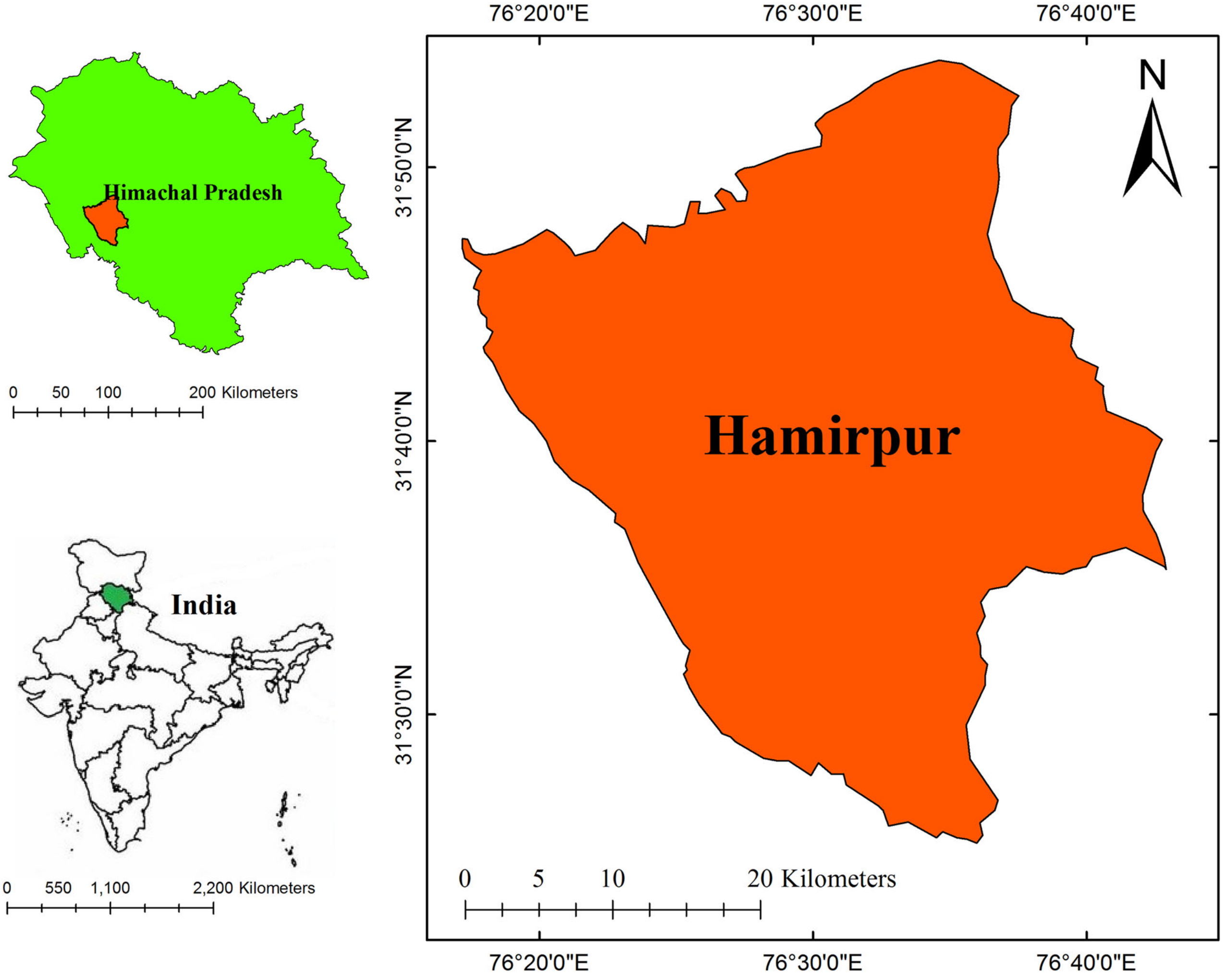

Fig. 1 Geographical outline of the study location Hamirpur

Fig. 2 Automatic weather station (AWS) located at National Institute of Technology Hamirpur

Sorghum, Indian mustard, Guar, and Potato during the study period (2017–2019) are summarized in Table 1. The entire growth period of crops is divided into four stages: I initial (ground cover < 10%), II development (ground cover: 70–80%), III mid-season (full ground cover to time of the start of maturing), and IV late season (full maturity or harvest) (Xiang et al. 2020).

The plant height is a variable that indirectly signifies the growth of the crop. The average height of crops grown was recorded on the observation days, along with root depth and leaf area. For this purpose, few crops were randomly selected (as a representation of the entire field crops) to measure height. The average height was recorded. Most of the crops achieve their maximum height in the mid-season stage. However, in the later stages, the crop gets slightly bent down, and the average height decreases. Figure 5 shows the variation of plant height for the crops considered.

Lysimeter set up

Two lysimeters for accurate and reliable measurement of ET_c were installed in the centre of the experimental station. The lysimeters (drainage type) were 2 m deep with a surface area of 2.25 m^2 as shown in Fig. 6. Soil-moisture measurement sensors (Watermark, Irrometer Inc. River-

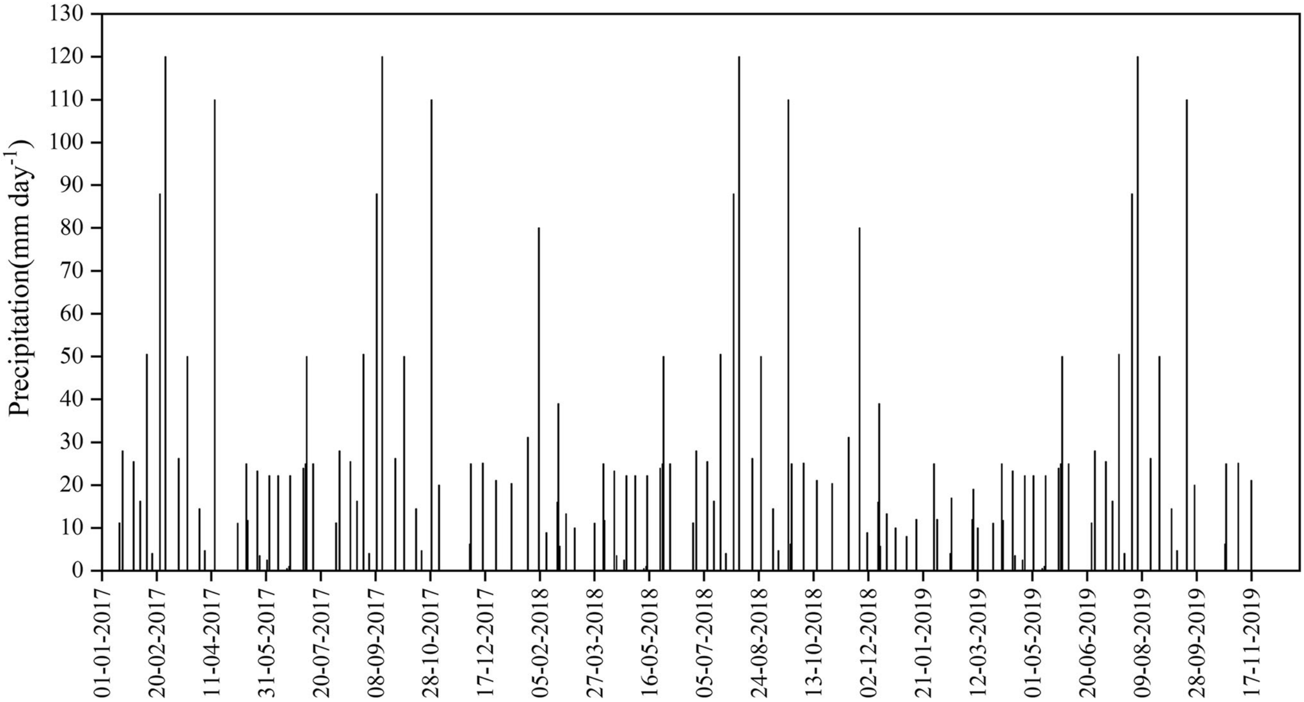

Fig. 3 Precipitation for the period from January 1st, 2017 to December 31st, 2019

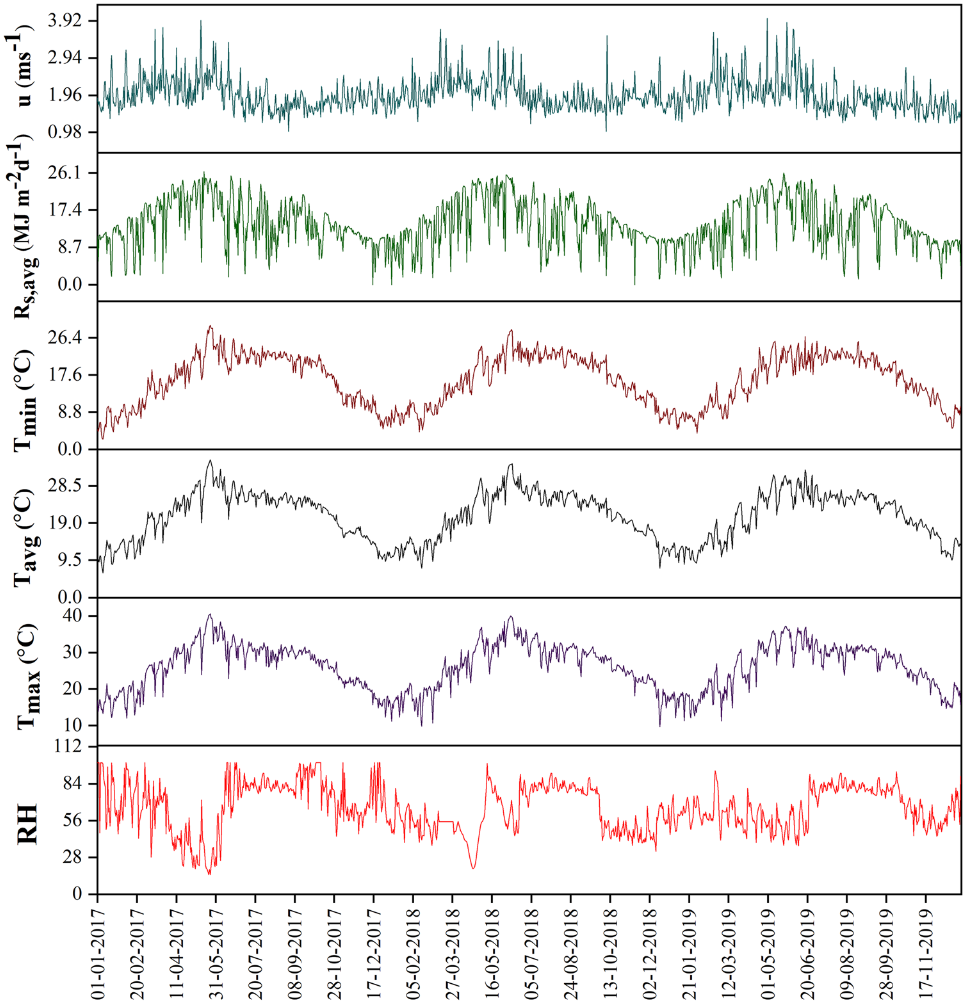

Fig. 4 Climatic parameters from January 1st, 2017 to December 31st, 2019

side, CA) were embedded at 0.2, 0.4, 0.6, 0.8, 1.0, and 1.2 m depths to determine the soil moisture status throughout the crop season for all crops. At the bottom, a perforated barrier is provided to drain off the percolated water uniformly to the collecting arrangement. A tipping bucket arrangement is placed to collect water from the bottom of the lysimeter. The measurements involve the amount of precipitation/irrigation applied, the percolated water from the lysimeter, and the soil moisture status at different times.

Computation of reference evapotranspiration

FAO-56 PM method is the most suitable indirect approach for accurate estimation of ET$_0$ and evaluation of other empirical models (Pandey et al. 2016 ; Pereira et al. 2015; Poddar et al. 2018). Hence, during the present study, FAO-56 PM method was used to determine ET$_0$ by using the following equation (Allen et al. 1998):

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

Computation of field crop evapotranspiration

Field crop evapotranspiration (ET$_{\text{c-field}}$) was determined by conducting water balance studies for the entire growth period of the crops. Since drainage type lysimeter was used, stage-wise ET$_{\text{c-field}}$ was determined. Precipitation (P), irrigation (I_r), and the quantity of water drained off from the bottom of the lysimeter (D_r) were carefully measured. The runoff component (RO) is assumed to be insignificant as the top level of the lysimeter was above ground level. The ET$_{\text{c-field}}$ was computed using the following water balance equation,

$$ET_{C-field} = P + I_r - D_r - RO \pm \Delta S. \tag{2}$$

The change in the soil moisture for the specific depth (d_z) and the period was calculated as:

Table 1 Details of the field crops, duration, growth stages, and irrigation days

Crop	Date of sowing	Date of harvesting	Duration	Growth stages (days)				Irrigation provided (days after sowing)	Spacing (cm)
				I	II	III	IV		
Wheat (*Triticum aestivum*)	3rd January, 2017	15th May, 2017	134	25	36	45	28	26th, 44th, 56th, 80th, 96th, 116th,	1 × 2
Indian mustard (*Brassica Juncea*)	22nd January, 2018	14th May, 2018	114	19	32	38	25	11th, 25th, 37th, 59th, 91st	2 × 4
Potato (*Solanum tuberosum L.*)	7th January, 2019	6th May, 2019	121	22	32	38	29	21st, 40th, 52nd, 64th, 87th, 104th	35 × 10
Maize (*Zea mays*)	20th May, 2017	10th September, 2017	114	20	34	36	24	22nd, 36th, 48th, 64th	5 × 2
Sorghum (*Sorghum bicolor L. Moench*)	16th May, 2018	22nd September, 2018	130	21	35	39	35	22nd, 48th, 75th, 93rd	20 × 15
Guar (*Cyamopsis tetragonoloba L.)*	28th May, 2019	1st September, 2019	97	20	26	28	23	26th, 53rd, 81st	25 × 15
Pea (*Pisum sativum*)	20th September, 2019	8th December, 2019	80	10	25	25	20	15th, 24th, 39th, 51st, 68th	40 × 15

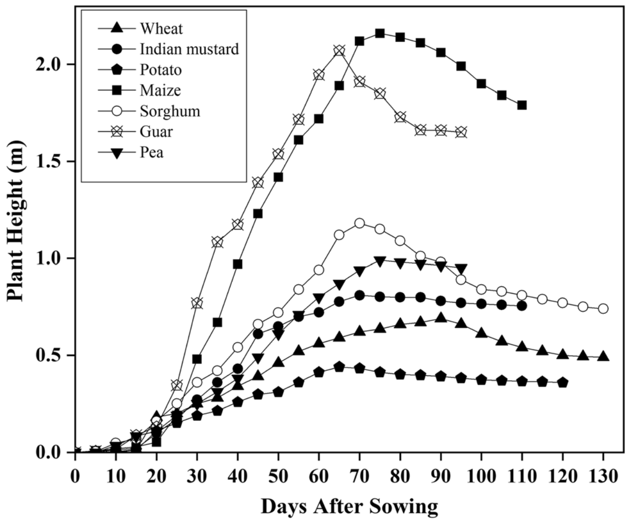

Fig. 5 Variation of plant height during crop period for Wheat, Indian mustard, Potato, Maize, Sorghum, Guar, and Pea

$$(\Delta S_z) = \left(\theta_{z,final} - \theta_{z,initial}\right) \times dz, \tag{3}$$

where ΔS = moisture storage change, $\theta_{z,\ final,}$ and $\theta_{z,\ initial}$ are final and initial water content in the soil profile in a discrete-time interval.

Modified crop coefficients

The standard crop coefficients ($K_{\text{c-FAO}}$) were modified using the modification equations given in FAO-56 (Allen et al. 1998). The procedure involves the computation of the impact of the time interval between wetting events, the magnitude of the wetting events, and the evaporative power of the atmosphere. The $K_{\text{c ini}}$ values for the local agro-climate were computed using the following equation:

$$K_{cini} = K_{c\ ini(FAO)} + \frac{(I-10)}{(40-10)}\left[K_{cini\ (heavywetting)} - K_{cini\ (lightwetting)}\right]. \tag{4}$$

The procedure for the modification of $K_{\text{c mid}}$ and $K_{\text{c end}}$ involves climatic variables and mean plant height ([mm] (0.1 mm < h < 10 mm) during the corresponding crop growth stage (h)). $K_{\text{c mid}}$ and $K_{\text{c end}}$ values were determined from the following equation:

$$K_{c\ mid/end} = K_{c\ mid/end\,(FAO)} + \left[0.04(u_2-2) - 0.004(RH_{\min}-45)\right]\left(\frac{h}{3}\right)^{0.3}. \tag{5}$$

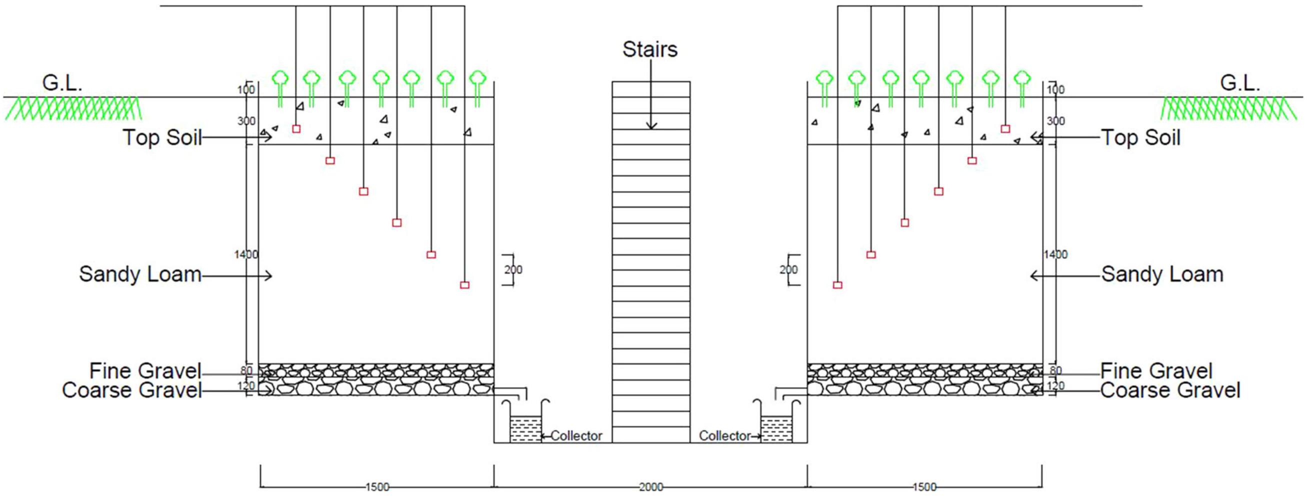

Fig. 6 Detailed sectional view of Lysimeter set-up

Field crop coefficients

The field crop coefficients ($K_{\text{c-field}}$) were estimated using the FAO-56 crop coefficient approach (Allen et al. 1998). According to this approach, K_c is defined as the ratio of crop evapotranspiration to the reference evapotranspiration. The following equation is used:

$$K_{c-field} = \frac{ET_{c-field}}{ET_0}. \tag{6}$$

Experimental and modeling methodology

The flowchart representing the methodology adopted in the present study is illustrated in Fig. 7. The modified $K_{\text{c-FAO}}$ ($K_{\text{c-FAO M}}$) values are compared with the $K_{\text{c-field}}$ values. Regression modeling is then applied to develop regression equations for predicting $K_{\text{c-field}}$ from $K_{\text{c-FAO M}}$. The regression modeling has been implemented in Microsoft Excel. K_c values derived using the regression equations are used for computing new ET_c. In the end, the comparison and evaluation between ET_c values are performed.

Statistical comparison

The comparative evaluation in the study is based on the error statistics i.e., square error (SE), coefficient of determination (R^2) and bias error (BE) given by Eqs. (7), (8), and (9), respectively.

$$SquareError = (x - x')^2 \tag{7}$$

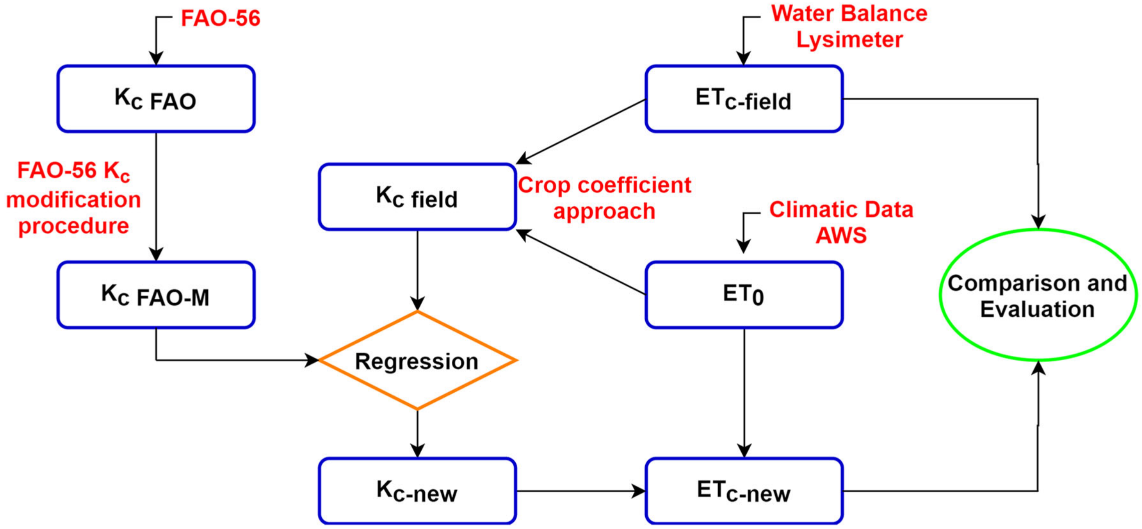

Fig. 7 Flowchart representing the methodology adopted in the study

$$R^2 = \left[\frac{n\sum xXx' - \sum x \sum x'}{\sqrt{\left[n\sum x^2 - \left(\sum x\right)^2\right]\left[n\sum x'^2 - \left(\sum x'\right)^2\right]}}\right]^2 \tag{8}$$

$$BiasError = (x - x'), \tag{9}$$

where x = observed value; $x^{'}$ = empirical/predicted value; and n = number of samples.

Result and discussion

Computed reference evapotranspiration

The ET_0 was computed using the FAO-56 PM method (Eq. 1). The variation of ET_0 values for the entire study period is shown in Fig. 8. During the respective crop periods, the maximum, minimum, and average ET_0 (mm day^{-1}) were 5.38, 1.23, and 2.49 for Wheat; 2.44, 1.23, and 1.83 for Indian mustard; 7.02, 0.55, and 3.39 for Potato; 6.54, 3.79, and 5.42 for Maize; 6.54, 2.84, and 4.85 for Sorghum; 5.49, 2.84, and 4.41 for Guar; and 5.49, 2.03, and 3.37 for Pea.

Computed field crop evapotranspiration

$ET_{c\text{-field}}$ measurements were conducted at specific intervals during each growth stage of the crop period. The cumulative $ET_{c\text{-field}}$ for Wheat, Indian mustard, Potato, Maize, Sorghum, Guar, and Pea are 353, 169, 182, 494, 416, 506, and 278 mm, respectively. The cumulative and stage-wise water balance components are summarized in Table 2 for Maize, Indian mustard, and Pea.

FAO modified K_c

The FAO modified K_c ($K_{c\ \text{FAO-M}}$) values for respective crops at different growth stages along with the magnitude of parameters involved in the modification are shown in Table 3. K_c values during the crop development stage and late-season stage were calculated using the linear interpolation technique (Shankar 2007). Based on the values presented in Table 3, it is observed that the $K_{c\ \text{ini (FAO-M)}}$

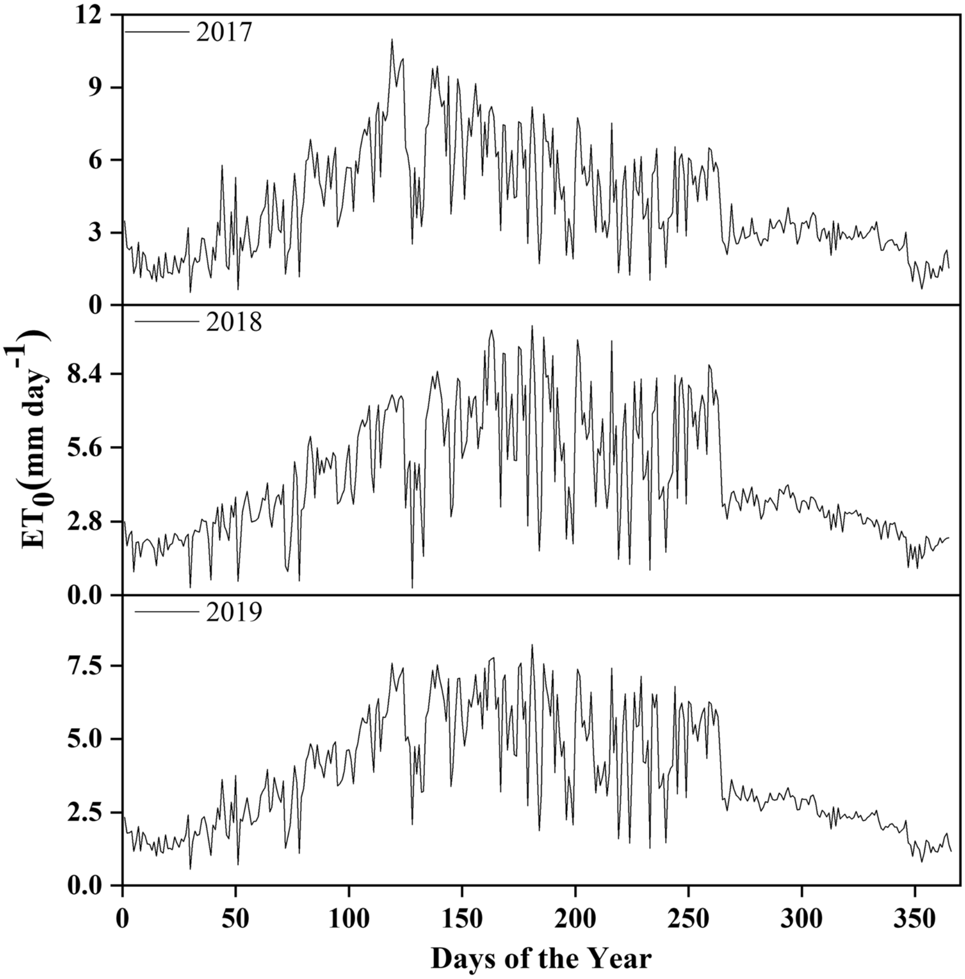

Fig. 8 Variation of Reference evapotranspiration during the study period

Table 2 Water balance components for Maize, Indian mustard, and Pea

Component (mm)	Crop Stage				Total
	Initial	Development	Mid-season	Late-season	(mm)
Maize					
P	98	77	214	77	466
I_r	0	130	0	0	130
D_r	28	38	36	24	126
ΔS	25	8	− 29	− 28	− 24
$\text{ETc}_{\text{-}field}$	45	161	207	81	494
Indian mustard					
P	0	0	50	0	50
I_r	0	80	44	40	164
D_r	6	18	24	12	60
ΔS	− 25	8	0	2	− 15
$\text{ETc}_{\text{-}field}$	19	54	70	26	169
Pea					
P	0	6	4	97	107
I_r	20	80	100	0	200
D_r	4	6	5	42	57
ΔS	− 11	− 11	− 22	16	− 28
$\text{ETc}_{\text{-}field}$	27	91	121	39	278

P Precipitation, I_r Irrigation, D_r Drainage to groundwater, ΔS change in soil moisture content in the crop root zone, $\text{ET}_{\text{c-field}}$ Field crop evapotranspiration

values show a significant increase when compared to the FAO-recommended $K_{\text{c ini}}$ values. This emphasizes the importance of calibrating the FAO-recommended $K_{\text{c ini}}$ values for this agro-climate. On the other hand, $K_{\text{c mid/end}}$ values are found to be in close agreement with the FAO-recommended K_c values.

Field observed K_c

Field observed values of K_c ($K_{\text{c-field}}$) were computed using Eq. (6). For maintaining brevity in the paper, a detailed calculation of the values is not given here. However, the stage-wise $K_{\text{c-field}}$ values are described in Table 4. It should be noted that these values represent the average $K_{\text{c-field}}$ in the duration considered for $\text{ET}_{\text{c-field}}$ estimation.

Comparison of FAO modified and field observed K_c

A comparison between $K_{\text{c FAO-M}}$ and $K_{\text{c-field}}$ is necessary to understand the accuracy of the modification procedure and reliability of the $K_{\text{c FAO-M}}$ values in the considered agro-climate. In this study, the comparison is based on error statistics SE, R^2, and BE as described earlier. Table 5 presents the values of error statistics for each crop. For all the crops considered, SE (0.0009–0.0225) and BE (− 0.09–0.15) values are small, and R^2 (0.81–0.89) values are close to unity, indicating a satisfactory agreement between $K_{\text{c-field}}$ and $K_{\text{c FAO-M}}$ values for the study agro-climate. From BE values, it is observed that $K_{\text{c FAO-M}}$ values overestimate $K_{\text{c-field}}$ values in the case of Potato and Sorghum, whereas, for all other crops, it underestimates $K_{\text{c-field}}$ values.

Regression modeling

The values of error statistics, as shown in Table 5, are acceptable and indicates the suitability of $K_{\text{c FAO-M}}$ values for the agro-climate under consideration. However, a certain degree of refinement in $K_{\text{c FAO-M}}$ values for the agro-climate considered will improve their reliability and minimize the errors associated. In the present study, this is achieved by performing regression modeling and developing regression equations between $K_{\text{c-field}}$ (as dependent variable), and $K_{\text{c FAO-M}}$ (as an independent variable). The developed regression equations are listed in Table 6. The scatter plots of the comparison between $K_{\text{c field}}$ and $K_{\text{c FAO-M}}$ values for all the crops are given in Fig. 9.

New crop coefficients ($K_{\text{c-new}}$) were predicted from the developed regression equations which exhibited a strong correlation with the $K_{\text{c-field}}$ values as indicated from high values of R^2 (0.94–0.97). For each crop, the regression equations developed in the present study are useful in estimating the actual $K_{\text{c-field}}$ from $K_{\text{c FAO-M}}$. The developed

Table 3 Modified values of K_c for actual field conditions of the study agro-climate

Crop	Crop coefficients								
	$K_{c\ ini}$			$K_{c\ mid}$			$K_{c\ end}$		
	FAO value	Modifying parameters	Modified value	FAO value	Modifying parameters	Modified value	FAO value	Modifying parameters	Modified value
Maize	0.3	Wetting frequency = 13 days, Avg. ET_0 = 5.60 mmday^{-1}	0.41	1.2	u_2 = 1.79 ms^{-1}, RH_{min} = 62.20, H = 1.43 m	1.14	0.6	u_2 = 1.71 ms^{-1}, RH_{min} = 69.64, H = 2.01 m	0.5
Pea	0.47	Wetting frequency = 7 days, Avg. ET_0 = 4.66 mmday^{-1}	0.7	1.32	u_2 = 1.91 ms^{-1}, RH_{min} = 35.54, H = 0.32 m	1.36	1.1	u_2 = 1.85 ms^{-1}, RH_{min} = 32.47, H = 0.54 m	1.13
Wheat	0.3	Wetting frequency = 10 days, Avg. ET_0 = 1.59 mmday^{-1}	0.58	1.15	u_2 = 2.17 ms^{-1}, RH_{min} = 41.13, H = 0.61 m	1.18	0.35	u_2 = 2.26 ms^{-1}, RH_{min} = 27.72, H = 0.68 m	0.4
Sorghum	0.3	Wetting frequency = 9 days, Avg. ET_0 = 6.27 mmday^{-1}	0.43	1.1	u_2 = 1.69 ms^{-1}, RH_{min} = 69.69, H = 0.76 m	1.03	0.55	u_2 = 1.69 ms^{-1}, RH_{min} = 56.84, H = 0.89 m	0.51
Indian mustard	0.35	Wetting frequency = 9 days, Avg. ET_0 = 2.36 mmday^{-1}	0.58	1.15	u_2 = 1.95 ms^{-1}, RH_{min} = 42.84, H = 0.61 m	1.17	0.35	u_2 = 1.93 ms^{-1}, RH_{min} = 45.99, H = 0.76 m	0.31
Guar	0.4	Wetting frequency = 7 days, Avg. ET_0 = 4.97 mmday^{-1}	0.67	1.15	u_2 = 1.68 ms^{-1}, RH_{min} = 61.76, H = 1.43 m	1.09	0.55	u_2 = 1.73 ms^{-1}, RH_{min} = 54.85, H = 1.74 m	0.51
Potato	0.5	Wetting frequency = 20 days, Avg. ET_0 = 1.54 mmday^{-1}	0.61	1.15	u_2 = 2.29 ms^{-1}, RH_{min} = 32.52, H = 0.33 m	1.18	0.75	u_2 = 2.44 ms^{-1}, RH_{min} = 15.47, H = 0.38 m	0.82

Table 4 Field observed crop coefficients obtained from field experiments

Crops	Stages			
	Initial	Crop development	Mid-season	Late season
Maize	0.36–0.38	0.46–0.94	1.10–1.18	0.55–1.16
Pea	0.54–0.55	0.70–1.15	1.29–1.37	1.14–1.35
Wheat	0.54–0.62	0.71–1.00	1.10–1.19	0.59–1.18
Sorghum	0.38–0.45	0.51–0.93	0.94–1.04	0.48–1.03
Indian mustard	0.55–0.56	0.64–0.98	1.13–1.18	0.46–1.17
Guar	0.62–0.65	0.71–1.03	1.01–1.11	0.59–1.09
Potato	0.56–0.58	0.62–1.10	1.09–1.19	0.83–1.18

equations are applicable for the study area as well as regions with similar agro-climate.

Crop evapotranspiration based on $K_{c\text{-new}}$

Regression modeling derived $K_{c\text{-new}}$ values were multiplied with the corresponding ET_0 to obtain new crop evapotranspiration ($ET_{c\text{-new}}$) values. Table 7 shows the cumulative $ET_{c\text{-new}}$ values for the crops considered in the present study. To assess the performance of $K_{c\text{-new}}$ values, a comparison was carried out between $ET_{c\text{-new}}$ and $ET_{c\text{-field}}$ values. This comparison was based on stage-wise ET_c values. The error statistics R^2 and BE are computed and summarized in Table 7. It is observed, that for each crop

Table 5 Error statistics between FAO modified and field observed crop coefficients of Maize, Pea, Wheat, Sorghum, Indian mustard, Guar, and Potato

Crop	Statistical parameters											
	SE				R^2				BE			
	Initial	Crop dev	Mid-season	Late season	Initial	Crop dev	Mid-season	Late season	Initial	Crop dev	Mid-season	Late season
Maize	0.0016	0.0025	0.0016	0.0036	0.89	0.88	0.83	0.8	0.04	0.05	0.04	0.06
Pea	0.0225	0.0049	0.0049	0.0025	0.87	0.87	0.88	0.87	0.15	0.07	0.07	0.05
Wheat	0.0016	0.0009	0.0064	0.0016	0.86	0.88	0.87	0.89	0.04	0.03	0.08	0.04
Sorghum	0.0025	0.0016	0.0081	0.0049	0.85	0.89	0.87	0.85	0.05	-0.04	-0.09	-0.07
Indian mustard	0.0009	0.0025	0.0016	0.0016	0.87	0.81	0.89	0.86	0.03	0.05	0.04	0.04
Guar	0.0025	0.0036	0.0064	0.0036	0.85	0.86	0.88	0.87	0.05	0.06	0.08	0.06
Potato	0.0025	0.0016	0.0081	0.0049	0.89	0.85	0.87	0.83	0.05	-0.04	-0.09	-0.07

SE squared error; *BE* bias error; R^2 coefficient of determination

Table 6 Developed regression equations for Maize, Pea, Wheat, Sorghum, Indian mustard, Guar, and Potato

Crop	Equation	R^2
Maize	$K_{\text{c-field}} = 1.035\ K_{\text{c FAO-M}} - 0.0578$	0.97
Pea	$K_{\text{c-field}} = 1.016\ K_{\text{c FAO-M}} - 0.0542$	0.97
Wheat	$K_{\text{c-field}} = 0.932\ K_{\text{c FAO-M}} + 0.0341$	0.94
Sorghum	$K_{\text{c-field}} = 1.005\ K_{\text{c FAO-M}} - 0.0324$	0.97
Indian mustard	$K_{\text{c-field}} = 0.985\ K_{\text{c FAO-M}} - 0.0142$	0.96
Guar	$K_{\text{c-field}} = 1.005\ K_{\text{c FAO-M}} - 0.0373$	0.96
Potato	$K_{\text{c-field}} = 0.982\ K_{\text{c FAO-M}} - 0.0103$	0.94

$K_{c\text{-}field}$ field crop coefficient, $K_{c\ FAO\text{-}M}$ FAO modified crop coefficient

considered, BE values are small (10–24 mm), and R^2 values are high (0.90–0.93), indicating a strong agreement between $ET_{\text{c-field}}$ and $ET_{\text{c-new}}$ values. This observation suggests that the $K_{\text{c-new}}$ values obtained from regression modeling are reliable in computing the ET_c.

Summary and conclusions

Crop coefficients (K_c) of seven crops in a humid subtropical agro-climate were calibrated using the FAO-56 modification procedure. Field observed K_c ($K_{\text{c-field}}$) values were obtained by computing the ratio between field crop evapotranspiration ($ET_{\text{c-field}}$) and reference evapotranspiration (ET_0). The FAO modified K_c values ($K_{\text{c FAO-M}}$) were found to provide acceptable estimates of K_c values when compared with the $K_{\text{c-field}}$. The error statistics i.e., SE (0.0009–0.0225) and BE (− 0.09–0.15) values were small, and R^2 (0.81–0.89) values are close to unity, indicating a satisfactory agreement between $K_{\text{c-field}}$ and $K_{\text{c FAO-M}}$ values for the crops considered. The $K_{\text{c FAO-M}}$ values were further refined to improve their reliability in the considered agro-climate by performing regression modeling and developing regression equations between $K_{\text{c-field}}$ (dependent variable) and $K_{\text{c FAO-M}}$ (independent variable). Regression modeling derived new field crop coefficients ($K_{\text{c-new}}$) exhibit a strong correlation with the $K_{\text{c-field}}$ values as indicated from high values of R^2. The performance of the $K_{\text{c-new}}$ values is assessed by comparing new crop evapotranspiration ($ET_{\text{c-new}}$) with $ET_{\text{c-field}}$. Based on the error statistics, it is observed, that for each crop considered, BE values are small (10–24 mm), and R^2 values are high (0.90–0.93), indicating a strong agreement between $ET_{\text{c-field}}$ and $ET_{\text{c-new}}$ values.

Following conclusions are drawn based on the results obtained in the study:

- Developed regression equations can be efficiently used for estimating $K_{\text{c-field}}$ values from the $K_{\text{c FAO-M}}$ for the study agro-climate.
- The comparative analysis between $ET_{\text{c-new}}$ and $ET_{\text{c-field}}$ suggests the efficacy of regression modeling in predicting crop coefficients for estimating ET_c.
- The regression modeling approach can be applied to other crops in different agro-climates to validate and generalize the findings of the study.

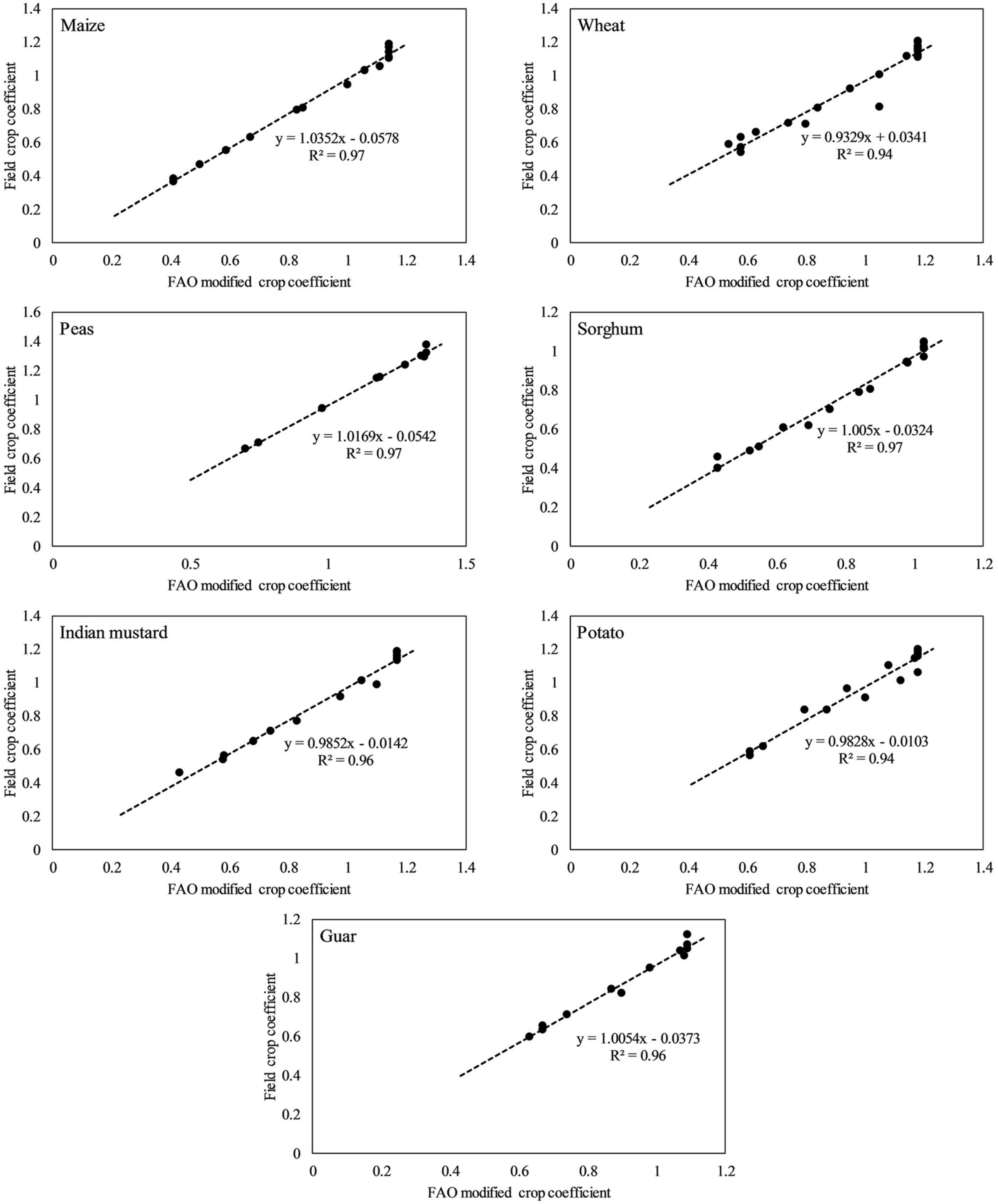

Fig. 9 Scatter plot of the comparison between observed and modified K_c values for all the crops

Table 7 Crop evapotranspiration values for Maize, Pea, Wheat, Sorghum, Indian mustard, Guar, and Potato

Crops	$ET_{c\text{-new}}$ (mm)	$ET_{c\text{-field}}$ (mm)	BE (mm)	R^2
Maize	518	494	24	0.93
Pea	294	278	16	0.93
Wheat	371	353	18	0.91
Sorghum	436	416	20	0.90
Indian mustard	179	169	10	0.92
Guar	529	506	23	0.93
Potato	194	182	12	0.90

$ET_{c\text{-new}}$ new crop evapotranspiration based on regression model predicted crop coefficient, $ET_{c\text{-field}}$ field crop evapotranspiration, *BE* bias error, R^2 coefficient of determination

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Declarations

Conflict of interest On behalf of all authors, the corresponding author states that there is no conflict of interest.

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