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

ABSTRACT

During the winter season (November–January) of 2016–2017and 2017–2018 a field study was carried outat the at the “C” Block Research Farm of the Bidhan Chandra Krishi Viswavidyalaya (Lat 22^0 $58^'$ N, Long 88^0 $31^'$ 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 irrigationregimesand water saving techniques on performance and water productivity functions of broccoli crop. The experiment wascomposed of four irrigation regimes ($I_{1.0}$,$I_{0.75}$, $I_{0.50}$ and $I_{0.25}$),where irrigation weregiven at attainment of 25, 33.3, 50 and 100 mm cumulative actual evapotranspiration (CAET) value, kept in main plots.The subplots consisted offive 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 μ thickness and paddy straw mulch (M_{PS}) @ 5 t/ha}. Net head fresh yield under $I_{1.0}$ was 15.17 Mg ha^{-1}; which reduced by 6, 19 and35% respectively under $I_{0.75}$;$I_{0.50}$and$I_{0.25}$. Different water saving techniques increased yield by 5-34% overnon-water saving techniques condition. Irrespective of WST, water use efficiency (WUE), net evapotranspiration useefficiency (ETWUE) and irrigation use efficiency (IWUE) were found to be the highest (11 kg m^{-3}, 15 kg $m^{-3}$and 17 kg m^{-3} respectively) under moderately wet ($I_{0.75}$) soil environment. Among different water saving techniques,M_{BP} recorded the highest WUE (13 kg m^{-3}), ETWUE (19 kg m^{-3}) and IWUE (18 kg m^{-3}) values. Criticalvalues of seasonal evapotranspiration (SET) against maximum WUE and maximum yield were computedthrough marginal analysis of water productivity function. It was observed that the difference betweenthese critical values was narrowed down under bio or polyethylene mulches and hydrogel compared to the baresituation.

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

UNDER PEER REVIEW

1. 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^3 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_c) 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_0) with crop coefficient (K_C) factor. Therefore, estimation of K_C 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

UNDER PEER REVIEW

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 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 2nd after china in production of combainlycauliflower and broccoli.Accoding 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 andthis 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

UNDER PEER REVIEW

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 feasibilityof increasing either the WUE or irrigation water use efficiency(IWUE) depends on the biophysical response of the crop and on economicfactors. The objective of producers is very often centered onincreasing profits rather than productivity. If water is the limitingfactor, increasing WUE and IWUE is desirable. Where water is not limiting,maximizing yield may be the most profitableoption. Determinatio of the level of irrigation, which required to optimiseprofits, is very complex and depends on both biophysical and economicfactor [18].In general, a linear relationship exists in between crop yield tothe SET during the cropping period [19].Inirrigated ecosystem magnitude of SET mainly dependent on totalamount of water irrigated to the crop. However, several researchersreported curvilinear relationship in between yield and SET [20]. Application of higher amount of waterreduces the value of air: water ratioand due to this beyond a criticallevel, unit increase in yield is not proportional per unit increasein SET [21]. The yield–SET relationship helps inthe development of various indices under crop water productivityfunctions (CWPF). The CWPF are useful tool to compute marginalwater use efficiency (MWUE) and elasticity of water productivityfunction (EWP) [22]. Various workers have developedCWPF for different crops and demonstrated their application indetermining optimal water demand for those crops. Consideringthese backgrounds

UNDER PEER REVIEW

present study has been formulated for broccolicrop with the following objectives: (i) to develop the relationshipbetween 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 WUEand maximum yield and finally (iv) to screen out most suitableand efficient water saving techniques on the basis of the above productionfunction.

2. Materials and methods

2.1. Experimentation

The field experiment was carried out during the winterseason (Oct. to Jan.) of 2016-17 and 2017-18, at the "C" Block Research Farm of Bidhan Chandra Krishi Viswavidyalaya (Lat 22^0 $58^'$ N, Long 88^0 $31^'$ 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 thestudy period is presented in Fig. 1. Importantsoil physical properties of different horizons are presented inTable 1 and 2.

UNDER PEER REVIEW

The present experiment was arranged in a split plot design, wherefour levels of irrigation regimes (IR) were kept in the main plotsand fivewater saving techniques (WST) were allotted to the subplots. Eachtreatment combination was replicated three times and distributedrandomly. Each treatment combination was repeated on the samesite during both the experimental years. The main plot treatmentswere: irrigationwas 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 μ 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 plantunder the experimentations [23].Depth of irrigation in each occasion was 25 mm. After attainment of25, 33.3, 50 and 100 mm cumulative actual evapotranspiration (CAET) value irrigations were applied to $I_{1.00}$, $I_{0.75}$, $I_{0.50}$ 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 directirrigation to each 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) andfurrow (30 cm) system. In each ridge, two rows of broccoli crop weretransplanted.In case of mulches a strip of 15 cm wide area at the middle part of the furrow remain uncoveredfor easy entry of rainfall and irrigation water respectively.Irrigation was applied in the furrows and water seeped into the rootzone of the crop in raised bed. This is common irrigation practicefollowed by the farmers of the locality. Farmers even deeped theraised bed during irrigation, however, in this study depth of irrigation wasfixed in such a manner that the furrows remain filled with water and no spilling of water into the raise bed.

2.2. Agronomic practices

Each individual plot was 2.5 m x 3.5 m (8.75 m^2) 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 9th and 6th November of 2016-17 and 2017-18 respectively.During land preparation, farm yard manure @ 15.0 t ha^{-1} was properlymixed with the soil. Fertilisers were applied @ 180 kg Nha^{-1} through urea, 80 kg$P_2O_5ha^{-1}$ through SSP and 80.0 kg K_2Oha^{-1} 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 at63 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

UNDER PEER REVIEW

plant^{-1}). The cumulated marketable net head fresh weight i.e, net head yield was calculated and represented as t ha^{-1}.

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 harvestdates as well as before and after each irrigation and after notable(≥20 mm) rainfall.Seasonal evapotranspiration (SET) during the entire croppingperiod (sowing to harvest) from the crop field was calculated byusing 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 ΔSWS 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 ET_O. Climatic data was obtained from the agrometeorological observtory, whichwas 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 (ΔSWS) from different layers was calculated by using following formula [14].

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

UNDER PEER REVIEW

Where, x is number of layer, in the presently study it was 4, θ_b is the moisture content two days after irrigation; θ_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 θ_b and θ_f.Soil water storage depletion during the cropping season was calculated by using equation 2and for calculation of seasonal AET, θ_b is the moisture content at transplanting and θ_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 statisticalmeasurements of coefficient of determination (R^2) of theequations 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 Mg ha^{-1}) was obtained under nowater stress ($I_{1.0}$) condition.Which declined by 6,19 and 35% respectively under light ($I_{0.75}$), moderate ($I_{0.50}$)and heavey($I_{0.25}$) 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 tecniques, better conservation of soil water boosted the curd yield to the maximum (15.45 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

UNDER PEER REVIEW

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 ofIR and WST, 15.03 t ha^{-1} 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) caused20% seedling mortality. Thus, re-transplanting was done in 2017-18. Re-transplanting crop took more days to establishwhich resulted inpoor growth and development resulted lower productivity.

3.2. Seasonal evapotranspiration

Irrespective of WST and experimental years, the maximum SET (150.5 mm) was recordes under $I_{1.0,}$which reduced to 132.9,120.9 and 102.8 mm under,$I_{0.75}$,$I_{0.50}$ and $I_{0.25}$ treatmentsrespectively (Table 4).Under $I_{1.0}$, total 100 mm irrigation water was applied at an interval of 8-10 days. In total 75 mm water under $I_{0.75}$ regime was applied at an interval of 12-15 days and only 50 mm water under $I_{0.50}$regime was applied at an interval of 20-30 days. In contrast, under $I_{0.25}$ 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 ETat the maximum level under $I_{1.0}$irrigation frequency and irrespective of irrigation treatments, there was no significant difference in SET value among various WST.Under highest stress ($I_{0.25}$) condition, SET status underM_C condition was slightly lower than the M_{BP}conditions, as well aslower than $M_{H,}$$M_{PS}$and M_K conditions.Greater proliferation of

UNDER PEER REVIEW

roots under mulched enhancedthe transpiration loss of water from mulched plots and might bethe 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 headyield (NHY)–evapotranspiration (SET) relationshipunder all WSTwas particularly assessed in the present study. Significant quadraticrelationship between NHY and SET was obtained. Theyield increased continuously up to certain level, followed by a gradualdecline with further increase in SET. The NHY–SET relationship was observedcurvilinear and similar results were reportedby [7]. Theregression equations obtained from Figs. 2–6showed that, about61, 80, 68,47 and 41 % variation in NHY could be explained only by SET valuesrespectively under $M_{C,}M_{H,}$ $M_{K,}M_{BP}$ and M_{PS}conditions.

3.4. Water use efficiency

Maximum (10.79 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%) compaired to $I_{0.25}$. This was the reason for the lowest (9.62 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 kg m^{-3}) under M_C condition and under M_{BP} condition highest (12.43 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

UNDER PEER REVIEW

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 thistreatment. Therefore, $I_{0.25}$with or without water saving techniques, has been consideredas the base line to compute the net evapotranspirationuse efficiency (ETWUE) for other fifteen treatment combinations. LikeWUE, the ETWUE also attained its highest level (14.87 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 bench mark level was greater than the difference (25%) in SETobtained in between $I_{0.75}$and benchmark level. This caused areduction in ETWUEunder $I_{1.0}$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 moe under $I_{0.75}$and $I_{0.25}$. That is the reason for having lower $ETWUE_{watbal}$ under $I_{0.50}$compare to $I_{0.75}$.This caused a reduction in ETWUEunder $I_{1.0}$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 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).

UNDER PEER REVIEW

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 irrigationlevel is expected under dry land condition [45] [14]. In the present studyIWUE was maximum(17.25 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 at3-4 occasions ($I_{1.0}$). Under $I_{1.0}$, higher drainage loss than $I_{0.75}$might be the reason for lower IWUE [14]. Irrespectiveof experimental years and irrigation regimesIWUEvalue was foundto be the lowest (10.2 kg m^{-3}) under M_{PS} condition. IWUE increasedby 30, 40, 61 and 75% under $M_{C,}M_{H,}$ M_K and M_{BP} respectively overM_{PS}condition (Table 4). Blackpolythene mulch (M_{BP}) recorded the maximum IWUE, which was34% 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 influences 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 awide 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 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 kg m^{-3}) value. However, the fruit yield at 285 mm SET was almost 54 higher than the yield (13000 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, 113mm)higher than the SET at maximum WUE (10.0, 11, 13, 9.0kg 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 higherin M_{BP} (6%) than the yield at maximum WUE compare to M_C(54 %) (Table 5 and Fig. 2).

UNDER PEER REVIEW

Under M_K condition, thelowest 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 wasalmost 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 thecritical 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, andblack 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 functionshowed 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 $M_{K,}M_H$andM_{PS} respectively. In compare to straw mulch,KNO_3 and hydrogel if we use M_{BP}, 12 %, 17and 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

UNDER PEER REVIEW

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 KNO_3,black poly mulch and straw mulch respectivelywith 38 %, 58 % and 46 % additional yield. Both $KNO_3$and Mulching (M_{BP} andM_{PS})are very good water saving techniques to be used in field in place of Mc, as both the treatment having low difference in between higest WUE at observed yield and WUE at highest yield level (5,1.5 and 1.2 kg m^{-3}).Similar results reported by [6] for cauliflower cropand [14]for tomato crop.

PEER REVIEW

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, 7.37Mg ha^{-1}) additional net head fresh yield respectively with the same amount (100 mm) of water.While, adaptation of rice straw mulch, hydrogel, KNO_3 and black polyethylene mulchescovered 5, 7, 12 and 34 percent more land to produce the sameamount 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 kg m^{-3}, 15 kg m^{-3} and 17 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 kg m^{-3}), ETWUE (19 kg m^{-3}) and IWUE (18 kg m^{-3}) values and in general values of water indices might be rankedin 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 functionin the present study showed thatin 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 mulchWST might be considered as the second most ideal situation, based on locally avilable water saving techniques material to adopt .

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UNDER PEER REVIEW

UNDER PEER REVIEW

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 (Mg ha^{-1}) of broccoli.

Irrigation	Water saving techniques					
	M_C	M_H	M_K	M_{BP}	M_{PS}	Mean
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) ±	0.45		0.57		1.15	
CD (P=0.05)	1.56		1.66		3.31	

Irrigation	Water saving techniques					
	M_C	M_H	M_K	M_{BP}	M_{PS}	Mean
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) ±	0.21		0.57		0.46	
CD (P=0.05)	0.74		1.66		NS	

Irrigation	Water saving techniques					
	M_C	M_H	M_K	M_{BP}	M_{PS}	Mean
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

UNDER PEER REVIEW

Mean	11.57	12.34	12.94	15.45	12.1

	IR	WST	IRxWST
SE (m) ±	0.43	0.54	1.07
CD (P=0.05)	1.33	1.51	NS

UNDER PEER REVIEW

Where as,

M_C: no water saving techniques (Control);	M_H : hydrogel application;
M_K: KNO_3 application;	M_{BP}: black polyethylene mulch;
M_{PS}: 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^{-3})	ETWUE (kg m^{-3})	IWUE (kg m^{-3})
$I_{1.0}$ - M_C	151.6	9.54	10.47	10.14
$I_{1.0}$ - M_H	142.6	10.81	14.06	11.69
$I_{1.0}$ - M_K	157.7	10.15	12.29	13.24
$I_{1.0}$ - M_{BP}	150.1	10.58	13.54	12.81
$I_{1.0}$ - M_{PS}	150.5	9.30	9.84	9.40
$I_{0.75}$ - M_C	136.6	10.16	12.62	16.36
$I_{0.75}$ - M_H	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		

UNDER PEER REVIEW

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^{-1})	Yield difference between max. WUE and max. yield level (kg ha-1)	SET (mm)		Additional area cover (%) compare to M_C	Additional yield compare to M_C (%)
							EWP	EWP difference with M_C		
M_C	At observed yield	138.0	9.2	9.2	13000	7000	147			
	At maximum	285.0	2.0	0.8	20000					

	yield									
M_H	At observed yield	195.0	10.0	10.0	24000	3000	25	122	23	17
	At maximum yield	220.0	5.0	4.0	27000					
M_K	At observed yield	140.0	11.0	11.0	14500	3000	50	97	33	38
	At maximum yield	190.0	9.5	1.0	17500					
M_{BP}	At observed yield	125.0	13.0	13.0	16000	1000	19	128	50	58
	At maximum yield	144.0	12.0	2.5	17000					
M_{PS}	At observed yield	144.0	10.0	10.0	14000	2500	34	114	38	46
	At maximum yield	178.0	8.8	1.0	16500					

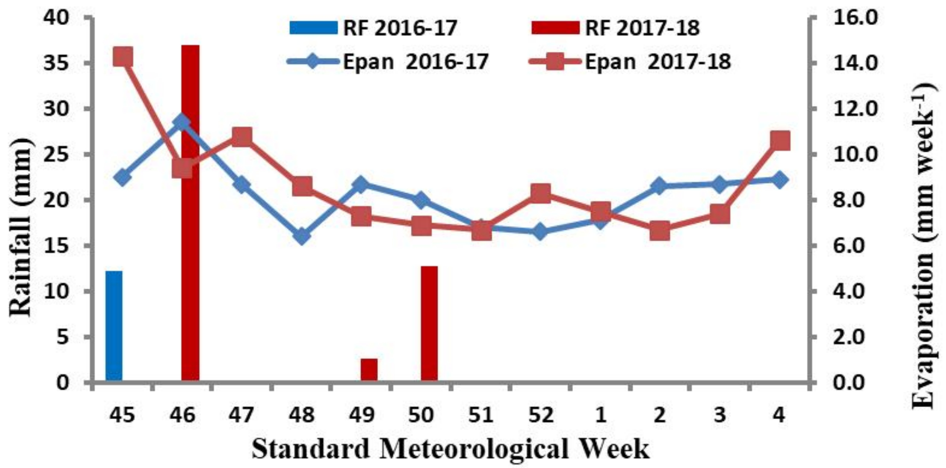

Fig. 1. Variation of weekly total rainfall (RF) and pan evaporation (Epan) during crop growingperiods.

UNDER PEER REVIEW

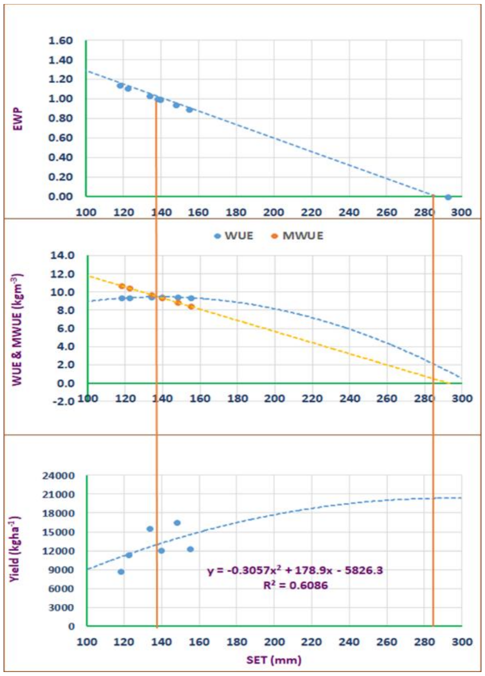

Fig. 2. Relation of yield, WUE and MWUE against ET for a quadratic ET production function for net head yield of broccoli grown under control (no soil moisture saving techniques) (averaged over irrigation regimes).

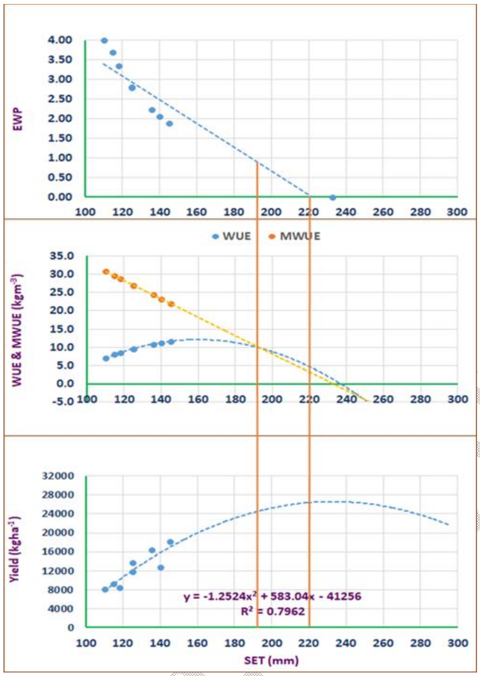

Fig.3. Relation of yield, WUE and MWUE against ET for a quadratic ET production function for net head yield of broccoli grown under hydrogel condition (averaged over irrigation regimes).

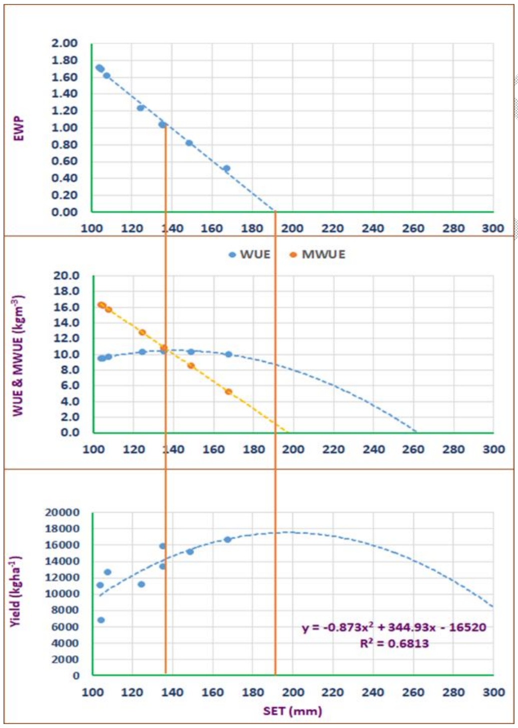

Fig.4. Relation of yield, WUE and MWUE against ET for a quadratic ET production function for net head yield of broccoli grown under potassium nitrate foliar application condition (averaged over irrigation regimes).

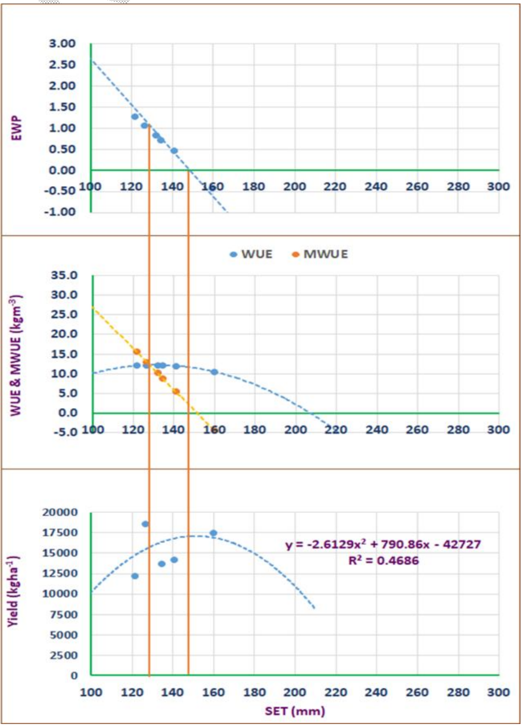

Fig. 5. Relation of yield, WUE and MWUE against ET for a quadratic ET production function for net head yield of broccoli grown under black polyethylene mulch condition (averaged over irrigation regimes).

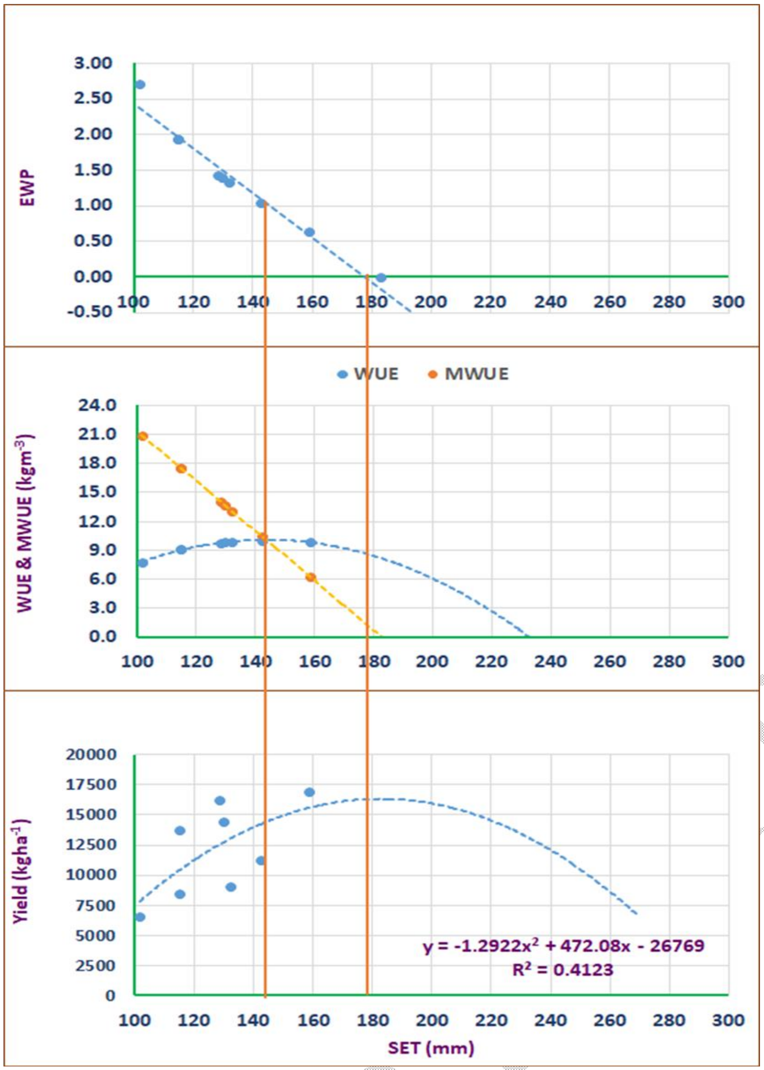

Fig. 6. Relation of yield, WUE and MWUE against ET for a quadratic ET production function for net head yield of broccoli grown under paddy straw mulchcondition (averaged over irrigation regimes).

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