

## Enhancing broccoli yield with efficient water use: A marginal analysis of irrigation and watersaving techniques

### ABSTRACT

During the winter season (November–January) of 2016–2017 and 2017–2018 a field study was carried out at the “C” Block Research Farm of the Bidhan Chandra Krishi Viswavidyalaya (Lat 22° 58' N, Long 88° 31' E and altitude 9.75 m above mean sea level) Kalyani, India. Aim of the study was to evaluate the sole and interactive effect of irrigation regimes and water saving techniques on performance and water productivity functions of broccoli crop. The experiment was composed of four irrigation regimes ( $I_{1.0}$ ,  $I_{0.75}$ ,  $I_{0.50}$  and  $I_{0.25}$ ), where irrigation were given at attainment of 25, 33.3, 50 and 100 mm cumulative actual evapotranspiration (CAET) value, kept in main plots. The subplots consisted of five water saving techniques (WST) {no water saving techniques ( $M_C$ –controlled); hydrogel ( $M_H$ ) @ 50 kg/ha; potassium nitrate ( $KNO_3$ ) ( $M_K$ ) @ 1.5 % ; black polyethylene mulch ( $M_{BP}$ ) @ 30  $\mu$  thickness and paddy straw mulch ( $M_{PS}$ ) @ 5 t/ha}. Net head fresh yield under  $I_{1.0}$  was 15.17 Mg ha<sup>-1</sup>; which reduced by 6, 19 and 35% respectively under  $I_{0.75}$ ;  $I_{0.50}$  and  $I_{0.25}$ . Different water saving techniques increased yield by 5–34% over non-water saving techniques condition. Irrespective of WST, water use efficiency (WUE), net evapotranspiration use efficiency (ETWUE) and irrigation use efficiency (IWUE) were found to be the highest (11 kg m<sup>-3</sup>, 15 kg m<sup>-3</sup> and 17 kg m<sup>-3</sup> respectively) under moderately wet ( $I_{0.75}$ ) soil environment. Among different water saving techniques,  $M_{BP}$  recorded the highest WUE (13 kg m<sup>-3</sup>), ETWUE (19 kg m<sup>-3</sup>) and IWUE (18 kg m<sup>-3</sup>) values. Critical values of seasonal evapotranspiration (SET) against maximum WUE and maximum yield were computed through marginal analysis of water productivity function. It was observed that the difference between these critical values was narrowed down under bio or polyethylene mulches and hydrogel compared to the bare situation.

Key Words: **Broccoli, Irrigation Regimes, Water saving Tecunique, WUE, ETWUE, IWUE.**

### 1. Introduction

**Comment [U1]:** Include general objective at the beginning, Experimental design used, treatments (quantity and its repetitions), parameters evaluated, analyzes used and the most important results.

**Comment [U2]:** Include scientific name

**Comment [U3]:** Use citations not older than 10 years. Include results of other previous studies, in addition the general objective is not observed at the end of the introduction

Food grain production need to be increased by 60 % during 2050 compared to 2005-2007 to feed the increasing population,[1]But now a days decrease in fresh water availability, (a major input towards crop production) makes the problem even more challenging.Due to rapid urbanization and industrialization fresh water share to agricultural sector is decreasing day by day. In India the share of irrigation for fresh water will declined to 77.76% and 69.25% respectively by the year 2025 and 2050 [2]. Thus, more food need to be produced with less available water resources. Such limitation compelled for over extraction of ground water resulting rapid depletion as well as degradation of ground water. Between 1960 and 2000, for instance, annual extraction of groundwater resources was more than doubled, from 126 to 284 km<sup>3</sup> in semi-humid to arid regions [3].

Over use of irrigation water by the farmers not only reduce the crop productivity but also reduce the water use efficiency. Thus judicious application of irrigation water based on crop water demand is of prime importance. In this aspect, irrigation frequency plays an important role in maximizing yield and water use efficiency (WUE). Quantification of water requirement (seasonal ET<sub>c</sub>) during the cropping period is the key factor towards efficient water management. This can be quantified with the help of field water balance study or by multiplying the magnitude of reference evapotranspiration (ET<sub>0</sub>) with crop coefficient (K<sub>c</sub>) factor. Therefore, estimation of K<sub>c</sub> for a particular crop and region are helps in getting more precise value of seasonal evapotranspiration (SET)[4].

In water deficit areas, there has been a shift from the traditional field crops towards horticultural crops, which generally have higher nutritional and economicvalue [5].Application of irrigation below or above optimum level reduces the productivity and WUE of winter vegetables in general and broccoli in particular [6,7,8].

Along with the irrigation methods, application of water saving techniques is todays urgent need, which can help to minimize the scarcity of water problem of agriculture sector. Hence, environmental friendly, biodegradable hydrogels arise lively interest for potential commercial application in agriculture. The hydrogel improves the soil water retention properties. Hydrogel is highly suitable for raising agricultural crops on sandy soils, because of the water range available to

plants was observed nearly four times higher in soils treated with hydrogel than in soils not treated with hydrogel; The time of arrival of critical SWC of hydrogel treated soil was almost 22 days, which matches the irrigation interval of most agricultural crops. In sandy soil with 0.7 % and 5 % hydrogel application in soil increases 2.0 % and 9.48 % crop production over non hydrogel application [9]. Osmoprotectants or antitranspirants are also one of the means to reduce the water loss from the crop. Antitranspirants reduce the stomatal opening and increase the leaf resistance to water vapour diffusion and it play an important role to protect plant from various environmental stresses. Potassium nitrate act as antitranspirant as well as osmoprotectant for any crop. Photosynthetic ability in plants with  $\text{KNO}_3$  application was positively related to plant dry weight [10]. By creating a barrier between the soil surface and atmosphere, mulching minimizes evaporation loss and can influence root zone moisture distribution [11,12] improving yield 23–57 % and water use efficiency in tomato [13,14].

Horticultural crops are considered as the best suitable alternative to the urgently needed balanced diversification along with the food security of Indian agriculture. Broccoli is one of the most important winter vegetables grown dominantly in countries like USA, China, England, Japan and Italy, and India ranks 2<sup>nd</sup> after china in production of combainlycauliflower and broccoli. According to FAO statistics, in 2022, India's production of cauliflower and broccoli was 9,566 kt, while the world's production was 26,058 kt. The area used for cauliflower and broccoli cultivation in India was about 481 kha, compared to the world total of 1,369 kha. [15]. The National Research Council Committee on Diet, Nutrition and Cancer has recommended consumption of broccoli due to its immense nutritional values [16] including anti-carcinogenic properties resulting from glucosinolate synthesization in broccoli florets. Recently broccoli is gaining popularity among the growers of West Bengal due to its palatability high nutritive value and good market potential. But for commercial cultivation it is still on infancy stage and need to be exploited fully at different vegetable growing belts. It grows best within average daily temperature between 18 °C and 23 °C and this situation present during winter season in the region of Jharkhand and many parts of West Bengal. Now a day's farmers are growing broccoli on small scale along with cauliflower. Like cauliflower, broccoli also needs a steady moisture supply

throughout its growing period. The complete production technology has not been standardized so far and therefore, the growers are not following any recommended package of practices. In the context of water crisis, it would be important to characterize the response of this crop to various irrigation levels to assess the optimum level of water application. Thus, there is a need for efficient management of irrigation water to reduce the ground water withdrawal. Both irrigation frequency and water conserving measures play imperative role towards crop water productivity enhancement. The appropriate numbers of irrigations are useful to create optimum growing conditions to the crop and minimizing over use of water. [17] explained that the water saving irrigation strategies could sustain the vegetable crops even under water scarcity in this region. To achieve improved control and management of water in broccoli production, irrigation schedules should be based on crop water requirements.

The feasibility of increasing either the WUE or irrigation water use efficiency (IWUE) depends on the biophysical response of the crop and on economic factors. The objective of producers is very often centered on increasing profits rather than productivity. If water is the limiting factor, increasing WUE and IWUE is desirable. Where water is not limiting, maximizing yield may be the most profitable option. Determination of the level of irrigation, which required to optimize profits, is very complex and depends on both biophysical and economic factor [18]. In general, a linear relationship exists in between crop yield to the SET during the cropping period [19]. In irrigated ecosystem magnitude of SET mainly dependent on total amount of water irrigated to the crop. However, several researchers reported curvilinear relationship in between yield and SET [20]. Application of higher amount of water reduces the value of air: water ratio and due to this beyond a critical level, unit increase in yield is not proportional per unit increase in SET [21]. The yield-SET relationship helps in the development of various indices under crop water productivity functions (CWPF). The CWPF are useful tool to compute marginal water use efficiency (MWUE) and elasticity of water productivity function (EWP) [22]. Various workers have developed CWPF for different crops and demonstrated their application in determining optimal water demand for those crops. Considering these backgrounds

present study has been formulated for broccolicrop with the following objectives: (i) to develop the relationship between ET and fruit yield, WUE, Net evapotranspiration efficiency (ETWUE) and IWUE; (ii) to develop the MWUE and EWP functions; (iii) to estimate the critical level of ET for obtaining maximum WUE and maximum yield and finally (iv) to screen out most suitable and efficient water saving techniques on the basis of the above production function.

## 2. Materials and methods

### 2.1. Experimentation

The field experiment was carried out during the winter season (Oct. to Jan.) of 2016-17 and 2017-18, at the "C" Block Research Farm of Bidhan Chandra Krishi Viswavidyalaya (Lat  $22^{\circ} 58' N$ , Long  $88^{\circ} 31' E$  and altitude 9.75 m above mean sea level) Kalyani, India on a sandy loamy soil classified as Aeric Haplaquept. Rainfall and pan evaporation status during the study period is presented in Fig. 1. Important soil physical properties of different horizons are presented in Table 1 and 2.

The present experiment was arranged in a split plot design, where four levels of irrigation regimes (IR) were kept in the main plots and five water saving techniques (WST) were allotted to the subplots. Each treatment combination was replicated three times and distributed randomly. Each treatment combination was repeated on the same site during both the experimental years. The main plot treatments were: irrigation was given (i)  $IW/CAET = 1.0 (I_{1.0})$ , (ii)  $IW/CAET = 0.75 (I_{0.75})$ , (iii)  $IW/CAET = 0.50 (I_{0.50})$  and (iv)  $IW/CAET = 0.25 (I_{0.25})$ . Sub-plot treatments were: (i) no water saving techniques ( $M_C$ —controlled), (ii) hydrogel ( $M_H$ ) @ 50 kg/ha, (iii) potassium nitrate ( $KNO_3$ ) ( $M_K$ ) @ 1.5 % (iv) black polyethylene mulch ( $M_{BP}$ ) @ 30  $\mu$  thickness and (v) paddy straw mulch ( $M_{PS}$ ) @ 5 t/ha. During both the experimental years mulching was imposed at the time of transplanting. Pusa hydrogel was applied next day after transplanting at the root zone (10 cm soil depth) of each plant under the experimentations [23]. Depth of irrigation in each occasion was 25 mm. After attainment of 25, 33.3, 50 and 100 mm cumulative actual evapotranspiration (CAET) value irrigations were applied to  $I_{1.0}$ ,  $I_{0.75}$ ,  $I_{0.50}$  and  $I_{0.25}$  treatment, respectively. Irrigation was applied initially to each plant by water can for plant establishment, which accounts in total 4.0 mm to each plot followed by direct irrigation to each

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parameters evaluated?  
used statistical analysis and software?

plot through discharge pipe. For each plot an amount of 219.0 liter of water were applied during irrigation every time. The experimental plot was composed of raised bed (100 cm) and furrow (30 cm) system. In each ridge, two rows of broccoli crop were transplanted. In case of mulches a strip of 15 cm wide area at the middle part of the furrow remain uncovered for easy entry of rainfall and irrigation water respectively. Irrigation was applied in the furrows and water seeped into the root zone of the crop in raised bed. This is common irrigation practice followed by the farmers of the locality. Farmers even deepened the raised bed during irrigation, however, in this study depth of irrigation was fixed in such a manner that the furrows remain filled with water and no spilling of water into the raised bed.

## 2.2. Agronomic practices

Each individual plot was 2.5 m x 3.5 m (8.75 m<sup>2</sup>) in size, which surrounded by 1.5 m wide buffer strip to restrict lateral seepage of water in-between adjoining plots. The land was prepared by two cross-wise passes with a rotary power tiller with 100 mm tillage depth, followed by surface levelling with a wooden leveller. Twenty five days old seedlings of broccoli (Cv. Centauro) were transplanted at 50 cm x 50 cm spacing on 9<sup>th</sup> and 6<sup>th</sup> November of 2016-17 and 2017-18 respectively. During land preparation, farm yard manure @ 15.0 t ha<sup>-1</sup> was properly mixed with the soil. Fertilisers were applied @ 180 kg N ha<sup>-1</sup> through urea, 80 kg P<sub>2</sub>O<sub>5</sub> ha<sup>-1</sup> through SSP and 80.0 kg K<sub>2</sub>O ha<sup>-1</sup> through MOP [24, 25]. Entire dose of phosphate and potassium were applied as basal; while, nitrogen was applied in three splits, 50 % as basal and 25 % at 30 DAT + 25 % at 50 DAT. Boron as a micronutrient @ 15.0 g/lit in the form of borax (20 %) was applied through foliar spray on plant at 30 and 50 DAT. The heads of broccoli were harvested as soon as they reach marketable size before yellow petals begin to appear with tight buds [26, 27]. Plants with fully matured net head were harvested at 63 and 65 DAT during the year 2017 and 2018 respectively. Most of the treatments reach marketable maturity at 72-78 DAT. A total of 4 harvestings at 2-3 day intervals were carried out. From each harvest the well-shaped net heads (head with 2-3 jacket leaf), which were green in colour and appeared marketable (head with a portion of 5-10 cm of the main stem) were harvested and weighed (g

plant<sup>-1</sup>). The cumulated marketable net head fresh weight i.e, net head yield was calculated and represented as t ha<sup>-1</sup>.

### 2.3. Observations and computation

Gravimetric soil water content was measured from 0–150, 150–300, 300–450 and 450–600 mm depths on sowing and harvest dates as well as before and after each irrigation and after notable ( $\geq 20$  mm) rainfall. Seasonal evapotranspiration (SET) during the entire cropping period (sowing to harvest) from the crop field was calculated by using the field water balance equation as [14]:

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

Where, P is precipitation (mm), I is total irrigation water applied (mm), C is capillary contribution (mm), D is vertical drainage (mm) and  $\Delta SWS$  is depletion in soil water storage (mm). Capillary contribution and deep drainage contribute negligible amount to the total seasonal evapotranspiration value of this region [28]. Hence we have not considered both C and D in the present study.

To schedule irrigation, daily ETC (AET) was calculated based on the product of daily ETO times a crop coefficient. The FAO-56 Penman–Monteith (FAO-56 PM) equation was used [29]. to calculate ETO. Climatic data was obtained from the agrometeorological observatory, which was located less than 500 m away from the experimental broccoli field (AICRP on Agrometeorology, Kalyani, B.C.K.V., Nadia). Crop coefficient (Kc) values used for calculation of AET were: 0.7 during the rosette development (RSD) period; 1.05 during heading (HD) and 0.95 during the harvesting (HT) growth stage [30, 7].

Soil water storage depletion ( $\Delta SWS$ ) from different layers was calculated by using following formula [14].

$$\Delta SWS = \sum_{x=1}^n [ (\theta_b - \theta_f) z_x ] dt \quad (2)$$

Where,  $x$  is number of layer, in the presently study it was 4,  $\theta_b$  is the moisture content two days after irrigation;  $\theta_f$  is the moisture content before the next irrigation,  $z_x$  is the thickness of particular soil layer,  $dt$  is the time interval between measurement of  $\theta_b$  and  $\theta_f$ . Soil water storage depletion during the cropping season was calculated by using equation 2 and for calculation of seasonal AET,  $\theta_b$  is the moisture content at transplanting and  $\theta_f$  is the moisture content at harvest taken. Various indices of water use efficiency were computed following [14].

#### 2.4. Statistical analysis

The statistical differences among irrigation frequencies and water saving techniques and their interaction on net head yield was tested by using SAS (ver. 9.3, SAS, Inc., Cary, NC) computer package program. The mean values were evaluated and analysis of variance was performed by the 'F' (variance ratio) test. The means were compared using the critical difference (CD) test at 5% significance level [31]. The statistical measurements of coefficient of determination ( $R^2$ ) of the equations were determined to indicate the degree of association between two variables.

### 3. Results and discussion

#### 3.1. Net head yield

Present study showed that, both the irrigation and water saving techniques caused a significant ( $P \leq 0.05$ ) variation in net head yield of broccoli (Table 3). Maximum head yield ( $15.17 \text{ Mg ha}^{-1}$ ) was obtained under no water stress ( $I_{1.0}$ ) condition. Which declined by 6, 19 and 35% respectively under light ( $I_{0.75}$ ), moderate ( $I_{0.50}$ ) and heavy ( $I_{0.25}$ ) soil water stress condition. Better utilisation of soil nutrients, higher photosynthetic rate as well as enhanced translocation of photosynthates [32, 33] under least-water stressed environment were responsible for achieving the highest yield under  $I_{1.0}$  regimes. Exposure of the crop to lower moisture status during the entire drying cycle under  $I_{0.25}$ , was well reflected in head yield. In case of water saving techniques, better conservation of soil water boosted the curd yield to the maximum ( $15.45 \text{ Mg ha}^{-1}$ ) under  $M_{BP}$  (Table 3). The yield significantly declined by 25, 20, 16 and 21%, respectively under  $M_C$ ,  $M_H$ ,  $M_K$  and  $M_{PS}$  conditions. Higher net head

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Improve considering material and methods

yield under black polyethylene mulched condition might be partly due to low weed population, causing a reduction in competition for nutrient and water [34] and partly for a better water availability due to moisture conservation by mulching [14]. Mulch acts as a barrier in between soil surface and microclimate, thus reduces the vapour pressure gradient at evaporating site and decreases the evaporation loss from soil [35] and efficient utilisation of water and nutrients under black polyethylene mulch might be an important reason for recording highest yield of capsicum [36]. Irrespective of IR and WST, 15.03 t ha<sup>-1</sup> net head yield was obtained in 2016-17, which was 24-35% lower in 2017-18 (Table 3). In addition to that during the second experimental year, the overall temperature (14.4 to 22.3 °C) was 0.5 to 2.5 °C lower compared to first year (17.4 to 23.0 °C), which caused less number of leaf [37]. Thus, the total source was less during second year, which might be one of the probable reasons for having lower net head yield. In addition to these during the second experimental year, unseasonal rainfall (37 mm) just after transplanting (Fig.1) caused 20% seedling mortality. Thus, re-transplanting was done in 2017-18. Re-transplanting crop took more days to establish which resulted in poor growth and development resulted lower productivity.

### 3.2. Seasonal evapotranspiration

Irrespective of WST and experimental years, the maximum SET (150.5 mm) was recorded under I<sub>1.0</sub>, which reduced to 132.9, 120.9 and 102.8 mm under I<sub>0.75</sub>, I<sub>0.50</sub> and I<sub>0.25</sub> treatments respectively (Table 4). Under I<sub>1.0</sub>, total 100 mm irrigation water was applied at an interval of 8-10 days. In total 75 mm water under I<sub>0.75</sub> regime was applied at an interval of 12-15 days and only 50 mm water under I<sub>0.50</sub> regime was applied at an interval of 20-30 days. In contrast, under I<sub>0.25</sub> treatment, only one irrigation amounting 25.0 mm was applied after 50 to 65 DAT during both the year of experimentation. Presence of adequate water to the evaporating site as well as minimum water potential difference at root–soil interface, enhanced the loss of ET at the maximum level under I<sub>1.0</sub> irrigation frequency and irrespective of irrigation treatments, there was no significant difference in SET value among various WST. Under highest stress (I<sub>0.25</sub>) condition, SET status under M<sub>C</sub> condition was slightly lower than the M<sub>Bp</sub> conditions, as well as lower than M<sub>H</sub>, M<sub>Ps</sub> and M<sub>K</sub> conditions. Greater proliferation of

roots under mulched enhanced the transpiration loss of water from mulched plots and might be the reason for such minor variation [38]. Lower availability of soil water resists evaporation process and also more or less transpiration, resulted lower SET values under water stress treatments in broccoli [39, 40, 14].

### 3.3. Net head yield–evapotranspiration relationship

Net head yield (NHY)–evapotranspiration (SET) relationship under all WST was particularly assessed in the present study. Significant quadratic relationship between NHY and SET was obtained. The yield increased continuously up to certain level, followed by a gradual decline with further increase in SET. The NHY–SET relationship was observed curvilinear and similar results were reported by [7]. The regression equations obtained from Figs. 2–6 showed that, about 61, 80, 68, 47 and 41 % variation in NHY could be explained only by SET values respectively under  $M_C$ ,  $M_H$ ,  $M_K$ ,  $M_{BP}$  and  $M_{PS}$  conditions.

### 3.4. Water use efficiency

Maximum ( $10.79 \text{ kg m}^{-3}$ ) WUE was obtained  $I_{0.75}$  (averaged over water saving techniques and experimental years) irrigation frequency and it declined by 6.6, 6.9 and 10.8 % respectively under  $I_{1.0}$ ,  $I_{0.50}$  and  $I_{0.25}$  (Table 4). Under moderate soil water status ( $I_{0.75}$ ), though quick drying of surface soil caused a rapid reduction in the rate of evaporation, but transpiration rate remained unaffected for a long time [41, 14]. This was probable reason for maximum WUE under  $I_{0.75}$ . This is in agreement with findings [7, 40] for broccoli. Due to increased water stress, both the evaporation and transpiration were declined with the concomitant reduction in net fresh head yield under  $I_{0.50}$  and  $I_{0.25}$  treatment. In case of  $I_{1.0}$ , the relative increase in SET was maximum among all the soil water regimes, but the relative fresh net head yield increase (5%) was less than  $I_{0.75}$  (18%) and  $I_{0.50}$  (21%) compared to  $I_{0.25}$ . This was the reason for the lowest ( $9.62 \text{ kg m}^{-3}$ ) level of WUE under  $I_{0.25}$  regime. Irrespective of irrigation regimes and experimental years, the magnitude of WUE was the lowest ( $9.24 \text{ kg m}^{-3}$ ) under  $M_C$  condition and under  $M_{BP}$  condition highest ( $12.43 \text{ kg m}^{-3}$ ) which was 34.6% greater than  $M_C$  condition, while, it was enhanced by 3.5%, 9.0% and 1.7% under  $M_H$ ,  $M_K$  and  $M_{PS}$  conditions, respectively compare to  $M_C$

condition (Table 4). Adaptation of hydrogel for broccoli [42], plastic and straw mulch for brinjal [43] potato [44] and tomato [14] reported more water use efficiency compared to control treatment.

### 3.5. Net evapotranspiration use efficiency

In the present study, the crop under  $I_{0.25}$  treatment faced maximum soil water stress, as lowest irrigation was applied in this treatment. Therefore,  $I_{0.25}$  with or without water saving techniques, has been considered as the base line to compute the net evapotranspiration use efficiency (ETWUE) for other fifteen treatment combinations. Like WUE, the ETWUE also attained its highest level ( $14.87 \text{ kg m}^{-3}$ ) under  $I_{0.75}$  regime (Table 4). Increase in frequency of irrigation under  $I_{1.0}$  regime and decrease in irrigation quantity under  $I_{0.50}$ , caused a reduction in ETWUE by 19% and 11% respectively as compared to  $I_{0.75}$  moisture regime. Relative increase in SET loss under  $I_{1.0}$  (42%) over the benchmark level was greater than the difference (25%) in SET obtained in between  $I_{0.75}$  and benchmark level. This caused a reduction in ETWUE under  $I_{1.0}$  and  $I_{0.50}$  over  $I_{0.75}$  frequency. The difference of yield between  $I_{0.50}$  and  $I_{0.25}$  was relatively more compare to difference between  $I_{0.75}$  and  $I_{0.25}$ . But the SET difference was more under  $I_{0.75}$  and  $I_{0.25}$ . That is the reason for having lower  $ETWUE_{\text{watbal}}$  under  $I_{0.50}$  compare to  $I_{0.75}$ . This caused a reduction in ETWUE under  $I_{1.0}$  over  $I_{0.50}$  IR treatment [14], quoted maximum value of ETWUE in tomato crop under more rate stress ( $CPE_{50}$ ) treatment and the lowest level under no stress ( $CPE_{25}$ ) condition. Water saving techniques reduced the loss of evaporation/ transpiration or both and effective utilisation of conserved water enhanced evapotranspiration rate and yield over control. This was reflected in the use of  $M_{BP}$ , which recorded the highest ETWUE ( $18.7 \text{ kg m}^{-3}$ ), which was 47, 29, 21 and 45% higher over  $M_C$ ,  $M_H$ ,  $M_K$  and  $M_{PS}$  condition under irrespective of irrigation regimes and experimental years (Table 4).

### 3.6. Irrigation use efficiency

Irrespective of experimental years, irrigation water use efficiency (IWUE) decreased with an increase in number of irrigation (Table 4). The decreasing tendency of IWUE with higher irrigation level is expected under dry land condition [45] [14]. In the present study IWUE was maximum ( $17.25 \text{ kg m}^{-3}$ ) under  $I_{0.75}$ , when crop was irrigated at an interval of 10-12 days. The IWUE declined by 51% when

crop was irrigated at 3-4 occasions ( $I_{1.0}$ ). Under  $I_{1.0}$ , higher drainage loss than  $I_{0.75}$  might be the reason for lower IWUE [14]. Irrespective of experimental years and irrigation regimes IWUE value was found to be the lowest ( $10.2 \text{ kg m}^{-3}$ ) under  $M_{PS}$  condition. IWUE increased by 30, 40, 61 and 75% under  $M_C, M_H, M_K$  and  $M_{BP}$  respectively over  $M_{PS}$  condition (Table 4). Black polythene mulch ( $M_{BP}$ ) recorded the maximum IWUE, which was 34% higher over  $M_C$  condition.

### 3.7. Marginal analysis of water productivity function

The ratio of yield to SET defines the WUE level of any crop at a particular SET level. The change of yield per unit change in SET reflects the dynamic feature of WUE and is denoted as MWUE. The ratio of MWUE to WUE is treated for broccolias elasticity of water productivity (EWP). When MWUE is greater than, equal to or smaller than WUE, EWP will be greater than, equal to or smaller than 1.0 respectively. Under water scarcity condition highest WUE is most essential. The relationship between yield and SET will be quadratic and maximum WUE will be observed in such a situation when WUE will be equal to Marginal WUE [14]. Therefore, how the different water saving techniques influence the status of the two critical values of SET in terms of WUE and yield was studied in the present two year research experiments with a wide range of irrigation regimes. WST has notable impact on SET value in any crop field (Table 5). Under  $M_C$  condition, to achieve maximum net head yield ( $20000 \text{ kg ha}^{-1}$ ), SET requirement would be 285 mm, which was 106% (147 mm) higher than the SET (138 mm) at maximum WUE ( $9.2 \text{ kg m}^{-3}$ ) value. However, the fruit yield at 285 mm SET was almost 54% higher than the yield ( $13000 \text{ kg ha}^{-1}$ ) at maximum WUE (Table 5 and Fig. 2).

To achieve maximum net head yield, SET requirement would be 220, 190, 144, 178 mm, which was 13, 36, 15, 24% (122, 97, 128, 113 mm) higher than the SET at maximum WUE ( $10.0, 11, 13, 9.0 \text{ kg m}^{-3}$ ) value under  $M_H, M_K, M_{BP}, M_{PS}$  respectively (Table 5 and Fig. 3 to 6). However, under  $M_H, M_K, M_{BP}, M_{PS}$  the maximum net head yield at 220, 190, 144, 178 mm SET was higher under  $M_H$  (12%),  $M_K$  (21%),  $M_{PS}$  (18%) and slightly higher in  $M_{BP}$  (6%) than the yield at maximum WUE compare to  $M_C$  (54%) (Table 5 and Fig. 2).

Under  $M_K$  condition, the lowest range of SET in between maximum WUE and maximum yield was 97 mm less than that of  $M_C$  condition. In case of  $M_{BP}, M_K, M_{PS}$  an SET (140, 125, 144 mm) was needed to produce the maximum net head yield and this was almost half than the amount of SET (285 mm) required achieving the maximum yield under  $M_C$  condition. Similar results reported by [14].

From the marginal analysis of water productivity function study, it was observed the critical values of seasonal evapotranspiration (SET) against maximum WUE and maximum yield of water productivity function and the difference between these two critical values was 147 mm under no mulch condition. Adoption of water saving techniques, hydrogel,  $KNO_3$ , black polyethylene and paddy straw mulch narrowed down the range respectively to 25, 50, 19 and 34 mm. Minimum difference, i.e. 19, 25 and 34 mm might be considered as the most ideal situation, and black polyethylene mulch, hydrogel and paddy straw mulch, might be adopted to get higher crop yield with better use efficiency level of irrigation water than other water saving techniques in the sandy loam soil condition. When the SET against maximum WUE is closer to the SET against maximum yield, it indicates that production of yield within the two SET limit is possible with having higher values of water use efficiency. Whereas, marginal analysis of water productivity function showed that in general the critical status of SET is against highest yield is always higher than maximum WUE. Under  $M_{BP}$  was needed to produce the maximum net head yield was almost half than the amount of SET (285 mm) required achieving the maximum yield under  $M_C$  condition. And by adoption of WST, hydrogel,  $KNO_3$ , black polyethylene and paddy straw mulch narrowed down range of SET in between maximum WUE and maximum yield was 13, 36, 15 and 24 mm respectively. Minimum difference, i.e. 13 and 15 mm might be considered as the most ideal situation to get higher crop yield. However,  $M_{BP}$  could increase low value irrigation by 12%, 15% and 25% more compared to  $M_K, M_H$  and  $M_{PS}$  respectively. In compare to straw mulch,  $KNO_3$  and hydrogel if we use  $M_{BP}$ , 12%, 17 and 27% more area can be brought under irrigation.

From the comparative analysis among the water saving techniques, it can be stated that the amount of water needed by control treatment for growing one hectare land with broccoli crop could be

used to grow 1.23 ha land with hydrogel amendment, with 17 % more yield. Increase in irrigation area could be 33 %, 50 % and 38 % if we adopt  $\text{KNO}_3$ , black poly mulch and straw mulch respectively with 38 %, 58 % and 46 % additional yield. Both  $\text{KNO}_3$  and Mulching ( $M_{BP}$  and  $M_{PS}$ ) are very good water saving techniques to be used in field in place of  $M_c$ , as both the treatment having low difference in between highest WUE at observed yield and WUE at highest yield level ( $5, 1.5$  and  $1.2 \text{ kg m}^{-3}$ ). Similar results reported by [6] for cauliflower crop and [14] for tomato crop.

#### 4. Conclusion

- Water saving techniques reduced the loss of evaporation/ transpiration or both and effective utilisation of conserved water enhanced evapotranspiration rate and yield over control. Adoption of  $I_{0.75}$ ,  $I_{0.50}$ ,  $I_{0.25}$  regime instead of  $I_{1.0}$  regime, would cover 1.25, 1.50, 1.75 times more land area under irrigation and produced 18 %, 21 %, 13 % ( $3.58, 6.11, 7.37 \text{ Mg ha}^{-1}$ ) additional net head fresh yield respectively with the same amount (100 mm) of water. While, adaptation of rice straw mulch, hydrogel,  $\text{KNO}_3$  and black polyethylene mulches covered 5, 7, 12 and 34 percent more land to produce the same amount of net head fresh yield over unit land area under non water saving technique condition.
- Irrespective of mulching, water use efficiency (WUE), net evapotranspiration use efficiency (ETWUE) and irrigation use efficiency (IWUE) were found to be the highest ( $11 \text{ kg m}^{-3}$ ,  $15 \text{ kg m}^{-3}$  and  $17 \text{ kg m}^{-3}$  respectively) under moderately wet ( $I_{0.75}$ ) soil environment and all the indices were at the lowest level when the crop was irrigated four times under  $I_{1.0}$  regimes. Where as, among different water saving techniques,  $M_{BP}$  recorded the highest WUE ( $13 \text{ kg m}^{-3}$ ), ETWUE ( $19 \text{ kg m}^{-3}$ ) and IWUE ( $18 \text{ kg m}^{-3}$ ) values and in general values of water indices might be ranked in the order of  $M_{BP} > M_K > M_H > M_{PS}$ . In general application of irrigation enhanced crop yield. However, after some threshold limit increase in yield is not proportional to increase in amount of irrigation or magnitude of AET. Thus proportional yield may decrease. Which is may be reason behind observed maximum water indices under  $I_{0.75}$  and  $M_{BP}$ .

- Marginal analysis of water productivity function in the present study showed that in general, on the basis of obtained results of net fresh head yield, WUE, ETWUE, IWUE, marginal analysis black polyethylene might be adopted to get higher crop yield with better use efficiency level of irrigation water than other WST in the sandy loam soil condition of the lower Gangetic plain of eastern India. Followed by  $KNO_3$  or paddy straw mulch WST might be considered as the second most ideal situation, based on locally available water saving techniques material to adopt.

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**Table 1.**

Soil texture, bulk density (BD) and saturated hydraulic conductivity ( $K_s$ ) at different horizon of soil profile.

Soil Layers (mm)	Textural status (%)			Bulk density ( $Mg\ m^{-3}$ )	$K_s$ ( $mm\ hr^{-1}$ )
	Sand	Silt	Clay		
0-80	60.2	19	20.8	1.46	7.23
80-220	52.2	23	24.8	1.59	0.56
220-670	52.2	23	24.8	1.62	0.49
670-1000	60.2	19	20.8	1.61	0.36

**Table 2.**

Moisture retention capacity of the horizons against specific matric suction.

Suction M pa	Soil layer (mm)			
	0-80	80-220	220-670	670-1000
Saturation	0.55	0.36	0.42	0.53
0.01	0.32	0.30	0.30	0.34
0.03	0.24	0.23	0.22	0.24
0.10	0.16	0.16	0.16	0.17
0.50	0.10	0.10	0.11	0.15
1.00	0.07	0.08	0.09	0.11
1.50	0.07	0.06	0.08	0.10

**Table 3**

Impact of different irrigation regimes and water saving techniques on net head fresh yield ( $\text{Mg ha}^{-1}$ ) of broccoli.

Irrigation	Water saving techniques					Mean
	$M_C$	$M_H$	$M_K$	$M_{BP}$	$M_{PS}$	
2016-2017						
$I_{1.0}$	16.50	18.21	16.70	17.58	16.97	17.19
$I_{0.75}$	15.58	16.43	15.95	18.67	16.26	16.58
$I_{0.50}$	11.33	13.67	12.75	20.05	14.43	14.45
$I_{0.25}$	8.84	8.14	11.17	17.66	13.73	11.91
Mean	13.06	14.11	14.14	18.49	15.35	
	IR		WST		IRxWST	
SE (m) $\pm$	0.45		0.57		1.15	
CD (P=0.05)	1.56		1.66		3.31	

Irrigation	Water saving techniques					Mean
	$M_C$	$M_H$	$M_K$	$M_{BP}$	$M_{PS}$	
2017-2018						
$I_{1.0}$	12.3	12.71	15.27	14.25	11.25	13.15
$I_{0.75}$	12.08	11.82	13.44	13.75	9.03	12.02
$I_{0.50}$	8.70	9.25	11.29	12.22	8.50	9.99
$I_{0.25}$	7.27	8.48	6.92	9.4	6.62	7.74
Mean	10.08	10.56	11.74	12.4	8.85	
	IR		WST		IRxWST	
SE (m) $\pm$	0.21		0.57		0.46	
CD (P=0.05)	0.74		1.66		NS	

Irrigation	Water saving techniques					Mean
	$M_C$	$M_H$	$M_K$	$M_{BP}$	$M_{PS}$	
Pooled						
$I_{1.0}$	14.4	15.46	15.99	15.91	14.11	15.17
$I_{0.75}$	13.83	14.12	14.7	16.21	12.64	14.30
$I_{0.50}$	10.01	11.46	12.02	16.14	11.46	12.22
$I_{0.25}$	8.06	8.31	9.04	13.53	10.17	9.82

Mean	11.57	12.34	12.94	15.45	12.1
SE (m) $\pm$	IR 0.43		WST 0.54		IRxWST 1.07
CD (P=0.05)	1.33		1.51		NS

Where as,

M<sub>C</sub>: no water saving techniques (Control); M<sub>H</sub> : hydrogel application;  
M<sub>K</sub>: KNO<sub>3</sub> application; M<sub>BP</sub>: black polyethylene mulch;  
M<sub>PS</sub>: paddy straw mulch.

**Table 4**

Impact of irrigation regimes and water saving techniques on seasonal evapotranspiration (SET), water use efficiency (WUE), net evapotranspiration efficiency (ETWUE) and irrigation use efficiency (IWUE) of broccoli.

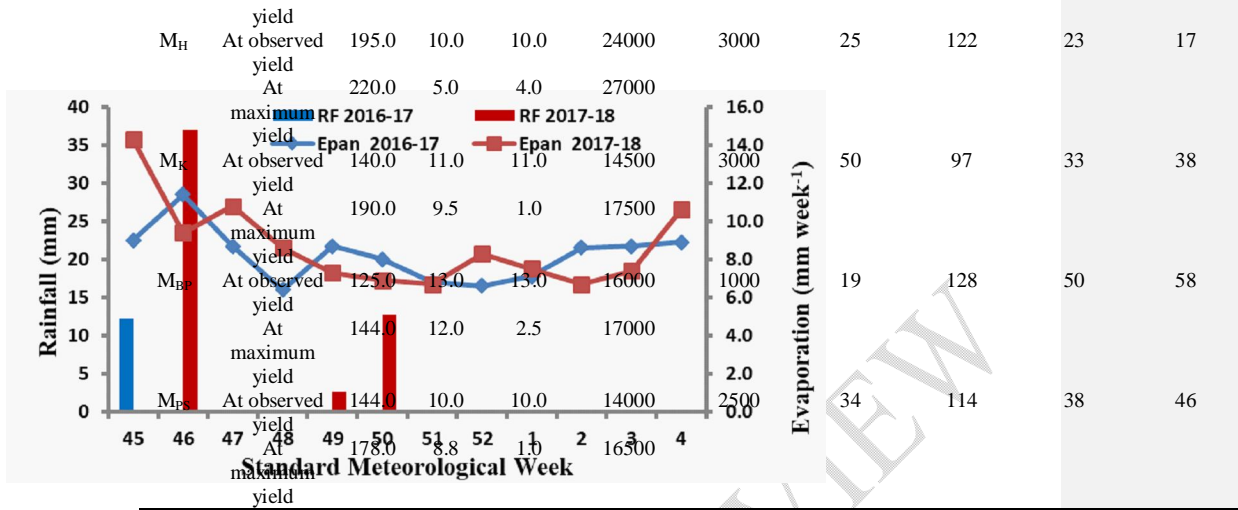
Treatment	SET(mm)	WUE (kg m <sup>-3</sup> )	ETWUE (kg m <sup>-3</sup> )	IWUE (kg m <sup>-3</sup> )
I <sub>1.0</sub> - M <sub>C</sub>	151.6	9.54	10.47	10.14
I <sub>1.0</sub> - M <sub>H</sub>	142.6	10.81	14.06	11.69
I <sub>1.0</sub> - M <sub>K</sub>	157.7	10.15	12.29	13.24
I <sub>1.0</sub> - M <sub>BP</sub>	150.1	10.58	13.54	12.81
I <sub>1.0</sub> - M <sub>PS</sub>	150.5	9.30	9.84	9.40
I <sub>0.75</sub> - M <sub>C</sub>	136.6	10.16	12.62	16.36
I <sub>0.75</sub> - M <sub>H</sub>	132.4	10.64	14.38	16.69

$I_{0.75} - M_K$	135.0	10.89	15.02	19.45
$I_{0.75} - M_{BP}$	130.3	12.52	20.82	22.79
$I_{0.75} - M_{PS}$	130.0	9.76	11.51	10.94
$I_{0.50} - M_C$	120.1	8.33	6.58	
$I_{0.50} - M_H$	119.9	9.50	11.18	
$I_{0.50} - M_K$	115.6	10.50	16.80	
$I_{0.50} - M_{BP}$	126.5	12.66	21.78	
$I_{0.50} - M_{PS}$	122.3	9.26	9.59	
$I_{0.25} - M_C$	90.8	8.91		
$I_{0.25} - M_H$	114.2	7.28		
$I_{0.25} - M_K$	103.9	8.71		
$I_{0.25} - M_{BP}$	97.0	13.96		
$I_{0.25} - M_{PS}$	108.2	9.24		

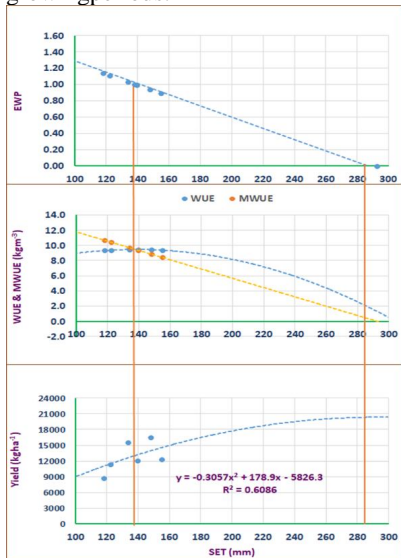
**Table 5**

Impact of water saving techniques on seasonal evapotranspiration (SET), water use efficiency (WUE), marginal water use efficiency (MWUE), elasticity of water productivity (EWP) and yield of broccoli.

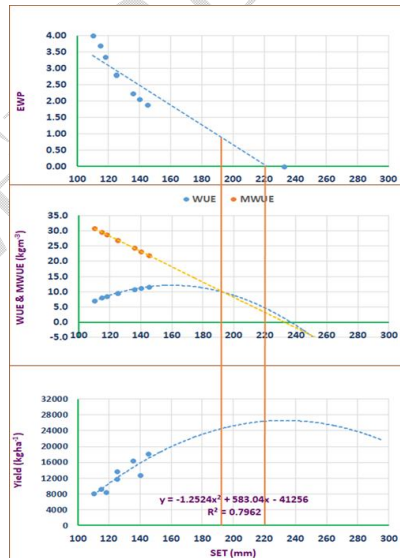
WST		SET (mm)	WUE	MWUE	Yield (kg ha <sup>-1</sup> )	Yield difference between max. WUE and max. yield level (kg ha <sup>-1</sup> )	SET (mm)		Additional area cover (%) compare to M <sub>C</sub>	Additional yield compare to M <sub>C</sub> (%)
							EWP	EWP difference with M <sub>C</sub>		
M <sub>C</sub>	At observed yield	138.0	9.2	9.2	13000	7000		147		
	At maximum	285.0	2.0	0.8	20000					



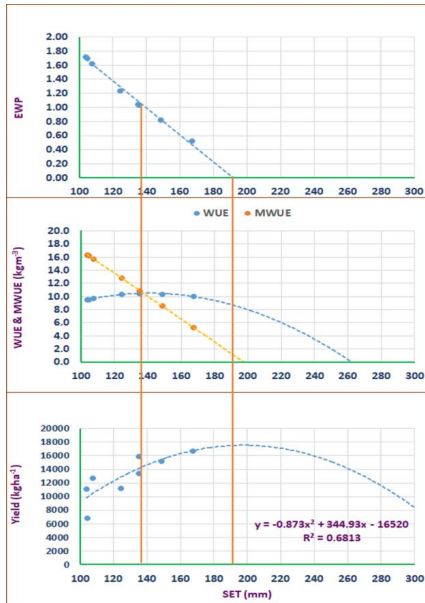
**Fig. 1.** Variation of weekly total rainfall (RF) and pan evaporation (Epan) during crop growing periods.



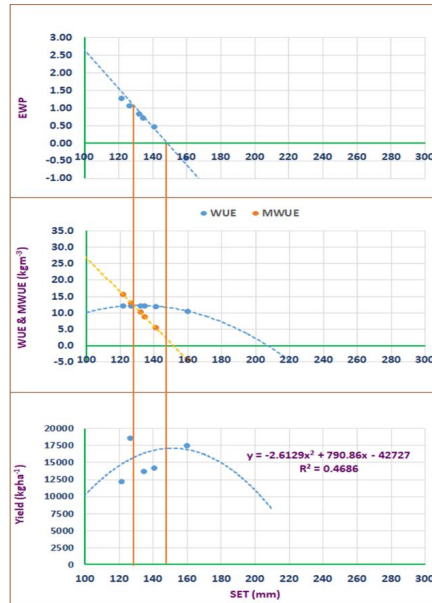
**Fig. 2.** Relation of yield, WUE and MWUE against ET for a quadratic ET production function for net head yield of broccoli grown under control (no soil moisture saving techniques) (averaged over irrigation regimes).



**Fig.3.**Relation of yield, WUE and MWUE against ET for a quadratic ET production function for net head yield of broccoli grown under hydrogel condition (averaged over irrigation regimes).

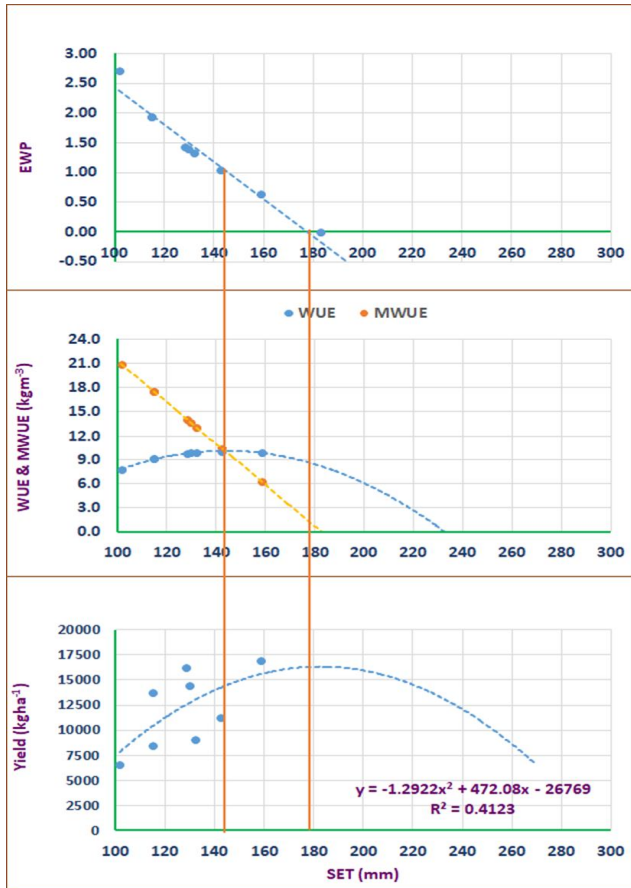


**Fig.4.** Relation of yield, WUE and MWUE against ET for a quadratic ET production function for net head yield of broccoli grown under potassium nitrate foliar application condition (averaged over irrigation regimes).



**Fig. 5.** Relation of yield, WUE and MWUE against ET for a quadratic ET production function for net head yield of broccoli grown under black polyethylene mulch condition (averaged over irrigation regimes).

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**Fig. 6.** Relation of yield, WUE and MWUE against ET for a quadratic ET production function for net head yield of broccoli grown under paddy straw mulchcondition (averaged over irrigation regimes).