Crop-coefficients of tomato as derived using monolithic weighing type lysimeter in mid hill region of Meghalaya

MOUTUSI TAHASHILDAR, PRADIP K. BORA*, LALA I. P. RAY and VISHRAM RAM

School of Natural Resource Management, Central Agricultural University, Umiam, Meghalaya – 793 103, India

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*e mail : pradip66@gmail.com

सार – 30 से. मी. व्यास और 120 से. मी. गहराई के UMS-GmBH बेलनाकार क्षेत्र वाले लाइसी मीटर और पेनमान मॉन्टीथ FAO-56 मॉडल की सहायता से टमाटर के लिए फसल गुणांक का (KC) पता लगाया था। दूसरे आठ मॉडल जैसे संशोधित पेनमान विधि, हार ग्रीव्स समीकरण, समानी-हार ग्रीव्स समीकरण, थोर्नवेट समीकरण, सौर विकिरण विधि, नेट विकिरण विधि, ब्लेनी-क्रिडल विधि और विकिरण विधि को भी ET₀ के अनुमान के लिए प्रयोग किए गए थे और सीमित मौसम प्राचलों के साथ अनुमान की सटीकता का पता करने के लिए पेनमान मॉडल से तुलना की। स्केटर प्लॉट और युग्मित टी- परीक्षण तुलना के लिए प्रयोग किए गए थे। इन सभी मॉडलों के अलावा ब्लेनी क्रिडल विधि, सौर और नेट विकिरण विधि से समान परिणाम पाए गए जैसे कि पेनमान मॉन्टीथ मॉडल के थे। फसल वाष्पोत्सर्जन के मान 2.54 मि.मी./घं. से 6.70 कि.मी./घं. परिवर्तित पाए गए। टमाटर की तीन बढ़ती हुई अवस्था जैसे:- आरम्भिक, मध्य और पकी हुई क्रमश: 0.55, 1.07 और 0.78 पाई गईं।

ABSTRACT. Crop coefficients (k_c) was determined for tomato (*Lycopersicon esculentum* Mill.*)* with the help of UMS-GmBH cylindrical field lysimeter of 30 cm diameter and 120 cm deep and Penman-Monteith FAO-56 model. Eight other models *viz.* Modified Penman Method, Hargreaves equation, Samani-Hargreaves equation, Thornthwaite equation, Solar Radiation Method, Net Radiation Method, Blaney-Criddle Method and Radiation Method were also used for estimation of ET_0 and compared with Penman-Monteith model to find out the accuracy of prediction with limited weather parameters. Scatter plot and paired *t*-test were used for comparison. Out of all these models, Blaney-Criddle method, Solar and Net Radiation method were found to yield similar results as given by Penman-Monteith model. The values of crop evapo-transpiration (ET_c) were varying from 2.54 mm d^{-1} to 6.70 mm d^{-1}. The crop-coefficients (k_c) for three growth stages of tomato *viz.*, initial, mid and maturity were found to be 0.55, 1.07 and 0.78, respectively.

Key words – Crop-coefficient, Reference evapo-transpiration, Crop evapo-transpiration, Lysimeter, Tomato.

1. Introduction

Increasing water use efficiency and reducing the water foot print through precision farming are the important characteristics of new paradigm in water management. Precise application of water to the crop root zone as per the requirement for meeting the evaporative and metabolic demands of the crops, require the knowledge of evapo-transpiration. Evapo-transpiration (ET) is the loss of water to the atmosphere by the combined processes of evaporation from soil and plant surfaces and transpiration from plants. Only about 1% of the water taken up by plants is actually involved in metabolic activity and about 99% of the water uptake by plants from soil is lost as evapo-transpiration. So, it is found that the measurement of crop evapo-transpiration (ET_c) for the whole vegetative cycle is equal to the water requirement of the given crop. However, overestimation and underestimation of crop water need cause both wastage of water and poor crop growth. So a correct knowledge of ET_c improves water management by changing the volume and frequency of irrigation to meet the crop water requirements during different phenophases.

Different weather parameters, crop factors such as crop type, variety, density, growth stage, management, besides soil conditions, salinity, fertility, crop disease and pests affect ET (Allen *et al.*, 1998). Because of the interdependence of most of these factors and their spatial and temporal variability, the formulation of a single equation to be used for ET estimation for various crops under different conditions is impossible. Therefore the idea of reference evapo-transpiration (ET_0) was introduced (Jensen, 1968; Jensen *et al.*, 1971; Doorenbos and Pruitt, 1975). ET_0 has been defined as the rate of ET from an extensive surface of green grass of uniform height

8 to 15 cm tall actively growing, completely shading the ground and not short of water (Doorenbos and Pruitt, 1977; Jensen *et al.*, 1990; Smith *et al.*, 1991; Allen *et al.*, 1994). There are number of equations reported for ET_0 estimation in literature (Gavila´n *et al.*, 2006; Alexandris *et al.*, 2005; Dehghani Sanij *et al.*, 2004; Pereira and Pruitt, 2004), but these results are valid for certain areas and climatic conditions of the world. American Society of Civil Engineers (ASCE) established a Task Committee that recommended standardized forms of ET estimation and FAO Irrigation and Drainage Paper No. 56 have adopted Penman- Monteith equation as the sole reference ET estimation method. International Scientific Community has accepted the Penman-Monteith equation as the most precise one for its good results in various regions of the entire world (Chiew *et al.*, 1995; Garcia *et al.*, 2004; Gavila´n *et al.*, 2006). Penman-Monteith (FAO-56 PM) equation had been considered as a universal standard for ET_0 estimation over other methods (Allen *et al.*, 1998) when comparing it with lysimetric measurements especially for daily computations (Chiew *et al.*, 1995; Cai *et al.*, 2007; Lo´pez-Urrea *et al.*, 2006; Garcia *et al.*, 2004).

The characteristics that distinguish field crops from the reference crop are integrated into a crop factor or crop coefficient (k_c) (Allen *et al.*, 1998; Allen, 2000). k_c is the multiplying factor to ET_0 for determining the ET_c with the relationship (Doorenbos and Pruitt, 1977; Wright, 1982; Jensen *et al.*, 1990; Smith *et al.*, 1991; Allen *et al.*, 1998) $ET_c = k_c \times ET_0$. So Crop coefficients (k_c) were and still, a major topic of study for any researcher concerned in crop water requirements under different environments and agricultural practices (Doorenbos and Pruitt, 1977; Wright, 1979). From the relationship, it appears that to determine k_c for any crop type and variety, one needs to know both ET_0 and ET_c. ET_0 is estimated with the help of PM model and ET_c can be measured accurately with the help of lysimeter. Hence, field lysimeter, replicating micro-climate of the crop field and parent soil profile is required to grow the crops with sufficient fetch, for measuring daily or weekly water loss through ET. Lysimeter measurements are adopted for hydrological balances of crops (Jones, 2004; da Silva *et al.*, 2005; Liu *et al.*, 2007, Ceccon *et al.*, 2008), or to determine k_c values (Tyagi *et al.*, 2003).

Tomato (*Lycopersicon esculentum* Mill.*)* is an important vegetable crop grown in the mid-hill region of Meghalaya both as rainfed and irrigated crop. This is also the largest vegetable crop in acreage, grown worldwide (Ho, 1996) for both fresh and processing markets (Opiyo and Ying, 2005; Gad and Hassan, 2013; Mehdizadeh *et al.*, 2013). The k_c for tomato is not available for NE region to estimate the water requirement particularly

TABLE 1

Soil chemical and physical properties of experimental field

Properties	Values
pH	5.2
OC (%)	0.82
CEC	1.30
Exchangeable Acidity	1.40
Available N (kg ha^{-1})	257.0
Available P(kg ha^{-1})	15.1
Available K(kg ha^{-1})	155.7

under irrigation. However, over the years, k_c is selected from literature to be 1.15 for both the developmental and mid-season stages. But Allen *et al.* (1998) reported k_c values of 1.15 and 0.70-0.90 for the mid-season and late season stages, respectively. The differences in the coefficients available in literature also made it pertinent to determine the location specific information. The present study was thus undertaken to determine the k_c values for the various growth stages of tomato in the mid hill region of Meghalaya, India.

2.   Materials and method

Experimental site

The experimental work was conducted during Feb-May of 2014 growing seasons in the experimental farm located at College of Post-Graduate Studies, Central Agricultural University, Barapani, Meghalaya (91°18′ to 92°18′ E, latitude, 951 m above mean sea level). The soil at the experimental area is sandy loam (texture with 62.9% sand, 21.6% clay and 15.5% silt) in texture with 1.35 g/cm^3 bulk density and chemically the soil is slightly acidic in nature. Other soil properties are given in Table 1. The minimum and maximum temperatures during the study period, ranges from 14 °C to 33 °C and 3 °C to 28 °C, respectively, with average annual precipitation of 2,000 mm.

3.   Description of weather station, lysimeter and tensiometer

An automatic weather station (Davis Vintage Pro-2) was installed within the farm area for collecting real time weather data. The standard weather data (rainfall; maximum and minimum temperature, morning and afternoon RH, wind speed and sun shine hours) were collected for the experiment at daily intervals. The operation of the lysimeter and weather station was automatic and data were allowed to be stored in the data-logger.
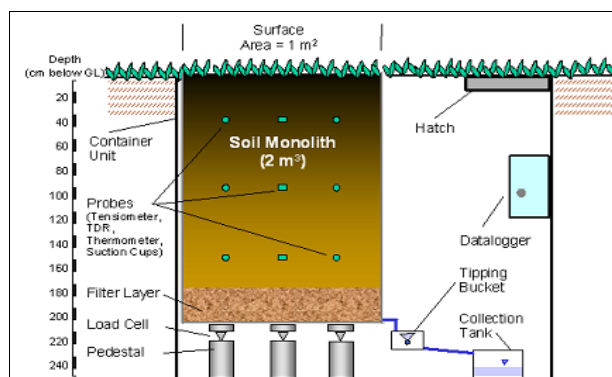
Fig 1. Weighing type of lysimeter (UMS-GmBH)

Two weighing type lysimeters (UMS-GmBH) were installed within crop area of the experimental field (Fig. 1). The present lysimeter is a cylindrical lysimeter with 30 cm diameter and 120 cm long. Unlike traditional lysimeters, these are filled up with undisturbed soil to maintain the exact soil profile of the parent soil. The soil is not disturbed across the profile only except for negligible shearing along the cutting plane of the lysimeter wall when inserted into the soil. Once the cylinder is inserted fully, it is lifted up and the bottom of the cylinder is made water tight with special designed seal. The soil filled watertight cylinder is then inserted in a casing and placed over a load cell which is connected to a data logger to record the change of weight of lysimeter due to loss or gain of water. Five number of each moisture sensors (EC5), Tensiometer (T4) and vacuum cup (SK20) were fixed on the wall of the lysimeter at different depth (10 cm, 30 cm, 55 cm, 80 cm and 115 cm). EC5 measures dielectric constant of the soil in order to find the volumetric water content. T4 Tensiometer is a precision tensiometer developed for outdoor monitoring works. Another Tensiometer is installed outside the lysimeter for balancing the metric potential inside and outside the lysimeter. VS Pro Vacuum system is also fitted to create constant vacuum condition at suction of -400 hPa to drain out excess water from the soil profile. SK20 vacuum cup is a simple ceramic cup with removable shaft. It is mainly suitable for continuous and discontinuous extraction. All the sensors are connected to a data logger for continuous data collection at pre-determined interval of 5 minutes. The gravitational water or the leachate is taken out through the vacuum cups and collected in the bottles kept in a buried chamber. The ceramic plate at the bottom of lysimeter is also connected to the vacuum pump to collect the excess water beyond field capacity (Fig. 1).

4. Moisture characteristics of soil

The moisture characteristics of the soil in the experimental site was determined with the help of

Pressure Plate Apparatus in order to ascertain the water holding capacity and soil moisture at field capacity level. Soil moisture at different suctions and at different depths of soil are given in the Table 2. The moisture content of the soil varies from 12 to 44% at different suction levels.

5. Crop coefficient

5.1. *Estimation of reference evapo-transpiration*

Reference evapo-transpiration (ET_0) was estimated using eight different methods, along with Penman Monteith method (Allen *et al.*, 1998) for comparison as a standard model, using real time weather data *viz.*, Maximum & minimum temperature, relative humidity, wind speed and net radiation as collected from the automatic weather station installed in the field. The ET_0 estimates made using the eight methods (Modified Pemman method, Hargreaves equation, Samani-Hargreaves equation, Thorthwaite equation, Solar Radiation Method, Net Radiation Method, Blaney-Criddle Method and Radiation Method) were compared with Pemman-Monteith Method. Statistical tools such as scatter plots and paired *t*-test were used to assess applicability of these methods in any situation where all the weather parameters might not be available.

5.2. *Measurement actual evapo-transpiration*

The crop evapo-transpiration (ET_c) was then calculated from the soil moisture values from lysimeter as recorded using the EC5 sensors and load cell data taken on daily basis using water balance approach. The ratio between the crop evapo-transpiration (ET_c) to the reference evapo-transpiration (ET_0) gave the Crop Coefficient (k_c).

$$k_c = ET_0 / ET_c \qquad (1)$$

6. Results and discussion

6.1. *Crop evapo-transpiration by lysimeter*

The values of ET_c as measured and calculated through Lysimeter during transplanting to reproductive stage was varying from 1.27 mm to 6.46 mm d^{-1} (Fig. 2). The average weekly ET_c (mm d^{-1}) of tomato rose from 1.61 to 5.99 mm d^{-1} during 1-12th weeks after transplanting (WAT), *i.e.*, from transplanting to reproductive stage, and thereafter fell to 4.95 mm d^{-1} (Table 3).

The highest weekly average values of ET_c, *i.e.*, 5.99 mm d^{-1} was obtained during the period of maximum reproductive growth (12th WAT). The crop
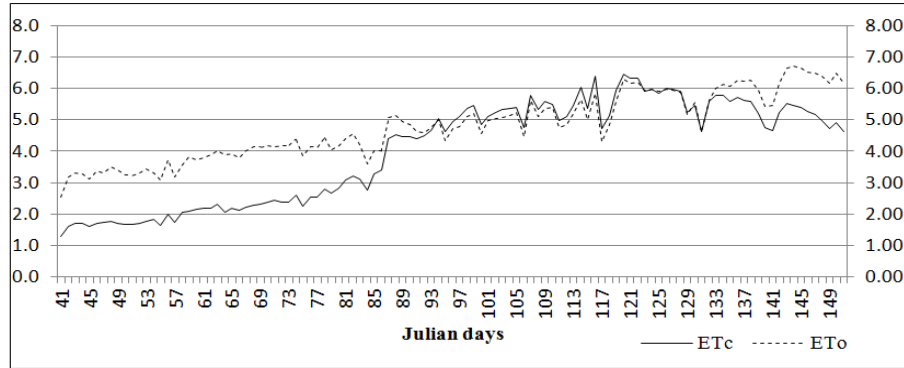
Fig. 2. Reference ET_0, ET_c during the period of tomato in Meghalaya by Penman Monteith method

TABLE 2

Soil moisture at different suction as determined with Pressure Plate Apparatus

Depth (cm)	0.33 bar	0.5 bar	1 bar	2 bar	4 bar	6 bar	10 bar	12 bar	15 bar
0-15	22.5883	20.91	18.41	17.23	16.03	15.1	14.11	12.71	7.92
15-30	33.9881	30.21	28.5	25.69	23.83	20.88	18.38	16.32	9.82
30-60	31.4727	28.76	27.08	25.53	22.51	19.71	17.52	15.59	8.25

TABLE 3

Average weekly ET_c by lysimeter (mm d^{-1}) in the month February to May, 2014

Date	16 Feb	23 Feb	02 Mar	09 Mar	16 Mar	23 Mar	30 Mar	06 Apr	13 Apr	20 Apr	27 Apr	04 May	11 May	18 May	25 May	31 May
ET_c	1.61	1.76	1.99	2.15	2.40	2.81	3.72	4.71	5.18	5.39	5.44	5.99	5.59	5.67	5.19	4.95

evapotranspiration gradually increased from the first week after transplanting till the crop entered into reproductive stage (8th to 12th week after transplanting). Thereafter a gradual reduction was observed in ET_c from 5.99 to 4.95 mm d^{-1} during 12-16th WAT. The total seasonal ET_c during the cropping season was 446.61 mm. The difference between ET_C and ET_0 by PM method during initial and final stage of tomato (Table 3 & 4) growth season proved that ET_0 was higher than ET_C (Fig. 2). But in middle stages, ET_C surpassed ET_0. It is due to increased foliage in the middle stage. This result is similar to the previous study on tomatoes (Hanson and May, 2006). With regard to variation of weather conditions especially the precipitation during crop growth, decrease in ET_C is logical. Similar results about garlic were reported by Villalobos *et al.* (2004) and Fabeiro *et al.* (2003). They obtained values for ET_C were low in that study, probably due to different climatic conditions, physiological differences of garlic varieties.

6.2. *Reference evapo-transpiration*

The daily trend of estimated ET_0 during tomato growing period (February to May) reflected a wide range from 2.54 mm d^{-1} to as high as 6.70 mm d^{-1} (Fig. 2) by Penman Monteith method with a mean value of 4.83 mm d^{-1} over the entire crop growing season. Weekly basis estimation revealed that the average weekly ET_0 was observed to be lowest on the 1st week after transplanting (WAT) in the month of February (3.2 mm d^{-1}) while in the month of March weekly average ET_0 losses increased to 4.4 mm d^{-1}. Sum total of monthly ET_0 loss was 62.91 mm (19 days duration) in February, 129.91 mm in March, 151.45 mm in the month of April and 187.22 mm in the month of May. In the entire crop growth period, *i.e.*, from 10th February till 31st May, total ET_0 loss during the crop season amounts to 531.49 mm. Variation in ET_0 loss was influenced by the three most important weather variables namely net radiation received, wind speed and mean air temperature. The sum total of daily ET_0 losses

TABLE 4

Calculated average weekly ET$_0$ for tomato for the month February-May, 2014

Week started on	Average weekly ET$_0$ (mm d^{-1})								
	Penman-Montieth	Modified Penman	Hargreaves equation	Samani Hargreaves equation	Thornthwaite equation	Solar Radiation method	Net Radiation method	Blaney Criddle method	Radiation method
16 Feb	3.2	5.0	6.6	6.7	14.9	2.8	0.9	3.0	10.1
23 Feb	3.3	5.2	7.2	7.6	14.9	2.8	1.0	3.0	10.0
02 Mar	3.6	5.8	8.2	7.5	15.2	3.1	1.2	3.3	10.8
09 Mar	4.0	6.4	8.4	8.1	15.9	3.3	1.3	3.5	12.0
16 Mar	4.2	7.2	10.6	12.7	15.9	3.6	2.1	3.8	13.2
23 Mar	4.3	7.2	10.2	9.7	15.9	3.6	2.1	3.7	12.8
30 Mar	4.4	7.7	9.4	9.1	15.9	3.7	3.5	4.0	12.7
06 Apr	4.7	8.1	12.0	12.4	15.5	4.0	2.3	4.2	13.9
13 Apr	5.0	8.9	11.3	10.9	15.4	4.1	6.1	4.4	14.8
20 Apr	5.2	9.4	12.8	12.6	15.4	4.4	6.3	4.6	15.4
27 Apr	5.1	9.3	12.8	15.5	15.4	4.4	6.4	4.7	14.9
04 May	5.9	11.1	11.4	11.7	17.0	4.8	6.9	5.2	17.1
11 May	5.6	10.2	12.5	11.2	18.1	4.5	6.4	4.9	16.5
18 May	6.1	11.6	12.8	11.7	18.1	5.0	6.1	5.2	18.2
25 May	6.1	11.5	11.2	11.3	18.1	4.9	5.4	5.0	18.0
31 May	6.4	12.0	10.5	10.9	18.1	4.9	4.2	5.8	19.0
Total	531.4	944.2	1164.5	117.7	1801.5	442.6	483.0	548.0	1586.3

during the season were found to be 944.27 mm (Modified Penman method), 1164.51 mm (Hargreaves method), 1177.74 mm (Samani Hargreaves method), 1801.53 mm (Thornthwaite method), 439.72 mm (Solar Radiation method), 483.02 mm (Net Radiation method), 548.01 mm (Blaney Criddle method) and 1586.30 mm (Radiation method). The values obtained by Radiation method (Doorenbos and Pruitt, 1977) were much higher than that obtained by other two radiation based methods *viz*., Net Radiation method and Solar Radiation method. This may be attributed to the calculation of the factors in the model, which are directly related to elevation of the location and slope. These factors are not included in Net Radiation and Solar Radiation methods. The radiation dependent methods which estimate ET$_0$ indirectly with factors estimated based on solar radiation and temperature may greatly vary depending on the methods and locations used to calculate the factors. Similar conclusion was given by (Xu and Singh, 2000) who concluded that accuracy of the radiation based methods depended on calculation of reliable values of the constants. In this study, the ET$_0$ values estimated directly with Net Radiation (Rn) and Solar Radiation (Rs) gave comparable results with the values obtained through Penman Monteith equation.

However in the Radiation method, the factor *w* is not only dependent on temperature but also related to altitude-dependent weighing factors. The coefficient Cr depends on relative humidity and wind speed. The present study location is at an altitude of 951 m above mean sea level with slope aspects towards southern direction. Therefore the high values obtained through Radiation method might be attributed to higher values of Cr and *w*.

Comparable values were obtained through Blaney-Criddle, Solar Radiation and Net Radiation methods, where the minimum and maximum values of ET$_0$ were 3.0 mm d^{-1}, 5.8 mm d^{-1}; 2.8 mm d^{-1}, 5.0 mm d^{-1} and 0.9 mm d^{-1} to 6.9 mm d^{-1}, respectively (Table 4). All other methods yielded ET$_0$ values much higher than that obtained through Penman-Monteith method. Previous researches also indicated that Hargreaves, Hamon and Radiation methods resulted in the overestimation of ET$_0$ relative to the FAO 56-PM method. Reference ET calculated by Thonthwaite method was found to be consistently higher from the 1st week after transplanting till the end of the plant growth period. Reference ET by Samani-Hargreaves equation gave over estimation throughout the season for tomato. Hargreaves-Samani
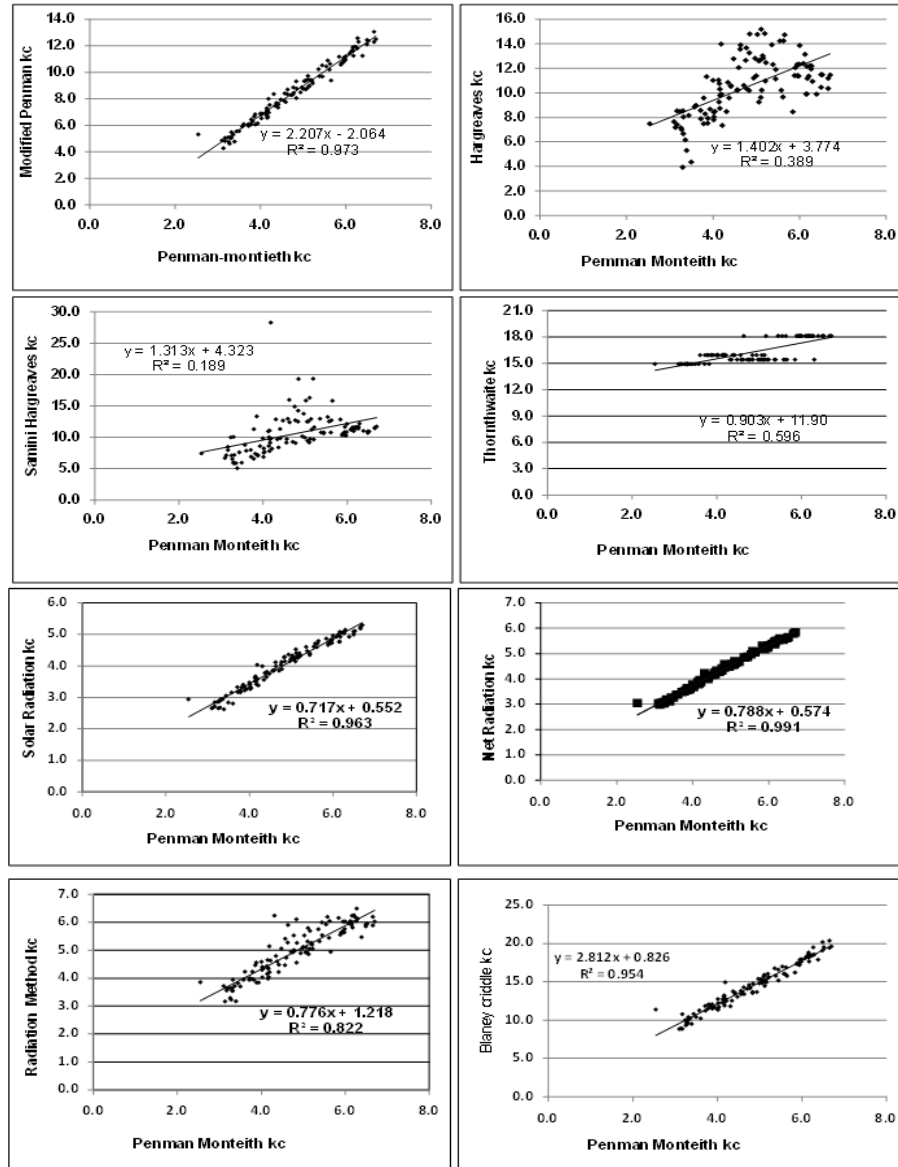
Fig. 3. Comparison of daily k_c values by eight different methods with Penman Monteith method (n = 111)

method systematically overestimated by as much as 20% giving the worst estimates among all other tested methods (Alexandris *et al.*, 2008). Similar behaviour of Hargreaves equation under humid conditions has been reported by Jensen *et al.* (1997), Droogers and Allen (2002), Temesgen *et al.* (2005) and Garcia *et al.* (2004). George *et al.* (2012) indicated that ET_0 estimated by Solar Radiation method under estimated as solar radiation data were often not available and were indirectly estimated from sunshine hours.

The linear regression statistics as obtained from scatter plots revealed that Modified Penman, Thornthwaite method, Solar Radiation method, Net Radiation method,

Balney Criddle method and Radiation methods had given statistically significant R^2 values with different slopes and intercepts as given in Table 5 and Fig. 3. Table 5 shows that statistical indicators, *viz.*, Correlation coefficient in combination with *t-statistics* (critical *t*-value = 1.66 for one tail and 1.98 for two tail, for directional *t*-test with $n = 111$) are more informative than R^2 alone. This indicated that these methods had similar trends of ET_0 over the crop season and could find use, with appropriate correction factors. From February 10th to May 31st better agreement was observed between Penman Monteith and Blaney-Criddle, Solar Radiation and Net Radiation methods followed by other methods. The values of R^2 and *t*-test suggested that Blaney-Criddle, Solar Radiation and

TABLE 5

Regression statistics between Penman Monteith and different methods of ET_0

Variables	Modified Penman	Hargreaves equation	Samani Hargreaves equation	Thornthwaite equation	Solar Radiation method	Net Radiation method	Blaney Criddle method	Radiation method
Regression line slope (m)	2.20	1.40	1.31	0.78	0.71	0.78	2.80	0.77
Regression line intercept (c)	2.0	3.7	4.3	0.57	0.55	0.57	0.82	1.21
Coefficient of determination (r^2)	0.97	0.38	0.18	0.59	0.96	0.99	0.95	0.82
Daily t-test value ($p = 0.05$) n = 111	-29.67	-31.83	-21.44	-153.50	25.50	19.66	-3.53	-49.97

TABLE 6

Crop coefficient (k_c) values for tomato

Date	k_c								
	Penman-montieth	Modified Penman	Hargreaves equation	Samani Hargreaves equation	Thornthwaite equation	Solar Radiation method	Net Radiation method	Blaney Criddle method	Radiation method
16 Feb 2014	0.51	0.32	0.25	0.24	0.11	0.57	0.55	0.53	0.16
23 Feb 2014	0.53	0.34	0.25	0.23	0.12	0.62	0.56	0.58	0.18
02 Mar 2014	0.56	0.35	0.24	0.26	0.13	0.65	0.60	0.60	0.18
09 Mar 2014	0.55	0.34	0.26	0.27	0.14	0.65	0.60	0.62	0.18
16 Mar 2014	0.58	0.33	0.23	0.19	0.15	0.66	0.87	0.63	0.18
23 Mar 2014	0.66	0.39	0.28	0.29	0.18	0.78	0.74	0.75	0.22
30 Mar 2014	0.84	0.48	0.39	0.41	0.23	1.00	0.94	0.94	0.29
06 Apr 2014	1.00	0.58	0.39	0.38	0.30	1.18	0.48	1.12	0.34
13 Apr 2014	1.04	0.58	0.46	0.47	0.34	1.26	1.17	1.17	0.35
20 Apr 2014	1.04	0.57	0.42	0.43	0.35	1.24	1.16	1.17	0.35
27 Apr 2014	1.07	0.58	0.42	0.35	0.35	1.25	1.17	1.17	0.37
04 May 2014	1.02	0.54	0.53	0.51	0.35	1.24	1.15	1.15	0.35
11 May 2014	1.00	0.55	0.45	0.50	0.31	1.24	1.14	1.15	0.34
18 May 2014	0.93	0.49	0.44	0.48	0.31	1.14	1.07	1.08	0.31
25 May 2014	0.84	0.45	0.46	0.46	0.29	1.06	1.04	1.03	0.29
31 May 2014	0.78	0.41	0.47	0.45	0.27	1.01	0.84	0.85	0.26

Net Radiation methods for estimation of ET_0 are similar to Penman Monteith Method in sub humid tropical climate for tomato. The paired *t*-statistics have however reaffirmed that only Blaney-Criddle, Solar Radiation and Net Radiation methods were capable of estimating the ET_0 which were comparable to Penman-Monteith equation, though statistically not significant as per paired *t*-test (Table 5). Hence, it can be inferred that with the availability of temperature and radiation data in this hilly region Blaney-Criddle, Solar Radiation and Net Radiation methods were applicable for estimating the ET_0 with some

degrees of accuracy. Allen *et al*. (2005) recommended the use of the FAO-56 Penman-Monteith (PM) reference evapo-transpiration (ET_0) for irrigation scheduling across the world because PM generally provides reasonably accurate results under various climatic conditions. The Penman-Monteith evapo-transpiration model has been shown to be adequate for estimating daily and hourly ET_0; however, the proper evaluation of surface resistance to vapour exchange has been a limiting factor for using the model to directly estimate daily evapo-transpiration rates for crops (Kjelgaard & Stockle, 2001).
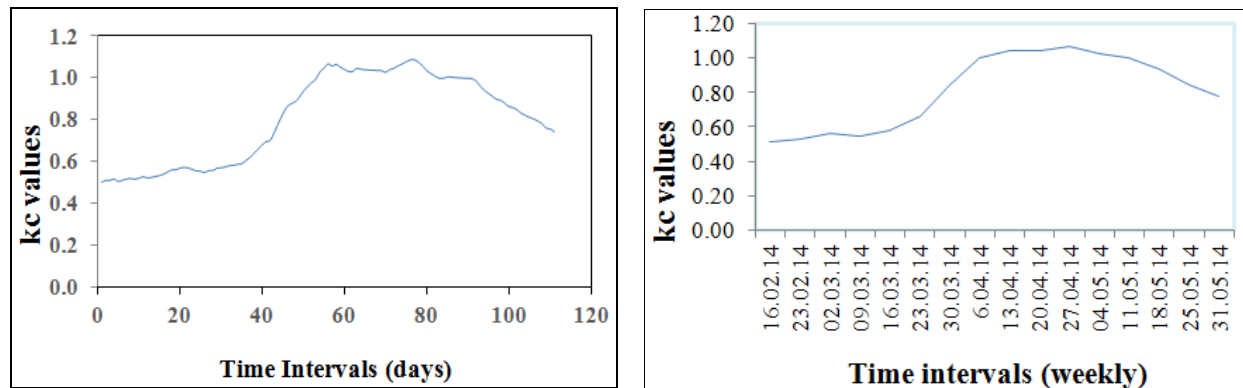
Fig. 4. Daily and weekly crop coefficient of tomato using Penman Monteith method

TABLE 7

Values of crop coefficient derived from different methods for tomato

S. No.	Name of the methods	Tomato		
		$k_{c\ ini}$	$k_{c\ mid}$	$k_{c\ end}$
1.	Penman Monteith method	0.55	1.04	0.78
2.	Modified Penman method	0.33	0.58	0.41
3.	Hargreaves method	0.23	0.46	0.44
4.	Samani Hargreaves method	0.26	0.47	0.44
5.	Thornthwaite method	0.14	0.34	0.27
6.	Solar Radiation method	0.66	1.26	1.01
7.	Net Radiation method	0.60	1.12	0.84
8.	Blaney Criddle method	0.62	1.12	0.85
9.	Radiation method	0.18	0.34	0.26

7. Crop coefficient

In the initial stage of growing period from transplanting to end of the 5th week after transplanting, crop coefficients increased from 0.51 to 0.58; 0.57 to 0.66; 0.55 to 0.60 and 0.53 to 0.63 with Penman Monteith method, Solar Radiation Method, Net Radiation method and Blaney-Criddle Method, respectively (Table 6). The k_c values during these days increased slowly as foliage increased. Results revealed that average weekly k_c values at different stages of growth varied at different magnitudes. Crop coefficients increased from 0.51 to 1.07 based on Penman Monteith method, 0.32 to 0.58 (Modified Penman method), 0.25 to 0.58 (Hargreaves Method), 0.24 to 0.51 (Samani Hargreaves method), 0.11 to 0.35 (Thornthwaite method), 0.57 to 1.26 (Solar Radiation Method), 0.55 to 1.17 (Net Radiation method), 0.53 to 1.17 (Blaney-Criddle method) and 0.16 to 0.37 (Radiation method). The lower values of k_c obtained

through Radiation method was because of very high denominator in the ratio between ET_c and ET_0. The k_c values were low in the early season due to small leaf area and thereby low water uptake and it increased as the canopy reached maximum development with corresponding increase in water use by the crop. Doorenbos and Pruitt (1979) also observed that plant height and total growing season influenced crop coefficient values. The higher the plant height and the longer the growing season, the higher was the crop coefficient values and vice versa. The maximum crop coefficients were also estimated as 1.07 and 1.26 by Penman Monteith method and Solar radiation method and 1.17 by both Net Radiation method and Blaney Criddle method during 9th and 11th WAT, respectively.

The tabulated FAO crop coefficients of tomato crop were 0.60, 1.15 and 0.7 for early-season ($k_{c\ ini}$) mid-season ($k_C\ mid$) and late-season growth stages ($k_C\ end$),

Fig. 5. A view of experimental setup

respectively (Allen *et al.*, 1998). The computed k_c values by Penman Monteith method during initial, mid and end stage were 0.55, 1.04 and 0.78, respectively (Table 7 and Fig. 4) and these values estimated as 0.66, 1.26 and 1.01; 0.60, 1.12 and 0.84 and 0.62, 1.12 and 0.85 in respective stages (Table 7) for Solar Radiation, Net Radiation and Blaney-Criddle methods, respectively. The measured k_c values deviated from the FAO values by about $\pm$ (0.02-0.06), $\pm$ (0.11-0.22) and $\pm$ (0.08-0.31) for $k_{c\,ini}$, k_c mid and k_c end , respectively. A view of experimental setup is given in Fig. 5.

8.   Summary and conclusions

Some of the simpler empirical models for estimating ET_0 are giving reasonably good results which are comparable to that calculated through Penman Monteith method. Based on regression analyses of the tested methods with Penman Monteith method it was found that Blaney Criddle, Solar and Net Radiation methods gave better results and significantly close to the Penman Monteith method results at 5% level of significance. It can be recommended that in the absence of all the requisite data for using Penman Monteith method, Blaney Criddle, Solar and Net Radiation methods can be successfully used in North Eastern Hilly Region of India during summer seasons. The k_{cini}, k_{cmid} and k_{cend} values of tomato crop were 0.55, 1.07 and 0.78, respectively. As environmental factors such as temperature, solar radiation, wind speed and relative humidity prevailing at the experimental site has influence on the crop water need of a plant, the minor variation from the k_c reported for tomato in different literature were anticipated.

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