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Enhancing Broccoli (*Brassica oleracea var. italica*) Growth, Yield and Water Productivity through Irrigation and Mulching Techniques in Local Climate

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Authors' contributions

This work was carried out in collaboration among all authors. The field trial was carried out in close collaboration with the authors. First draft was prepared by the corresponding author. All the authors read, incorporated their ideas, proof read the final paper and approved it for final publication.

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ABSTRACT

Introduction: Broccoli's efficient irrigation management is critical with changing climatic patterns and increasing water scarcity. The study aimed to assess the impacts of various irrigation methods and mulching techniques on broccoli cultivation.
Methodology: A randomized complete block design with three replications was used, considering two factors: irrigation methods (drip and surface) and mulching materials (black polythene, white polythene, grass straw, and no mulching).
Results: Drip irrigation, combined with black polythene mulching (I_1M_{BP}), consistently demonstrated its superiority that significantly improved multiple aspects of plant growth, yield and water

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productivity. In particular, I_1M_{BP} resulted in the highest plant heights at different growth stages, with the tallest plants at harvest (43.87 cm). However, surface irrigation with the same mulching (I_2M_{BP}) also showed higher plant heights but slightly shorter than drip irrigation. A similar trend was observed for the number of leaves per plant, with the I_1M_{BP} treatment having the most leaves. In curd development, the treatment (I_1M_{BP}) produced curds with larger diameters and lengths at harvest. In contrast, surface irrigation with the same mulching (I_2M_{BP}) also showed a larger curd size but, again, slightly lower than drip irrigation. In terms of curd initiation time, the I_1M_{BP} treatment had a longer duration, while the I_1M_N treatment had a shorter duration. Surface irrigation treatments followed a similar trend. With respect to yield, the I_1M_{BP} consistently had the highest unit weight of curd (423.14 g plant^{-1}), yield per plot (25.39 Kg plot^{-1}), and total yield (16.93 t ha^{-1}), regardless of the mulching condition. However, surface irrigation with the same mulching (I_2M_{BP}) also showed higher yields (15.93 t ha^{-1}) but slightly less than drip irrigation. On the other hand, the I_1M_{BP} demonstrated superior water use efficiencies (74.68 kg/ha-mm) and productivity (7.47 Kg m^{-3}) compared to other treatments. Still, surface irrigation with the same mulching (I_2M_{BP}) also exhibited better water use efficiency (64.98 kg/ha-mm) and productivity (6.50 Kg m^{-3}) than treatments with no mulch. Environmental factors, including temperature, humidity, wind speed, sunshine hours, and evaporation, were found to correlate with broccoli growth stages, emphasizing their influence on crop development.

Conclusion: Finally, drip irrigation and black polythene mulching are pivotal for improved growth, yield, and water management, contributing to sustainable agriculture practices.

Keywords: Broccoli; irrigation; mulching; growth; yield; water productivity.

1. INTRODUCTION

In broccoli (*Brassica oleracea* L. *var. italica*), it has nutritional abundance, encompassing vitamins, minerals, and antioxidants [1]. Initially cultivated in temperate regions, its adaptation to sub-tropical and tropical areas, like Bangladesh, has expanded its reach [2]. Broccoli's potential health benefits, notably in cancer prevention, are attributed to glucosinolates, active phytochemicals [3]. However, successful broccoli cultivation hinges on diverse factors, notably irrigation methods and mulching techniques [4].

Climate change forecasts indicate declining rainfall, amplifying water scarcity concerns [5]. For regions facing shifting climatic patterns and reduced rainfall, efficient irrigation management becomes paramount [6]. Drip irrigation's precision water delivery, saving water and fertilizers, enhancing growth, and augmenting yields have succeeded in horticultural crops [7]. While irrigation is indispensable, its costs can burden broccoli production, rendering it unprofitable and disheartening for growers. Conversely, mulching can be a pivotal tool for preserving water and maintaining optimal soil conditions. Varied mulching materials, such as poly mulch and organic options, exhibit diverse impacts on soil moisture, temperature, weed control, and nutrient availability [8-10]. Mulching enhances soil porosity and suppresses weed proliferation [11]. Islam [12] demonstrated that poly mulch can enhance nutrient enrichment, specifically in soil organic carbon and NPK content. Additionally, it positively influences quality characteristics like dry matter, sugars, β-carotene, and vitamin C [13, 14].

Despite acknowledging the potential of efficient irrigation and mulching, research concerning their combined effects on broccoli growth, yield, and water productivity still needs to be completed. Patra et al. [15], Yasmin et al. [16], and Kumari et al. [17] studies underscore the importance of irrigation methods and mulching materials in influencing these outcomes. This highlights the intricate interplay of factors affecting broccoli responses and emphasizes the significance of the proposed research.

In the face of global water scarcity and climate change challenges, this research is poised to provide actionable insights for sustainable broccoli production practices. Addressing the knowledge gap surrounding the combined influence of irrigation methods and mulching materials in specific environmental contexts is essential. This research's significance lies in its potential to elevate broccoli cultivation practices through optimized irrigation and mulching techniques, offering valuable insights to researchers and farmers alike. Given the intensifying water scarcity due to climate change, adopting water-efficient practices becomes pivotal for maintaining sustainable agriculture while sustaining or enhancing broccoli yield and quality. Furthermore, this research bridges the gap in the current literature by explicitly investigating the joint impact of irrigation methods and mulching materials on broccoli cultivation. This comprehensive approach acknowledges the complex relationships between these factors and offers a more realistic portrayal of actual cultivation conditions.

The necessity to gain insight into how various irrigation methods and a range of mulching materials influence plant growth, yield, and water utilization of broccoli drives this research. The objectives include to examine the impact of irrigation methods and mulches across different broccoli growth stages of plant growth parameters and yield components, to determine broccoli's water needs throughout its growth cycle and to analyze the relationship between local climatic parameters, such as temperature, humidity, wind speed, sunshine hours, and evaporation, and their influence on different stages of broccoli growth and development.

2. MATERIAL AND METHODS

2.1 Study Location and Weather Conditions

The research occurred at the Agricultural Field Research Center within Bangladesh Open University, Gazipur, from October 2022 to March 2023. The site had a consistent, flat topography with sandy loam soil, pH 6.06, and a field capacity of 29.6%. The area experienced a subtropical monsoon climate characterized by heavy rainfall during the *kharif* season and dry periods during the rest of the year. Monthly meteorological information, including air temperature, sunshine duration, precipitation, and relative humidity, was gathered from the research site and the Gazipur weather station, as detailed in Table 1.

2.2 Seed Acquisition and Sowing

F_1 hybrid broccoli seeds were purchased from the Kazi fertilizer, Gazipur, packed by Sakata Seed Co., Japan. Sowing began on October 10, 2022, with seeds planted 2 cm deep and spaced at 5 cm intervals. After germination, straw covers were removed, and seedlings were lightly watered and weeded. Transplanting of seedlings with 5-6 true leaves occurred on November 14, 2022, with a 50 cm × 50 cm spacing.

2.3 Experimental Design

The study adhered to a Randomized Complete Block Design (RCBD), which included three replications and encompassed two key factors: irrigation methods (drip and surface) and mulching techniques (black polythene, white polythene, grass straw, and no mulching). There were eight treatment combinations as T_1 = Drip irrigation @ 3 days interval (I_1) × Black polythene mulch (M_{BP}); T_2 = Drip irrigation @ 3 days interval (I_1) × White polythene mulch (M_{WP}); T_3 = Drip irrigation @ 3 days interval (I_1) × Grass straw mulch (M_{GS}); T_4 = Drip irrigation @ 3 days interval (I_1) × Non-mulch (M_N); T_5 = Surface irrigation @ 3 days interval (I_2) × Black polythene mulch (M_{BP}); T_6 = Surface irrigation @ 3 days interval (I_2) × White polythene mulch (M_{WP}); T_7 = Surface irrigation @ 3 days interval (I_2) × Grass straw mulch (M_{GS}); and T_8 = Surface irrigation @ 3 days interval (I_2) × Non-mulch (M_N).

2.4 Field Management

Land preparation included thorough plowing and removal of weeds and stubbles. Chemical fertilizer was applied at recommended rates of 135-60-135-21-3-1.5 kg ha^{-1} for N-P-K-S-Zn-B [18]. Additionally, the recommended dosage used cow dung at a rate of 5 t ha^{-1}. A uniform mixture of manures and fertilizers was manually applied during field preparation. Triple Super Phosphate (TSP) was administered during the last plowing for the total phosphorus (P) requirement. At the same time, nitrogen (N) and potassium (K) in the form of urea and MoP were evenly distributed in 4 applications, each separated by 15-day intervals, throughout the growing season.

2.5 Transplanting and Mulching

Transplanting was carried out on November 14, 2022, with seedlings having 35 days of emergence, 5-6 true leaves and an average height of about 7-10 cm. Two rows of seedlings were grown in each bed, each plot measuring 4.0 m × 1.0 m and containing 16 seedlings spaced at 0.50 m × 0.50 m. Transplanting was performed in the afternoon, followed by light irrigation. Covering and irrigation were maintained until the seedlings had firmly established themselves. Black and white polythene of 200 gauge was placed on beds with holes (0.0254 m × 0.0254 m) for planting, while grass straw mulch was applied to the topsoil according to the experimental design.

Table 1. Monthly air temperature, sunshine hours, relative humidity, and rainfall data for the experimental area during the study period

Month	*Air temperature (^{0}C)			*Sunshine hour	*Mean relative humidity (%)	**Rainfall (mm)
	Max.	Min.	Mean			
November, 2022	18.72	31.03	24.875	7.55	80.87	0
December, 2022	15.33	27.24	21.29	5.51	81.73	0
January, 2023	12.78	25.49	19.14	5.51	82.55	0
February, 2023	16.03	29.29	22.66	6.06	77.02	0

**Monthly average; **Monthly total (Source: Weather Station, Gazipur)*

2.6 Irrigation Management

Plants were irrigated immediately after transplanting, followed by additional watering until seedlings were established. Irrigation was then carried out according to the treatment schedule (3-day intervals) using either drip irrigation (T_1 to T_4) or conventional surface irrigation by hand (T_5 to T_8).

2.7 Data Collection

Plant height (cm), leaf count (number), and broccoli curd measurements were taken at specific intervals. Broccoli curds were harvested between January 25, 2023 (72 DAP) and February 7, 2023 (85 DAP). The broccoli was harvested, collected in an earlier categorized ploy bag, and taken to the laboratory for more analysis. Data related to yield, such as yield per plant (in grams) and yield per plot (in kilograms), were collected and subsequently converted to yield per hectare (in t ha^{-1}).

2.8 Water Management, Water Use Efficiency and Water Productivity

After the plants were established, soil moisture levels were assessed before irrigation initiation and harvest time. The gravimetric method was employed for these measurements. Afterward, irrigation water is used to restore soil moisture to its optimal level, considering the depth of the root zone. The plants started irrigation treatments once they had become established. In the experimental field, two irrigation levels were implemented at 3-day intervals. Drip irrigation was used for treatments T_1 to T_4, while conventional surface irrigation by hand was employed for T_5 to T_8 treatments. Throughout the experiment, irrigation was applied 22 times to the plots at 3-day intervals. The depth of irrigation water is calculated based on the provided equation by Michael [19]:

$$\mathrm{d} = \frac{\mathrm{FC} - \mathrm{MCi}}{100} \times \mathrm{As} \times \mathrm{D}$$

Where d represents the irrigation depth in cm, FC signifies the soil's field capacity as a percentage (%), MCi indicates the soil's moisture content before irrigation as a percentage (%), A_s the soil apparent specific gravity, and D is the effective root zone depth (cm).

The seasonal water demand was determined by considering the sum of irrigation water used (mm), seasonal effective rainfall (mm), and soil water contribution (mm).

The formula determined water use efficiency (WUE):

$$\text{Water use efficiency, WUE}\left(\frac{\mathrm{Kg}}{\mathrm{ha-mm}}\right) = \frac{\text{Yield of broccoli (Kg ha}^{-1})}{\text{Seasonal water requirement (mm)}}$$

The formula determined water productivity (WP):

$$\text{Water productivity, WP (Kg m}^{-3}) = \frac{\text{Yield of broccoli (Kg ha}^{-1})}{\text{Seasonal water requirement (mm)}}$$

2.9 Statistical Investigation

Statistical investigation of all data was carried out using R 4.2.2 software to identify significant differences among the results about the irrigation and mulching methods employed in the treatments. Mean values within each treatment group underwent comparison using the LSD test, where significance levels were established at both 1% and 5% (i.e., P≤0.01 and P≤0.05).

3. RESULTS AND DISCUSSION

3.1 Irrigation and Mulching Effects on Broccoli Growth

The impacts of irrigation and various mulching on growing factors on different days after planting (DAP) of broccoli are shown in Table 2. Significantly, when comparing irrigation methods, a consistent and notable impact was observed on broccoli plant height and the number of leaves. Throughout all growth stages, from 30 days after transplanting (DAP) to harvest, drip irrigation consistently outperformed surface irrigation in promoting greater plant height and a higher number of leaves per plant. The pivotal role of drip irrigation in influencing both vertical growth (plant height) and leaf development in broccoli plants.

Shifting our focus to the effects of different mulches, it becomes evident that black polythene mulch consistently yielded outstanding results in plant height and the number of leaves per plant. For plant height, measurements of 15.04 cm, 27.27 cm, 36.12 cm, and 43.42 cm were recorded at 30 days after transplanting (DAP), 45 DAP, 60 DAP, and at harvest, respectively, under black polythene mulch. In contrast, the lowest plant height values were observed in the non-mulch condition, with 12.63 cm, 24.36 cm, 32.81 cm, and 38.61 cm for the corresponding growth stages. Similarly, regarding the number of leaves per plant, black polythene mulch exhibited impressive values, surpassing white polythene, grass straw, and non-mulch conditions. Precise measurements of 7.44, 13.94, 20.81, and 22.16 were recorded at 30 DAP, 45 DAP, 60 DAP, and at harvest, respectively, under black polythene mulch. Conversely, the lowest number of leaf values were observed in the non-mulch condition, with measurements of 6.23, 12.08, 18.63, and 19.68 for the corresponding growth stages. The analysis highlights the consistent superiority of black polythene mulching in promoting both plant height and leaf development in broccoli plants, underscoring its effectiveness as a mulching material in this cultivation context.

Furthermore, the interactive effects of irrigation methods and mulching materials significantly impacted plant height and leaf numbers at various days after planting (DAP) for broccoli. Under drip irrigation, combining irrigation and mulching treatments resulted in diverse plant height values. The highest plant height values (15.24 cm, 27.47 cm, 36.37 cm, and 43.87 cm for 30 DAP, 45 DAP, 60 DAP, and at harvest, respectively) were observed in the I_1M_{BP} (T_1) treatment, while the lowest values (12.78 cm, 24.51 cm, 33.01 cm, and 39.01 cm for the corresponding growth stages) were found in the I_1M_N (T_4) treatment. Similarly, under surface irrigation, the interactive effects of irrigation and mulching also led to variations in plant height. I_2M_{BP} (T_5) exhibited the highest values (14.84 cm, 27.07 cm, 35.87 cm, and 42.97 cm for the corresponding growth stages), whereas I_2M_N (T_8) displayed the lowest values (12.48 cm, 24.21 cm, 32.61 cm, and 38.21 cm for the corresponding growth stages). Drip irrigation consistently resulted in higher plant heights compared to surface irrigation. This observation aligns with previous studies [20, 21] highlighting the positive impact of effective irrigation methods on plant height in broccoli cultivation.

Similarly, the interactive effects of irrigation methods and mulching materials significantly impacted the number of leaves per plant. Under drip irrigation, the highest number of leaves per plant values (7.54, 14.14, 21.27, 22.67 for 30 DAP, 45 DAP, 60 DAP, and at harvest, respectively) were observed in the I_1M_{BP} (T_1) treatment, while the lowest values (6.30, 12.30, 18.97, 20.07 for the corresponding growth stages) were found in the I_1M_N (T_4) treatment. Similarly, under surface irrigation, the interactive effects of irrigation and mulching also led to variations in the number of leaves per plant. I_2M_{BP} (T_5) exhibited the highest values (7.34, 13.74, 20.35, 21.65 for the corresponding growth stages), whereas I_2M_N (T_8) displayed the lowest values (6.15, 11.85, 18.29, 19.29 for the corresponding growth stages). Furthermore, the study revealed a consistent increase in leaves with advancing days after planting (DAP), specifically at 30, 45, and 60 DAP. Additionally, it highlighted that the number of leaves significantly increased with drip irrigation and black polythene mulching, in line with findings by Nahar [22] in broccoli. This investigation is consistent with prior studies by El-Magd [23] in broccoli, and Hasan & Solaiman [24] in Cabbage, providing further support for the positive influence of appropriate irrigation methods and mulching materials on leaf development in broccoli cultivation. These findings underscore the importance of carefully selecting irrigation methods and mulching materials to optimize plant height and leaf development in broccoli cultivation.

3.2 Irrigation and Mulching Effects on Broccoli Yield and Yield Contributing Parameters

The effects of irrigation methods and various mulches on broccoli yield and yield-contributing parameters are shown in Table 3. Significant variations were observed in terms of curd

Table 2. Effects of irrigation methods and various mulching on growth parameters at different days after planting (DAP) of broccoli

Factors/ Treatments	Plant height (cm) and number of leaves per plant at different DAP							
	30 DAP		45 DAP		60 DAP		At harvest	
	Height (cm)	Leaves/plant	Height (cm)	Leaves/ plant	Height (cm)	Leaves/plant	Height (cm)	Leaves/ plant
Irrigation methods								
I_1	13.91a	6.87a	25.88a	13.12a	34.55a	19.83a	41.30a	21.08a
I_2	13.48b	6.61b	25.45b	12.61b	34.03b	19.22b	40.40b	20.37b
CV (%)	1.963	0.150**	1.397	0.227***	1.093	0.317***	0.949	0.325***
LSD	0.235**	2.550	0.314*	2.020	0.328**	1.857	0.339***	1.794
Mulching								
M_{BP}	15.04a	7.44a	27.27a	13.94a	36.12a	20.81a	43.42a	22.16a
M_{WP}	13.88b	6.83b	26.01b	13.03b	34.66b	19.65b	41.51b	20.90b
M_{GS}	13.23c	6.45c	25.01c	12.40c	33.56c	19.00c	39.86c	20.15c
M_N	12.63d	6.23d	24.36d	12.08d	32.81d	18.63c	38.61d	19.68d
CV (%)	1.963	0.213***	1.397	0.322***	1.093	0.449***	0.949	0.460***
LSD	0.333***	2.550	0.444***	2.020	0.464***	1.857	0.480***	1.794
Interactions								
$T_1 = I_1 \times M_{BP}$	15.24a	7.54a	27.47a	14.14a	36.37a	21.27a	43.87a	22.67a
$T_2 = I_1 \times M_{WP}$	14.13b	6.98b	26.26b	13.28b	34.96b	19.88bc	41.96c	21.18bc
$T_3 = I_1 \times M_{GS}$	13.48c	6.65c	25.26cd	12.75cd	33.86cd	19.20d	40.36e	20.40de
$T_4 = I_1 \times M_N$	12.78de	6.30d	24.51e	12.30de	33.01e	18.97d	39.01f	20.07de
$T_5 = I_2 \times M_{BP}$	14.84a	7.34a	27.07a	13.74a	35.87a	20.35b	42.97b	21.65b
$T_6 = I_2 \times M_{WP}$	13.63c	6.68bc	25.76bc	12.78c	34.36bc	19.43cd	41.06d	20.63cd
$T_7 = I_2 \times M_{GS}$	12.98d	6.25d	24.76de	12.05e	33.26de	18.80de	39.36f	19.90ef
$T_8 = I_2 \times M_N$	12.48e	6.15d	24.21e	11.85e	32.61e	18.29e	38.21g	19.29f
CV (%)	1.963	0.301*	1.397	0.455*	1.093	0.635*	0.949	0.651*
LSD	0.471*	2.550	0.628*	2.020	0.657*	1.857	0.679*	1.794

*Note: DAP= Days after planting; Drip irrigation (I_1), Surface irrigation (I_2), Black polythene (M_{BP}), White polythene (M_{WP}), Grass straw (M_{GS}), Non mulch (M_N); Statistical analysis using the LSD (Least Significant Difference) test revealed significant differences among means associated with the same parameter. These differences were denoted by letters, with distinct letters indicating statistical significance. The levels of significance were indicated as follows: ***denoted a 0.1% level of significance; **indicated statistical significance at the 1.0% level & *represented statistical significance at the 5.0% level*

Table 3. Effects of irrigation methods and various mulching on yield and yield contributing parameters of broccoli

Factors/ Treatments	Curd initiation from transplant (days)	Curd diameter (cm)	Curd length (cm)	Curd weight (g $plant^{-1}$)	Yield (kg $plot^{-1}$)	Yield (t ha^{-1})
Irrigation methods						
I_1	62.17	15.16a	14.04b	398.75a	23.93a	15.95a
I_2	60.67	14.49b	14.34a	380.05b	22.81b	15.20b
LSD	1.901^{ns}	0.252***	0.242*	6.278***	0.314***	0.242***
CV (%)	3.535	1.944	1.946	1.841	1.534	1.773
Mulching						
M_{BP}	63.22a	15.90a	13.69c	410.66a	24.64a	16.43a
M_{WP}	61.90ab	15.52b	13.93c	399.56b	23.98b	15.98b
M_{GS}	60.69ab	14.16c	14.38b	384.77c	23.09c	15.39c
M_N	59.88b	13.71d	14.77a	362.62d	21.76d	14.51d
LSD	2.689*	0.357***	0.342***	8.879***	0.444***	0.342***
CV (%)	3.535	1.944	1.946	1.841	1.534	1.773
Interactions						
$T_1 = I_1 \times M_{BP}$	63.87a	16.15a	13.54e	423.14a	25.39a	16.93a
$T_2 = I_1 \times M_{WP}$	62.45ab	15.86a	13.78de	409.51b	24.57b	16.38b
$T_3 = I_1 \times M_{GS}$	61.74ab	14.46c	14.23bcd	394.78c	23.69c	15.79c
$T_4 = I_1 \times M_N$	60.63ab	14.16cd	14.62ab	367.57de	22.05de	14.70de
$T_5 = I_2 \times M_{BP}$	62.57ab	15.65ab	13.84de	398.17bc	23.89c	15.93bc
$T_6 = I_2 \times M_{WP}$	61.35ab	15.17b	14.08cd	389.61c	23.38c	15.58c
$T_7 = I_2 \times M_{GS}$	59.64b	13.86d	14.53abc	374.75d	22.49d	14.99d
$T_8 = I_2 \times M_N$	59.13b	13.26e	14.92a	357.67e	21.46e	14.31e
LSD	3.802*	0.505*	0.484*	12.556*	0.628*	0.484*
CV (%)	3.535	1.944	1.946	1.841	1.534	1.773

*Note: DAP= Days after planting; Drip irrigation (I_1), Surface irrigation (I_2), Black polythene (M_{BP}), White polythene (M_{WP}), Grass straw (M_{GS}), Non mulch (M_N); Statistical analysis using the LSD (Least Significant Difference) test revealed significant differences among means associated with the same parameter. These differences were denoted by letters, with distinct letters indicating statistical significance. The levels of significance were indicated as follows: ***denoted a 0.1% level of significance; *represented statistical significance at the 5.0% level & ^{ns} indicated statistical non-significant* initiation time from transplant, curd diameter at harvest, curd length at harvest, unit weight of curd (g plant^{-1}), plot yield (in kilograms), and total yield (per hectare) of broccoli when considering individual and interactive effects of irrigation methods and various mulches. In evaluating irrigation methods, the days taken for curd initiation from transplant were 62.17 days for drip irrigation and 60.67 days for conventional surface irrigation. Curd diameter at harvest measured 15.16 cm for drip irrigation and 14.49 cm for conventional surface irrigation. Likewise, curd length at harvest exhibited values of 14.34 cm for drip irrigation and 14.04 cm for conventional surface irrigation. The unit weight of curd measured 398.75 g plant^{-1} for drip irrigation and 380.05 g plant^{-1} for conventional surface irrigation. Correspondingly, the yield per plot stood at 23.93 kg plot^{-1} for drip irrigation and 22.81 kg plot^{-1} for conventional surface irrigation. Regarding yield, the values were 15.95 t ha^{-1} for drip irrigation and 15.20 t ha^{-1} for conventional surface irrigation. These findings highlight the distinct impacts of the two irrigation methods on various aspects of broccoli growth and yield.

The impact of different mulches' distinct trends emerged in terms of various yield-contributing parameters. The highest values for days taken for curd initiation from transplant and curd diameter at harvest, at 63.22 days and 15.90 cm, respectively, were observed under black polythene mulching. Conversely, curd length at harvest was at its lowest, measuring 13.69 cm under this mulching condition. White polyethylene and grass straw mulches followed closely, ranking second and third for all these parameters. In contrast, the lowest values for days taken for curd initiation from transplant and curd diameter at harvest, at 59.88 days and 13.71 cm, respectively, were recorded in the non-mulch condition for broccoli cultivation. However, curd length at harvest reached its highest value at 14.77 cm under this non-mulching condition. The unit weight of curd under this mulching condition measured 410.66 g plant^{-1}, while the yield per plot and yield reached 24.64 kg plot^{-1} and 16.43 t ha^{-1}, respectively. In contrast, the non-mulch condition for broccoli cultivation yielded the lowest values across these parameters, with the unit weight of curd, yield per plot, and yield at 362.62 g plant^{-1}, 21.76 kg plot^{-1}, and 14.51 t ha^{-1}, respectively. These findings underscore the significant impact of mulching materials, mainly black polythene mulch, on various aspects of broccoli growth and yield.

The interactive effects of irrigation methods and mulching materials significantly impacted various aspects of broccoli yield and yield contributing parameters. In the case of drip irrigation, the I_1M_{BP} (T_1) treatment showed the highest values for days taken for curd initiation (63.83 days) and curd diameter at harvest (16.15 cm), while curd length at harvest was lowest in the same treatment (13.54 cm). Conversely, the I_1M_N (T_4) treatment had the lowest values for days taken for curd initiation (60.63 days) and curd diameter at harvest (14.16 cm) but the highest value for curd length at harvest (14.62 cm). Similar trends were observed under surface irrigation, with the I_2M_{BP} (T_5) treatment exhibiting 62.57 days for curd initiation, 15.65 cm for curd diameter at harvest, and 13.84 cm for curd length at harvest. In contrast, the I_2M_N (T_8) treatment displayed values of 59.13 days for curd initiation, 13.26 cm for curd diameter at harvest, and 14.92 cm for curd length at harvest. These results were influenced by the water retention capabilities of black polythene mulch, which played a significant role, particularly under drip irrigation. Additionally, the period required for curd initiation increased with drip irrigation and black polythene mulching, emphasizing the positive role of regulated irrigation water, in line with previous research by Kumar & Choudhary [25]. Moving on to the unit weight of curd, yield per plot and yield, the interactive effects of irrigation methods and mulching materials also led to significant variations. Under both drip and surface irrigation, the I_1M_{BP} (T_1) treatment consistently yielded the highest values for unit weight of curd (423.14 g plant^{-1}), yield per plot (25.39 kg plot^{-1}), and yield (16.93 t ha^{-1}). Conversely, the I_1M_N (T_4) treatment produced the lowest values (367.57 g plant^{-1}, 22.05 kg plot^{-1}, and 14.70 t ha^{-1}) under drip irrigation, while the I_2M_N (T_8) treatment yielded the lowest values (357.67 g plant^{-1}, 21.46 kg plot^{-1}, and 14.31 t ha^{-1}) under surface irrigation. These findings align with previous research on cauliflower by Murlee *et al.* [26] and highlight the significant impact of mulching and irrigation strategies on broccoli yield and productivity. Notably, black polyethylene mulch consistently resulted in the highest yields, which is in line with the findings reported by Islam et al. [27]. This performance remained consistent across all irrigation levels, as previously reported by Pervin et al. [28]. In another way, the non-mulch condition resulted in the lowest growth and yield outcomes for broccoli, consistent with findings from multiple studies by Saloom & Al-Sahaf [29]; Verma *et al.* [30]; and Punetha [31].

3.3 Irrigation and Mulching Impacts on Broccoli Water Management

Significant variations in seasonal water requirements, water use efficiencies, and water productivity for broccoli were observed due to different irrigation methods and various mulching materials. It is worth noting that the number of irrigation events remained consistent in both methods at 22 times (as shown in Table 4). The individual and interactive effects of irrigation methods and mulches significantly influenced these water-related parameters in broccoli cultivation. When evaluating irrigation methods, distinct characteristics of broccoli plants emerged. Seasonal water requirements were measured at 226.13 mm for drip irrigation and 244.75 mm for conventional surface irrigation. Correspondingly, water use efficiencies (WUE) were computed as 70.53 kg/ha-mm for drip irrigation, which is in line with the findings reported by Islam [32], while conventional surface irrigation exhibited WUE of 62.11 kg/ha-mm. The water productivity values stood at 7.06 Kg m^{-3} for drip irrigation and 6.21 Kg m^{-3} for conventional surface methods.

Shifting the focus to the influence of different mulches, the highest values for seasonal water requirements, water use efficiency, and water productivity were consistently recorded under black polythene mulching. Measurements revealed 235.88 mm for seasonal water requirements, 69.83 kg/ha-mm for water use efficiency, and 6.99 Kg m^{-3} for water productivity. Conversely, the lowest values for these parameters were observed in the non-mulch condition for broccoli cultivation.

The interactive effects of irrigation methods and mulching materials resulted in significant variations in seasonal water requirements, water use efficiencies, and water productivity for broccoli. Under drip irrigation, the combination of the highest values for seasonal water requirement (226.65 mm), water use efficiency (74.68 kg/ha-mm), and water productivity (7.47 Kg m^{-3}) were observed in the I_1M_{BP} (T_1) treatment. In contrast, the lowest values (255.55 mm, 65.19 kg/ha-mm, and 7.47 Kg m^{-3}) were found in the I_1M_N (T_4) treatment. A similar trend was observed for surface irrigation, with I_2M_{BP} (T_5) exhibiting the highest values (245.10 mm, 64.98 kg/ha-mm, and 6.50 Kg m^{-3}), and I_2M_N (T_8) displaying the lowest values (244.40 mm, 58.54 kg/ha-mm, and 5.85 Kg m^{-3}). The enhanced water retention capabilities of black polythene mulch contributed to these findings.

In summary, drip irrigation with black polythene mulching demonstrated superior water use efficiencies and productivity in broccoli cultivation. These results align with previous studies by Berihun [33], Mukherjee et al. [34], and Biswas et al. [35]. The enhanced water use efficiency and productivity associated with drip irrigation and black polythene mulching are attributed to precise water delivery to the root zone, minimizing water wastage due to evaporation and runoff. Additionally, mulching practices help retain soil moisture and suppress weed growth, improving water use efficiency. The study's findings emphasize the significant benefits of adopting drip irrigation and black polythene mulching, highlighting their role in optimizing water use efficiency and enhancing water productivity in broccoli cultivation. The results also show that treatments with drip irrigation and various mulching techniques at a 3-day irrigation interval exhibited superior water use efficiency and productivity performance, ultimately leading to higher broccoli yields (Fig. 1). This correlation between water use efficiency, water productivity, and yield underscores the effectiveness of the selected irrigation methods and practices. These observations are consistent with earlier research conducted by Bahadur et al. [36], further reinforcing the importance of appropriate irrigation methods and agronomic practices in maximizing water use efficiency and crop productivity, as demonstrated in the context of broccoli cultivation.

3.4 Influence of Climatic Parameters on Different Stages of Broccoli Growth and Development

Fig. 2 (a & b) illustrates temperature and humidity variations during the broccoli growth from 30 days after planting (DAP) to harvest at 85 DAP. Maximum and minimum temperatures were highest before curd initiation, averaging 27.41°C and 15.50 °C for drip irrigation (around 60 DAP) and 27.40°C and 15.59°C for surface irrigation (around 59 DAP). These temperatures decreased during curd initiation (25.53°C and 12.22°C for drip, 26.33°C and 12.40°C for surface). Post-curd initiation to harvest had lower temperatures (26.69°C and 13.37°C for drip, 26.54°C and 13.40°C for surface). Curd growth correlated with rising temperatures after initiation, peaking around 21-22°C. Morning relative

Table 4. Irrigation events, seasonal water requirement, water use efficiency (WUE) and water productivity for broccoli cultivation during growing season as influenced by irrigation methods and different mulching

Factors/ Treatments	Irrigation events (number)	Irrigation water applied (mm)	Effective rainfall (mm)	Soil moisture contribution (mm)	Seasonal water requirement (mm)	Water use efficiency (kg/ha-mm)	Water productivity (Kg m^{-3})
Irrigation methods							
I_1	22	215.75	0	10.38a	226.13b	70.53a	7.06a
I_2	22	235.50	0	9.25b	244.75a	62.11b	6.21b
LSD	-	-	-	0.047***	0.139***	1.901***	0.317***
CV (%)	-	-	-	0.544	0.067	3.274	5.462
Mulching							
M_{BP}	-	-	0	10.25a	235.88a	69.83a	6.99a
M_{WP}	-	-	0	10.00b	235.63b	68.01ab	6.80a
M_{GS}	-	-	0	9.65c	235.28c	65.59b	6.56ab
M_N	-	-	0	9.35d	234.98d	61.87c	6.19b
LSD	-	-	-	0.066***	0.196***	2.689***	0.449*
CV (%)	-	-	-	0.544	0.067	3.274	5.462
Interactions							
$T_1 = I_1 \times M_{BP}$	22	215.75	0	10.90a	226.65c	74.68a	7.47a
$T_2 = I_1 \times M_{WP}$	22	215.75	0	10.60b	226.35d	72.37ab	7.24a
$T_3 = I_1 \times M_{GS}$	22	215.75	0	10.20c	225.95e	69.89b	6.99ab
$T_4 = I_1 \times M_N$	22	215.75	0	9.80d	225.55f	65.19c	6.52bc
$T_5 = I_2 \times M_{BP}$	22	235.50	0	9.60e	245.10a	64.98cd	6.50bc
$T_6 = I_2 \times M_{WP}$	22	235.50	0	9.40f	244.90a	63.64cd	6.36bcd
$T_7 = I_2 \times M_{GS}$	22	235.50	0	9.10g	244.60b	61.28de	6.13cd
$T_8 = I_2 \times M_N$	22	235.50	0	8.90h	244.40b	58.54e	5.85d
LSD	-	-	-	0.093***	0.277*	3.802*	0.634*
CV%	-	-	-	0.544	0.067	3.274	5.462

*Note: Drip irrigation (I_1), Surface irrigation (I_2), Black polythene (M_{BP}), White polythene (M_{WP}), Grass straw (M_{GS}), Non mulch (M_N); Statistical analysis using the LSD (Least Significant Difference) test revealed significant differences among means associated with the same parameter. These differences were denoted by letters, with distinct letters indicating statistical significance. The levels of significance were indicated as follows: ***denoted a 0.1% level of significance; *represented statistical significance at the 5.0% level*

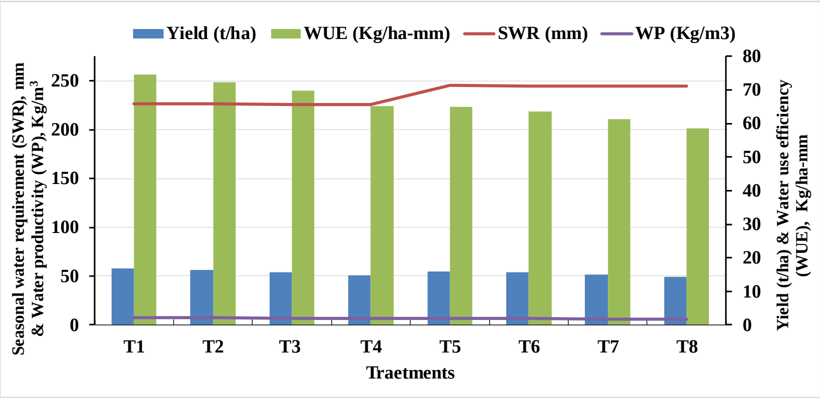
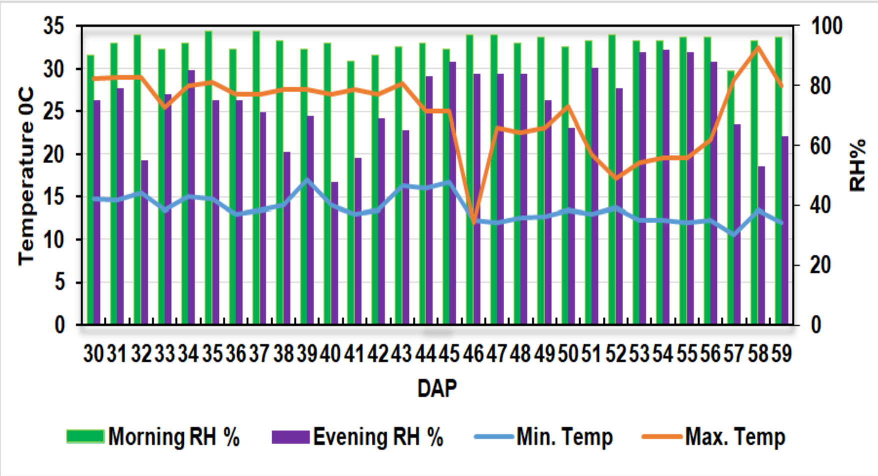
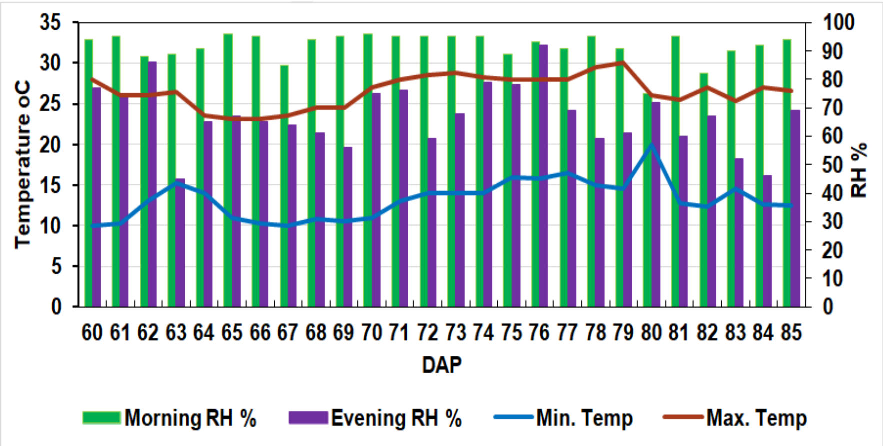


Fig. 1. Effect of seasonal water requirement on yield, water use efficiency and water productivity of broccoli at different treatments

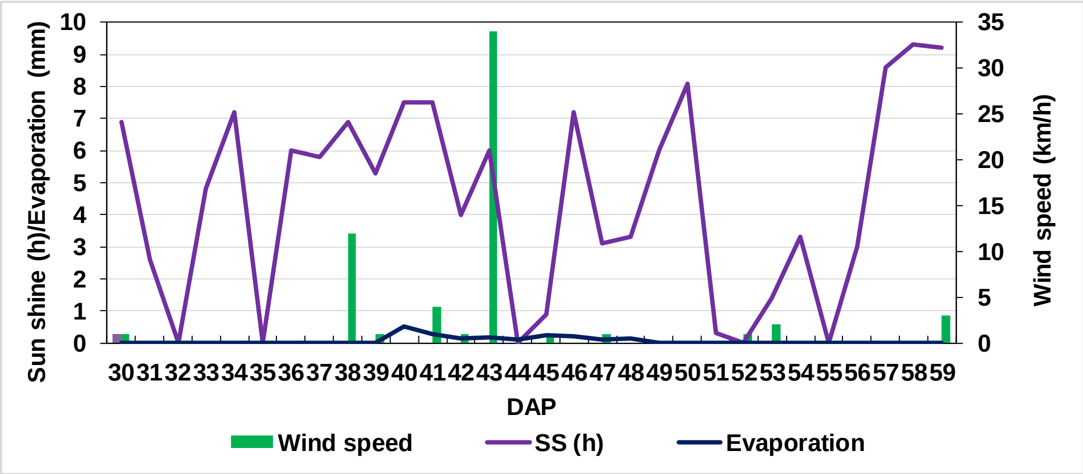


(a) 30 DAP to 59 DAP

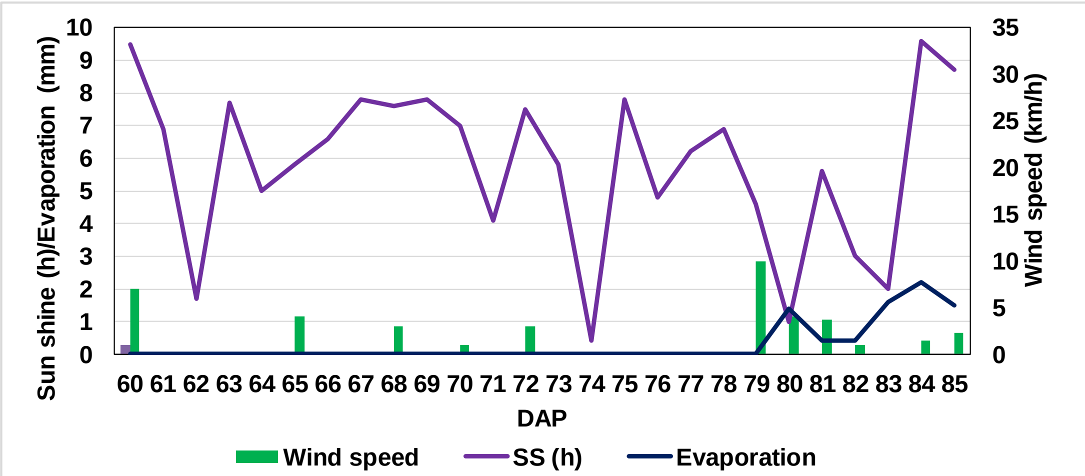


(b) 60 DAP to end of harvesting (85 DAP)

Fig. 2. Maximum and minimum temperature with morning and evening relative humidity (RH) during broccoli growth duration of (a) 30 DAP to 59 DAP; and (b) 60 DAP to end of harvesting (85 DAP)



(a) 30 DAP to 59 DAP



(b) 60 DAP to end of harvesting (85 DAP)

Fig. 3. Wind speed with sunshine hour and evaporation during broccoli growth duration of (a) 30 DAP to 59 DAP; and (b) 60 DAP to end of harvesting (85 DAP)

humidity remained constant at 92% until curd initiation, then decreased slightly to 91%. Evening relative humidity decreased from 72% pre-curd initiation to 69% during initiation and 66% post-initiation to harvest. The study emphasizes how temperature and humidity affect broccoli growth and yield, highlighting the importance of environmental factors in crop production. These findings align with previous research on cauliflower by Sharma & Parashar [37].

Fig. 3 (a & b) shows variations in wind speed, sunshine hours, and evaporation during broccoli growth at 30 days after planting (DAP) to harvest at 85 DAP. The highest wind speeds occurred from planting to curd initiation (15.97 Km h^{-1} for drip and 16.12 Km h^{-1} for surface irrigation). Wind speeds decreased during curd initiation (1.83 Km h^{-1} for drip, 1.67 Km h^{-1} for surface) and remained low from curd initiation to harvest (1.59 Km h^{-1} for drip, 1.52 Km h^{-1} for surface). The average wind speed over the crop period was 11.66 Km h^{-1}. Sunshine hours were minimal from curd initiation to harvest (5.74 h for drip, 5.71 h for surface). Throughout most of the growing season, an average of 5.92 hours of sunshine was observed, influenced by cloudy conditions. Excessive sunshine negatively affected curd weight during certain growth stages, aligning with the insights of Ray & Mishra [38]. These findings highlight the complex relationship between environmental factors like wind speed and sunshine hours and their varying effects on broccoli growth. Wind speed had a limited impact on curd weight in later stages, while excessive sunlight negatively affected curd development during specific phases. Understanding these relationships is crucial for effective cultivation strategies.

4. CONCLUSIONS

This study focuses on the impacts of irrigation and mulching techniques, offering significant findings with implications for sustainable agriculture. Drip irrigation proved superior to surface irrigation, enhancing broccoli growth, particularly plant height and leaf numbers. Black polythene mulch emerged as the most effective choice, significantly improving plant characteristics. The combination of drip irrigation and black polythene mulch consistently yielded the best yield and water use efficiency results, emphasizing the need for optimized practices. The study also highlights the intricate relationship between environmental factors like temperature, humidity, wind speed, sunshine hours, and broccoli growth, which are essential for effective cultivation strategies. In regards to global water scarcity and climate change, this research provides actionable insights for sustainable broccoli production. Bridging the knowledge gap on irrigation methods and mulching materials is vital, offering valuable guidance to researchers and farmers alike, especially in water-scarce environments. The study advances broccoli cultivation and sustainable agriculture practices, emphasizing tailored irrigation and mulching strategies to optimize yield and water efficiency, promoting food security and agricultural sustainability.

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COMPETING INTERESTS

The authors have declared no conflicts of interest of this article.

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