Lysimeter based crop coefficients for estimation of crop evapotranspiration of black gram (*Vigna Mungo L.*) in sub-humid region

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Abstract: Black gram is dominant pulse crop of the region. Crop coefficient is an important parameter, which needs to be determined for accurate estimates of the crop water requirement. Crop coefficient, the ratio of potential crop evapotranspiration to reference evapotranspiration, is an important parameter in irrigation planning and management. However, this information is not available for many important crops in the study region. A study was undertaken to develop crop coefficients for black gram crop, and a comparison is made of single and dual crop coefficient approaches to estimate actual crop evapotranspiration under the climatic conditions of Udaipur, India. Crop coefficient was developed from daily measured black gram evapotranspiration (ETBG) data by electronic weighing lysimeter and reference evapotranspiration calculated using standard Penman-Monteith method. The measured values of crop coefficient for the crop were 0.48, 1.18 and 0.33 during initial, mid-season and late-season stages. The evaluation of different approaches showed that daily ET_{BG} estimate based on dual crop coefficient method have been found best (SE=0.40, r=0.96). Furthermore, a quadratic curve (second-order polynomial) method were fitted well (SE=0.47, r=0.94) to predict crop coefficient values as function of days after sowing (DAS). These locally developed and evaluated values can be used for proper irrigation planning in water scarcity area of Udaipur and other areas with similar agro-ecological conditions.

Keywords: lysimeter, evapotranspiration, crop coefficient, electronic weighing lysimeter, reference evapotranspiration, black gram (*Vigna Mungo L.*), irrigation

DOI: 10.3965/j.issn.1934-6344.2011.04.050-058

Citation: Pankaj K Pandey, Vanita Pandey. Lysimeter based crop coefficients for estimation of crop evapotranspiration of black gram (*Vigna Mungo L.*) in sub-humid region. Int J Agric & Biol Eng, 2011; 4(4): 50－58.

1 Introduction

To estimate crop evapotranspiration for irrigation planning for regional sector the crop coefficient, Kc, which is ratio of crop ET to grass reference ET, is needed. The crop coefficient value represents crop specific water use and is required for accurate estimation of irrigation requirements of different crops grown under different climatic conditions[1]. Improved crop coefficients for Pacific Northwest irrigated crops for estimating crop evapotranspiration from estimates or measurements of reference evapotranspiration was developed by Wright[2]. Pruitt[3] carried out the lysimeter based crop coefficient studies and developed the seasonal curves for the both crop coefficient Kc and basal coefficient Kcb. Tarantino[4] studied the comparison between the

Received date: 2010-02-24 **Accepted date:** 2011-12-06

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measured grass ET and evapotranspiration calculated by the FAO method and in some cases by Penman-Monteith and Thornthwaite methods. Wright[2] provided the results taken from two lysimeters installed at research site near Kimberly, Idaho and results were used for developing functional relationships and coefficients for the use with reference ET-crop coefficient approach for estimating crop ET from metrological, crop and soil data. Tyagi et al.[5] conducted lysimeter experiments on rice during rainy season (July-October) and sunflower during summer (March-June) in a set of two electronic weighing lysimeter of 2 m×2 m×2 m size to measure the hourly ET for these crops from 1994 to 1995 at Karnal, India. The estimated values of sunflower ET were 11.6%-74.2% higher than suggested values[6]. Kashyap and Panda[7] evaluated the crop evapotranspiration estimation methods and developed a crop coefficient for potato in the sub-humid region.

The variation of the crop coefficient during a growing season is obtained experimentally[1,2,8-10] although there are published list of single (Kc) and dual (Kcb) crop coefficient values based on four crop growth stage length period, and discussed estimation of the crop effects on water use based on computed grass reference evapotranspiration[6]. Kcb is coefficients when soil surface is visually dry but transpiration is not restricted by soil water deficit; and Ke is the coefficient representing the soil water evaporation from wet soil surface[2]. The single Kc approach assume a more generalized approach in determining the crop water use that cannot account for some of the soil factor embodied in dual (Kcb) approach, especially different soil water evaporation rates that may be important with high frequency irrigation. Tabulated Kc values for different crops are commonly used in places where local data are not available. As these values vary from place to place and from season to season, there is a strong need for local calibration of crop coefficients under given climatic conditions[5]. There is, therefore, a need to develop crop coefficients locally, so that irrigation projects can be planned correctly.

Black gram is a very important pulse crop in most parts of India. At present, farmers are opting for the production of this crop under irrigation due to changing pattern and uneven distribution of rainfall. However, the water requirement data and crop coefficient of this crop is not locally available. Hence, knowledge of experimentally determined Kc value is important for proper irrigation scheduling and efficient water management of the selected crop. In order to fulfill this, proposed study has been taken for the determination of black gram ET and its crop coefficient. The results obtained will be useful for planning the supplemental or life saving irrigation.

2 Materials and methods

2.1 General description of the study area

The study was carried out at the experimental farm of College of Technology and Engineering (CTAE) Udaipur (24°35 N, 73°42 E and 582.17 m altitude), southwest Rajasthan India, during the 2001 black gram cropping season. The mean annual rainfall in the region is about 662 mm and more than 80% of this amount is received as a part of south – west monsoon during the period of 16th June to 15th September. As per USDA, soil is classified as sandy loam.

2.2 Measurement of evapotranspiration and metrological data

An electronic weighing lysimeter installed at the centre of the field consisting of two steel tanks of size 1.17 m×1.47 m for the inner and 1.23 m×1.53 m for the outer tanks was used for this study. The weighing arrangement was made with the help of load cells and data logger. When filled with soil, all the four load cells were calibrated. A drain pipe was installed at the corner of the inner tank. This pipe was covered with synthetic filter. The weighing lysimeter can read correctly up to 500.0 g. The least count of the measurement of lysimeter is 0.28 mm.

The data of pan evaporation, air temperature, relative humidity, wind speed, sunshine hours, for a period of growing season were collected from Meteorological Observatory of the College of Technology and Engineering, Udaipur India.

2.3 Crop detail

Black gram crop of variety T- 9 was grown from 19th

July 2001 to 8th October 2001 for measurement of daily evapotranspiration. The row-to-row spacing was kept 30 cm and plant to plant spacing was kept 15 cm. The seed of black gram was placed 5 cm below the soil surface. The seed rate was taken as 15 kg per hectare. All the agronomical practices were done in accordance with the standard recommendations.

2.4 Soil moisture and irrigation management

Soil samples were collected daily basis at three depths (0-10, 10-30, 30-60 cm), during entire growing period of black gram crop. The average field capacity and permanent wilting points of the root zone profile were 21.0% and 6.0% respectively. The values of bulk density of soil at depth 0-30 cm and below 30 cm were found to be 1.57 and 1.62 g/cm^3 respectively. Average rate of infiltration is about 2.2 cm/h. The moisture content was determined using conventional gravimetric method.

Irrigation water was applied to the crop when there was 50% depletion of the available soil moisture within the crop root zone[11]. The application of irrigation was carried with furrow method.

2.5 Estimation of reference evapotranspiration

The following FAO Penman-Monteith Equation[6] was used for calculation of reference evapotranspiration (ET_0).

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

where, R_n is the net radiation at the crop surface (MJ m^{-2} day^{-1}); G the soil heat flux density (MJ m^{-2} day^{-1}) = 0 for daily calculations; T the mean daily air temperature at 2 m height (℃); u_2 the wind speed at 2 m height (m·s^{-1}); e_s the saturation vapor pressure (kPa); e_a the actual vapor pressure (kPa); (e_s−e_a) the saturation vapor pressure deficit (kPa); Δ the gradient of the saturated vapor pressure–temperature curve (kPa/℃), and the γ psychometric constant (kPa/℃).

2.6 Development of crop coefficient

In FAO-56, two forms of K_C are presented. The first approach uses a mean or “single” K_C where time–averaged effects of evaporation from soil surface are averaged in the K_C value. The second K_C approach is the dual K_C method where the K_C value is divided into a basal crop coefficient (K_{cb}) and a separate component, K_e representing evaporation from soil surface.

2.6.1 Single crop coefficient approach

It may be represented as:

$$ET_c = K_C \times ET_0 \qquad (2)$$

2.6.2 Dual crop coefficient approach

It may be represented as:

$$ET_c = (K_{cb} + K_e) \times ET_0 \qquad (3)$$

where, ET_c = crop evapotranspiration, mm/day; ET_0 = grass based reference evapotranspiration, mm/day.

The crop coefficient (K_C) incorporates crop characteristics and averaged effect of evaporation from the soil. The calculation procedure for crop evapotranspiration (ET_c), consists of: Identifying the crop growth stage, determining their length, and selecting three K_C values corresponding to average $K_{Cini,}$ K_{Cmid} and K_{Cend}, Adjusting the selected K_C for frequency of wetting or climatic conditions during the stage, Constructing the crop coefficient curves (allowing one to determine K_C values for any period during the growth period), and calculating ET_c from Equation (2), or (3) depending upon approach used.

The crop coefficient curves for black gram crop (K_{CBG}) were developed by the following methods: (i) FAO-56 curve method, (ii) Dual crop coefficient curve method and (iii) Quadratic curve method

2.6.3 Determination of $K_{Cini,}$ K_{Cmid} and K_{Cend}

Since localized $K_{Cini,}$ K_{Cmid} and K_{Cend} values were not available for the study area, the values suggested by FAO-56[6] were used. These recommended values must be adjusted in other areas, where $RH_{\min}$ differs from 45% and the wind speed is sometimes greater than 2 m/s or sometimes less than 2 m/s. The K_C values for the mid-season and late season stages were adjusted using the following equation:

$$K_{Cmid} = K_{Cmid(TAB)} + \left[0.04(U_2 - 2) - 0.004(RH_{\min} - 45)\right]\left(\frac{h}{3}\right)^{0.3} \qquad (4)$$

where, $K_{Cmid(TAB)}$ = tabulated value of K_{Cmid}; U_2 = mean value of daily wind speed at 2 m height during mid season growth stage for 1 m/s ≤ U_2 ≤ 6 m/s; $RH_{\min}$ = mean value of daily minimum relative humidity during the mid season growth stage for 20 % ≤ $RH_{\min}$ ≤ 80%, per cent; h = mean plant height during mid season stage for 0.1 m ≤ h ≤ 10 m.

2.6.4 Determination of basal crop coefficients: K_{cbini}, K_{cbmid} and K_{cbend}

The basal crop coefficient (K_{cb}) is defined as a ratio of the crop evapotranspiration over the reference evapotranspiration (ET_c/ET_0) when the soil surface is dry but transpiration occurring at a potential rate, i.e. water is not limiting the transpiration[12]. Therefore, 'K_{cb} ET_0' represents primarily the transpiration component of ET_c. After dividing the growing period into four general growth stages and selecting, adjusting the K_{cb} values using Equation (4), with above mention limitations and by replacing K_C notation corresponding to the initial (K_{cbini}), mid season (K_{cbmid}) and late season stage (K_{cbend}) the daily K_{cb} value was determined by assuming K_{cb} to be constant during the initial and mid-season stages and assuming linear relationship between the K_{cb} value at the end of the previous stage (K_{cb}, prev) and the K_{cb} value at the beginning of the next stage (K_{cb}, next) during the crop development and late season stages. The daily K_{cb} values during the crop development and late season stages could be calculated as:

$$K_{cbi} = K_{cb,prev} + \left[\frac{i - \sum(L_{prev})}{L_{stage}}\right](K_{cb,next} - K_{cb,prev}) \quad (5)$$

Where, i is the day number within the growing season (length of the growing season); K_{cbi} the crop coefficient on day i; L_{stage} the length of the stage under consideration (days), and ($\Sigma(L_{prev})$) sum of the lengths of all previous stages (days).

2.6.5 Soil evaporation coefficient (K_e)

When the soil surface layer is wet, following rain or irrigation K_e is the maximum, and when soil surface layer is dry, K_e is small and can approach zero. When soil is wet, evaporation occurs at some maximum rate where K_{cb}+K_e is limited by a maximum value of $K_{c\max}$. K_e may be written as:

$$K_e=K_r(K_{c\max}-K_{cb})\leq fewK_{c\max} \quad (6)$$

where, $K_{c\max}$ is maximum value of K_c following rain or irrigation; K_r is dimensionless evaporation reduction coefficient and is dependent on the cumulative depth of water depleted; few is exposed and wetted soil fraction. The evaporation rate is restricted by the estimated amount of energy available at exposed soil fraction, i.e., K_e cannot exceed $fewK_{c\max}$ for the ET_0 basis ($K_{c\max}$) ranges from about 1.05 to 1.30[6,13]:

$$K_{c\max} = \max\begin{pmatrix}\{1.2 + [0.04(U_2 - 2) - 0.004(RH\min - 45)]\left(\frac{h}{3}\right)^{0.3}\}, \\ \{Kcb + 0.05\}\end{pmatrix} \quad (7)$$

Soil evaporation from the exposed soil is presumed to take place in two stages[12,14]: an energy limiting stage (stage 1) and a falling rate stage (stage 2). During stage 1, following rain or irrigation, K_r is 1, and evaporation is only determined by the energy available for evaporation. Stage 1 lasts until the cumulative depth of evaporation is such that the hydraulic properties of the upper soil become limiting and water cannot be transported to the soil surface at a rate that can meet the potential demand. Stage 2 begins, and K_r becomes less than 1 and evaporation is reduced. K_r becomes zero when no water is left for evaporation in the upper soil layer, K_r is calculated as follows:

$$K_r = \frac{TEW - De,i-1}{TEW - REW} forDe,i-1 > REW \quad (8)$$

where, total evaporable water (TEW) is the maximum depth of water that can be evaporated from the soil. The topsoil has been initially completely wetted, with TEW=1000(θFC–0.5θWP), θFC is the soil water content at field capacity and θWP is the soil water content at the wilting point, and readily evaporable water (REW) is the cumulative depth of evaporation at the end of stage 1. The threshold REW is dependent on the physical properties of the soil[15,16]. The threshold REW is 3 mm for very sandy soils, 6 mm for sandy soils, 9 mm for loamy soils, and 12 mm for clayey soils[14]. The threshold value of 4 mm is adopted here for the study.

The calculation of cumulative depth of evaporation (depletion) (D_e), and dual (K_{cb}+K_e), was carried out using spreadsheet programs described by FAO[6], which describe steps for calculation of different components of dual K_c.

2.7 Quadratic curve method

The quadratic crop coefficient curve for black gram was developed by fitting quadratic equation by least square method. This approach describes K_c as a function of days after sowing (DAS). A second-order polynomial was fitted using multiple regressions[17].

3 Results and discussion

3.1 Measured crop coefficient (K_{CBG})

Average value of observed KC (Equation 2) for the four stage: initial stage 10 days (19th July to 28th July), crop development stage, 25 days (29th July to 22nd August), mid season stage, 30 days (23rd August to 21st September), and late season stage 17 days (22nd September to 8th October) was drawn considering linear KC values from data measured by the lysimeter in growth days were calculated and plotted in Figure 2. Crop coefficient values of black gram (Figure 2) at the initial, midseason and final development stages were 0.48, 1.8 and 0.33, respectively.

As the crop develops and shade more and more of the ground, evaporation becomes restricted and transpiration gradually becomes the major process. Figure 2 shows that the K_{CBG} value increases during the crop development stage to the beginning of the mid season.

The midseason stage runs from full effective cover to start of the maturity. The start of maturity is indicated by senesce of black gram leaves. It is evident from Figure 1 that at mid-season stage the value of K_{CBG} is higher than other stages of black gram crop. Allen et al.[6] indicated that some crop coefficient values might be higher following wetting of soil by irrigation or rainfall. These higher values may be neglected while constructing crop coefficient curves. Neglecting the higher values, the K_{CBG} value for mid season stage was found to be 1.18.

The K_{CBG} values are reduced during the late season stage. The reduction is linear from the end of mid season stage to the end of maturity. The K_{CBG} value at the end of late season was found to be 0.33. By joining all stages the K_{CBG} curve was constructed, amount of irrigation applied and rainfall are also indicated in Figure 1. An estimated amount of irrigation was applied at the mid of late season stage by furrow method. It is clear from Figure 1, that in the initial and mid season stages the value of K_{CBG} are higher compare to FAO-56 tabulated values. However, at the late season stage, the value of K_{CBG} is lower than tabulated values. This suggests utilizing the measured values of crop coefficient for development of curve.

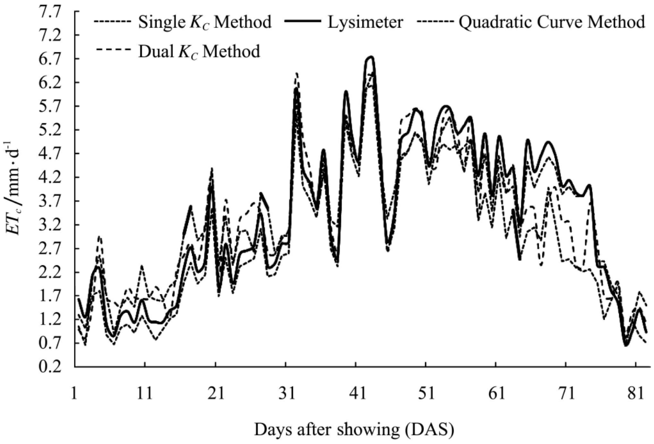

Figure 1 Daily ET_c variations derived from different methods (single KC, lysimeter, quadratic curve and dual KC)

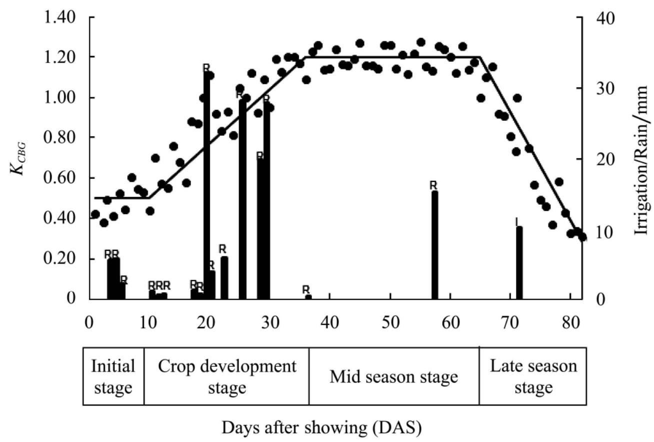

Figure 2 Daily observed crop coefficient (K_{CBG}) values and the four stage linear K_c values for black gram derived from data measured by the lysimeter

3.2 Development of crop coefficient curves

3.2.1 FAO-56 curve method

The FAO-56 crop coefficient curve (K_{CBGF}) for the black gram crop was developed (Figure 3a)[6] proposed three values of crop coefficients K_{Cini}, K_{Cmid} and K_{Cend} for initial, mid and late stages respectively of crop for the development of crop coefficient curve.

The value of K_{Cini} affected by the evaporating power of atmosphere, magnitude of wetting event and time interval between wetting event. The estimated value of K_{Cini} for black gram crop is 0.4 similar to values given by FAO-56[6].

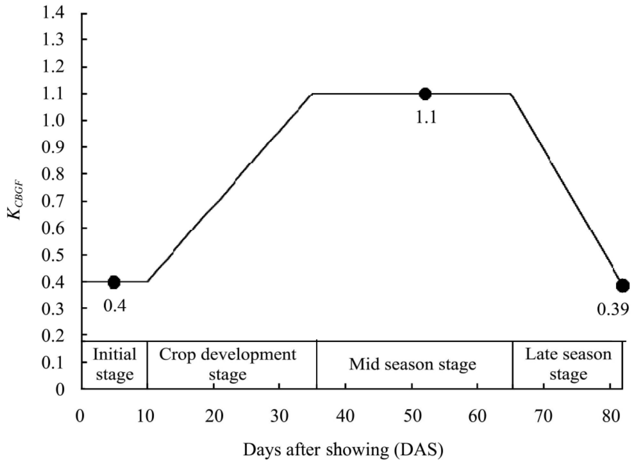

Figure 3a Development of crop coefficient curve for black gram by FAO-56 curve (K_{CBGF}) method

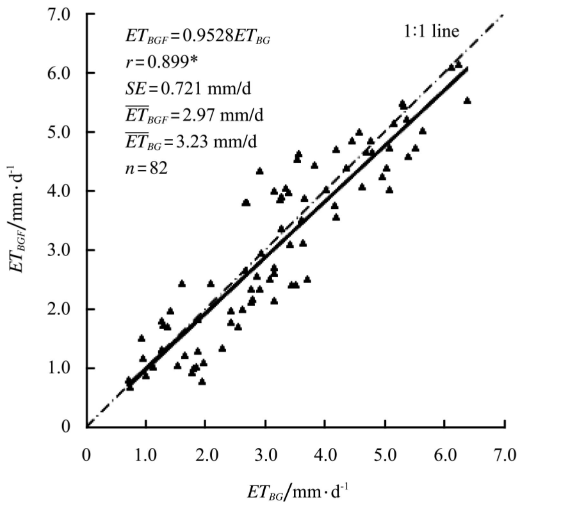

Figure 3b Estimated black gram evapotranspiration by FAO-56 curve method (ET_{BGF}) and measured black gram evapotranspiration (ET_{BG})

The value of K_{Cmid} is less affected by wetting frequency than K_{Cini}. The vegetation during this stage is generally near full groundcover so that the effect of surface evaporation on K_{Cmid} is smaller. During the mid season stage, mean wind speed was 1.02 m/s. Mean value of minimum relative humidity was 55.8 per cent and height of the crop was 36 cm. The K_{Cmid} value for black gram crop was worked out to be 1.1. The Equation (4) is only applied when the tabulated value of K_{Cend} exceeds 0.45. Therefore, tabulated value to K_{Cend} for black gram crop was taken as 0.39.

Using values of K_{Cini}, K_{Cmid} and K_{Cend} the crop coefficient curve for the black gram crop was developed (Figure 1a). Analysis of results showed that there is linear relationship between the crop evapotranspiration estimated by FAO-56 curves method and the measured crop evapotranspiration by electronic weighing lysimeter for black gram (Figure 1b). The SE was found 0.721 mm/d and the correlation coefficient was found to be 0.890, which is significant at 5% level (Table 1). FAO-56 overestimates the measured ET_{BG} by 8.04% at the site. Therefore, this method does not appear to predict ET_{BG} accurately.

Table 1 Linear regression equations showing relationship between measured black gram evapotranspiration and estimated black gram evapotranspiration by various methods

Methods		Values of constants of the equation $Y = bX$	SE /mm · day^{-1}	Correlation coefficient	% Deviation
X	Y	b	SE	r*	
ET_{BG}	ET_{BGD}	1.0155	0.721	0.962	+2.47
ET_{BG}	ET_{BGQ}	0.9579	0.473	0.946	+4.02
ET_{BG}	ET_{BGF}	0.9528	0.721	0.721	+8.04

Note: * Significant at 1% level.

3.2.2 Dual crop coefficient curve method

3.2.2.1 Basal crop coefficient (K_{cb})

As described in FAO-56 curve method, only three point values are required to describe and construct the crop coefficient curve. After dividing the growing period into four general growth stages and selecting, adjusting the K_{cb} values using Equation (5) with above mentioned limitations and by replacing K_c notation by corresponding to the initial $K_{cbini}=0.15$, $K_{cbmid}=1.15$ and late season stage $K_{cbend}=0.45$, the crop coefficient curve was drawn for black gram crop and is presented in Figure 4a.

3.2.2.2 Soil evaporation coefficient (K_e)

K_e, as function of growth period, is affected by soil water characteristics, exposed and wetted soil fraction and soil water balance. In initial stage, the effective fraction soil surface cover was 0.1, and thus, soil evaporation losses were considerable. K_e had a sharp fall when proceed towards development stage. As effective fraction of cover during development stage increased K_e value decreased in step manner. In the mid-season stage, the effective fraction of soil surface cover reached 0.94,

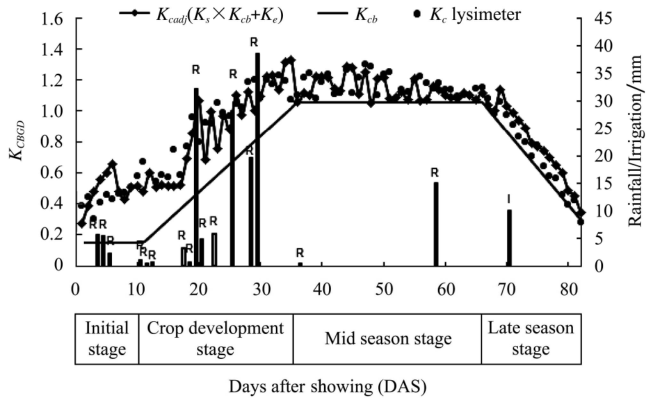

Figure 4a Measured and predicted daily K_{CBGD} and basal crop curve (K_{cb}) and amount of irrigation and rainfall during growing season of black gram

the soil water loss mainly due to transpiration. As effective cover during late season starts decreased up to 0.2 due to aging and falling of leaves, the K_e value reached higher then those during mid season.

3.2.3 Dual crop coefficient curve

The observed black gram crop characteristics, which are input to other calculations, are: crop height: 10-40 cm, crop root depth: 0.1-0.6 cm, fraction of soil surface wetted (fw)$irrgation$ = 1.0, effective fraction of soil surface covered by vegetation (fc)=0.1 during initial stage and maximum fw=0.94 during late midseason, fw = 0.2 during initial stage then approach 1.0 throughout the crop period, exposed and wetted soil fraction (few)=0.2 during initial days approached up to 0.99, TEW = 28.56 mm. Dual crop coefficient curve was developed for observed input parameters for black gram crop under climatic conditions of Udaipur by using a spread sheet program as described by Allen et al.[6] (Figure 4a). Comparison between the crop evapotranspiration estimated by dual crop coefficient curve method and the measured crop evapotranspiration by electronic weighing lysimeter for black gram shows that their exists a linear relationship between crop evapotranspiration estimated from dual crop coefficient curve method and a measured crop evapotranspiration by lysimeter (Figure 4b). The correlation coefficient was found to be 0.962, which is significant at 1% level. The standard error was found to be 0.403 mm/day. The dual crop coefficient curve method overestimates the ET_{BG} values by 2.47%. Therefore, this method appears to predict black gram evapotranspiration very accurately under climatic conditions of Udaipur.

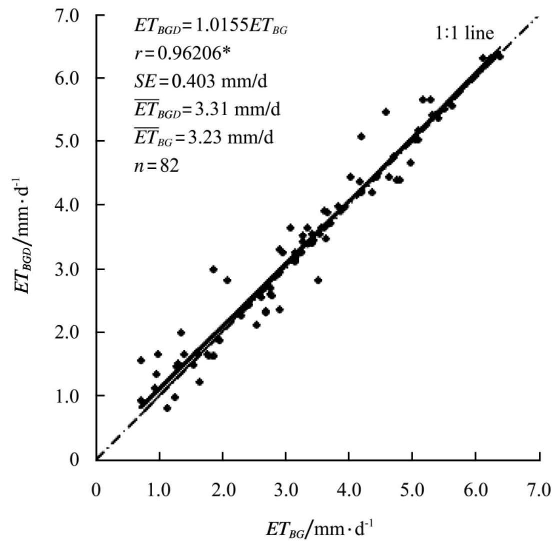

Figure 4b Estimated black gram evapotranspiration by dual crop coefficient curve method (ET_{BGD}) and measured black gram evapotranspiration (ET_{BG})

3.2.4 Quadratic curve method

The quadratic crop coefficient curve for black gram was developed by fitting observed K_c values in the quadratic equation by least square method. The quadratic crop coefficient curve for black gram (K_{CBGQ}) is presented in Figure 5a, which shows that K_{CBG} values increases during initial stage and crop development stage. The K_{CBG} attains its maximum value at the mid season stage. The K_{CBG} value starts decreasing during the late season stage till harvesting. The fitted quadratic equation is given as follows:

$$K_{CBGQ}=-0.006(DAS^2)+0.0461(DAS)+0.2776 \quad (9)$$

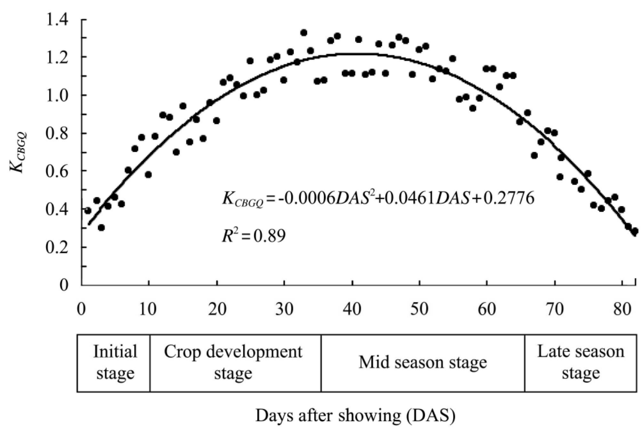

Figure 5a Development of crop coefficient curve for black gram by quadratic curve (K_{CBGQ}) method

where, K_{CBG} = crop coefficient for black gram; DAS = days after sowing.

The quadratic curve method was found to be in good agreement with measured ET_{BG} at the location. SEE of this method was found to be 0.16 mm/day.

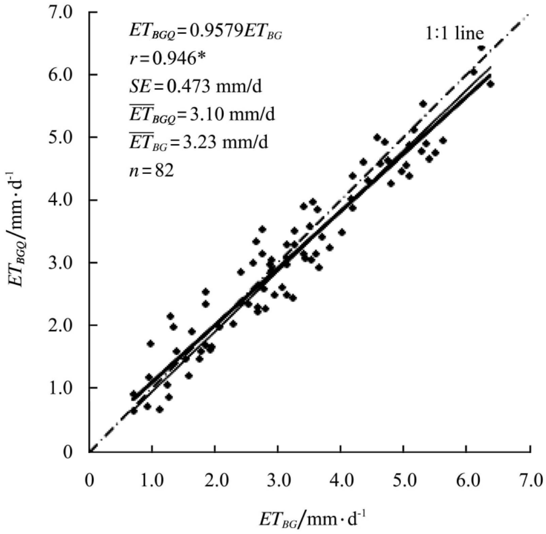

Figure 5b Estimated black gram evapotranspiration by quadratic curve method (ET_{BGQ}) and measured evapotranspiration (ET_{BG}) for black gram crop

3.3 Comparison among various ET_{BG} estimates methods

The estimated ET from different crop coefficient approaches was validated with measured ET_{BG}. It is evident from Table 1 and Figure 1 that there is variability of daily black gram values obtained from different methods. Table 1 also depicted that daily black gram evapotranspiration estimate based on dual crop coefficient curve method (SE=0.40, r=0.96) was found best followed by quadratic curve method (SE=0.47, r= 0.94), and FAO-56 curve method (SE=0.72, r=0.89) in order of superiority may be used for estimation of black gram evapotranspiration under climatic conditions of Udaipur.

4 Conclusions

All the selected methods; FAO-56 curve method (ET_{BGF}), and Dual curve method (ET_{BD}) and also Quadratic curve method (ET_{BGQ}) deviates from measured daily black gram evapotranspiration (ET_{BG}). The deviation was highest in case of FAO-56 curve method. In all the methods there are linear relationships between estimated and measured values of crop evapotranspiration by lysimeter. Estimated values by quadratic curve compared well with the (ET_{BG}) and (ET_{BD}) values. The average daily (ET_{BGQ}) obtained is 3.10 mm, which is very close to average daily (ET_{BG}=3.23 mm) and (ET_{BD}=3.31) values. Therefore, quadratic curve method can be used as alternatives to estimate ET_{BG} under normal irrigation scheduling or development of dual crop coefficient is not feasible due to limiting availability of soil moisture data.

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