Evapotranspiration and Responses to Irrigation of Headed Broccoli under Indian Hot and Sub-Humid Climatic Condition

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Abstract: Crops grown under irrigation rather than the monsoon season in India is not an easy farming practice, because of water scarcity under changing climate and market limitations. The present experiment was designed and executed to measure the water use (evapotranspiration) of heading broccoli under furrow irrigation and different water saving techniques. In general, consumptive water use reached a maximum of 118 mm and a minimum of 55 mm for the period of 70 days after transplanting. Single crop coefficient (K_c) values were recorded higher than calculated FAO-K_c values during initial, mid and end stages. The response of given irrigation water through flood irrigation method (four treatments, from 25 to 100% of ET_c) to the yield of broccoli, formed a production function that gave the highest yields (near 15 t ha^{-1}) at an irrigation level of 118 mm, and a 12.61 kg m^{-3} water use efficiency. Broccoli cultivation during the winter season is an economically feasible alternative for diversification of crops around the year at a time where irrigation water demand for other crops is maximum.

Keywords: Broccoli, SET$_{watbal}$, SET$_{FAO}$, WUE, K_c

Across the globe, increasing population, urbanization, modernization in developing countries has created a significant risk on water quality. Globally, 44 countries are projected to either extremely high or high-water stress level (ratio of water withdrawals to water supply) in 2040 and India is one of them, having a high water stress level country (Rana and Bhardwaj 2021, Armstrong 2022). Due to water related losses in agriculture, health, income and prosperity, some regions of the world may see their growth rates decline by 6 % of GDP by 2050 (WB 2023). Increasing urbanization, civilization and industrialization of India, decreases drastically share of fresh water for agriculture, and it will be declined up to 78 % in the year 2050 as against increasing demand 40 % (Jaybhaye et al., 2023). Use of ground water in agriculture causes arsenic contamination in India, and which also deteriorates the environment. Under such situations, more food, fruits and fresh vegetables production need to increases with less available water resources. Considering these actualities, avoidance of the peak summer ET_O demand, could mitigate aquifer over exploitation and make irrigation more sustainable by reducing seasonal irrigation to growing various crops.

Depletion in evapotranspiration rate by using the ET reducing techniques may increase water productivity, but water productivity can also be improved by increasing its yield or the gross income (Jaybhaye et al., 2023). Areas of water scares, a shifting from traditional field crops into higher valued horticultural crops has been observed (Fereres et al., 2003). Therefore, an accurate quantification of crop evapotranspiration is supportive for proper planning and management of irrigation (Meshram et al., 2018). Reduction of water losses in agricultural crop production is highly valuable to lessen impact of water scarcity and changing climatic condition. Among different crops, horticultural crops are considered as the best, suitable alternative to the urgently needed balanced diversification along with the staple food of Indian agriculture. Similarly, introducing a horticultural crop like broccoli with their high cost-effectively (and risk) in an area mainly devoted to annual field crops could rejuvenate a sector vulnerable to decrease in the subsidies from the Common Agricultural Policy of the West Bengal. Therefore, it's required accurate calculation of crop water requirements, usually used the standard FAO approach (Allen et al., 1998a) that uses ET_O and a crop coefficient (K_c).

Information on K_c is widely available for many crops and it was originally obtained by measuring crop ET, usually with lysimeters, and then relating it to ET_o). The progression of K_c over time during the crop growing season is represented by K_c curve. Lopez-Urrea et al. (2009) described that the measured K_c values at any rate, do not best fit the linear or even the curvilinear model, as there are significant fluctuations above and below the fitted lines. From the above, it appears advisable to carry out regional or local alterations of broccoli K_c for improvement in the estimates of ET precisely. Therefore, there is the need for the assessment of K_c value of any crop for a particular region. Likewise, it would be important to clarify the response of this crop to different

irrigation regimes to assess the ideal level of water application to fall plantings. Therefore, we conducted an experiment to (a) determine the Kc value of broccoli crop and (b) to evaluate the response of broccoli to deficit irrigation.

MATERIAL AND METHODS

The research experiment was carried out during 2016-17 and 2017-18 (during the period of November to January) at Bidhan Chandra Krishi Viswavidyalaya, Kalyani, West Bengal, (India) to find out response of irrigation regimes (IR) and water saving techniques (WST's). The experimental site climate is hot and sub-humid, continental with 1600 mm of annual average rainfall and 85 % of it is received during the monsoon period i. e. from 18-24 June (25th SMW) to 24-30 September (39th SMW). January is the coldest month with a mean temperature value ranging from 15.5°C to 21.3°C. The atmospheric mean temperature begins to rise towards the beginning of February and reaches its mean maximum (27.6 to 31.1 $^{\circ}$C) during May. Higher mean relative humidity (97%) experienced during the 50th to 3rd standard meteorological week (SMW) and is at the lowest level (39%) in the 10th SMW. Normal pan evaporation value reaches its maximum level 3.4 mm/day during the 10th SMW and it remains at its lowest level (1.0 mm/day) during the 51st SMW. While, the 47th and 48th SMW were the driest period with no rainfall; whereas, the maximum rainfall received during the 46th SMW. The experimental plot soil was classified as a sandy loam hyperthermic Aeric Haplaquept (Jaybhaye and Mukharjee 2020). Average depth of the soil at the experimental site was >100 cm. The Texture was sandy-clay–silt, in general with 56% of sand, 21% of silt and 23% of clay, and the basic pH was 5.5 to 6.5. The soil was rich in organic matter as well as in nitrogen. Experimental sites geo-coordinates and experimental details (viz., irrigation treatments and water saving techniques as sub treatments details, statistical design, agronomical practices, harvesting etc.) are given thoroughly by Jaybhaye et al. (2023).

Gravimetric soil water content was measured from 0-150, 150-300, 300-450 and 450-600 mm depths weekly in between period of sowing and harvest; as well as before and after each irrigation and after notable (≥20 mm) rainfall. During the whole cropping period (sowing to harvest) seasonal evapotranspiration (SET) from the crop field was calculated by using the field water balance equation.

$$ET = P + I + C - D \pm \Delta SWS \qquad (1)$$

Where, P- precipitation (mm), I- total irrigation water applied (mm), C- capillary contribution (mm), D- vertical drainage (mm) and ΔSWS - depletion in soil water storage (mm). It was considered, the capillary contribution and deep drainage contribute negligible amount to the total seasonal evapotranspiration value for this region (Mukherjee et al 2010). Hence, not considered both C and D in the present study. The resulting data was computed for measurement of broccoli ET under the regional climatic condition. Cumulative GDD ($^{\circ}$C day) was computed by using the 3.0°C T_{base} and the equation which was earlier used by Diputado et al (1989).

$$GDD = \sum_{x=1}^{n} [(TD_{max} + TD_{min})/2] - T_{base} \qquad (2)$$

Where, T_{base} is the base temperature of broccoli; TD_{max} is the maximum temperature of the day and TD_{min} is the minimum temperature of the day.

Statistical analysis: Entire collected data was analyzed by using SAS (ver. 9.3, SAS, Inc., Cary, NC) computer package program. The statistical measurements of coefficient of determination (R^2) of the equations was determined to show the proportion of the variation in the dependent variable that is predictable form the independent variable, and descriptive analysis was done with the new Microsoft Excel (Windows v. 10.0) to indicate the degree of association between two variables (i.e. dependent and independent variable).

RESULTS AND DISCUSSION

Evapotranspiration: The seasonal ET records of broccoli as well as the water contribution from irrigation and rainfall is depicted in Figure 1. The within SET values which were obtained by SET_{watbal} and SET_{FAO} (Fig. 2), shows a very good relationship for the seasonal comparison and the similar results were reported by Lopez-Urrea et al. (2009). The measured mean ET_C for the crop growing season were between 1.4 and 2.0 mm per day under $I_{0.25}$ and $I_{1.00}$, irrigation regimes respectively. The seasonal mean calculated values was 1.6, 1.3, 0.9 and 0.7 mm per day under $I_{1.00}$, $I_{0.75}$, $I_{0.50}$ and $I_{0.25}$ irrigation regimes respectively and the slope of the regression line was very close to unity (Fig. 2). SET_{watbal} shows an overestimate compared to the SET_{FAO} (22, 30, 44 and 46 percent under $I_{1.00}$, $I_{0.75}$, $I_{0.50}$ and $I_{0.25}$ irrigation regimes respectively). The irrigation regime wise individual value of SET_{watbal} showed significant increment seasonal it's value shows a very good agreement and differ results from those reported by Lopez-Urrea et al (2009). Figure 2 depicts the linear relationship between measured values by SET_{watbal} and obtained values through SET_{FAO} and similar results were shown by Lopez-Urrea et al (2009). The regression equation shows that, about 25 percent variation in SET_{FAO} can be explained by SET_{watbal} value. It may be due to the differing climatic conditions at a specific location (Kalyani) than the referred climate for calculation of SET_{FAO}. Lopez-Urrea et al (2009) also emphasized on conduct regional studies for improvement in the precision estimation of ET in broccoli

crop. SET_C by water balance - SET_C by FAO relationship obtained for broccoli crop is -

$$SET_{FAO} = 1.97 \, SET_{watbal} - 32.749; R^2 = 0.75 \qquad (3)$$

Single crop coefficient curves: Besides, soil water redistribution processes were unaffected when the crop was grown under control condition. For this reason, out of twenty combinations AET under $I_{1.00}$-M_C combination was used to compute the K_C values of broccoli. During 1st and 2nd year, drying cycles were recorded 5 and 4, respectively. Thus, we got a total of nine sets of K_C value, which was computed based on our experiments. K_C values of the broccoli crop at a 7-day interval averaged for three important crop growth stages viz., initial (Rosette development, RSD), mid (Heading, HD) and end (Maturity, HT) were 0.94, 1.46 and 1.63 at RSD, HD and HT respectively. In comparison to the FAO-K_C K_C values were higher by 26, 28 and 48% during initial, mid and end stages, respectively. The K_C curves fit to the K_C values computed by using measured SET_{watbal} and which does not follow the conventional shape of the crop coefficient curve recommended (FAO-K_C) for broccoli (Fig. 3). Subsequently, the obtained K_C value was observed highest at commercial harvest recommended FAO-K_C, with a slightly declining rate, differing in K_C values recommended by Allen et al. (1998b). During the present field experiment, broccoli heads were harvested at terminal head maturity stage, where the leaf area index and foliage growth remain at the highest level. It may be the probable reason for having higher K_C value at later crop growth stage (harvesting stage) and these results are similar to the results of Lopez-Urrea et al (2009). The extrapolation of the results of present investigation may be useful to other areas and the K_C values computed from the water balance method were fitted to the evaluating of GDD values (Fig. 4), which tracks the crop development pattern. The relationship obtained between GDD and water balance K_C for a broccoli crop is;

$$K_C = -7E^{-6} \, GDD^2 - 0.009 GDD + 3.644; R^2 = 1 \qquad (4)$$

By reducing crop canopy temperature, reduction in GDD and early maturity period (1-2 week) are possible, and vice-versa to escape crop from weather abortion events (i.e. unseasonal dramatic change in weather parameters), which helps for getting more yield and also for getting profitable price in market to producers by adjusting harvesting period according to market demand as well as non-congenial probable weather condition. The reduction of GDD values by 30-50% under supply of ample of water in broccoli crop by adjustment of irrigation schedule.

Net head yield response to applied water and water use efficiency of broccoli: Regardless of irrigation regimes and water saving techniques, 15.03 t/ha NHY was obtained in 2016-17, which was 29 % lower in 2017-18. During the

second experimental year, the overall temperature was 0.5 to 2.5°C lower compared to the first year, which caused less number of leaf (Tan et al., 2000). During the second year, unexpected rainfall (37.0 mm) occurred just after
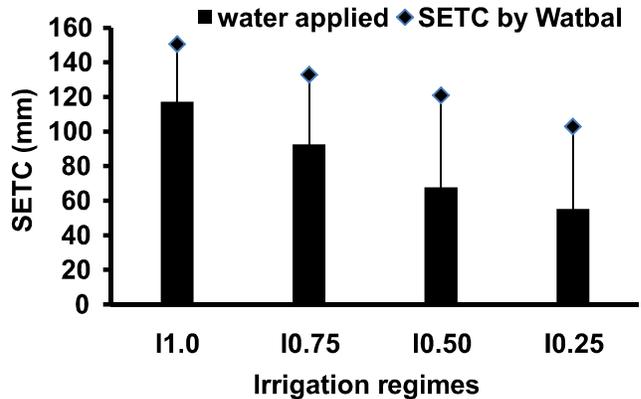

Fig. 1. Seasonal ET values measured by water balance method, water applied (irrigation + rainfall) in mm
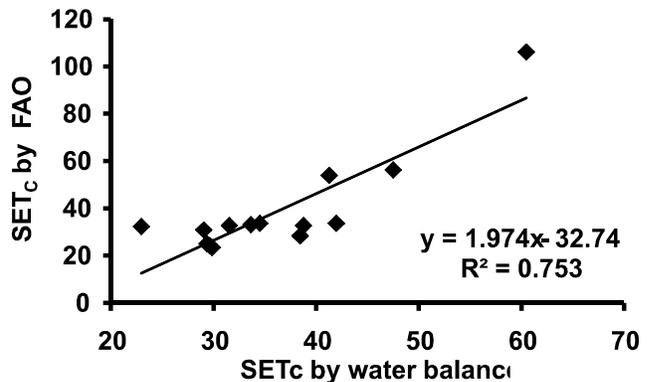

Fig. 2. Simple regression analysis of calculated SETc (mm) by FAO over measured and water depletion method
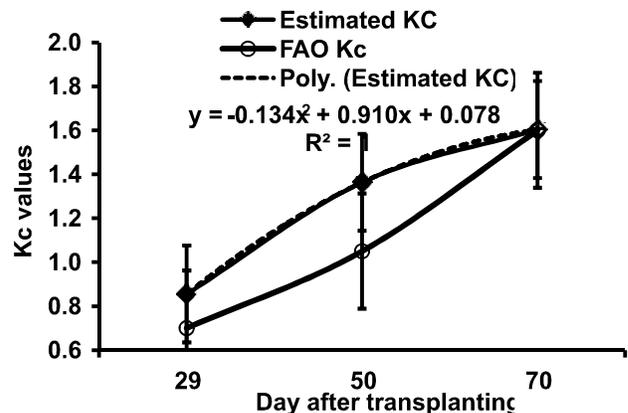

Fig. 3. Crop coefficient curves: (a) recommended in Allen et al (1998a; circles), (b) recommended for fall plantings based on the data measured in the water balance method (squares). Bars indicate the standard error

transplanting, which caused 20 % seedling mortality. Thus, re-transplanting was done in 2017-18. Re-transplanted crops took more days to establish and also the productivity of those plants was not at par with the first transplanted crop. This might be another reason for lower net head yield during the second year of the experimentation. In general, during the second year of experimentation, the length of seasonal duration and prevailed weather parameters (prominently temperature) variation was observed more than those that are common in the first year of experimentation, and might be the major reason to record lower NHY during the second year and the similar reason was quoted by Lopez-Urrea et al (2009) for broccoli.

Irrespective of water saving measures, variation in two years average of NHY was found statistically significant among the irrigation regimes (Table 1). The maximum NHY (15.17 t/ha) observed under $I_{1.0}$, which was at par with $I_{0.75}$ (14.30 t/ha). The NHY of broccoli decreased significantly by 19 and 35 % with a decrease in status of soil water stress respectively under $I_{0.50}$ and $I_{0.25}$ treatments. The NHY was recorded at par within the $I_{1.0}$ and $I_{0.75}$ treatments, might be because of the crop may not experience water stress under $I_{1.0}$ and $I_{0.75}$ treatments significantly. In conformity to this results, Jaybhaye and Mukherjee (2020) reported that water stress was not found under $I_{1.0}$ and $I_{0.75}$ treatments during the

y = 7E-06x² - 0.009x + 3.644
R² = 1

Fig. 4. Relationship between the water depletion crop coefficients-GDD for broccoli under $I_{1.00}$ irrigation regime

study of leaf water potential in broccoli crop.

AET was estimated and water use efficiency (WUE) values were also computed (WUE_{watbal}) by water balance approach. The efficiency of applied water (WUE_{watbal}) reached at maximum level of 12.61 kg/m³ for applied water of 92.7 mm under $I_{0.75}$. Crop water use in the $I_{1.0}$ irrigation regime was more (117.7 mm) and WUE of that was less (11.08 kg/m³). The higher ET_C and the lower WUE in the $I_{1.0}$, may be due to an increase in the 'E' component (evaporation of crop) under frequently irrigation, relative with the 'E' losses under no frequent irrigation of the yield response in the present experiment. The relatively high water use rates are associated with the high frequency of irrigation required for the crop establishment and at the time of high E demand period. The non-frequent irrigation/ deficit irrigation or use of mulching should drastically reduce the need of water for wetting the whole soil surface by irrigation, and thus, reduce the irrigation needs as well as ET of broccoli crop during the early crop growth stages.

Irrespective of water saving techniques (WST), maximum (12.61 kg/m³) WUE_{watbal} was recorded under $I_{0.75}$ irrigation regime and it was declined by 12 and 7 % respectively under $I_{1.0}$ and both $I_{0.50}$ and $I_{0.25}$ (Table 1). In general, the application of irrigation enhanced crop yield. However, after some threshold limits, the increase in yield is not proportional to increases amount of irrigation or magnitude of AET. Thus, proportional yield may decrease (Kang et al., 2002). At lower IW/CPE ratio might be decreases cell turgidity, low opening of stomata, which are finally affecting on partitioning of photosynthates to sink and it may because of variations in stomatal density are attribute to the total WUE (Salimath et al., 2023). This was a probable reason for recorded maximum WUE under moderate soil water status ($I_{0.75}$) though quick drying of surface soil caused a rapid reduction in the rate of evaporation, transpiration rate remained unaffected for a long time (Mukherjee et al., 2012) and hence, the broccoli crop was may not face soil moisture stress physiologically in its period under $I_{0.75}$ treatment; in general, leaf water potential value increased with increasing water stress (at normal climatic condition) but a negligible difference in leaf water
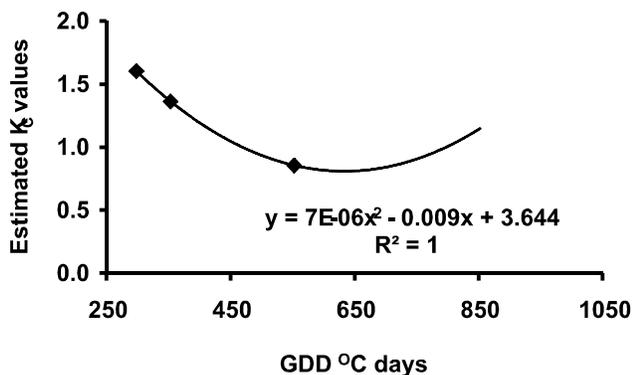
Table 1. Net head yield and water use efficiency (WUE) corresponding to each treatment and net head length and width

Treatments	ET_C fulfilment percentage for each treatment (%)	Water supply (irragation+rainfall) (mm)	WUE_{watbal} (kg/m³)	Net head yield (kg/ha)	Net head length (cm)	Net head width (cm)
$I_{1.00}$	100	117.7	11.08	15173	11.78	14.77
$I_{0.75}$	75	92.7	12.61	14300	11.11	13.71
$I_{0.50}$	50	92.7	11.69	12218	10.10	11.90
$I_{0.25}$	25	55.2	11.69	9822	9.67	12.01
CD (p=0.05)				1329	1.01	NS

potential value of broccoli was recorded (3 %) in between $I_{1.0}$ and $1_{0.75}$ irrigation regimes (Jaybhaye and Mukherjee 2020). Thus, yield of broccoli is not affected more by under minor/moderate soil water stress i.e. irrigation regimes ($I_{0.75}$) resulting in high WUE. This is in agreement with the findings of Lopez-Urrea et al. (2009) for broccoli.

Among the treatments, statistically significant differences were observed in the net head length of broccoli heads (NHL) and no statistically significant differences were noted in the width of broccoli heads (NHW) (Table 1). Irrespective of irrigation regimes and water saving techniques, during the first year of experimentation, the net head length (NHL) was 11.83 cm, which decreased by 20% in 2017-18. It might be due to rainfall immediate after transplanting fevers attack Lepidoptera spp. pest; Cutworm (*Agrotis ipsilon* Hufnagel) and also, due to consequently, more attack of (the pest complex recorded on the broccoli crop viz., Leaf webber (*Crocidolomia binotalis* Zeller), beet army worm (*Spodoptera exigua*), Cabbage looper or Leaf eating caterpillar (*Trichoplusia ni* Hübner) and Cross-striped cabbage worm (*Evergestis rimosalis*) during the whole crop growing season of the second year. Furthermore, it might be due of the variation in environmental condition, which is supportive to the statement. The most frequently recharging to the root zone profile of the broccoli crop with irrigation water ($I_{1.0}$) produced the highest NHL (11.78 cm), which was decreased significantly by 6, 14 and 18 % with decrease in status of soil water respectively under $I_{0.75,}$ $I_{0.50 \text{ and}}$ $I_{0.25}$ treatments. In general, though there was no significant statistical difference between NHW under different irrigation regimes, NHW shows a similar pattern to NHL. The treatments with the least applied water had the lowest NHL and NHW, and this is in agreement with the findings of Lopez-Urrea et al. (2009) for broccoli.

CONCLUSION

The planting time, application of irrigation levels/irrigation time and water saving techniques significantly affected evapotranspiration, growth and yield of headed broccoli. As the application of water increases, the ET_C, WUE and yield increased to some extent and thereafter, it decreases; therefore, we tried to quantify the application of water. Net head yield-supplied water relationship, suggested that for obtaining maximum net head yield may require applications of 118 mm water and maximum WUE may require 93 mm of water, while net head yield was found at par under treatment of applied 118 and 93 mm water. The measured K_C values were higher by 26%, 28% and 48% during initial (rosette development), mid (heading) and end (maturity) stages, respectively compare to the calculated FAO-K_C value of headed broccoli in hot and sub-humid climate. Therefore, it is

recommended that application of 25 % more irrigation to headed broccoli over reference crop evapotranspiration under Indian Hot and Sub-Humid Climatic condition for obtaining economical optimum net head yield.

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