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Enhancing Broccoli (*Brassica oleracea* L. var. *italica* Plenk) Yield with Efficient Water Use: A Marginal Analysis of Irrigation and Water Saving Techniques

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Authors' contributions

This work was carried out in collaboration between both authors. Both authors read and approved the final manuscript.

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ABSTRACT

Climate change impacts are more evident in agriculture sector at micro level in general, and technological interventions (e.g. cropping patterns, crop diversification, soil health management, rainwater harvesting, use of modern irrigation system with precise irrigation quantity etc.) are some of the interventions which can play a significant role in enhancing the current capacity of farmers to cope with climate change. The experiment was conducted at the "C" Block Research Farm at Kalyani of the BCKV, Mohanpur, India during winter season (November–January) of the year 2016–2017and 2017–2018; to study the relationship between ET and fruit yield, water use efficiency

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(WUE), net evapotranspiration efficiency (ETWUE) and irrigation use efficiency (IWUE), to develop the MWUE and EWP functions, to estimate the critical level of ET for obtaining maximum WUE and maximum yield, to screen out most suitable and efficient water saving techniques on the basis of the above production function. The experimental design was a split plot with four irrigation regimes ($I_{1.0}$, $I_{0.75}$, $I_{0.50}$ and $I_{0.25}$) as main treatment and five water saving techniques {no water saving techniques (M_C – controlled); M_H - hydrogel; M_K - potassium nitrate (KNO_3) ; M_{BP} - black polyethylene mulch and M_{PS} - paddy straw mulch as sub treatment. Net head fresh yield under $I_{1.0}$ was 15.17 Mg ha^{-1}; 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 water saving techniques, WUE, ETWUE and 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. The marginal analysis showed difference in critical values of SET against maximum WUE and maximum yield was narrowed down under bio or polyethylene mulches and hydrogel compared to the bare situation.

Keywords: Broccoli; WUE; ETWUE; IWUE and marginal analysis.

1. INTRODUCTION

The projected increase in global population 9.8 billion in 2050, overall food demand is on course to by more than 50 %, and demand for animal based foods by nearly 70 % compared to year the 2010 [1]. The 1.67 billion people of India by 2050 will require more agricultural production and a 15% increasing water demands; while, the water scarcity in India could lead to 50% decline in agricultural productivity by 2050. India has only 4% of the fresh water resources, despites housing a staggering 18 % of the global population. It is creating imbalance in demand and supply of the fresh water for agricultural production system. Because of rapid growing urbanization and industrialization, a fresh water share of agricultural sector is decreasing day by day, and its demand in India will be increase by 40 %, the share of irrigation for fresh water will declined to 69 % by the year 2050 [2, 3].

In general, over or more deficit application of irrigation water by the farmers reduce the crop productivity and it has been observed in broccoli crop [4,5,6]. Hence, the precise application of irrigation water based on crop water demand are useful to maximizing yield and water use efficiency (WUE) and quantification of water requirement (seasonal ET_c) during the cropping period is the key factor towards efficient water management. Therefore, estimation of K_C for a particular crop and region are helps in getting more precise value of seasonal evapotranspiration (SET) [7].

Along with the improved irrigation methods, application of water saving techniques is todays urgent need, which can help to minimize the scarcity of water problem of agriculture sector, and environmental friendly, biodegradable hydrogels improves the soil water retention properties. Hydrogel application in soil 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 [8]. Osmoprotectants or 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 and reduces water loss from the crop. Potassium nitrate (KNO_3) act as antitranspirant as well as osmoprotectant for any crop and it application increases photosynthetic ability in plants which reflected positively in to plant dry weight" [9]. "By creating a barrier between the soil surface and atmosphere, mulching minimizes evaporation loss and can influence root zone moisture distribution improving yield 23–57 % and water use efficiency in tomato [10].

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 combine cauliflower 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 area under cauliflower and broccoli cultivation in India was recorded about 481 kha, worlds of 1,369 kha. [11]. The National Research Council Committee on Diet, Nutrition and Cancer has recommended consumption of broccoli due to its immense nutritional values [12] including anti-carcinogenic properties resulting from glucosinolate synthesization in broccoli florets. Recently broccoli is gaining popularity among the growers of Jharkhand and many parts of West Bengal due to its palatability high nutritive value, good market potential and availability of weather during the winter season. While, appropriate numbers of irrigations are useful to create optimum growing conditions to the crop and minimizing over use of water, and the water saving irrigation strategies could sustain the vegetable crops even under water scarcity in this region [13]. Irrigation schedules should be based on crop water requirements for achievement improved and controlled management of water in broccoli production.

However, the objective of producers is very often centred on increasing profits rather than productivity. If water is the limiting factor, increasing WUE and IWUE is desirable and water is not a limiting, maximizing yield may be the most profitable option. Determination of the level of irrigation, which required to optimise profits, is very complex and depends on both biophysical and economic factor [14]. 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 [15]. 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 [16]. “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) [17]. 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 broccoli crop 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 22^0 58′ N, Long 88^0 31′ E and altitude 9.75 m above mean sea level) at 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 Tables 1 and 2.

The statistical design for conduct the field trial was taken a split plot design, and 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 3 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 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 plant under the experimentations [18]. 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 $I_{1.00}$, $I_{0.75}$, $I_{0.50}$ and $I_{0.25}$ treatments, 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 plot through discharge pipe. For each plot an amount of 219.0

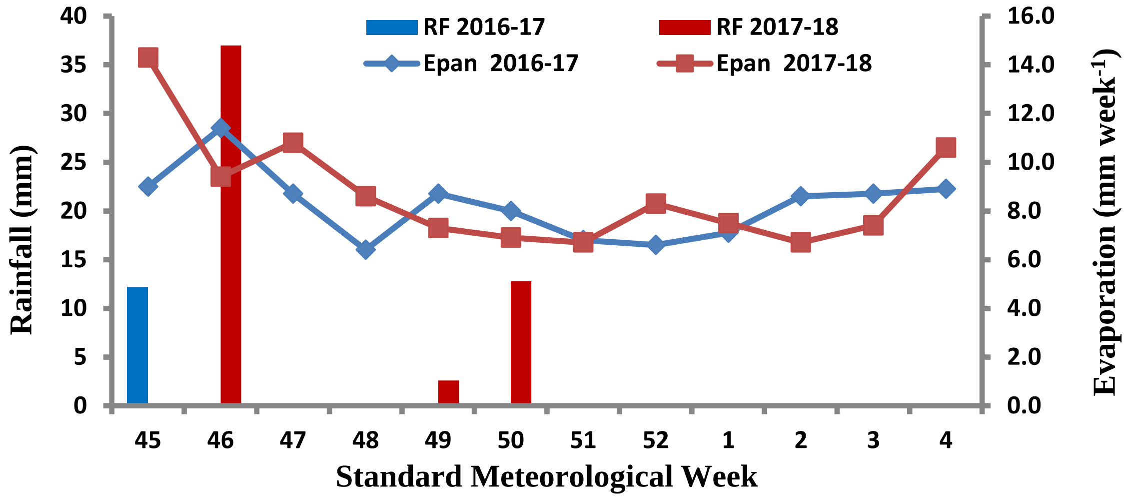

Fig. 1. Variation of weekly total rainfall (RF) and pan evaporation (Epan) during crop growing periods

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

liter of water was 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 more dipping 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 raise bed [10].

2.2 Agronomic Practices

Each individual plot was 2.5 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 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 properly mixed with the soil. Fertilisers were applied @ 180 kg N ha^{-1} through urea, 80 kg P_2O_5 ha^{-1} through SSP and 80.0 kg K_2O ha^{-1} through MOP [18]. 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. The well-shaped fresh heads (head with 2-3 jacket leaf), which were green in colour and appeared marketable size, harvested with a portion of 5-10 cm of the main stem adjoining to head [18]. 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, and from each harvest the fresh heads were weighed (g $plant^{-1}$). 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 harvest dates as well as before and after each irrigation and after notable (≥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 [10]:

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

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 [19]. Hence we have not considered both C and D in the present study.

To schedule irrigation, daily ET_C (AET) was calculated based on the product of daily ET_O–Monteith (FAO-56 PM) equation was used [20]. to calculate ET_O. 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 [21,5]. Soil water storage depletion (ΔSWS) from different layers was calculated by using following formula [10].

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

Where, x is number of layer, in the presently study it was 4, 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 2 and 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 [10].

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. The statistical measurements of coefficient of determination (R^2) of the equations were determined to indicate the degree of association between two variables. The marginal analysis was computed with the help of Microsoft Excel Spreadsheet software tool-Excel for Windows 7 [18, 22].

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})

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		IR x WST	
SE (m) ±	0.45		0.57		1.15	
CD (P=0.05)	1.56		1.66		3.31	
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		IR x WST	
SE (m) ±	0.21		0.57		0.46	
CD (P=0.05)	0.74		1.66		NS	
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	
	IR		WST		IR x WST	
SE (m) ±	0.43		0.54		1.07	
CD (P=0.05)	1.33		1.51		NS	

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.

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 [23, 24] 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 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 yield under black polyethylene mulched condition might be partly due to low weed population, causing a reduction in competition for nutrient and water and partly for a better water availability due to moisture conservation by mulching [10]. 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 and efficient utilisation of water and nutrients under black polyethylene mulch might be an important reason for recording highest yield of capsicum [25,26]. Irrespective of IR 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 [27]. 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

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 $I_{0.25}$ treatments respectively (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 $I_{0.75}$ regimes was applied at an interval of 12-15 days and only 50 mm water under $I_{0.50}$ regimes was applied at an interval of 20-30 days. In contrast, under $I_{0.25}$ treatments, 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 $I_{1.0}$ 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 under M_C condition was slightly lower than the M_{BP} conditions, as well as lower than $M_{H,}$ M_{PS} and M_K 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 [28]. Lower availability of soil water resists evaporation process and also more or less transpiration, resulted lower SET values under water stress treatments in broccoli [29,30,10].

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.

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		

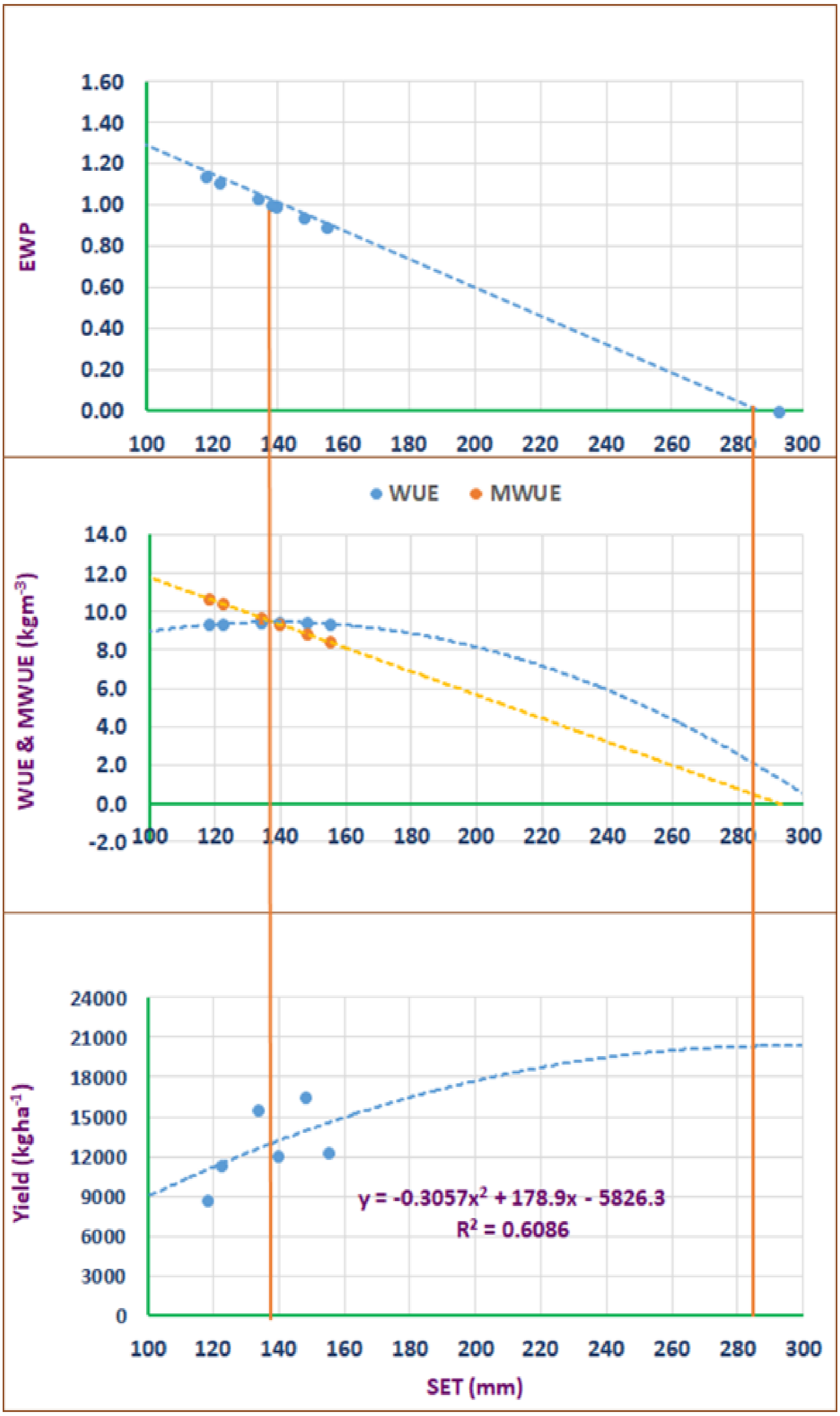

Fig. 2. Relation of yield, WUE and MWUE against ET for a quadratic ET production function for net head yield of broccoli grown under control (no soil moisture saving techniques) (averaged over irrigation regimes)

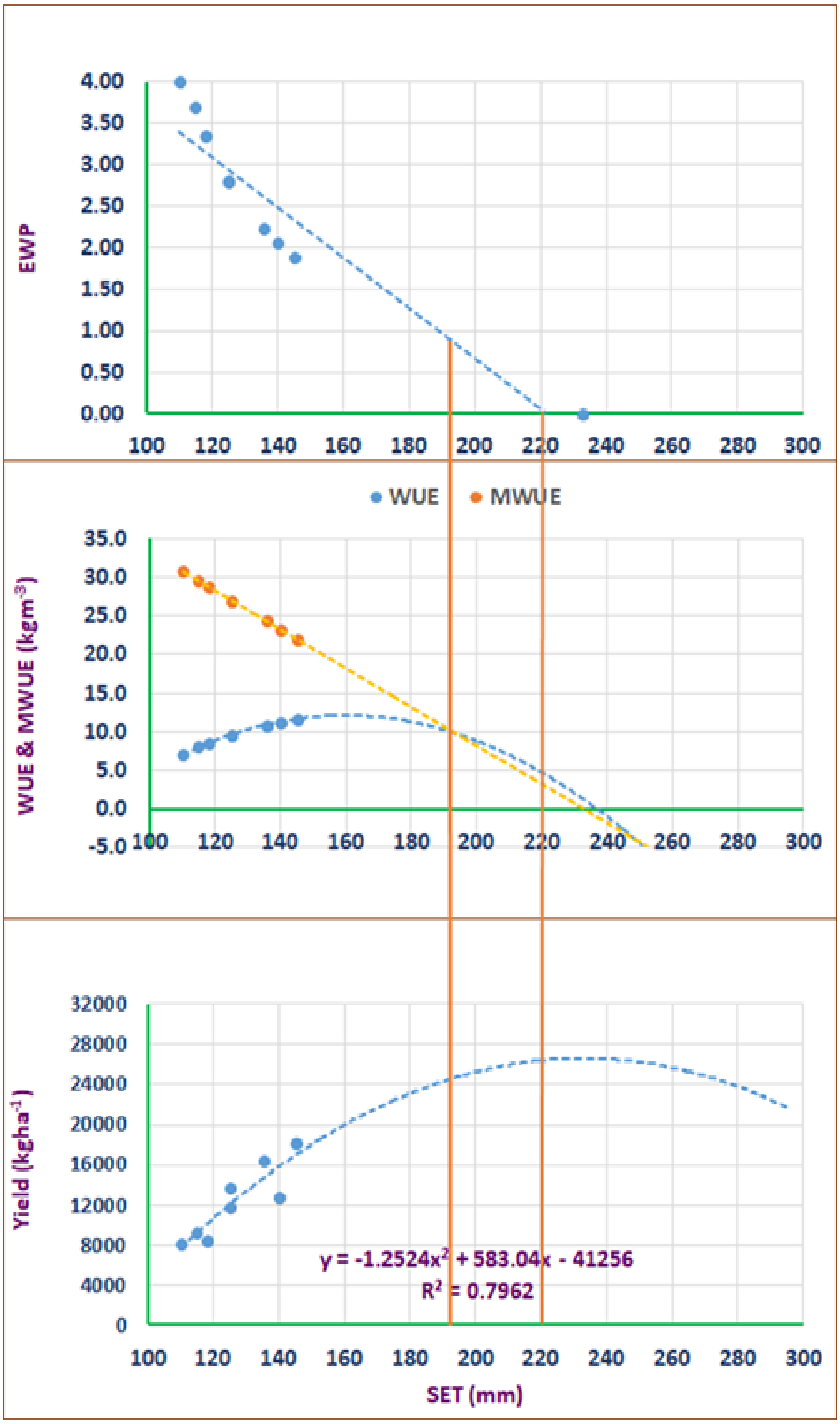

Fig. 3. Relation of yield, WUE and MWUE against ET for a quadratic ET production function for net head yield of broccoli grown under hydrogel condition (averaged over irrigation regimes)

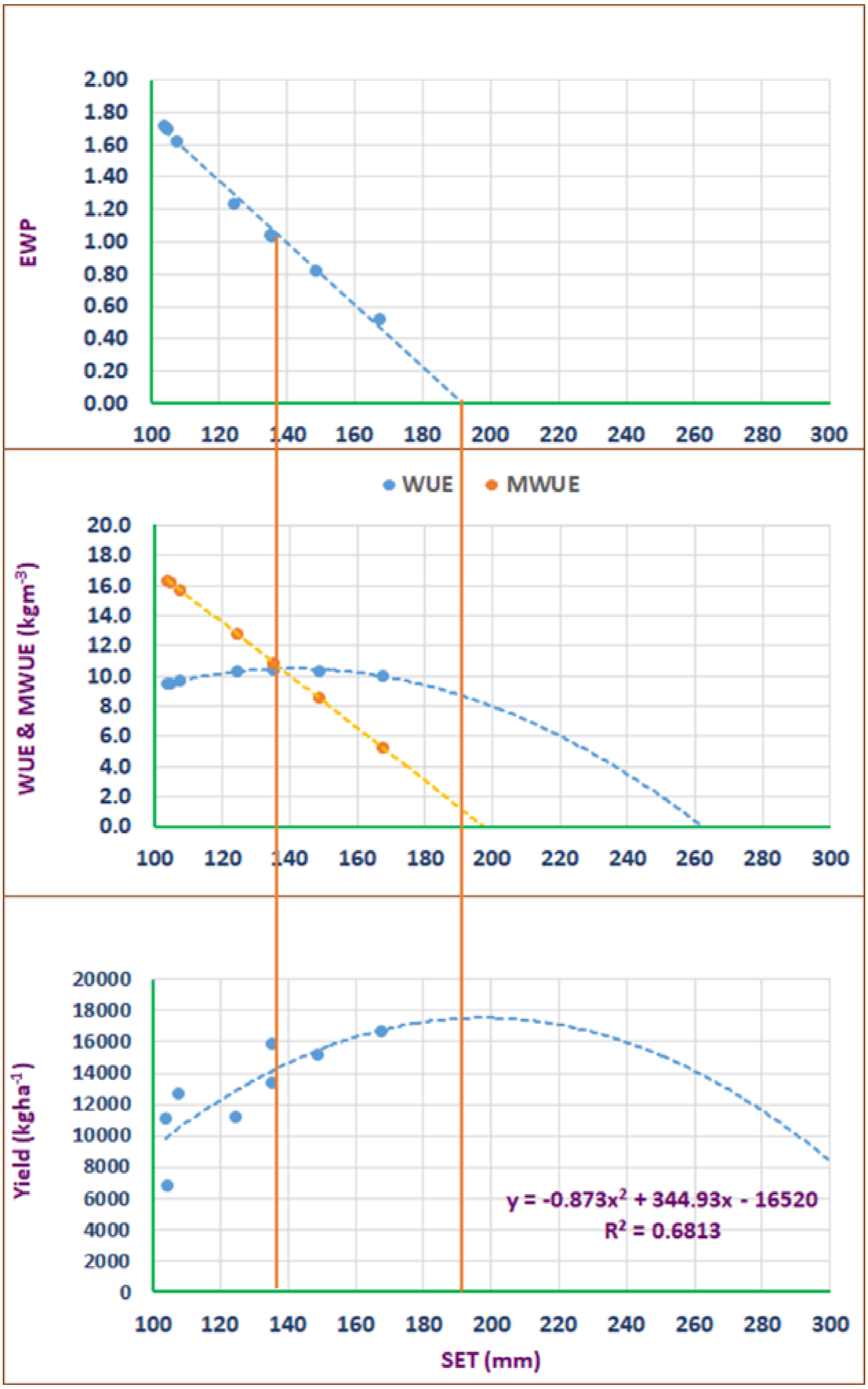

Fig. 4. Relation of yield, WUE and MWUE against ET for a quadratic ET production function for net head yield of broccoli grown under potassium nitrate foliar application condition (averaged over irrigation regimes)

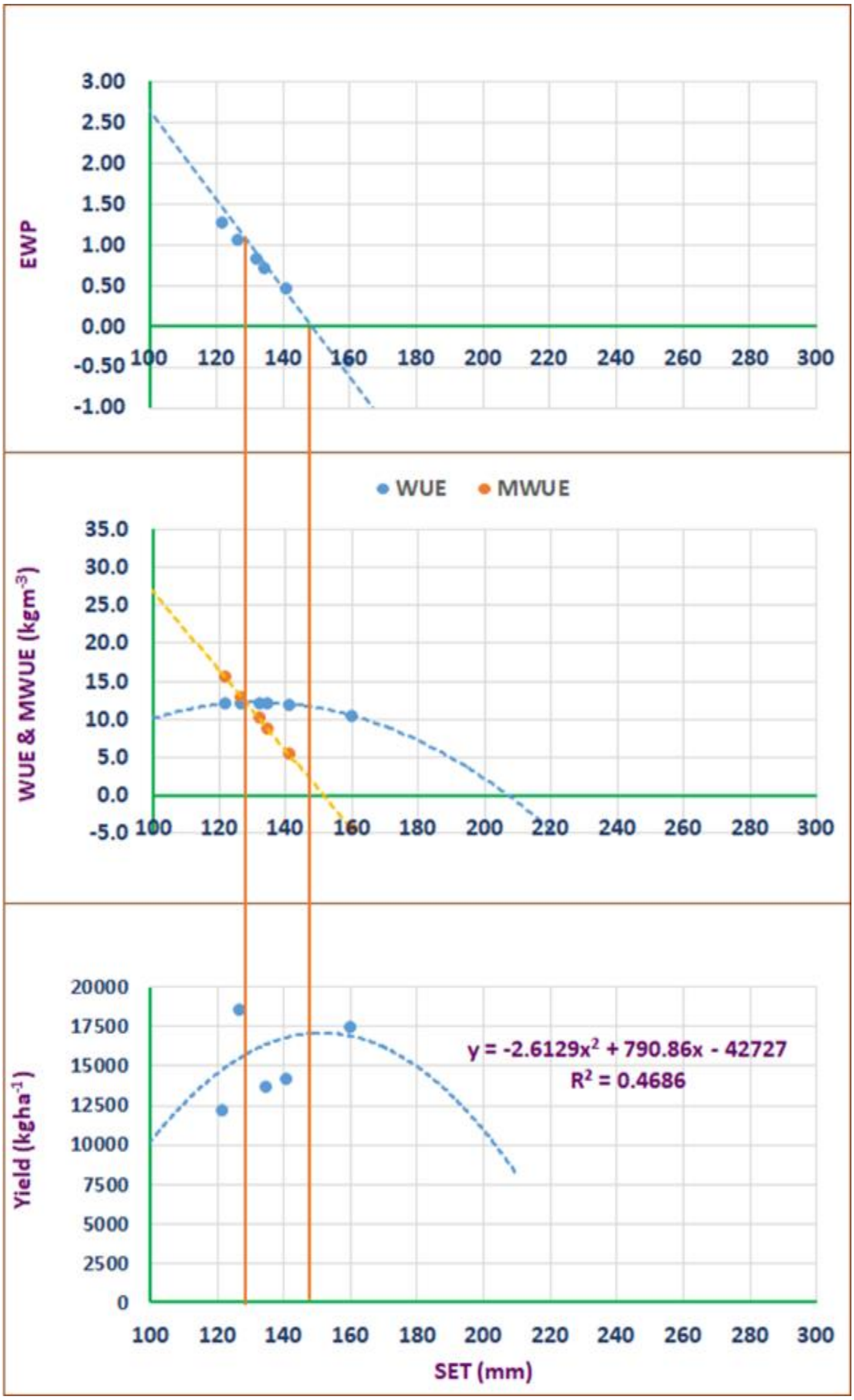

Fig. 5. Relation of yield, WUE and MWUE against ET for a quadratic ET production function for net head yield of broccoli grown under black polyethylene mulch condition (averaged over irrigation regimes)

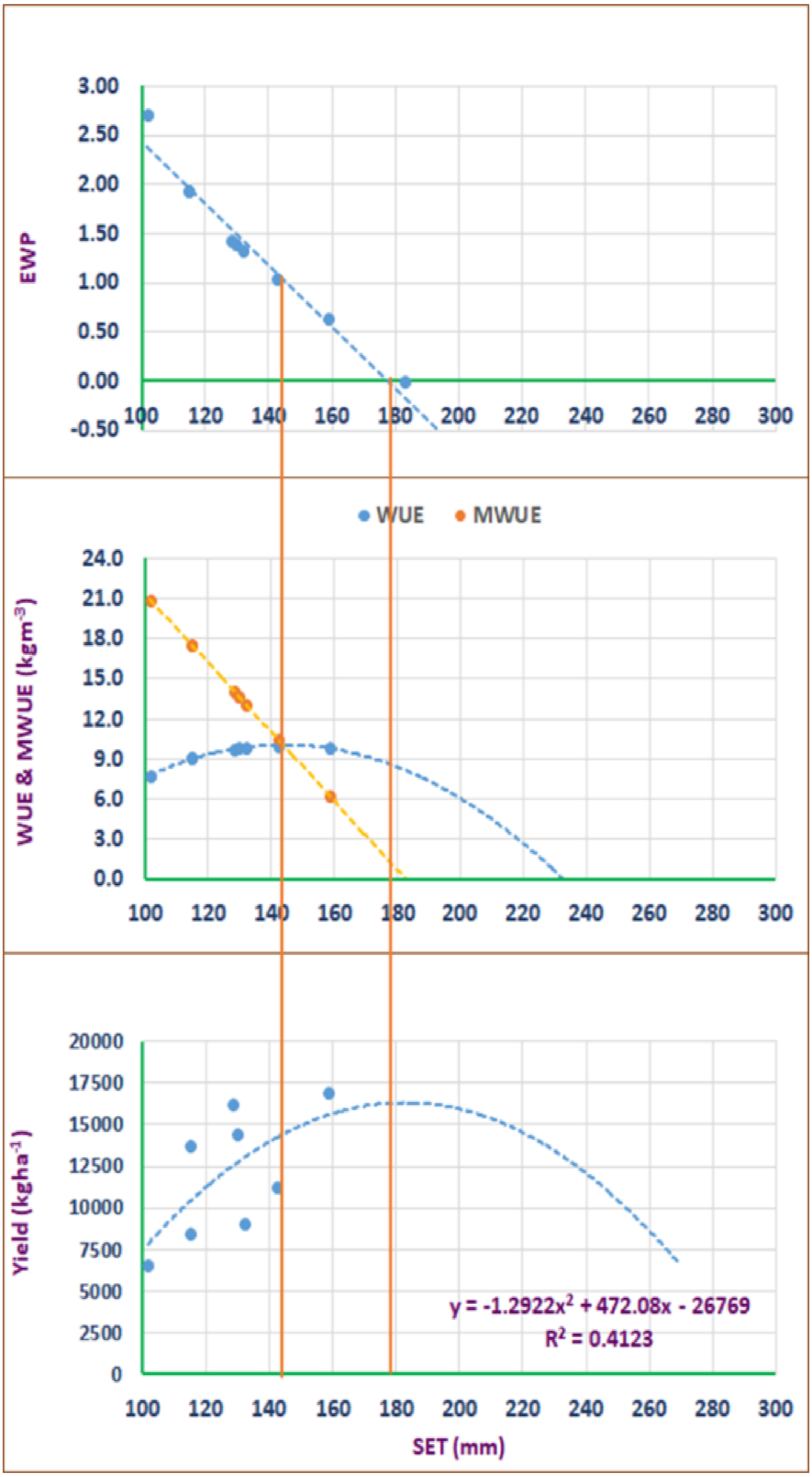

Fig. 6. Relation of yield, WUE and MWUE against ET for a quadratic ET production function for net head yield of broccoli grown under paddy straw mulch condition (averaged over irrigation regimes)

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 [10,31]. This was probable reason for maximum WUE under $I_{0.75}$. This is in agreement with findings [5,30] 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 $I_{0.25}$ treatments. 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 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 condition (Table 4). Adaptation of hydrogel for broccoli [32], plastic and straw mulch for brinjal [33] potato [34] 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 kg m^{-3}) under $I_{0.75}$ regime (Table 4). The 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 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 $ETWUE_{watbal}$ 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 [10]. 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 utilization 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).

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 [10,35]. In the present study IWUE 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 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 [10]. Irrespective of experimental years and irrigation regimes IWUE value was found to be the lowest (10.2 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 broccoli as 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 [10]. "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 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 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) [10].

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 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 [10].

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 of 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 KNO_3, black polythene mulch and straw mulch respectively with 38, 58 and 46 % additional yield. Both KNO_3 and Mulching (M_{BP} and M_{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 highest WUE at observed yield and WUE at highest yield level (5, 1.5 and 1.2 kg m^{-3}). Similar results reported by [4] for cauliflower crop and [10] for tomato crop.

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 yield	285.0	2.0	0.8	20000					
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					

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 $I_{0.75}$, $I_{0.50}$, $I_{0.25}$ regimes 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 Mg 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 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, 15 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. Whereas, 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 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 being a 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.

DISCLAIMER (ARTIFICIAL INTELLIGENCE)

We hereby declare that NO generative AI technologies such as Large Language Models (ChatGPT, COPILOT, etc.) and text-to-image generators have been used during the writing or editing of this manuscript.

COMPETING INTERESTS

Authors have declared that no competing interests exist.

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