

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

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10 **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 consistently outperformed surface irrigation, promoting greater plant height and leaf numbers, underscoring its importance in enhancing broccoli growth. Black polythene mulch emerged as the most effective mulching material, significantly improving plant height and leaf numbers. In terms of yield, the arrangement of drip irrigation and black polythene mulch produced the highest curd diameter, length, unit weight (423.14 g plant⁻¹), plot yield (25.39 kg plot⁻¹), and total yield (16.93 t ha⁻¹), highlighting its superior performance. Drip irrigation with black polythene mulching demonstrated superior water use efficiencies (74.68 kg/ha-mm) and productivity (7.47 Kg m⁻³) attributed to precise water delivery and moisture retention capabilities. 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, this research provides valuable insights into optimizing broccoli cultivation under local climatic conditions. Drip irrigation and black polythene mulching are pivotal for improved growth, yield, and water management, contributing to sustainable agriculture practices.

11
12 *Keywords: Broccoli, drip irrigation, mulching, growth, yield, water productivity*

13 **1. INTRODUCTION**

14 In broccoli (*Brassica oleracea* L. *var. italica*), it has nutritional abundance, encompassing
15 vitamins, minerals, and antioxidants [1]. Initially cultivated in temperate regions, its
16 adaptation to sub-tropical and tropical areas, like Bangladesh, has expanded its reach [2].
17 Broccoli's potential health benefits, notably in cancer prevention, are attributed to

18 glucosinolates, active phytochemicals [3]. However, successful broccoli cultivation hinges on
19 diverse factors, notably irrigation methods and mulching techniques [4].

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

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

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

51 The necessity to gain insight into how various irrigation methods and a range of mulching
 52 materials influence plant growth, yield, and water utilization of broccoli drives this research.
 53 The objectives include to examine the impact of irrigation methods and mulches across
 54 different broccoli growth stages of plant growth parameters and yield components, to
 55 determine broccoli's water needs throughout its growth cycle and to formulate an effective
 56 water management strategy aligned with local weather patterns and environmental
 57 circumstances.

58 2. MATERIAL AND METHODS

60 2.1 Study location and weather conditions

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

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

Month	*Air temperature (^o 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

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

71 2.2 Seed acquisition and sowing

72 F₁ hybrid broccoli seeds were purchased from the Kazi fertilizer, Gazipur, packed by Sakata
 73 Seed Co., Japan. Sowing began on October 10, 2022, with seeds planted 2 cm deep and
 74 spaced at 5 cm intervals. After germination, straw covers were removed, and seedlings were
 75 lightly watered and weeded. Transplanting of seedlings with 5-6 true leaves occurred on
 76 November 14, 2022, with a 50 cm x 50 cm spacing.

77 2.3 Experimental design

78 The study adhered to a Randomized Complete Block Design (RCBD), which included three
 79 replications and encompassed two key factors: irrigation methods (drip and surface) and

80 mulching techniques (black polythene, white polythene, grass straw, and no mulching).
81 There were eight treatment combinations as T_1 = Drip irrigation @ 3 days interval (I_1) × Black
82 polythene mulch (M_{BP}); T_2 = Drip irrigation @ 3 days interval (I_1) × White polythene mulch
83 (M_{WP}); T_3 = Drip irrigation @ 3 days interval (I_1) × Grass straw mulch (M_{GS}); T_4 = Drip
84 irrigation @ 3 days interval (I_1) × Non-mulch (M_N); T_5 = Surface irrigation @ 3 days interval
85 (I_2) × Black polythene mulch (M_{BP}); T_6 = Surface irrigation @ 3 days interval (I_2) × White
86 polythene mulch (M_{WP}); T_7 = Surface irrigation @ 3 days interval (I_2) × Grass straw mulch
87 (M_{GS}); and T_8 = Surface irrigation @ 3 days interval (I_2) × Non-mulch (M_N).

88 **2.4 Field management**

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

97 **2.5 Transplanting and mulching**

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

106 **2.6 Irrigation management**

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

111 **2.7 Data collection**

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

118 **2.8 Water management, water use efficiency and water productivity**

119 After the plants were established, soil moisture levels were assessed before irrigation
120 initiation and harvest time. The gravimetric method was employed for these measurements.
121 Afterward, irrigation water is used to restore soil moisture to its optimal level, considering the
122 depth of the root zone. The plants started irrigation treatments once they had become
123 established. In the experimental field, two irrigation levels were implemented at 3-day
124 intervals. Drip irrigation was used for treatments T₁ to T₄, while conventional surface
125 irrigation by hand was employed for T₅ to T₈ treatments. Throughout the experiment,
126 irrigation was applied 22 times to the plots at 3-day intervals. The depth of irrigation water is
127 calculated based on the provided equation by Michael [19]:

$$d = \frac{FC - MC_i}{100} \times A_s \times D$$

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

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

133 The formula determined water use efficiency (WUE):

$$134 \text{ Water use efficiency WUE (Kg/ha - mm)} = \frac{\text{Yield of broccoli (Kg ha}^{-1}\text{)}}{\text{Seasonal water requirement (mm)}}$$

135 The formula determined water productivity (WP):

$$136 \text{ Water productivity, WP (Kg m}^{-3}\text{)} = \frac{\text{Yield of broccoli (Kg ha}^{-1}\text{)}}{\text{Seasonal water requirement (mm)}}$$

137

138

139 **2.9 Statistical investigation**

140 Statistical investigation of all data was carried out using R 4.2.2 software to identify
 141 significant differences among the results about the irrigation and mulching methods
 142 employed in the treatments. Mean values within each treatment group underwent
 143 comparison using the LSD test, where significance levels were established at both 1% and
 144 5% (i.e., $P \leq 0.01$ and $P \leq 0.05$).

145 3. RESULTS AND DISCUSSION

146

147 3.1 Irrigation and mulching effects on broccoli growth

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

155 **Table 2. Effects of irrigation methods and various mulching on growth parameters at**
 156 **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 × M _{BP}	15.24a	7.54a	27.47a	14.14a	36.37a	21.27a	43.87a	22.67a
T ₂ = I ₁ × M _{WP}	14.13b	6.98b	26.26b	13.28b	34.96b	19.88bc	41.96c	21.18bc
T ₃ = I ₁ × M _{GS}	13.48c	6.65c	25.26cd	12.75cd	33.86cd	19.20d	40.36e	20.40de
T ₄ = I ₁ × M _N	12.78de	6.30d	24.51e	12.30de	33.01e	18.97d	39.01f	20.07de
T ₅ = I ₂ × M _{BP}	14.84a	7.34a	27.07a	13.74a	35.87a	20.35b	42.97b	21.65b
T ₆ = I ₂ × M _{WP}	13.63c	6.68bc	25.76bc	12.78c	34.36bc	19.43cd	41.06d	20.63cd
T ₇ = I ₂ × M _{GS}	12.98d	6.25d	24.76de	12.05e	33.26de	18.80de	39.36f	19.90ef
T ₈ = I ₂ × 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
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157 Note: DAP= Days after planting; Drip irrigation (I_1), Surface irrigation (I_2), Black polythene (M_{BP}), White
 158 polythene (M_{WP}), Grass straw (M_{GS}), Non mulch (M_N); Statistical analysis using the LSD (Least
 159 Significant Difference) test revealed significant differences among means associated with the same
 160 parameter. These differences were denoted by letters, with distinct letters indicating statistical
 161 significance. The levels of significance were indicated as follows: ***denoted a 0.1% level of
 162 significance; **indicated statistical significance at the 1.0% level & *represented statistical significance
 163 at the 5.0% level.

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

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

193 Similarly, the interactive effects of irrigation methods and mulching materials significantly
194 impacted the number of leaves per plant. Under drip irrigation, the highest number of leaves
195 per plant values (7.54, 14.14, 21.27, 22.67 for 30 DAP, 45 DAP, 60 DAP, and at harvest,
196 respectively) were observed in the I_1M_{BP} (T_1) treatment, while the lowest values (6.30, 12.30,
197 18.97, 20.07 for the corresponding growth stages) were found in the I_1M_N (T_4) treatment.
198 Similarly, under surface irrigation, the interactive effects of irrigation and mulching also led to
199 variations in the number of leaves per plant. I_2M_{BP} (T_5) exhibited the highest values (7.34,
200 13.74, 20.35, 21.65 for the corresponding growth stages), whereas I_2M_N (T_8) displayed the
201 lowest values (6.15, 11.85, 18.29, 19.29 for the corresponding growth stages). Furthermore,
202 the study revealed a consistent increase in leaves with advancing days after planting (DAP),
203 specifically at 30, 45, and 60 DAP. Additionally, it highlighted that the number of leaves
204 significantly increased with drip irrigation and black polythene mulching, in line with findings
205 by Nahar [22] in broccoli. This investigation is consistent with prior studies by El-Magd [23] in
206 broccoli, and Hasan & Solaiman [24] in Cabbage, providing further support for the positive
207 influence of appropriate irrigation methods and mulching materials on leaf development in
208 broccoli cultivation. These findings underscore the importance of carefully selecting irrigation
209 methods and mulching materials to optimize plant height and leaf development in broccoli
210 cultivation.

211 **3.2 Irrigation and mulching effects on broccoli yield and yield contributing parameters**

212 The effects of irrigation methods and various mulches on broccoli yield and yield-contributing
213 parameters are shown in [Table 3](#). Significant variations were observed in terms of curd
214 initiation time from transplant, curd diameter at harvest, curd length at harvest, unit weight of
215 curd (g plant^{-1}), plot yield (in kilograms), and total yield (per hectare) of broccoli when
216 considering individual and interactive effects of irrigation methods and various mulches. In
217 evaluating irrigation methods, the days taken for curd initiation from transplant were 62.17
218 days for drip irrigation and 60.67 days for conventional surface irrigation. Curd diameter at
219 harvest measured 15.16 cm for drip irrigation and 14.49 cm for conventional surface
220 irrigation. Likewise, curd length at harvest exhibited values of 14.34 cm for drip irrigation and
221 14.04 cm for conventional surface irrigation. The unit weight of curd measured 398.75 g
222 plant^{-1} for drip irrigation and 380.05 g plant^{-1} for conventional surface irrigation.
223 Correspondingly, the yield per plot stood at 23.93 kg plot^{-1} for drip irrigation and 22.81 kg
224 plot^{-1} for conventional surface irrigation. Regarding yield, the values were 15.95 t ha^{-1} for drip
225 irrigation and 15.20 t ha^{-1} for conventional surface irrigation. These findings highlight the
226 distinct impacts of the two irrigation methods on various aspects of broccoli growth and yield.

227 **Table 3. Effects of irrigation methods and various mulching on yield and yield**
 228 **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 × M _{BP}	63.87a	16.15a	13.54e	423.14a	25.39a	16.93a
T ₂ = I ₁ × M _{WP}	62.45ab	15.86a	13.78de	409.51b	24.57b	16.38b
T ₃ = I ₁ × M _{GS}	61.74ab	14.46c	14.23bcd	394.78c	23.69c	15.79c
T ₄ = I ₁ × M _N	60.63ab	14.16cd	14.62ab	367.57de	22.05de	14.70de
T ₅ = I ₂ × M _{BP}	62.57ab	15.65ab	13.84de	398.17bc	23.89c	15.93bc
T ₆ = I ₂ × M _{WP}	61.35ab	15.17b	14.08cd	389.61c	23.38c	15.58c
T ₇ = I ₂ × M _{GS}	59.64b	13.86d	14.53abc	374.75d	22.49d	14.99d
T ₈ = I ₂ × 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

229 Note: DAP= Days after planting; Drip irrigation (I₁), Surface irrigation (I₂), Black polythene (M_{BP}), White
 230 polythene (M_{WP}), Grass straw (M_{GS}), Non mulch (M_N); Statistical analysis using the LSD (Least
 231 Significant Difference) test revealed significant differences among means associated with the same
 232 parameter. These differences were denoted by letters, with distinct letters indicating statistical
 233 significance. The levels of significance were indicated as follows: ***denoted a 0.1% level of
 234 significance; *represented statistical significance at the 5.0% level & ^{ns} indicated statistical non-
 235 significant.

236 The impact of different mulches' distinct trends emerged in terms of various yield-
 237 contributing parameters. The highest values for days taken for curd initiation from transplant
 238 and curd diameter at harvest, at 63.22 days and 15.90 cm, respectively, were observed
 239 under black polythene mulching. Conversely, curd length at harvest was at its lowest,
 240 measuring 13.69 cm under this mulching condition. White polyethylene and grass straw
 241 mulches followed closely, ranking second and third for all these parameters. In contrast, the
 242 lowest values for days taken for curd initiation from transplant and curd diameter at harvest,
 243 at 59.88 days and 13.71 cm, respectively, were recorded in the non-mulch condition for
 244 broccoli cultivation. However, curd length at harvest reached its highest value at 14.77 cm
 245 under this non-mulching condition. The unit weight of curd under this mulching condition
 246 measured 410.66 g plant⁻¹, while the yield per plot and yield reached 24.64 kg plot⁻¹ and
 247 16.43 t ha⁻¹, respectively. In contrast, the non-mulch condition for broccoli cultivation yielded

248 the lowest values across these parameters, with the unit weight of curd, yield per plot, and
249 yield at $362.62 \text{ g plant}^{-1}$, $21.76 \text{ kg plot}^{-1}$, and 14.51 t ha^{-1} , respectively. These findings
250 underscore the significant impact of mulching materials, mainly black polythene mulch, on
251 various aspects of broccoli growth and yield.

252 The interactive effects of irrigation methods and mulching materials significantly impacted
253 various aspects of broccoli yield and yield contributing parameters. In the case of drip
254 irrigation, the I_1M_{BP} (T_1) treatment showed the highest values for days taken for curd
255 initiation (63.83 days) and curd diameter at harvest (16.15 cm), while curd length at harvest
256 was lowest in the same treatment (13.54 cm). Conversely, the I_1M_N (T_4) treatment had the
257 lowest values for days taken for curd initiation (60.63 days) and curd diameter at harvest
258 (14.16 cm) but the highest value for curd length at harvest (14.62 cm). Similar trends were
259 observed under surface irrigation, with the I_2M_{BP} (T_5) treatment exhibiting 62.57 days for curd
260 initiation, 15.65 cm for curd diameter at harvest, and 13.84 cm for curd length at harvest. In
261 contrast, the I_2M_N (T_8) treatment displayed values of 59.13 days for curd initiation, 13.26 cm
262 for curd diameter at harvest, and 14.92 cm for curd length at harvest. These results were
263 influenced by the water retention capabilities of black polythene mulch, which played a
264 significant role, particularly under drip irrigation. Additionally, the period required for curd
265 initiation increased with drip irrigation and black polythene mulching, emphasizing the
266 positive role of regulated irrigation water, in line with previous research by Kumar &
267 Choudhary [25]. Moving on to the unit weight of curd, yield per plot and yield, the interactive
268 effects of irrigation methods and mulching materials also led to significant variations. Under
269 both drip and surface irrigation, the I_1M_{BP} (T_1) treatment consistently yielded the highest
270 values for unit weight of curd ($423.14 \text{ g plant}^{-1}$), yield per plot ($25.39 \text{ kg plot}^{-1}$), and yield
271 (16.93 t ha^{-1}). Conversely, the I_1M_N (T_4) treatment produced the lowest values (367.57 g
272 plant^{-1} , $22.05 \text{ kg plot}^{-1}$, and 14.70 t ha^{-1}) under drip irrigation, while the I_2M_N (T_8) treatment
273 yielded the lowest values ($357.67 \text{ g plant}^{-1}$, $21.46 \text{ kg plot}^{-1}$, and 14.31 t ha^{-1}) under surface
274 irrigation. These findings align with previous research on cauliflower by Murlee *et al.* [26] and
275 highlight the significant impact of mulching and irrigation strategies on broccoli yield and
276 productivity. Notably, black polyethylene mulch consistently resulted in the highest yields,
277 which is in line with the findings reported by Islam *et al.* [27]. This performance remained
278 consistent across all irrigation levels, as previously reported by Pervin *et al.* [28]. In another
279 way, the non-mulch condition resulted in the lowest growth and yield outcomes for broccoli,
280 consistent with findings from multiple studies by Saloom & Al-Sahaf [29]; Verma *et al.* [30];
281 and Punetha [31].

282 **3.3 Irrigation and mulching impacts on broccoli water management**

283 Significant variations in seasonal water requirements, water use efficiencies, and water
 284 productivity for broccoli were observed due to different irrigation methods and various
 285 mulching materials. It is worth noting that the number of irrigation events remained
 286 consistent in both methods at 22 times (as shown in [Table 4](#)). The individual and interactive
 287 effects of irrigation methods and mulches significantly influenced these water-related
 288 parameters in broccoli cultivation. When evaluating irrigation methods, distinct
 289 characteristics of broccoli plants emerged. Seasonal water requirements were measured at
 290 226.13 mm for drip irrigation and 244.75 mm for conventional surface irrigation.
 291 Correspondingly, water use efficiencies (WUE) were computed as 70.53 kg/ha-mm for drip
 292 irrigation, which is in line with the findings reported by Islam [32], while conventional surface
 293 irrigation exhibited WUE of 62.11 kg/ha-mm. The water productivity values stood at 7.06 Kg
 294 m⁻³ for drip irrigation and 6.21 Kg m⁻³ for conventional surface methods.

295 **Table 4. Irrigation events, seasonal water requirement, water use efficiency (WUE)**
 296 **and water productivity for broccoli cultivation during growing season as influenced**
 297 **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 × M _{BP}	22	215.75	0	10.90a	226.65c	74.68a	7.47a
T ₂ = I ₁ × M _{WP}	22	215.75	0	10.60b	226.35d	72.37ab	7.24a
T ₃ = I ₁ × M _{GS}	22	215.75	0	10.20c	225.95e	69.89b	6.99ab
T ₄ = I ₁ × M _N	22	215.75	0	9.80d	225.55f	65.19c	6.52bc
T ₅ = I ₂ × M _{BP}	22	235.50	0	9.60e	245.10a	64.98cd	6.50bc
T ₆ = I ₂ × M _{WP}	22	235.50	0	9.40f	244.90a	63.64cd	6.36bcd
T ₇ = I ₂ × M _{GS}	22	235.50	0	9.10g	244.60b	61.28de	6.13cd
T ₈ = I ₂ × 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

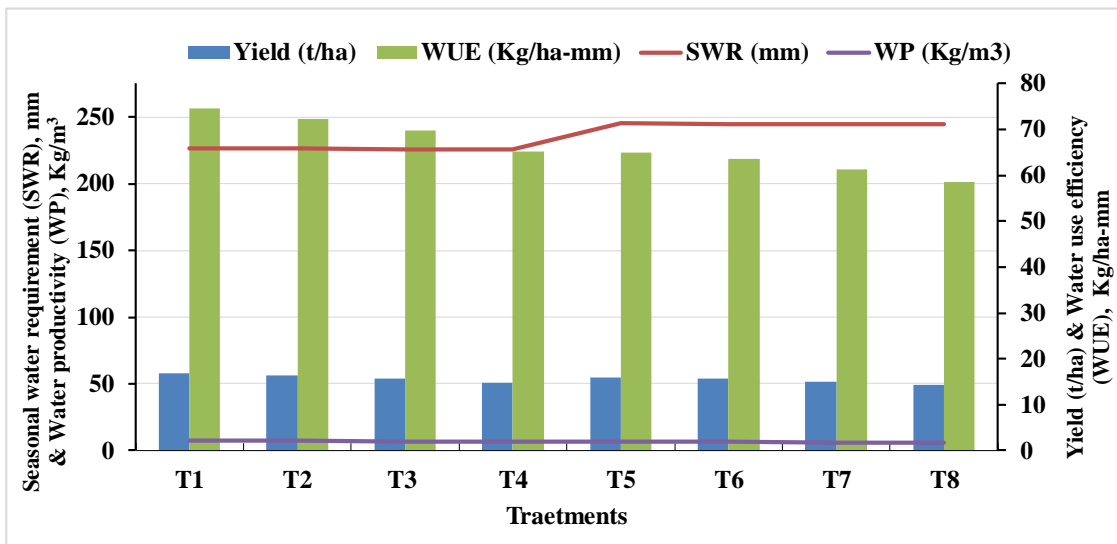
298 Note: Drip irrigation (I_1), Surface irrigation (I_2), Black polythene (M_{BP}), White polythene (M_{WP}), Grass straw
299 (M_{GS}), Non mulch (M_N); Statistical analysis using the LSD (Least Significant Difference) test revealed
300 significant differences among means associated with the same parameter.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

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

309 The interactive effects of irrigation methods and mulching materials resulted in significant
310 variations in seasonal water requirements, water use efficiencies, and water productivity for
311 broccoli. Under drip irrigation, the combination of the highest values for seasonal water
312 requirement (226.65 mm), water use efficiency (74.68 kg/ha-mm), and water productivity
313 (7.47 Kg m⁻³) were observed in the I_1M_{BP} (T_1) treatment. In contrast, the lowest values
314 (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
315 similar trend was observed for surface irrigation, with I_2M_{BP} (T_5) exhibiting the highest values
316 (245.10 mm, 64.98 kg/ha-mm, and 6.50 Kg m⁻³), and I_2M_N (T_8) displaying the lowest values
317 (244.40 mm, 58.54 kg/ha-mm, and 5.85 Kg m⁻³). The enhanced water retention capabilities
318 of black polythene mulch contributed to these findings.

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

334 importance of appropriate irrigation methods and agronomic practices in maximizing water
 335 use efficiency and crop productivity, as demonstrated in the context of broccoli cultivation.



336 **Figure 1. Effect of seasonal water requirement on yield, water use efficiency and water**
 337 **productivity of broccoli at different treatments**

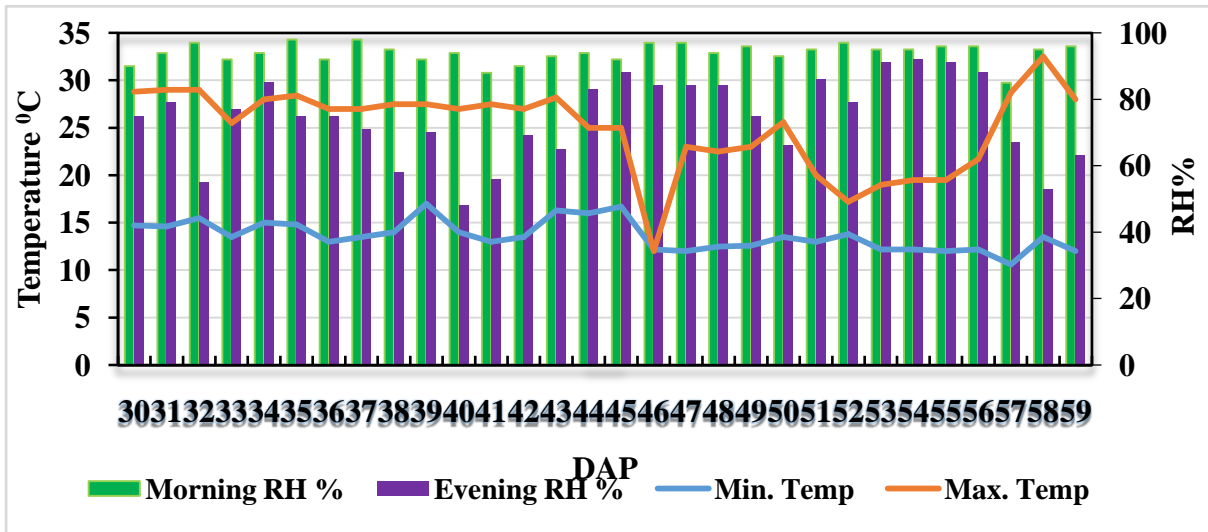
338 **3.4 Climatic conditions experienced by the broccoli growth and yield**

339 **Figure 2 (a & b)** illustrates temperature and humidity variations during the broccoli growth
 340 from 30 days after planting (DAP) to harvest at 85 DAP. Maximum and minimum
 341 temperatures were highest before curd initiation, averaging 27.41°C and 15.50 °C for drip
 342 irrigation (around 60 DAP) and 27.40 °C and 15.59 °C for surface irrigation (around 59
 343 DAP). These temperatures decreased during curd initiation (25.53 °C and 12.22 °C for drip,
 344 26.33 °C and 12.40 °C for surface). Post-curd initiation to harvest had lower temperatures
 345 (26.69 °C and 13.37 °C for drip, 26.54 °C and 13.40 °C for surface). Curd growth correlated
 346 with rising temperatures after initiation, peaking around 21-22 °C. Morning relative humidity
 347 remained constant at 92% until curd initiation, then decreased slightly to 91%. Evening
 348 relative humidity decreased from 72% pre-curd initiation to 69% during initiation and 66%
 349 post-initiation to harvest. The study emphasizes how temperature and humidity affect
 350 broccoli growth and yield, highlighting the importance of environmental factors in crop
 351 production. These findings align with previous research on cauliflower by Sharma &
 352 Parashar [37].

353

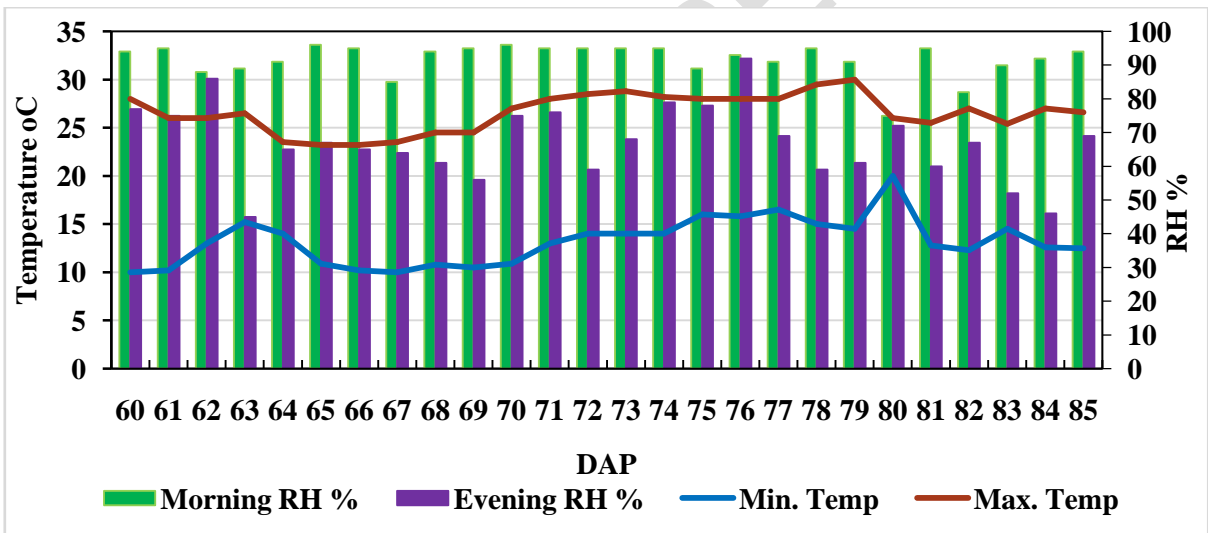
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356

(a) 30 DAP to 59 DAP



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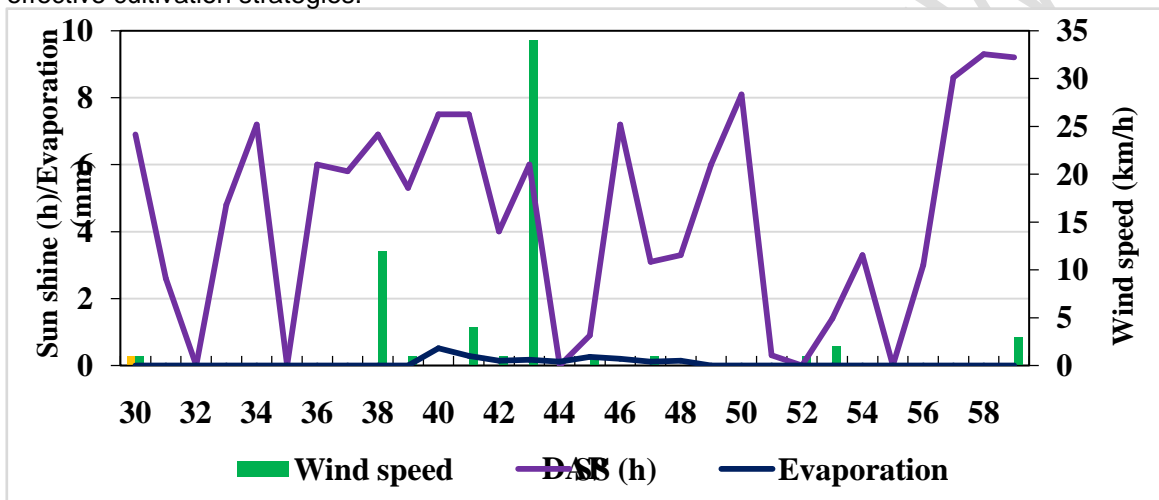
(b) 60 DAP to end of harvesting (85 DAP)

358

359 **Figure 2. Maximum and minimum temperature with morning and evening relative**
 360 **humidity (RH) during broccoli growth duration of (a) 30 DAP to 59 DAP; and (b) 80**
 361 **DAP to end of harvesting (85 DAP)**

362 **Figure 3 (a & b)** shows variations in wind speed, sunshine hours, and evaporation during
 363 broccoli growth at 30 days after planting (DAP) to harvest at 85 DAP. The highest wind
 364 speeds occurred from planting to curd initiation (15.97 Km h^{-1} for drip and 16.12 Km h^{-1} for
 365 surface irrigation). Wind speeds decreased during curd initiation (1.83 Km h^{-1} for drip, 1.67
 366 Km h^{-1} for surface) and remained low from curd initiation to harvest (1.59 Km h^{-1} for drip,
 367 1.52 Km h^{-1} for surface). The average wind speed over the crop period was 11.66 Km h^{-1} .

368 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
 369 observed, influenced by cloudy conditions. Excessive sunshine negatively affected curd
 370 weight during certain growth stages, aligning with the insights of Ray & Mishra [38]. These
 371 findings highlight the complex relationship between environmental factors like wind speed
 372 and sunshine hours and their varying effects on broccoli growth. Wind speed had a limited
 373 impact on curd weight in later stages, while excessive sunlight negatively affected curd
 374 development during specific phases. Understanding these relationships is crucial for
 375 effective cultivation strategies.
 376



(a) 30 DAP to 59 DAP

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

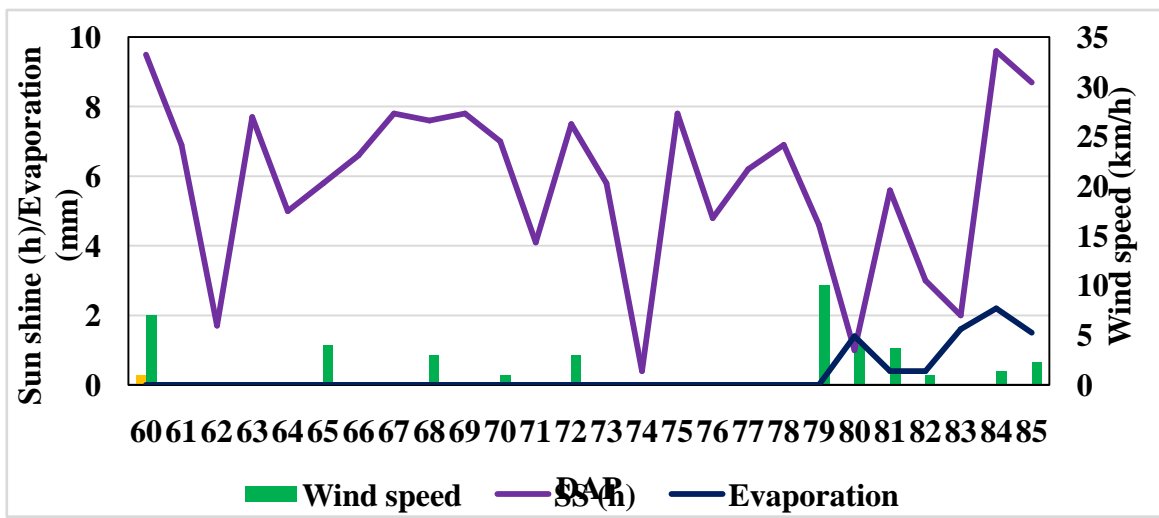
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379 **Figure 3. Wind speed with sunshine hour and evaporation during broccoli growth**
 380 **duration of (a) 30 DAP to 59 DAP; and (b) 60 DAP to end of harvesting (85 DAP)**

381 **4. CONCLUSIONS**

382 This study focuses on the impacts of irrigation and mulching techniques, offering significant
 383 findings with implications for sustainable agriculture. Drip irrigation proved superior to
 384 surface irrigation, enhancing broccoli growth, particularly plant height and leaf numbers.
 385 Black polythene mulch emerged as the most effective choice, significantly improving plant
 386 characteristics. The combination of drip irrigation and black polythene mulch consistently



387 yielded the best yield and water use efficiency results, emphasizing the need for optimized
388 practices. The study also highlights the intricate relationship between environmental factors
389 like temperature, humidity, wind speed, sunshine hours, and broccoli growth, which are
390 essential for effective cultivation strategies. In regards to global water scarcity and climate
391 change, this research provides actionable insights for sustainable broccoli production.
392 Bridging the knowledge gap on irrigation methods and mulching materials is vital, offering
393 valuable guidance to researchers and farmers alike, especially in water-scarce
394 environments. The study advances broccoli cultivation and sustainable agriculture practices,
395 emphasizing tailored irrigation and mulching strategies to optimize yield and water efficiency,
396 promoting food security and agricultural sustainability.

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401 **COMPETING INTERESTS**

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

403 **AUTHORS' CONTRIBUTIONS**

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

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