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Improving yield and heat use efficiency of broccoli (*Brassica oleracea* L. var *italica*) grown under abiotic stresses in the mid-hill of Himachal Pradesh

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Abstract

A field experiment was conducted in the mid-hill zone of Himachal Pradesh representing the sub-humid zone to study the phenological behaviour and heat use efficiency of broccoli crop under abiotic stresses. The broccoli variety (Sakata) was evaluated under three thermal environments (T_1- 8th October, T_2 -28th October and T_3- 18th November). To expose the crop to different thermal environments, two mulching levels (M_1-with black mulch and M_2- without mulch) and two irrigation levels (I_1- Irrigation at different phenological stages I_2- rainfed conditions) were applied during *rabi* season of 2021-22. The experiment was laid out in a factorial randomized complete block design with three replications. Different agroclimatic indices were computed *viz*., accumulated growing degree days, helio-thermal units, photothermal units and heat use efficiency. The regression models were developed between the agroclimatic indices, yield and dry matter accumulation of crop. It was found that the broccoli crop sown on 28th October (the normal date of transplanting) took maximum (132) days to reach maturity. The number of days required to attain different phenological stages decreased with delayed sowing. The accumulated growing degree days requirement at the harvesting stage (921.4 ºC day) was observed maximum in timely transplanted (28th October) crop resulting in a higher yield per plot (10.4 kg) and decreased with late transplanted (18th November) crop. The crop utilized heat more efficiently under a timely sown crop. The highest heat use efficiency (HUE) was observed in the crop sown on 28th October and 8th October (27.37 and 25.35 kg/ha/°C/day), respectively. The regression models were developed between curd yield, dry matter accumulation and thermal units of the crop. The model explained 0.50, 0.44 and 0.47 variations in curd yield whereas 0.69, 0.58 and 0.63 variations in dry matter accumulation with different agroclimatic indices under different transplanted dates, mulching and irrigation levels, respectively. Broccoli cultivation yielded a profit of ₹5.17 lakhs/ha, demonstrating its profitability for farmers. The study highlighted that timely sowing, black mulch, and optimal irrigation significantly improved heat utilization efficiency in mid-hill sub-humid regions. Black mulch improved soil moisture and temperature, creating ideal conditions for broccoli, a thermo-sensitive crop.

Key words: Mid-hill, agroclimatic indices, heat use efficiency, regression models, yield, broccoli, benefit-cost ratio

Introduction

Originating in the Mediterranean and East Asia, broccoli is grown worldwide, especially in China, India, the United States, Spain, Mexico, and Italy. In India, broccoli is grown mostly in the mountainous areas of the Nilgiri Hills, Himachal Pradesh, Uttar Pradesh, J&K, and the Northern plains. China is the world's largest producer of broccoli, while India ranks second. According to FAOSTAT (2020), broccoli is grown on over 4.5 lakh hectares of land in India, producing 8.8 metric tons. Ideal growth conditions for broccoli entail exposure to an average daily temperature of 17 to 23°C. Specific temperature ranges are crucial for different stages of its growth cycle: 12-16°C for seed germination, 18-23°C for vegetative growth, and 12-18°C for head development. Deviations from these optimal temperature ranges can delay maturity and result in the production of poor-quality sprouts.

The timing of planting is crucial for maximizing broccoli yield and biomass. Phenological development correlates with the accumulation of heat units above a threshold temperature. During the greenhead development stage, extremely high temperatures can cause bolting and harm crop production and productivity. Crop output is impacted by late transplanting because it exposes the crops to high temperatures during crucial growth phases. For instance, Gogoi *et al.* (2016) found that in Assam, late sowings failed to produce viable seeds, with significant differences in head yield observed among planting dates, ranging from 137.81 q/ha to 6.75 q/ha. Singh and Kumar (2017) found that the maximum yield of 24.75 q/acre, was achieved using black mulch. The microclimate that surrounds the broccoli crop, which varies from the soil surface to the canopy, has a big impact on its growth and productivity. Pineda *et al.* (2024) found that a moderate increase in temperature would not reduce broccoli crop yields. Dark mulches have been shown to enhance broccoli growth and yield compared to light-coloured mulches, as they maintain optimum soil temperatures.

Agroclimatic indices based on temperature, like heat use efficiency (HUE), helio-thermal units (HTU), and growing degree days (GDD), are useful indices for forecasting crop output and growth. The ambient temperature and crop physiological changes controlled by hormone activity have an impact on the cumulative GDD demand. Dhankhar and Chandanshive (2017) concluded that understanding the requirements and utilization of different agrometeorological indices by broccoli crops can aid in predicting crop performance. Numerous studies have shown that crop yield depends on the use of fertilizer. The current study was carried out to assess the phenology, heat unit requirement, and heat use efficiency of broccoli under various thermal regimes, mulching, and irrigation practices in the mid-hill sub-humid zone of Himachal Pradesh, given the necessity to improve crop heat use efficiency in the face of global warming scenarios. The heat use efficiency and mulching in broccoli under stress in mid-hill climates is lacking. Applying different biofertilizers had a substantial impact on the green curd diameter performance (Meena *et al.,* 2020). Kumar *et al.* (2024) concluded that the use of FYM@ 25 t/ha using biofertilizers was found to higher curd yield of 109.57 q/ha. Sai *et al.* (2024) recommended that the combined use of FYM and vermicompost significantly improves broccoli growth. The present study aims to grow broccoli using black mulching and only FYM with a better cost-benefit ratio mitigating climate stresses. It also reduces the toxicity of pesticides. This study aims to evaluate the phenology and HUE of broccoli under varying transplant timings, mulching, and irrigation practices.

Materials and methods

Site characteristics: The study was carried out in the field in 2021-2022, at the Research Farm, Department of Environmental Science, Dr. YSP University of Horticulture and Forestry, Nauni, Solan, Himachal Pradesh.

Climate: A zone II sub-tropical to sub-temperate climate prevails in the region. The region's annual average temperature range (T_{max} and T_{min}), relative humidity, sunshine hours, and rainfall are 25.3°C, 11.4°C, 61%, 7.7 hours, and 111.9 cm, respectively. at an elevation of 1275 meters above sea level, with latitudes of 30.52 degrees North and longitudes of 77.11 degrees East.

Soil analysis: The experimental field conditions have moderate drainage conditions. The soil's different chemical and physical properties before transplanting were analysed (Pooran *et al.,* 2024). The soil colour was deep brown, soil texture (loam), pH (7.5), electrical conductivity (EC) 0.711µs/cm, organic carbon (OC) 1.77%, bulk density (BD) 1.32 Mg/m^3, particle density (PD) 2.63 Mg/m^3, porosity 49.65%, and water holding capacity (WHC) 52%. Various soil parameters, methods of estimation and references are presented in (Table 1).

Plot management and treatments: The crop nursery was sown on 12th September, 2nd October and 23rd October. The crop was transplanted on 8th October, 28th October and 18th November with two mulching and irrigation during 2021-22 (Table 2). The design of the experiment was a randomized complete block design. The FYM was provided @ 10 kg/bed 45 days after transplanting. No fertilizers and pesticides were provided for broccoli production. About 4.05 m^2 of the plot was covered with the UV-resistant black plastic mulch. Depending on the weather, manual irrigation was administered every 20 days. There were 12 treatments with 3 replications and control.

Agroclimatic indices

Growing degree days (GDD): The following formula was used to determine the growing degree days for each phenophase:

$$\text{GDDs } (°\text{C day}) = \frac{(\text{Tmax} + \text{Tmin})}{2} - \text{Tb}$$

Table 1. Details of the analytical methods followed before transplanting

Soil characteristics	Method of estimation	Reference
pH	pH meter (1:2.5 soil: water)	Jackson (1973)
Electrical conductivity	EC meter (1:2.5 soil: water)	Jackson (1973)
Organic carbon	Walkley and Black method	Walkley and Black wet Oxidation method (1934)
Bulk density	Core sampler method	Blake and Hairtge (1986)
Particle density	Pycnometer method	Blake and Hairtge (1986)
Porosity	One minus ratio of bulk density to particle density multiplied by 100	Blake and Hairtge (1986)
Water holding capacity	International pipette method	Piper 1966

Table 2. Treatment details concerning the date of transplanting, mulching, and irrigation conditions

Code	Treatments
$T_1M_1I_1$	Main season transplanting (8th Oct) + Mulch + Irrigation
$T_1M_1I_2$	Main season transplanting (8th Oct) + Mulch + Rainfed
$T_2M_1I_1$	Mid-season transplanting (28th Oct) + Mulch + Irrigation
$T_2M_1I_2$	Mid-season transplanting (28th Oct) + Mulch + Rainfed
$T_3M_1I_1$	Late season transplanting (18th Nov) + Mulch + Irrigation
$T_3M_1I_2$	Late season transplanting (18th Nov) + Mulch + Rainfed
$T_1M_2I_1$	Main season transplanting (8th Oct) + No Mulch + Irrigation
$T_1M_2I_2$	Main season transplanting (8th Oct) + No Mulch + Rainfed
$T_2M_2I_1$	Mid-season transplanting (28th Oct) + No Mulch + Irrigation
$T_2M_2I_2$	Mid-season transplanting (28th Oct) + No Mulch + Rainfed
$T_3M_2I_1$	Late season transplanting (18th Nov) + No Mulch + Irrigation
$T_3M_2I_2$	Late season transplanting (18th Nov) + No Mulch + Rainfed

T_1 = Transplanting first, M_1 = Mulching, I_1 = Irrigation. $_2$ = Transplanting second, M_2 = No mulching, I_2 = No Irrigation. T_3 = Transplanting third

T_b is the base temperature which is 5°C for the crop

Helio-thermal units (HTU): The calculation for the Helio-thermal units was done using following formula:

HTU = Growing Degree Days × Actual Hours of Bright Sunshine (°C Day Hours)

Photo-thermal units (PTU): Calculating the Photo Thermal Units was calculated as:

PTU = Growing Degree Days × Length of Day (°C of the day)

Heat use efficiency (HUE): The efficiency of heat use was determined as

$$\text{HUE (kg/ha/°C day)} = \frac{\text{(Head fresh weight) (kg/ha)}}{\text{AGDD (°C day)}}$$

Benefit-cost ratio: The total production cost (₹ ha^{-1}) was calculated by summing all input and operating costs. Gross returns were obtained by multiplying the yield by current market rates (₹ ha^{-1}). Net returns were determined by subtracting the cost of cultivation from gross returns, and the benefit-cost ratio was calculated by dividing net returns by the cost of cultivation for each treatment.

Results and discussion

Crop phenology: Compared to early transplanted crops (8 October) and late transplanted crops (18 November), the crop transplanted on October 28 took 132 days, the highest number of days from the vegetative to maturity stage, as shown in Table 3. The crop planted on 28th October meets the optimum environmental conditions. Early head development without enough vegetative growth due to a temperature rise might have resulted in a lower number of days accumulated by the late sown crop, thus smaller heads leading to the decreased yield, which was also observed by Karistsapol *et al.* (2013).

Table 3. Number of days taken by each phenophases of broccoli

Treatment	Crop phenology			
	Vegetative	Heading	Harvesting	Yield/plot
T_1	49.00	72.00	104.00	8.58
T_2	65.00	112.00	132.00	10.44
T_3	55.00	71.00	94.00	6.35
SE (m) ±	0.31	0.24	0.29	0.09
C.D 0.05	0.90	0.71	8.86	0.26
M_1 (Mulching)	58.00	85.00	111.00	9.71
M_2 (No Mulching)	55.00	84.00	109.00	7.20
SE (m) ±	0.25	0.20	0.24	0.07
C.D 0.05	0.73	0.58	0.70	0.21
I_1 (Irrigation)	57.00	85.00	110.00	9.16
I_2 (No Irrigation)	56.00	84.00	109.00	7.75
SE (m) ±	0.25	0.20	0.24	0.07
C.D 0.05	0.73	0.58	0.70	0.21
Interaction (Tx M)				
C.D 0.05	NS	NS	NS	0.37
Interaction (Tx I)				
C.D 0.05	NS	NS	NS	0.37
Interaction (Mx I)				
C.D 0.05	NS	NS	NS	NS
Interaction (TxMxI)				
C.D 0.05	NS	NS	NS	0.52

The number of days needed for the start and finish of different phenological events was significantly influenced by mulching and irrigation levels. The maximum number of days attained with the application of mulching (M_1) and irrigation level (I_1) by the crop at each phenological stage as mulching helps to reduce weed growth, maintain soil temperature and moisture, and also helps to produce healthier plants and enhance the yield of the crop. Islam *et al.* (2023) found that mulch-assisted irrigation increased plant heights, but it was marginally shorter than drip irrigation. Patra *et al.* (2022) found that drip irrigation and black polyethylene mulch increased the yield of broccoli. Broccoli growth and yield increased by using mulches and biofertilizers (Thangjam *et al.,* 2024).

Agro climatic indices

Growing degree days: The thermal requirement of different treatments from the vegetative to the harvesting stage was presented in Table 4-6. The accumulated growing degree days, helio-thermal unit and photo-thermal units' requirement at the harvesting stage (921.4 ºC day, 7248.74 ºC and 10031.5 ºC day hr) was observed maximum in timely transplanted (28th October) crop resulting in a higher yield per plot (10.4 kg) and decreased with late transplanted (18th November) crop. The less accumulation of growing degree days of 569.8 (ºC day) decreases the yield with 6.35 kg/plot transplanted on 18th November. The yield difference is of 4.05 kg/plot. The 28th October crop accumulated 351.6 ºC days more heat units than the late transplanted crop. All indices' values were found to be maximum with the application of mulch M_1 and irrigation level I_1 at different phenological stages. The less accumulation of GDD in late transplanted crops might be due to a smaller number of days taken at different crop phenological stages. Temperatures above 20°C during harvest were shown to have led to the development of loose broccoli heads. Prevailing a suitable temperature range of 13-18 °C after transplanting can be attributed to better vegetative growth in October sown crop. On the other hand, 20th November and 10th December sowing produced negligible or no seed formation of broccoli crops (Ahmed and Siddique, 2004). Dhankar and Chandanshive (2017) also observed that crops transplanted later experienced shorter growing periods and accumulated fewer heat units compared to those transplanted earlier. The results also indicated that applying black polyethylene mulch to the soil helps to buffer against low night temperatures in December-January. The black mulch always

Table 4. Accumulated growing degree days (°C day) from vegetative to maturity under different transplanting dates, mulching, and irrigation levels during the *rabi* season of 2021-222 of broccoli crop

Treatment	Accumulated growing degree days			Yield/plot (kg)
	Vegetative	Heading	Harvesting	
T_1	576.84	749.74	921.38	8.58
T_2	525.50	765.08	940.10	10.44
T_3	361.77	437.60	569.86	6.35
SE (m) ±	4.78	1.15	2.66	0.09
C.D 0.05	14.02	3.37	7.80	0.26
M_1	494.27	654.40	816.75	9.71
M_2	481.81	647.21	804.14	7.20
SE (m) ±	3.90	0.94	2.17	0.07
C.D 0.05	11.45	2.75	6.37	0.21
I_1	489.14	652.39	816.75	9.16
I_2	486.93	642.22	804.14	7.75
SE (m) ±	3.90	0.94	2.17	0.07
C.D 0.05	NS	2.75	6.37	0.21
Interaction (Tx M)				
C.D 0.05	NS	NS	NS	0.37
Interaction (Tx I)				
C.D 0.05	NS	NS	NS	0.37
Interaction (Mx I)				
C.D 0.05	NS	3.89	NS	NS
Interaction (TxMxI)				
C.D 0.05	NS	NS	NS	0.52

Table 5. Accumulated helio-thermal units (°C day hr) from vegetative to maturity under different transplanting dates, mulching, and irrigation levels during the *rabi* season of 2021-222 of broccoli crop

Treatment	Accumulated helio-thermal units			Yield/plot (kg)
	Vegetative	Heading	Harvesting	
T_1	5179.51	6237.97	7248.74	8.58
T_2	4219.38	5779.50	6926.32	10.44
T_3	2427.11	2800.57	3939.68	6.35
SE (m) ±	17.96	9.88	22.07	0.09
C.D 0.05	52.69	28.98	64.75	0.26
M_1	4003.90	4909.34	6111.38	9.71
M_2	3880.10	4969.36	5965.11	7.20
SE (m) ±	14.67	8.07	18.02	0.07
C.D 0.05	43.02	23.66	52.87	0.21
I_1	3967.39	4950.80	6084.23	9.16
I_2	3916.62	4927.89	5992.26	7.75
SE (m) ±	14.67	8.07	18.02	0.07
C.D 0.05	43.02	NS	52.87	0.21
Interaction (Tx M)				
C.D 0.05	NS	NS	91.57	0.37
Interaction (Tx I)				
C.D 0.05	NS	NS	NS	0.37
Interaction (Mx I)				
C.D 0.05	NS	NS	NS	NS
Interaction (TxMxI)				
C.D 0.05	NS	NS	NS	0.52

gives better results during the winter season in the mid-to-high hill zone of HP. The lower soil temperatures with no mulching to the crop appear to be the main reason for the lower yields of broccoli. Mulching is also a good way to conserve moisture in the soil.

Table 6. Accumulated photo-thermal units (°C day hr) from vegetative to maturity under different transplanting dates, mulching, and irrigation levels during the *rabi* season of 2021-222 of broccoli crop

Treatment	Accumulated photo-thermal units			Yield/plot (kg)
	Vegetative	Heading	Harvesting	
T_1	6606.78	8306.20	10031.55	8.58
T_2	7941.81	8022.13	9926.56	10.44
T_3	7132.13	4482.84	5843.28	6.35
SE (m) ±	24.83	11.80	27.70	0.09
C.D 0.05	72.84	34.62	81.26	0.26
M_1	7336.46	6976.07	8700.23	9.71
M_2	7117.36	6898.04	8500.69	7.20
SE (m) ±	20.27	9.64	22.62	0.07
C.D 0.05	59.47	28.27	66.35	0.21
I_1	7272.29	6951.35	8660.67	9.16
I_2	7181.52	6922.76	8540.26	7.75
SE (m) ±	20.27	9.64	22.62	0.07
C.D 0.05	59.47	28.27	66.35	0.21
Interaction (Tx M)				
C.D 0.05	NS	NS	NS	0.37
Interaction (Tx I)				
C.D 0.05	NS	NS	NS	0.37
Interaction (Mx I)				
C.D 0.05	NS	NS	NS	NS
Interaction (TxMxI)				
C.D 0.05	NS	NS	NS	0.52

Heat use efficiency: The heat use efficiency of broccoli for the 2021-2022 growing season under various sowing dates, mulching, and irrigation levels are depicted in Table 7. The crop sown on 28th October had significantly highest heat use efficiency (HUE) (27.37 Kg/ha/°C/day) followed by 8th October (25.37 Kg/ha/°C/day), transplanted crop and significantly lowest heat use efficiency was observed under 18th November (24.56 Kg/ha/°C/day) sown crop at during the year 2021-22. The heat use efficiency was maximum with the application of mulch M_1 (27.71 Kg/ha/°C/day) and irrigation level I_1 (26.38 Kg/ha/°C/day). The efficiency of thermal energy conversion for curd yield depends upon sowing dates, time of head initiation, and maturity and accomplishment of different stages. Early planted crops resulted in longer duration and produced taller plants with a greater number of leaves, higher plant spread and more leaf area index as well as the lowest percentage of abnormal curds than late-planted crops and finally attributed to higher curd yield. Mulching insulates the soil, keeping it slightly warmer, which protects the broccoli roots from frost damage. This helps farmers avoid losses and ensures that the plants grow consistently through winter. As noted by Karistsapol *et al.* (2013), early head development without vegetative growth brought on by a temperature increase may have led to less heat accumulation.

Regression relationship between thermal units, curd yield, and dry matter accumulation of broccoli: The regression models were developed between curd yield, dry matter accumulation, and thermal units of the crop as depicted in Fig. 1. The thermal units consumed for curd yield for the year 2021-22 expressed positive association values. The model explained 0.50, 0.44, and 0.47 variations in curd yield whereas 0.69, 0.58, and 0.63 variations in dry matter accumulation with accumulated growing degree days,

Table 7. Heat use efficiency (kg/ha/°C day) under different transplanting dates, mulching and irrigation levels of broccoli crops during the *rabi* season of 2021-22

Treatment	Heat use efficiency
T_1	25.35
T_2	27.37
T_3	24.56
SE (m) ±	0.531
C.D 0.05	1.10
M_1	27.71
M_2	23.75
SE (m) ±	0.433
C.D 0.05	0.899
I_1	26.88
I_2	25.59
SE (m) ±	0.750
C.D 0.05	1.557

helio-thermal and photo-thermal units under different transplanted dates, mulching and irrigation levels, respectively. Thus, different agroclimatic indices requirement and their efficient utilization by broccoli crops can be used to predict the performance of the crop in a particular region depending upon the thermal environment. The crop sown at an optimum time grows in ideal conditions, enhancing its quality in terms of size, colour, taste, and nutrient content, as higher-quality produce fetches better market prices. Meena *et al.* (2023) also discussed that due to maximum leaf area index and higher photosynthetically active radiation, and proper maintenance of soil moisture, increases the dry matter production and enhance the curd yield of broccoli crops during timely transplanted crop that delayed transplanting of crops.

Benefit-cost ratio: The cultivation expenses for broccoli encompass various inputs such as ploughing, seed material, black plastic mulching, farmyard manure (FYM) and labor cost. The total cost of cultivation is ₹ 197,493.46, gross cultivation (₹ 12,18,336) and net return of ₹ 10,20,842.54 (Table 8). The profit is ₹ 5.16899 ha^{-1} with a significant BCR of 4.49 during the 2021-22 *rabi* crop season with no fertilizers or pesticides utilized in broccoli production indicating substantial returns on investment. For comparison, during their research on broccoli growth, Srichandan *et al.* (2015) achieved a BCR of ₹ 3.45 with a yield of 149.43 q/ha. Similarly, Ferdousi *et al.* (2014) recorded a BCR of ₹ 3.32, while Santosh *et al.* (2018) obtained a BCR of ₹ 2.81 in their respective studies.

Table 8. Broccoli production cost and gross return (₹)

Paramater	Value
Plot area (ha)	0.0158
Ploughing	500.00
Seed material	702.00
Mulching	511.00
FYM	780.00
Labour	1,000.00
Total cost	3,493.00
The gross return	19,200
Profit in field trial	15,707
Profit in one hectare of broccoli plot	5.17 lakhs
BCR:	4.49

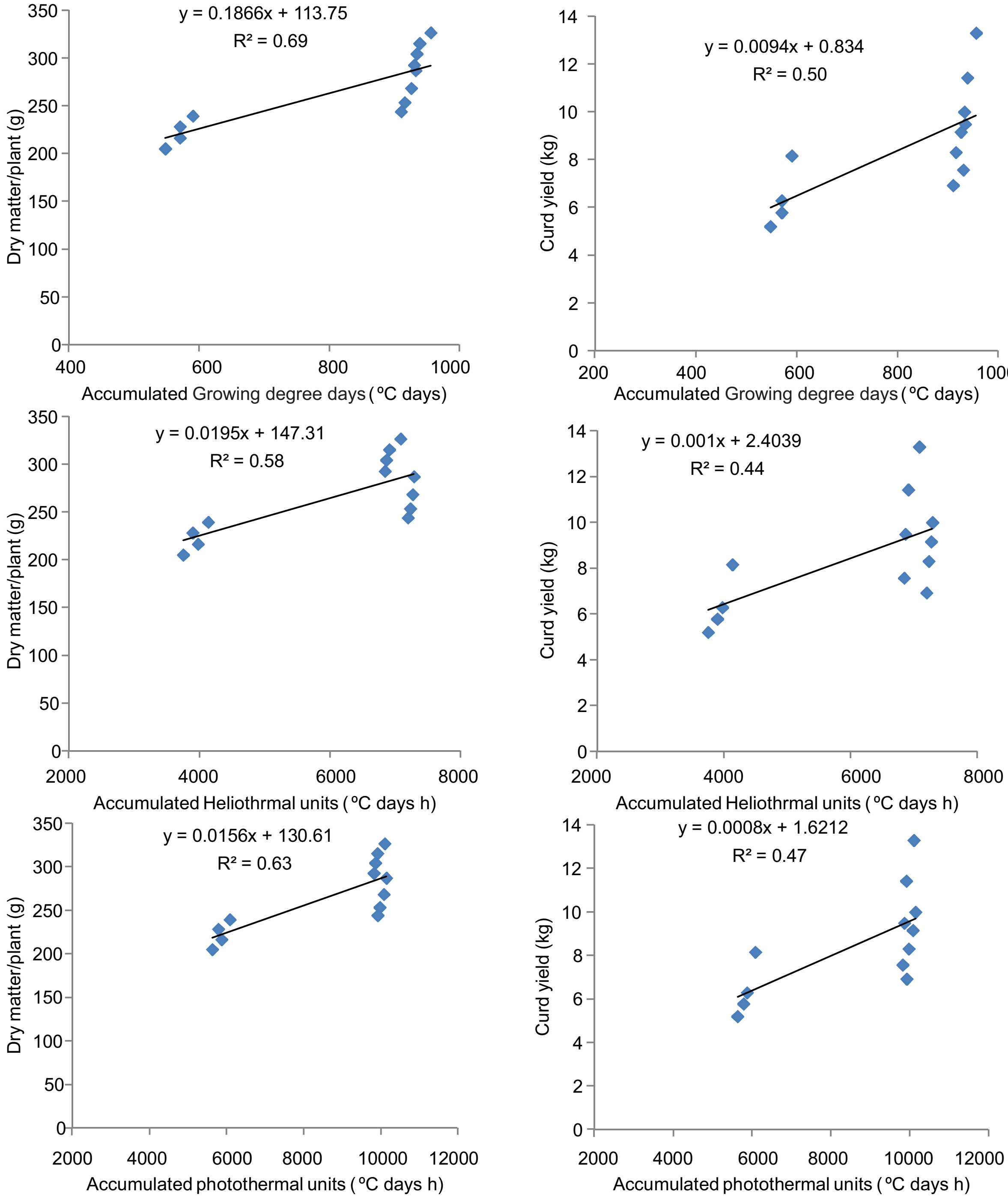

Fig. 1. Regression relationship between accumulated growing degree days and helio-thermal units, curd yield and dry matter accumulation of broccoli

Considering broccoli's remarkable yield of 2kg/sqm without resorting to fertilizers or chemicals and its high BCR, transitioning to broccoli cultivation could enable farmers to avoid bank loans and secure better market prices. It indicates that the broccoli estimated production benefits significantly outweigh its costs. Furthermore, this shift aligns with the United Nations Sustainable Development Goal 12, fostering sustainable consumption and production patterns.

The crop transplanted on 28th October took maximum days and accumulated the highest GDDs and PTUs, which got reduced significantly with the subsequent delay in transplanting time and recorded the lowest value on the 18th November transplanted crop. There was a decline in yield with a delay in the transplanting of crops. The crop that was transplanted on time showed superior heat unit accumulation and usage. The study concluded that timely transplanting of broccoli (28th October) along with mulching and optimal irrigation schedule led to more efficient heat utilization. Consequently, implementing appropriate transplanting timing and irrigation schedules emerges as a promising strategy to enhance both the quality and quantity of broccoli yields, particularly in the context of global warming scenarios. The benefit-cost ratio was ₹ 5.17 ha^{-1}, indicating substantial returns on investment. Considering broccoli's remarkable yield of 2kg/sqm without resorting to fertilizers or chemicals, along with its high BCR, transitioning to broccoli cultivation could enable farmers to avoid bank loans. By improving yield and reducing resource requirements like water and labour, these practices can lead to higher profitability for farmers. With higher market demand for broccoli, particularly in urban areas, farmers stand to gain financially.

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