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Thermal Response of Spring–Summer-Grown Black Gram (*Vigna mungo* L. Hepper) in Indian Subtropics

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Abstract: The thermal environment of a crop is one of the prime factors enhancing growth and production by regulating its physiological processes at different phenophases. To study the impact of thermal regime on spring–summer-grown black gram (variety Pant Urd 31), an experiment was conducted with different sowing dates (from the first to the third week of March), soil application of cobalt (Co) and foliar sprays of potassium (K) and boron (B) in various combinations in the split–split plot design during 2020 and 2021. The first-week-of-March-sown crop recorded more accumulated growing degree-days (GDD), photothermal units (PTU) and heliothermal units (HTU) with a longer duration than the later sown crop. Higher daily mean temperature during the reproductive stage of the later sown crop compelled it to complete the phenophases earlier than the normally sown crop, leading to yield reduction. Soil application of Co at 4 kg ha^{-1} and foliar sprays of K at 1.25% and B at 0.2% mitigated the adversities of excess heat irrespective of sowing dates. Variations in GDD and HTU, respectively, explained variations of about 75.8% and 87.3% in the final dry matter accumulation and of 72.9% and 84.8% in seed yield through polynomial regressions in the respective years. The maximum mean thermal use efficiency (TUE) for biomass production (0.24 g m^{-2}/°C/day^{-1}) and seed yield (0.11 g m^{-2}/°C/day^{-1}) were observed with Co soil application and combined foliar sprays of K and B due to higher dry matter production or seed yield with lower heat units accumulation in the first sown crop.

Keywords: black gram; thermal requirement; growing degree-days; photothermal unit; heliothermal unit

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1. Introduction

The physiological processes of any crop are immensely dependent on various microclimatic parameters irrespective of the region [1–3]. Among them, air temperature, day length, and duration of bright sunshine take important stands to impose exuberant impacts on crop plant growth and yield, which are closely related to their phenological behaviour [4,5]. The duration of a crop's different phenophases, as well as its maturation time, are largely determined by the temperature and photoperiodic conditions it endures over its entire growing period [6,7]. In fact, the thermal environment exercises a fantastic role to determine the accumulation of dry matter and its subsequent partitioning in other parts from the crop growth point of view [8] by playing a pivotal role in various physicochemical and biological processes of crop plants [9].

The rising air temperature has been reported to bring about a considerable shift in distribution and growing periods of crops [10]. Prevalence of higher temperatures was reported earlier to bring about a series of morphophysiological, biochemical, and reproductive alterations in field crops, severely affecting their production economics [11–13]. This heat stress is especially pertinent in the reproductive phase of grain legumes for reduction of flower production, pollen viability, and fertilization, pod set and seed filling and ultimately curtailment in seed yield [14,15].

Exposure to a higher daily means temperature well above the optimum during the window from the end of February to the middle of June is extremely severe in terms of crop growth. In this context, estimation of accumulated heat requirements of a crop in light of growing degree-days (GDD), photothermal units (PTU) and heliothermal units (HTU) is useful to characterize the thermal response of crops [16,17]. The overall requirements of cumulative heat units are governed by the physiological stage of the crop as well as by the ambient temperature [18]. However, quantification of thermal use efficiency (TUE) is of great concern for realizing the production potential of a crop grown under varied agroclimatic conditions [19].

Black gram is an important short-duration, hardy, and stress-resistant legume crop of India grown in the summer [20,21]. Although the crop can thrive at up to 42 °C, the optimum temperature for its growth ranges between 25 °C and 32 °C [22]. Being a short-day plant, black gram is also sensitive to photoperiodic alterations [23]. Sowing of the black gram crop at the optimum time ensures proper harmony between its vegetative and reproductive phases [6], which eventually substantiates the optimum yield potential of the crop [2,24]. Besides, this crop suffers from several physiological drawbacks [25–27], e.g., inappropriate canopy structure [28], photothermal sensitivity [29], imbalanced partitioning of photoassimilates and lower photosynthesizing capacity [30], premature flower and pod abscission [31], poor pod set [32], etc. Hence, improvement in assimilate production along with a delay in senescence of reproductive parts are the major areas to be focused on regarding black gram cultivation.

Numerous research efforts have established the indispensable role of the nutrient elements, i.e., of cobalt (Co), potassium (K), and boron (B) in the overall growth of pulse crops. Exogenous application of nutrients has already been documented as a potent tool to mitigate the deleterious effects of heat stress [33]. Cobalt is involved with vital physiological and biochemical functions in plants [34], especially the synthesis of the leghemoglobin protein required for rhizobial activity in legumes and subsequent nitrogen fixation manifesting momentous impact on enzyme systems [35,36]. Cobalt increases amino acid and antioxidant enzymes like SOD content [37]. Side-by-side increment of drought resistance and inhibition of ethylene biosynthesis in legume crops through application of cobalt has also been reported [38]. Potassium functions as a catalytic agent in the activation of various enzymes while facilitating assimilate translocation and maintaining osmoregulation in plants [39]. Specifically, it eliminates water imbalances in plants. Potassium prevents stress-induced accumulation of reactive oxygen species (ROS) [40]. Besides, it acts as a catalytic agent in activating several enzymes, synthesis of peptide bonds and phosphate group transferases [41]. Boron is associated with sugar transportation, photosynthetic activity, pollen germination, formation of flowers, and seed development of pulse crops [42]. It is technically associated with cell wall structure and membrane integrity as well as carbohydrate transport in plants' life [43]. It also regulates protein and nucleic acid metabolism. Boron has been found to be very essential for photosynthetic activity, pollen germination, formation of flowers, and seed development of pulse crops [44]. In the context of black gram, however, no sufficient documentation has been found to analyze the combined influence of sowing dates and these specific plant nutrients on agrometeorological indices. This research was a holistic attempt to determine the best sowing date and nutrition schedule for a spring–summer-grown black gram crop taking into account its thermal requirements and use efficiency in the Indian subtropics.

2. Materials and Methods

2.1. Location Details

The experiment on black gram was conducted during two consecutive spring–summer seasons of 2020 and 2021 in a split–split plot design replicated thrice at District Seed Farm, 'A–B' block (22° 93′ N, 88° 53′ E, 9.75 m above mean sea level), Kalyani, Bidhan Chandra Krishi Viswavidyalaya (BCKV), West Bengal, India. The location is very popular for legume husbandry and has been allotted for various research works of the university related to pulse crops for many years. Thus, the site was considered to be sufficiently suitable for conducting this experiment. The principal features of the site regarding meteorological and soil properties are elucidated later on.

2.2. Experimental Soils and Weather Conditions

The details of the soil of the research plots are depicted in Table 1.

Table 1. Soil properties of the experimental site.

Soil Properties	Content	
	2020	2021
Sand (%)	65.61	64.65
Silt (%)	17.86	18.25
Clay (%)	16.53	17.1
pH	7.5	7.4
Bulk density (g/cm^{-3})	1.26	1.25
Organic carbon (%)	0.52	0.52
Available nitrogen (kg/ha^{-1})	263.56	264.15
Available phosphate (kg/ha^{-1})	38.17	39.72
Available potassium (kg/ha^{-1})	195.43	197.92
Available cobalt (ppm)	9.18	9.31
Available boron (ppm)	0.46	0.45

The daily data of meteorological parameters with respect to the maximum and minimum temperature and duration of bright sunshine at Kalyani for the overall period of experimentation (from 2 March to 3 June 2020 and from 1 March to 30 May 2021) encompassing both sowing dates in the spring–summer season were collected from the All India Coordinated Research Project (AICRP) on Agrometeorology, Bidhan Chandra Krishi Viswavidyalaya (BCKV), West Bengal, India. The thermal regimes during the whole growing period covering both dates of sowing in 2020 and 2021 are presented graphically in Figure 1 and Table 2.

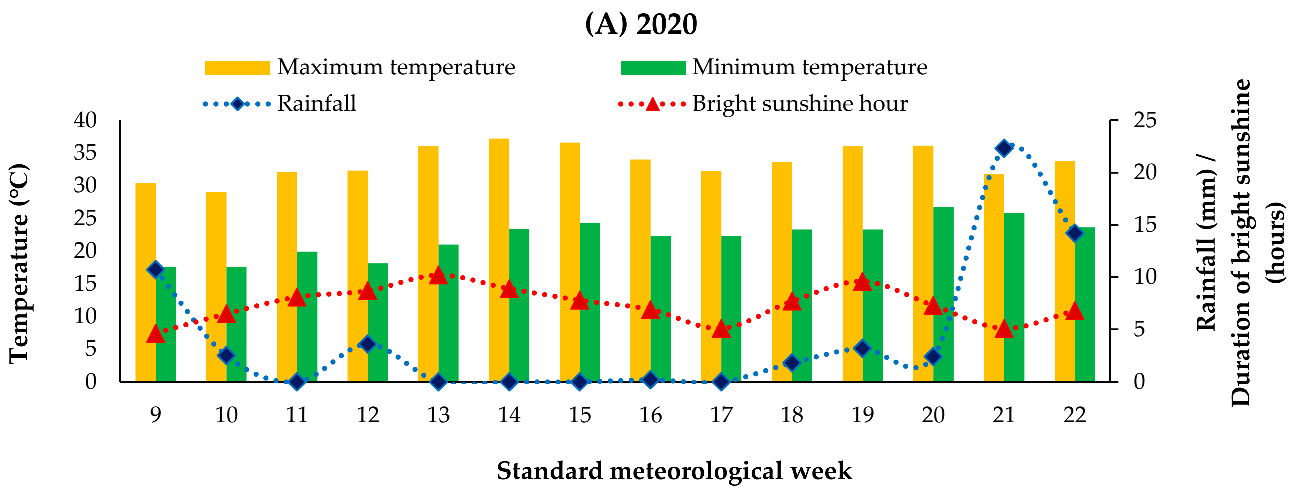

Figure 1. *Cont.*

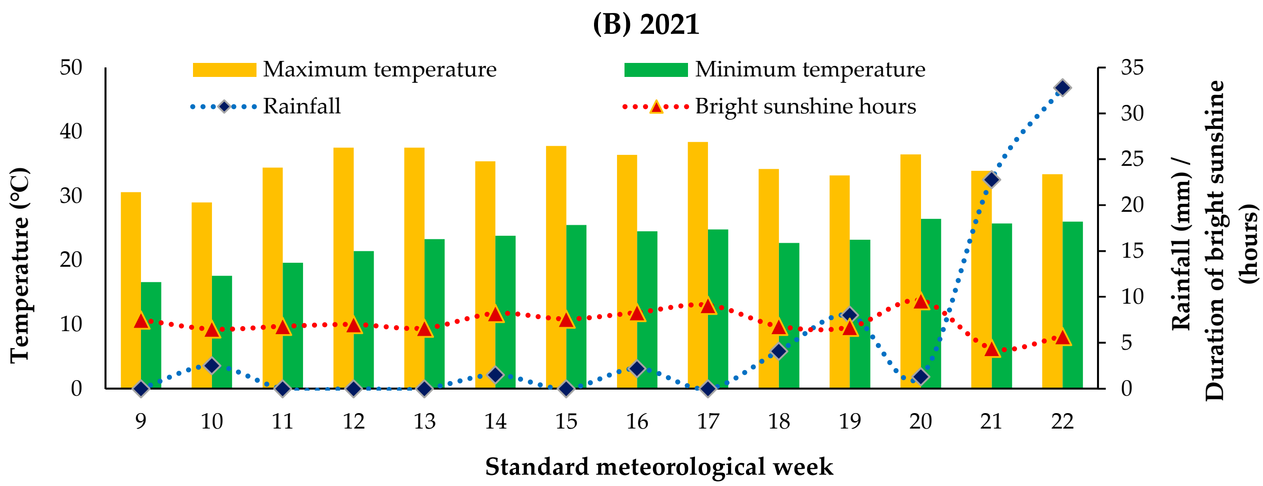

Figure 1. (**A**,**B**) Thermal regimes of the experimental site during the entire growing period of black gram during the spring–summer season in 2020 and 2021.

Table 2. Day lengths at the experimental site during the entire growing period of black gram during the spring–summer season in 2020 and 2021.

Day Length (hours)								
Date	**March**		**April**		**May**		**June**	
	2020	**2021**	**2020**	**2021**	**2020**	**2021**	**2020**	**2021**
1	–	11.5	12.2	12.2	12.9	12.9	13.3	–
2	11.6	11.5	12.3	12.2	12.9	12.9	13.3	–
3	11.6	11.6	12.3	12.3	12.9	12.9	13.3	–
4	11.6	11.6	12.3	12.3	12.9	12.9	–	–
5	11.6	11.6	12.3	12.3	12.9	12.9	–	–
6	11.6	11.6	12.3	12.3	13	12.9	–	–
7	11.7	11.6	12.4	12.3	13	13	–	–
8	11.7	11.7	12.4	12.4	13	13	–	–
9	11.7	11.7	12.4	12.4	13	13	–	–
10	11.7	11.7	12.4	12.4	13	13	–	–
11	11.8	11.7	12.5	12.4	13	13	–	–
12	11.8	11.8	12.5	12.5	13.1	13	–	–
13	11.8	11.8	12.5	12.5	13.1	13.1	–	–
14	11.8	11.8	12.5	12.5	13.1	13.1	–	–
15	11.8	11.8	12.5	12.5	13.1	13.1	–	–
16	11.9	11.8	12.6	12.5	13.1	13.1	–	–
17	11.9	11.9	12.6	12.6	13.1	13.1	–	–
18	11.9	11.9	12.6	12.6	13.2	13.1	–	–
19	11.9	11.9	12.6	12.6	13.2	13.2	–	–
20	12	11.9	12.7	12.6	13.2	13.2	–	–
21	12	12	12.7	12.7	13.2	13.2	–	–
22	12	12	12.7	12.7	13.2	13.2	–	–
23	12	12	12.7	12.7	13.2	13.2	–	–
24	12.1	12	12.7	12.7	13.2	13.2	–	–
25	12.1	12.1	12.8	12.7	13.2	13.2	–	–
26	12.1	12.1	12.8	12.8	13.3	13.2	–	–
27	12.1	12.1	12.8	12.8	13.3	13.3	–	–
28	12.1	12.1	12.8	12.8	13.3	13.3	–	–
29	12.2	12.1	12.8	12.8	13.3	13.3	–	–
30	12.2	12.2	12.9	12.8	13.3	13.3	–	–
31	12.2	12.2	–	–	13.3	13.3	–	–

2.3. Experimental Details

The field experiment was framed in a split–split plot design replicated thrice in a total 720 m^2 area with individual plots sized 4 m × 3 m. It comprised two dates of sowing, viz., D_1, first week of March (2 March 2020 and 1 March 2021), and D_2, the third week of March (16 March 2020 and 15 March 2021), at the main plots, with two soil applications of nutrients, viz. S_1, no cobalt, and S_2, Co at 4 kg/ha^{-1} (as $Co(NO_3)_2$) at the subplots and five foliar sprays at the flower initiation stage, viz. F_1, no spray, F_2, foliar spray with tap water, F_3, foliar spray with K at 1.25% (as muriate of potash), F_4, foliar spray with B at 0.2% (as borax), and F_5, foliar spray with K at 1.25% and B at 0.2% at the sub-subplots. The variety Pant Urd 31 used in this experiment is an eminent variety performing very well in the spring–summer and kharif season with higher yield potential [45]. A detailed description of the crop variety used is presented in Table 3.

Table 3. Variety description.

Black Gram Variety	Parents	Duration	Released from	Year of Release	Specifications
Pant Urd 31	UPU 89-6-7 × 7668/4B	75–85 days	G.B. Pant University of Agriculture and Technology, Pant Nagar, Uttarakhand	2005	Dark green-colored leaves and yellow mosaic disease resistance

2.4. Crop Management

Black gram seeds were sown at 30 cm × 10 cm row spacing in individual experimental plots of 4 m × 3 m at different sowing dates. The recommended dose of fertilizers (20:40:40, $N/P_2O_5/K_2O$ kg/ha^{-1}) was applied at the time of land preparation prior to seed sowing. One-hand weeding was practiced at 25–30 days after sowing in each sowing plot. As the crop faced a bit of rainfall deficit during both spring–summer seasons of 2020 and 2021, every time one pre-sowing irrigation was provided followed by occasional irrigation at a dry interval of 7–10 days up to 30 DAS (pre-flowering) for proper stand establishment. Fungicide spraying including SAAF (mancozeb + carbendazim) at 2.5 g/L^{-1} of water at 25 DAS and insecticide named Chlorantraniliprole 18.5 SC at 0.2 mL/L^{-1} of water at 45 DAS was performed to protect the crop from disease and insect damage.

2.5. Data Collection and Collection Procedures

The phenophases (viz. emergence, flower initiation, pod initiation, and maturity) of black gram at two different sowing dates were recorded by field inspections at two-day intervals. Growing degree-days were calculated phenophase-wise following the formula of Nuttonson [46]:

$$\text{GDD}\ (^\circ\text{C day}) = \frac{T_{max} + T_{min}}{2} - T_b \quad (1)$$

where T_{max} = daily maximum temperature; T_{min} = daily minimum temperature; T_b = base temperature (10 °C).

Accordingly, photothermal units were determined using the equations proposed by Singh et al. [47]:

$$\text{PTU}\ (^\circ\text{C hour}) = \text{GDD} \times \text{day length} \quad (2)$$

Heliothermal units were estimated using the equations as per Nuttonson [48]:

$$\text{HTU}\ (^\circ\text{C hour}) = \text{GDD} \times \text{duration of bright sunshine} \quad (3)$$

Dry matter accumulation in the aerial portion of the crop was estimated just before harvesting by collecting five random plants from each plot, drying in a hot air oven at the temperature of 80–90 °C for 24–48 h till constant weights were obtained, measuring the dry weight and converting it into g/m^{-2}. The seed yield from each plot (4 m × 3 m) was measured and converted to t/ha^{-1}.

Furthermore, thermal use efficiency at harvest maturity was measured in terms of dry matter accumulation and seed yield using the following formula [49]:

$$\text{TUE}\left(\text{g m}^{-2}\ {}^\circ\text{C day}^{-1}\right) = \frac{\text{Dry matter accumulation during harvest maturity or seed yield}\left(\text{g m}^{-2}\right)}{\text{GDD}\left({}^\circ\text{C day}^{-1}\right)} \quad (4)$$

2.6. Statistical Analysis

Data for dry matter and seed yield were analyzed with analysis of variance (ANOVA) as per the standard method of split–split design [50]. The significant differences between treatments were compared by critical difference at the 5% level of significance. The impact of heat units on the growth and production of black gram was worked out by following the statistical regression technique. Factor-wise statistical significance, interaction effects, as well as treatment-wise coefficient of variation were computed for better understanding of the impact of the factors allotted to different treatments.

3. Results and Discussion

3.1. Phenophase Duration

In general, the onset of phenophases in black gram is mostly governed by the atmospheric temperature. The duration declined with delay in sowing from the first week of March to the third week of March in both years (Tables 4 and 5). On average, black gram sown on the first week of March finished its life cycle in 82 days (Table 5). On the other hand, the crop sown on the third week of March took only 78 days from sowing to maturation. However, the time of maturity significantly varied in the range of 78–86 days and 75–81 days among the different nutrient applied treatments, respectively, in two sowing dates during the first year and those of 76–87 days and 72–84 days, respectively, in the second year (Tables 4 and 5). Values of coefficient of variation (CV) are presented along with the treatment means in Table 4.

Table 4. Effect of the date of sowing, soil application of Co, and foliar spray with K and B on the phenology of black gram during the spring–summer season.

Treatment	Days to Emergence			Days to Flower Initiation			Days to Pod Initiation			Days to Maturity		
	2020	2021	Mean	2020	2021	Mean	2020	2021	Mean	2020	2021	Mean
$D_1S_1F_1$	7 ± 0.08	7 ± 0.09	7	32 ± 0.02	33 ± 0.00	32	39 ± 0.01	42 ± 0.01	40	78 ± 0.01	76 ± 0.01	77
$D_1S_1F_2$	7 ± 0.08	6 ± 0.00	7	32 ± 0.03	33 ± 0.00	33	39 ± 0.00	43 ± 0.01	41	79 ± 0.01	78 ± 0.00	79
$D_1S_1F_3$	7 ± 0.08	7 ± 0.09	7	32 ± 0.05	33 ± 0.02	33	40 ± 0.01	43 ± 0.00	41	80 ± 0.00	81 ± 0.01	80
$D_1S_1F_4$	8 ± 0.07	6 ± 0.00	7	32 ± 0.02	33 ± 0.02	33	41 ± 0.01	44 ± 0.01	43	82 ± 0.01	83 ± 0.01	82
$D_1S_1F_5$	8 ± 0.07	7 ± 0.09	7	33 ± 0.02	35 ± 0.02	34	42 ± 0.01	45 ± 0.00	43	83 ± 0.01	85 ± 0.01	84
Mean	7	7		32	33		40	43		80	81	
$D_1S_2F_1$	6 ± 0.10	5 ± 0.10	6	35 ± 0.02	33 ± 0.02	34	40 ± 0.01	43 ± 0.01	42	81 ± 0.01	79 ± 0.01	80
$D_1S_2F_2$	6 ± 0.10	4 ± 0.13	5	35 ± 0.04	34 ± 0.02	35	41 ± 0.01	44 ± 0.01	43	82 ± 0.01	81 ± 0.01	82
$D_1S_2F_3$	5 ± 0.12	6 ± 0.00	6	35 ± 0.03	35 ± 0.00	35	42 ± 0.01	45 ± 0.01	44	85 ± 0.01	83 ± 0.01	84
$D_1S_2F_4$	5 ± 0.12	5 ± 0.12	5	35 ± 0.03	36 ± 0.02	35	43 ± 0.01	46 ± 0.01	45	85 ± 0.01	86 ± 0.01	86
$D_1S_2F_5$	5 ± 0.12	5 ± 0.12	5	35 ± 0.02	36 ± 0.02	36	44 ± 0.01	47 ± 0.01	46	86 ± 0.01	87 ± 0.00	86
Mean	5	5		35	35		42	45		84	83	
$D_2S_1F_1$	8 ± 0.07	9 ± 0.07	9	30 ± 0.02	30 ± 0.02	30	37 ± 0.01	40 ± 0.01	39	75 ± 0.01	72 ± 0.00	74
$D_2S_1F_2$	9 ± 0.07	8 ± 0.07	9	31 ± 0.03	31 ± 0.00	31	38 ± 0.01	41 ± 0.02	39	76 ± 0.01	74 ± 0.01	75
$D_2S_1F_3$	8 ± 0.07	8 ± 0.07	8	31 ± 0.03	32 ± 0.02	31	38 ± 0.03	42 ± 0.01	40	77 ± 0.01	75 ± 0.01	76
$D_2S_1F_4$	8 ± 0.00	7 ± 0.08	8	31 ± 0.02	32 ± 0.00	32	38 ± 0.01	43 ± 0.01	41	77 ± 0.00	77 ± 0.00	77
$D_2S_1F_5$	8 ± 0.07	8 ± 0.07	8	32 ± 0.00	32 ± 0.02	32	39 ± 0.00	43 ± 0.00	41	78 ± 0.01	79 ± 0.01	78
Mean	8	8		31	31		38	42		77	75	
$D_2S_2F_1$	7 ± 0.09	7 ± 0.00	7	32 ± 0.02	32 ± 0.02	32	38 ± 0.03	42 ± 0.00	40	78 ± 0.01	76 ± 0.00	77
$D_2S_2F_2$	7 ± 0.09	6 ± 0.09	7	32 ± 0.02	33 ± 0.02	33	40 ± 0.00	43 ± 0.01	42	79 ± 0.01	78 ± 0.01	78
$D_2S_2F_3$	6 ± 0.09	7 ± 0.08	7	32 ± 0.00	33 ± 0.00	33	41 ± 0.01	44 ± 0.01	43	80 ± 0.01	80 ± 0.01	80
$D_2S_2F_4$	6 ± 0.09	7 ± 0.09	7	33 ± 0.02	34 ± 0.02	34	42 ± 0.01	45 ± 0.01	43	80 ± 0.01	82 ± 0.01	81
$D_2S_2F_5$	7 ± 0.09	8 ± 0.07	7	33 ± 0.00	35 ± 0.00	34	42 ± 0.00	46 ± 0.01	44	81 ± 0.01	84 ± 0.00	83
Mean	7	7		32	33		41	44		80	80	

D_1: first week of March, D_2: third week of March; S_1: RDF (20:40:40, $N/P_2O_2/K_2O$ kg/ha^{-1}), S_2: RDF + soil application of Co at 4 kg/ha^{-1} ($Co(NO_3)_2$); F_1: no spray, F2: foliar spray with tap water, F_3: foliar spray with K at 1.25% (muriate of potash), F_4: foliar spray with B at 0.2% (borax), F_5: foliar spray with K at 1.25% + B at 0.2%.

Table 5. Statistical significance and interaction effects of the date of sowing, soil application of Co, and foliar spray with K and B on the phenology of black gram during the spring-summer season.

Phenological Parameters	Seasons	Statistical Significance	Factor-Wise Effect			Interaction Effect of All Treatments			
			D	S	F	D × S	D × F	S × F	D × S × F
Days to emergence	2020	SEM (±)	0.09	0.08	0.17	0.15	0.23	0.23	0.33
		LSD	0.58	0.32	NS	NS	NS	NS	NS
	2021	SEM (±)	0.08	0.07	0.16	0.22	0.09	0.22	0.35
		LSD	0.52	0.26	NS	0.64	NS	NS	NS
Days to flower initiation	2020	SEM (±)	0.06	0.32	0.21	0.23	0.37	0.37	0.52
		LSD	0.38	1.26	0.60	0.67	NS	NS	NS
	2021	SEM (±)	0.04	0.12	0.13	0.18	0.02	0.18	0.26
		LSD	0.25	0.47	0.38	0.053	NS	NS	NS
Days to pod initiation	2020	SEM (±)	0.15	0.06	0.17	0.08	0.24	0.24	0.33
		LSD	0.95	0.22	0.48	NS	NS	0.68	NS
	2021	SEM (±)	0.05	0.10	0.13	0.16	0.18	0.18	0.26
		LSD	0.29	0.41	0.37	NS	NS	NS	NS
Days to maturity	2020	SEM (±)	0.07	0.14	0.17	0.20	0.25	0.25	0.35
		LSD	0.44	0.55	0.50	0.43	0.71	0.72	1.01
	2021	SEM (±)	0.02	0.06	0.13	0.09	0.08	0.18	0.25
		LSD	0.14	0.24	0.36	0.34	0.51	0.51	0.73

NS: nonsignificant; D, date of sowing; S, soil application; F, foliar spray.

There was no uniform variation as such between the phenological stages (Table 5). The first-week-of-March-sown crop took more days from pod initiation to maturity, implying the availability of more time for seed filling and consequently better yield. However, the prevailing higher atmospheric temperature in the reproductive stage compelled the third-week-of-March-sown crop to flower early for completion of the life cycle earlier [51]. This might have hampered the process of conversion from flower to pod in the later sowing condition of black gram. Similar observations of early maturation in summer-sown black gram due to later sowing were reported by Rani et al. [24] and Mane et al. [52]. Soil application of Co and combined foliar sprays of K and B separately recorded increases in the number of days to attain maturity when compared to control in both years. This might be attributed to the ability of Co and foliar nutrition in accelerating the production of flowers, aiding in extending maturity [7]. Though the three factors had negligible interaction effect from emergence to pod initiation of the crop, they interacted significantly in terms of days to maturity in both the experimental years (Table 5) as well as in their pooled estimation (Table 6).

Table 6. Factor-wise effect of the date of sowing, soil application of Co, and foliar spray with K and B on the phenology of black gram during the spring–summer season (pooled over two years).

Treatment		Days to Emergence	Days to Flowering	Days to Pod Initiation	Days to Maturity
Date of sowing (D)					
First week of March (D1)		6.3 ± 0.00	34.2 ± 0.00	43.0 ± 0.00	82.2 ± 0.00
Third week of March (D2)		7.7 ± 0.33	34.3 ± 0.00	41.3 ± 0.00	78.2 ± 0.00
LSD $_{(0.05)}$		0.29	0.38	0.29	0.29
Soil application (S)					
RDF (S1)		7.8 ± 0.58	32.3 ± 0.67	41.0 ± 0.00	78.4 ± 1.33
RDF + Co at 4 kg/ha^{-1} (S2)		6.2 ± 0.33	34.2 ± 0.67	43.3 ± 0.00	82.0 ± 1.33
LSD $_{(0.05)}$		0.18	0.44	0.18	0.26
Foliar spray (F)					
No spray (F1)		7.1 ± 0.00	32.3 ± 0.33	40.4 ± 0.07	77.17 ± 0.08
Tap water (F2)		6.9 ± 0.00	32.9 ± 0.13	41.4 ± 0.07	78.7 ± 0.04
K at 1.25% (F3)		7.1 ± 0.00	33.2 ± 0.29	42.2 ± 0.11	80.4 ± 0.15
B at 0.2% (F4)		6.8 ± 0.00	33.7 ± 0.36	43.0 ± 0.07	81.5 ± 0.04
K + B (F5)		7.2 ± 0.00	34.1 ± 0.00	43.7 ± 0.07	83.0 ± 0.11
LSD $_{(0.05)}$		NS	0.40	0.33	0.39
Interaction					
DXS	SEM (±)	0.07	0.16	0.07	0.09
	LSD $_{(0.05)}$	0.21	0.44	0.20	0.23
DXF	SEM (±)	0.18	0.19	0.16	0.19
	LSD $_{(0.05)}$	NS	0.56	0.46	0.55
SXF	SEM (±)	0.18	0.19	0.16	0.19
	LSD $_{(0.05)}$	NS	0.56	0.46	0.55
DXSXF	SEM (±)	0.25	0.28	0.23	0.27
	LSD $_{(0.05)}$	NS	NS	0.60	0.64

Values imply means ± SEM (n = 3). D_1: first week of March, D_2: third week of March; S_1: RDF (20:40:40, N/P_2O_2/K_2O kg/ha^{-1}), S_2: RDF + soil application of Co at 4 kg/ha^{-1} ($Co(NO_3)_2$); F_1: no spray, F2: foliar spray with tap water, F_3: foliar spray with K at 1.25% (muriate of potash), F_4: foliar spray with B at 0.2% (borax), F_5: foliar spray with K at 1.25% + B at 0.2%.

3.2. *Thermal Requirements of Black Gram*

The GDD, PTU, and HTU requirements of black gram differed due to variations in dates of sowing in both 2020 and 2021 (Table 7). The mean requirement of total heat units in terms of GDD ranged from 1403.6 to 1532 °C days in the first-week-of-March-sown crop and from 1418.4 to 1585.3 °C days in the third-week-of-March-sown crop in the first year, whereas in the second year, these values ranged from 1435.3 to 1666.8 °C days in the first-week-of-March-sown crop and from 1442.7 to 1680 °C days in the third-week-of-March-sown crop. The later sown crop experienced higher maximum and minimum temperature during the whole growth period compared to the first one in both years (Figure 1). This higher mean daily temperature caused the accumulation of more heat units within shorter periods, thereby hastening flower and pod initiation and consequently reducing the overall crop duration.

Table 7. Requirements of accumulated GDD, PTU and HTU of black gram at different phenophases.

Parameters	Treatment	Days to Emergence		Days to Flower Initiation		Days to Pod Initiation		Days to Maturity	
		Years of Experimentation							
		2020	2021	2020	2021	2020	2021	2020	2021
AGDD (°C days)	$D_1S_1F_1$	95.1	103.1	503.6	576.8	645.2	776.9	1418.4	1435.3
	$D_1S_1F_2$	95.1	91.1	503.6	576.8	645.2	776.9	1432.9	1480.0
	$D_1S_1F_3$	95.1	103.1	503.6	576.8	666.2	776.9	1447.1	1545.7
	$D_1S_1F_4$	107.8	91.1	503.6	576.8	688.2	799.2	1485.4	1589.8
	$D_1S_1F_5$	107.8	103.1	524.1	618.3	706.5	821.8	1506.4	1631.6
	$D_1S_2F_1$	80.6	77.1	543.8	576.8	666.2	776.9	1464.9	1503.3
	$D_1S_2F_2$	80.6	64.5	543.8	597.5	688.2	799.2	1485.4	1545.7
	$D_1S_2F_3$	68.6	91.1	543.8	618.3	706.5	821.8	1564.7	1589.8
	$D_1S_2F_4$	68.6	77.1	543.8	634.0	727.0	844.0	1564.7	1649.3
	$D_1S_2F_5$	68.6	77.1	543.8	634.0	748.8	864.8	1585.3	1666.8
	$D_2S_1F_1$	123.5	166.1	549.6	592.6	679.9	800.3	1403.6	1442.7
	$D_2S_1F_2$	139.3	145.9	569.5	615.2	696.5	821.0	1424.1	1477.8
	$D_2S_1F_3$	123.5	145.9	569.5	637.4	696.5	843.8	1439.6	1496.6
	$D_2S_1F_4$	123.5	125.9	569.5	637.4	696.5	865.8	1439.6	1536.8
	$D_2S_1F_5$	123.5	145.9	587.2	637.4	713.5	865.8	1457.8	1574.5
	$D_2S_2F_1$	108.7	125.9	587.2	637.4	696.5	843.8	1457.8	1516.8
	$D_2S_2F_2$	108.7	106.8	587.2	658.2	731.5	865.8	1477.8	1554.3
	$D_2S_2F_3$	95.8	125.9	587.2	658.2	749.2	888.3	1496.5	1594.0
	$D_2S_2F_4$	95.8	125.9	606.4	677.7	767.8	910.4	1496.5	1637.3
	$D_2S_2F_5$	108.7	145.9	606.4	694.4	767.8	932.1	1532.0	1680.4
APTU (°C hours)	$D_1S_1F_1$	1105.4	1192.7	6007.6	6865.4	7756.1	9338.9	17,789.8	17,761.8
	$D_1S_1F_2$	1105.4	1053.6	6007.6	6865.4	7756.1	9338.9	18,062.5	18,348.9
	$D_1S_1F_3$	1105.4	1192.7	6007.6	6865.4	8017.3	9338.9	18,268.8	19,212.5
	$D_1S_1F_4$	1254.7	1053.6	6007.6	6865.4	8291.4	9616.6	18,268.8	19,794.2
	$D_1S_1F_5$	1254.7	1192.7	6259.4	7374.0	8519.2	9899.8	18,511.9	20,346.7
	$D_1S_2F_1$	935.8	890.2	6501.8	6865.4	8017.3	9338.9	18,511.9	18,655.1
	$D_1S_2F_2$	935.8	744.1	6501.8	7119.1	8291.4	9616.6	18,778.5	19,212.5
	$D_1S_2F_3$	796.4	1053.6	6501.8	7374.0	8519.2	9899.8	19,027.3	19,794.2
	$D_1S_2F_4$	796.4	890.2	6501.8	7567.1	9048.5	10,177.9	19,027.3	20,581.7
	$D_1S_2F_5$	796.4	890.2	6501.8	7567.1	8775.5	10,438.2	19,054.8	20,813.5
	$D_2S_1F_1$	1475.8	1980.1	6716.4	7208.4	8359.1	9824.9	17,680.5	18,173.4
	$D_2S_1F_2$	1666.3	1736.9	6966.1	7491.5	8569.8	10,088.1	17,871.7	18,637.9
	$D_2S_1F_3$	1475.8	1736.9	6966.1	7769.6	8569.8	10,379.0	18,058.5	18,887.4
	$D_2S_1F_4$	1475.8	1497.2	6966.1	7769.6	8569.8	10,659.6	18,564.7	19,421.5
	$D_2S_1F_5$	1475.8	1736.9	7189.1	7769.6	8785.9	10,659.6	18,842.6	19,923.9
	$D_2S_2F_1$	1297.1	1497.2	7189.1	7769.6	8569.8	10,379.0	18,293.6	19,156.4
	$D_2S_2F_2$	1297.1	1268.7	7189.1	8029.9	9015.1	10,659.6	18,564.7	19,654.3
	$D_2S_2F_3$	1142.2	1497.2	7189.1	8029.9	9241.5	10,946.4	19,615.6	20,183.7
	$D_2S_2F_4$	1142.2	1497.2	7430.8	8275.0	9241.5	11,229.1	19,615.6	20,760.4
	$D_2S_2F_5$	1297.1	1736.9	7430.8	8485.8	9479.1	11,507.8	19,888.8	21,335.8

Table 7. *Cont.*

Parameters	Treatment	Days to Emergence		Days to Flower Initiation		Days to Pod Initiation		Days to Maturity	
		Years of Experimentation							
		2020	2021	2020	2021	2020	2021	2020	2021
AHTU (°C hours)	$D_1S_1F_1$	463.5	688.9	4158.2	4015.4	5426.9	5496.6	11,010.1	10,874.9
	$D_1S_1F_2$	463.5	651.8	4158.2	4015.4	5426.9	5496.6	11,102.3	11,245.7
	$D_1S_1F_3$	463.5	688.9	4158.2	4015.4	5605.4	5496.6	11,151.9	11,420.5
	$D_1S_1F_4$	591.0	651.8	4158.2	4015.4	5788.0	5716.9	11,151.9	11,579.6
	$D_1S_1F_5$	591.0	688.9	4346.8	4301.4	5928.5	5932.1	11,287.0	11,681.3
	$D_1S_2F_1$	357.6	577.4	4722.8	4015.4	5605.4	5496.6	11,287.0	11,519.7
	$D_1S_2F_2$	357.6	529.5	4722.8	4176.9	5788.0	5716.9	11,487.0	11,589.7
	$D_1S_2F_3$	320.6	651.8	4722.8	4301.4	5928.5	5932.1	11,675.4	11,764.3
	$D_1S_2F_4$	320.6	577.4	4722.8	4447.4	6082.2	6131.9	11,675.4	11,984.8
	$D_1S_2F_5$	320.6	577.4	4722.8	4447.4	6274.1	6138.1	11,675.4	12,346.2
	$D_2S_1F_1$	1034.5	1344.9	4960.8	4399.5	5866.2	6141.3	11,382.3	11,240.4
	$D_2S_1F_2$	1181.4	1223.4	5032.4	4614.7	5955.9	6348.3	11,382.3	11,361.0
	$D_2S_1F_3$	1034.5	1223.4	5032.4	4814.5	5955.9	6576.8	11,382.3	11,900.8
	$D_2S_1F_4$	1034.5	1065.4	5032.4	4814.5	5955.9	6774.8	11,719.1	12,316.5
	$D_2S_1F_5$	1034.5	1223.4	5185.1	4814.5	6008.6	6774.8	11,880.8	12,545.4
	$D_2S_2F_1$	899.4	1065.4	5185.1	4814.5	5955.9	6576.8	11,540.7	11,591.7
	$D_2S_2F_2$	899.4	914.5	5185.1	4820.7	6107.6	6774.8	11,719.1	11,900.8
	$D_2S_2F_3$	787.1	1065.4	5185.1	4820.7	6231.8	6976.9	12,084.8	12,316.5
	$D_2S_2F_4$	787.1	1065.4	5356.0	5006.0	6298.8	7175.8	12,084.8	12557.8
	$D_2S_2F_5$	899.4	1223.4	5356.0	5166.8	6298.8	7375.9	12,130.1	12,563.1

AGDD: accumulated GDD; APTU: accumulated PTU; AHTU: accumulated HTU. D_1: first week of March, D_2: third week of March; S_1: RDF (20:40:40, $N/P_2O_2/K_2O$ kg/ha^{-1}), S_2: RDF + soil application of Co at 4 kg/ha^{-1} ($Co(NO_3)_2$); F_1: no spray, F2: foliar spray with tap water, F_3: foliar spray with K at 1.25% (muriate of potash), F_4: foliar spray with B at 0.2% (borax), F_5: foliar spray with K at 1.25% + B at 0.2%.

Apart from this, day length also had notable significance for the photothermal requirements of black gram. In each year, both the first-week-of-March- and the third-week-of-March-sown crops received more or less similar day lengths before and after the vernal equinox (21 March), i.e., equal day and night length (each of 12 h). However, the day length increased towards the time of maturation starting from 21 March (Table 2). As the third-week-of-March-sown crop matured nearly two weeks later than the third-week-of-March-sown crop (D_1 on 22 May 2020 and 19 May 2021 and D_2 on 3 June 2020 and 30 May 2021, respectively), the later sown crop received a comparatively longer day length at its final stages of growth than the earlier one. This variation was clearly reflected in the photothermal units accumulation in black gram crops sown on different dates. Among the treatments, combined Co and foliar K + B application accumulated the maximum mean PTU (19,054.8 and 20,813.5 °C hours in the first-week-of-March sowing and 19,888.8 and 21,335.8 °C hours in the third-week-of-March sowing) irrespective of sowing dates in the respective years (Table 7). Additionally, the variation in the duration of bright sunshine between the two dates of sowing contributed to the variation in HTU as basically, it is the product of the GDD value and the average duration of bright sunshine for the corresponding period. Though the phenophase from germination to flower initiation for the third-week-of-March-sown crop was shorter than that of the earlier sown crop, the higher mean duration of bright sunshine it faced led to greater accumulation of HTU ranging from 11,382.3 to 12,130.1 °C hours and 11,240.4 to 12,563.1 °C hours compared to the first-week-of-March-sown crop varying between 11,010.1 to 11,675.4 °C hours and 10,874.9 to 12,346.2.1 °C hours, respectively, in 2020 and 2021. However, the higher accumulated GDD from flower initiation to maturation in the later sown crop escalated the accumulation of HTU in comparison with the first-week-of-March-sown crop on average (Table 8). All the results obtained regarding greater values of agroclimatic indices, i.e., GDD, PTU, and

HTU with respect to the higher mean daily temperature and duration of bright sunshine even under shorter growing periods were supported by the findings of Agarwal et al. [53] and Singh et al. [2] in black gram.

Table 8. Factor-wise requirements of accumulated GDD, PTU, and HTU of black gram at different phenophases.

Parameters	Treatment	Days to Emergence		Days to Flower Initiation		Days to Pod Initiation		Days to Maturity	
		Years of Experimentation							
		2020	2021	2020	2021	2020	2021	2020	2021
AGDD (°C days)	Date of sowing (D)								
	D_1	86.8	87.8	525.8	598.6	688.8	805.8	1495.5	1563.7
	D_2	115.1	136.0	582.0	644.6	719.6	863.7	1462.5	1551.1
	Soil application (S)								
	S_1	113.4	122.1	538.4	604.6	683.4	814.8	1445.5	1521.1
	S_2	88.5	101.7	569.3	638.7	854.7	854.7	1512.6	1593.8
	Foliar spray (F)								
	F_1	102.0	118.1	546.1	595.9	799.5	799.5	1436.2	1474.5
	F_2	105.9	102.1	551.0	611.9	815.7	815.7	1455.1	1514.5
	F_3	95.8	116.5	551.0	622.7	832.7	832.7	1487.0	1556.5
	F_4	98.9	105.0	555.8	631.5	854.9	854.9	1496.6	1603.3
	F_5	102.2	118.0	565.4	646.0	871.1	871.1	1520.4	1638.3
APTU (°C hours)	Date of sowing (D)								
	D_1	1008.6	1015.4	6279.9	7132.8	8299.2	9700.5	18,530.2	18,530.2
	D_2	1374.5	1618.5	7123.3	7859.9	8840.1	10,633.3	18,699.6	18,699.6
	Soil application (S)								
	S_1	1339.5	1437.3	6509.4	7284.4	8319.5	9914.4	18,192.0	18,192.0
	S_2	1043.7	1196.6	6893.8	7708.3	8819.9	10,419.3	18,699.6	18,699.6
	Foliar spray (F)								
	F_1	1203.5	1390.1	6603.7	7177.2	8175.6	9720.4	18,069.0	18,069.0
	F_2	1251.2	1200.8	6666.2	7376.5	8408.1	9925.8	18,319.4	18,319.4
	F_3	1130.0	1370.1	6666.2	7509.7	8587.0	10,141.0	18,742.6	18,742.6
	F_4	1167.3	1234.4	6726.6	7619.3	8787.8	10,420.8	18,869.1	18,869.1
	F_5	1206.0	1389.2	6845.3	7799.1	8889.9	10,626.4	19,074.5	19,074.5
AHTU (°C hours)	Date of sowing (D)								
	D_1	425.0	628.4	4459.4	4175.2	5785.4	5755.4	11,350.3	11,600.7
	D_2	959.2	1141.5	5151.0	4808.6	5948.5	6749.6	11,730.6	12,029.4
	Soil application (S)								
	S_1	789.2	945.1	4622.3	4382.1	5791.8	6075.5	11,345.0	11,616.6
	S_2	594.9	824.8	4988.1	4601.7	5942.1	6429.6	11,736.0	12,013.5
	Foliar spray (F)								
	F_1	688.8	919.2	4756.7	4311.2	5713.8	5927.8	11,305.0	11,306.7
	F_2	725.5	829.8	4774.6	4406.9	5819.6	6084.2	11,422.7	11,524.3
	F_3	615.4	907.4	4774.6	4488.0	5930.4	6245.6	11,573.6	11,850.5
	F_4	683.3	840.0	4817.4	4570.8	6031.2	6449.9	11,657.8	12,109.7
	F_5	711.4	928.3	4902.7	4682.5	6127.5	6555.2	11,743.3	12,284.0

AGDD: accumulated GDD; APTU: accumulated PTU; AHTU: accumulated HTU. D_1: first week of March, D_2: third week of March; S_1: RDF (20:40:40, N/P_2O_2/K_2O kg/ha^{-1}), S_2: RDF + soil application of Co at 4 kg/ha^{-1} ($Co(NO_3)_2$); F_1: no spray, F2: foliar spray with tap water, F_3: foliar spray with K at 1.25% (muriate of potash), F_4: foliar spray with B at 0.2% (borax), F_5: foliar spray with K at 1.25% + B at 0.2%.

3.3. Dry Matter Accumulation and Yield during Harvest Maturity

Delay in sowing from the first week of March to the third week of March significantly reduced the final dry matter accumulation (D_1 ranging from 195.8 to 367.7 g/m^{-2} vs. D_2 ranging from 180.8 to 315.2 g/m^{-2}) and seed yield (D_1 ranging from 822.0 to 1707 kg/ha^{-1} vs. D_2 ranging from 743.1 to 1437.0 kg/ha^{-1}) in the spring–summer-sown black gram in this study (Tables 9 and 10).

Table 9. Effect of the date of sowing, soil application of Co, and foliar spray with K and B on the final dry matter accu-mulation and seed yield of black gram during the spring-summer season.

Parameter	Soil Application	Foliar Spray	First Week of March			Third Week of March		
			2020	2021	Mean	2020	2021	Mean
Dry matter accumulation at harvest maturity (g/m^{-2})	RDF (20:40:40, N/P_2O_5/K_2O kg/ha^{-1})	No spray	206.2 ± 0.02	185.5 ± 0.04	195.8	200.2 ± 0.04	161.5 ± 0.05	180.8
		Tap water	246.9 ± 0.01	220.9 ± 0.06	233.9	241.5 ± 0.01	187.6 ± 0.05	214.6
		K at 1.25%	279.5 ± 0.02	253.6 ± 0.03	266.6	275.4 ± 0.05	216.6 ± 0.03	246.0
		B at 0.2%	309.9 ± 0.01	280.1 ± 0.01	295.0	304.3 ± 0.02	244.1 ± 0.05	274.2
		K + B	342.6 ± 0.02	304.2 ± 0.05	323.4	324.9 ± 0.03	274.9 ± 0.03	299.9
		Mean	277.0	248.9		269.2	216.9	
	RDF + Co at 4 kg/ha^{-1}	No spray	232.2 ± 0.02	223.7 ± 0.01	227.9	216.1 ± 0.05	182.0 ± 0.03	199.0
		Tap water	277.4 ± 0.00	258.3 ± 0.05	267.8	255.7 ± 0.01	216.4 ± 0.03	236.0
		K at 1.25%	313.9 ± 0.02	295.9 ± 0.01	304.9	284.0 ± 0.02	247.7 ± 0.01	265.8
		B at 0.2%	358.2 ± 0.03	320.6 ± 0.02	339.4	305.6 ± 0.01	273.0 ± 0.03	289.3
		K + B	388.5 ± 0.01	346.8 ± 0.02	367.7	329.2 ± 0.01	301.2 ± 0.03	315.2
	Mean		314.0	314.0		301.5	278.1	
Seed yield (kg/ha^{-1})	RDF (20:40:40, N/P_2O_5/K_2O kg/ha^{-1})	No spray	860.7 ± 0.04	783.3 ± 0.05	822.0	756.6 ± 0.07	729.7 ± 0.07	743.1
		Tap water	1044.0 ± 0.01	998.3 ± 0.05	1021.2	922.8 ± 0.02	853.3 ± 0.06	888.1
		K at 1.25%	1188.5 ± 0.04	1101.0 ± 0.03	1144.8	1123.9 ± 0.07	983.7 ± 0.03	1053.8
		B at 0.2%	1320.2 ± 0.02	1261.3 ± 0.05	1290.8	1279.3 ± 0.03	1139.3 ± 0.05	1209.3
		K + B	1461.3 ± 0.03	1391.0 ± 0.03	1426.1	1429.3 ± 0.01	1280.7 ± 0.01	1355.0
	Mean		1174.9	1107.0		1102.4	997.3	
	RDF + Co at 4 kg/ha^{-1}	No spray	1002.4 ± 0.05	977.0 ± 0.03	989.7	895.3 ± 0.01	863.3 ± 0.04	879.3
		Tap water	1204.9 ± 0.01	1191.7 ± 0.03	1198.3	1131.2 ± 0.03	1041.0 ± 0.06	1086.1
		K at 1.25%	1371.2 ± 0.02	1382.0 ± 0.01	1376.6	1273.8 ± 0.01	1177.7 ± 0.03	1225.7
		B at 0.2%	1592.2 ± 0.01	1492.0 ± 0.02	1542.1	1379.1 ± 0.01	1279.3 ± 0.02	1329.2
		K + B	1738.7 ± 0.01	1676.3 ± 0.03	1707.5	1493.2 ± 0.01	1380.7 ± 0.01	1437.0
	Mean		1381.9	1343.8		1234.5	1148.4	

Table 10. Statistical significance and interaction effects of the date of sowing, soil application of Co, and foliar spray with K and B on the final dry matter accumulation and seed yield of black gram during the spring-summer season.

Parameter	Years	Statistical Significance	Factor-Wise Effect			Interaction Effect of All Factors			
			D	S	F	D × S	D × F	S × F	D × S × F
Dry matter accumulation at harvest maturity	2020	SEM (±)	0.68	1.27	2.01	1.80	2.85	2.85	4.03
		LSD	4.21	3.65	5.78	5.17	8.17	NS	11.55
	2021	SEM (±)	1.96	1.75	2.30	2.48	3.26	3.26	4.61
		LSD	12.07	6.85	6.64	6.94	9.55	9.55	13.64
Seed yield	2020	SEM (±)	8.69	6.42	10.15	9.08	14.36	14.36	20.31
		LSD	53.61	18.43	29.13	26.06	43.02	43.02	56.27
	2021	SEM (±)	9.89	7.01	11.80	9.91	16.69	16.69	23.60
		LSD	61.06	27.37	34.00	23.60	48.09	48.00	71.03

NS: nonsignificant; D, date of sowing; S, soil application; F, foliar spray.

Sowing time imposed a great influence on the overall biological yield. This may have been due to the longer timespan available for the development of pods and seeds of the crop in case of the first date of sowing. Irrespective of the dates of sowing, the crop registered greater biomass production and seed yield with soil application of cobalt at 4 kg/ha^{-1} in the respective years which were statistically significant over control (S_1) in each case (Table 10). This finding might be related to the involvement of Co in vital physiological and biochemical functions, especially the synthesis of the leghemoglobin protein required for rhizobial activity in legumes and subsequent nitrogen fixation manifesting momentous impact on enzyme systems [34] Among the five foliar spray treatments, the combined spray with K at 1.25% and B at 0.2% recorded the highest dry matter production and seed yield in both 2020 and 2021, which were statistically significant over their single application, no spray, or tap water spray. A similar positive role of foliar nutrition was previously cited by many earlier sources [54,55].

Stagnation in yield in the later sown crops could be attributed to higher air temperature during the pod development stage. Though the greater duration of sunshine in this crop might have contributed to better solar radiation interception and corresponding photosynthetic activity, the shorter phenophasic duration did not allow this total procedure to linger more. Coupled with this, higher mean daily temperature might have eventually caused higher canopy temperature and stomatal diffusion resistance, which ultimately led to the hampered rate of photosynthesis and yield reduction. Similar findings were reported by Maji et al. [16]. Additionally, unexpectedly intense rainfall due to severe cyclonic storms just on the verge of maturation of the later sown crops during both 2020 (known as Amphun) and 2021 (known as Yash) drastically hampered the seed yield of black gram.

Notably, treatment F_5 achieved about 45.9% and 41.5% increase in seed yield in the respective two years in comparison with those of the treatment with no foliar spray (F_1). Irrespective of treatments, inter-year variation in seed yield might be attributed to the fluctuation in atmospheric conditions, especially with respect to the duration of bright sunshine between 2020 and 2021 during different phenophases of the crops. The results are in line with the observations of Kaisher et al. [56], Kataria et al. [40], and Iram et al. [36] in green gram and of Math et al. [57] in black gram. Interaction effects of all the three factors on both dry matter accumulation and seed yield were statistically significant in the maximum cases (Table 11).

Table 11. Factor-wise effect of the date of sowing, soil application of Co, and foliar spray with K and B on the final dry matter accumulation and seed yield of black gram (pooled over two years) during the spring-summer season.

Treatment	**Dry Matter Accumulation at Harvest Maturity (g/m^{-2})**	**Seed Yield (kg/ha^{-1})**
	Date of sowing (D)	
First week of March	282.24 ± 5.56	1251.92 ± 7.07
Third week of March	252.08 ± 3.96	1120.67 ± 1.92
LSD $_{(0.05)}$	4.59	17.94
	Soil application (S)	
RDF	253.01 ± 3.90	1095.42 ± 6.48
RDF + Co at 4 kg/ha^{-1}	281.31 ± 2.72	1277.17 ± 0.86
LSD $_{(0.05)}$	3.58	16.59
	Foliar spray (F)	
No spray	200.90 ± 2.20	858.56 ± 9.18
Tap water	238.10 ± 0.73	1048.43 ± 5.08
K at 1.25%	270.82 ± 0.93	1200.22 ± 4.59
B at 0.2%	299.44 ± 0.13	1342.85 ± 1.42
K + B	326.55 ± 1.45	1481.40 ± 11.40
LSD $_{(0.05)}$	4.34	26.13

Table 11. *Cont.*

Treatment		Dry Matter Accumulation at Harvest Maturity (g/m^{-2})	Seed Yield (kg/ha^{-1})
		Interaction	
DXS	SEM (±)	1.30	6.01
	LSD $_{(0.05)}$	5.07	23.46
DXF	SEM (±)	2.13	12.82
	LSD $_{(0.05)}$	6.14	35.87
SXF	SEM (±)	2.13	12.82
	LSD $_{(0.05)}$	6.14	35.87
DXSXF	SEM (±)	3.01	18.13
	LSD $_{(0.05)}$	10.21	52.25

Values indicate means ± SEM (n = 3); D, date of sowing; S, soil application; F, foliar spray.

Dry matter accumulation in black gram crops was found to be a second-order polynomial function of GDD irrespective of the date of sowing, soil and foliar application of nutrients in both years. Variations in GDD for two different dates of sowing were found to be significantly related to dry matter production under different soil and foliar application of nutrients. About 75.8% and 87.3% variation in biomass production could be explained through the variations in GDD in 2020 and 2021, respectively (Figure 2A,B).

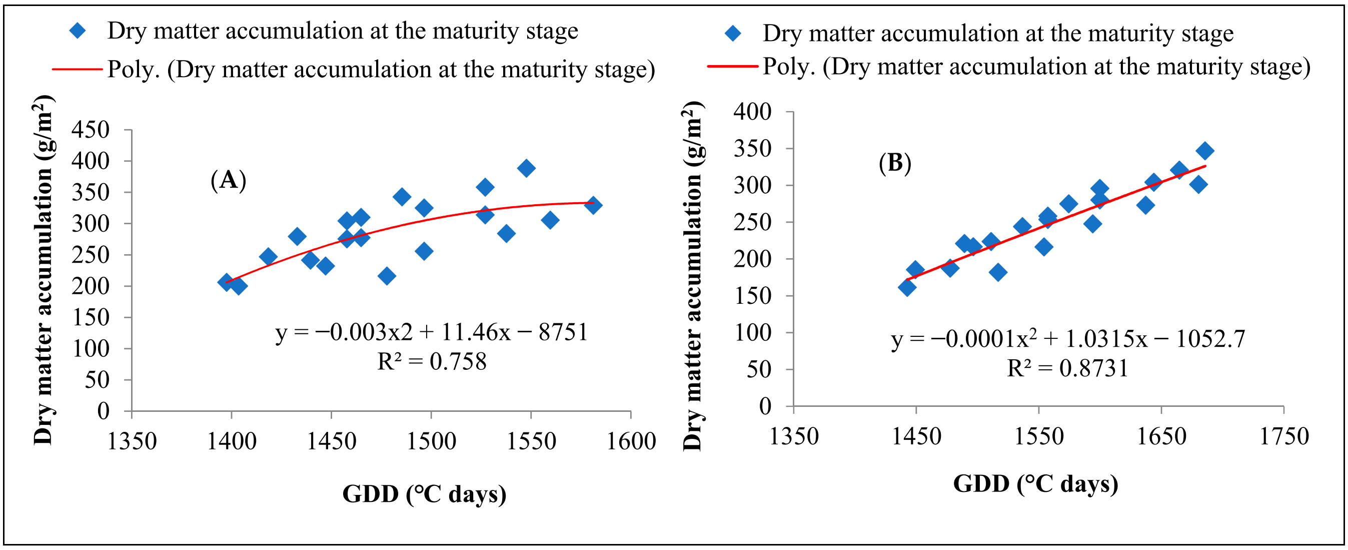

Figure 2. Impact of GDD on the final dry matter accumulation in black gram in (**A**) 2020 and (**B**) 2021.

Accordingly, the seed yield of black gram was found to be a second-order polynomial function of HTU in both 2020 and 2021. An increment in HTU up to 12,000 day °C hours gradually escalated the seed yield, and thereafter a marginal improvement was observed in the first year and the second year (Figure 3A,B). However, the rise in HTU up to 13,000 day °C hours progressively increased the seed yield of the black gram sown in 2021. Variations in HTU could contribute to about 72.9% and 84.8% variation in seed yield of black gram irrespective of sowing dates in 2020 and 2021 (Figure 3A,B), respectively.

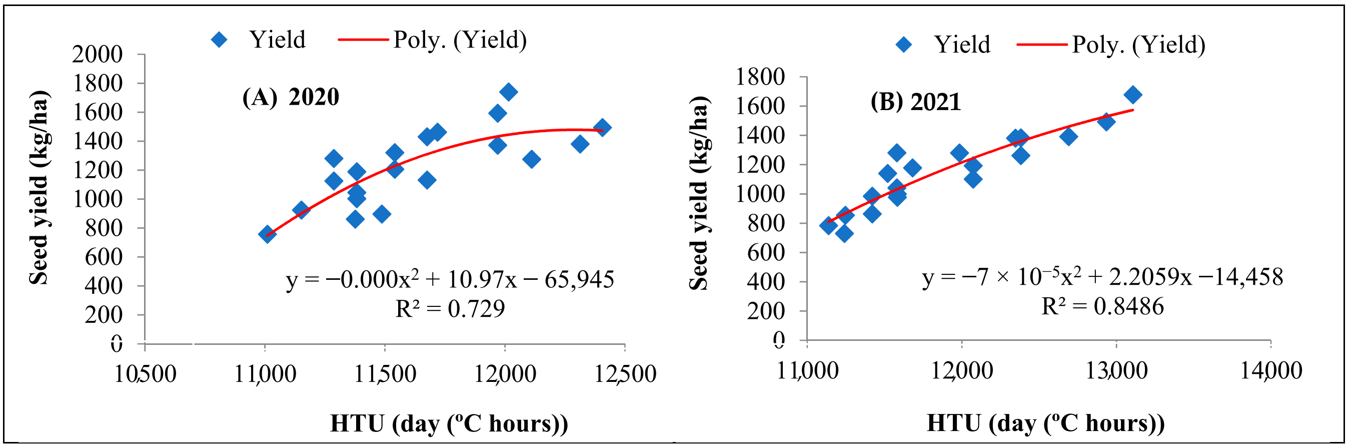

Figure 3. Impact of HTU on seed yield of black gram in (**A**) 2020 and (**B**) 2021.

3.4. Thermal Use Efficiency (TUE) of Black Gram

The TUE of black gram for the final dry matter production and seed yield were found to be higher for the first date of sowing in both years of sowing (Table 12). The mean TUE ranged to the tune of 0.19 and 0.16 $g/m^{-2}/°C/day^{-1}$ for dry matter accumulation and 0.08 and 0.07 $g/m^{-2}/°C/day^{-1}$ for seed yield with respect to the first-week-of-March- and the third-week-of-March-sown black gram, respectively.

Table 12. Thermal use efficiency (TUE) of spring–summer black gram sown on different dates and at different nutrient schedules.

Thermal Use Efficiency	Soil Application	Foliar Spray	First Week of March			Third Week of March		
			2020	2021	Mean	2020	2021	Mean
TUE for dry matter accumulation ($g/m^{-2}/°C/day^{-1}$)	RDF (20:40:40, $N/P_2O_5/K_2O$ kg/ha^{-1})	No spray	0.14	0.13	0.14	0.13	0.11	0.12
		Tap water	0.17	0.15	0.16	0.16	0.13	0.15
		K at 1.25%	0.19	0.16	0.18	0.18	0.14	0.16
		B at 0.2%	0.21	0.18	0.20	0.20	0.16	0.18
		K + B	0.23	0.19	0.21	0.22	0.17	0.20
	RDF + Co at 4 kg/ha^{-1}	No spray	0.16	0.15	0.16	0.14	0.12	0.13
		Tap water	0.19	0.17	0.18	0.17	0.14	0.16
		K at 1.25%	0.21	0.18	0.20	0.19	0.16	0.18
		B at 0.2%	0.24	0.19	0.22	0.20	0.17	0.19
		K + B	0.27	0.21	0.24	0.22	0.18	0.20
		Mean	0.20	0.17	0.19	0.18	0.15	0.16
TUE for seed yield ($g/m^{-2}/°C/day^{-1}$)	RDF (20:40:40, $N/P_2O_5/K_2O$ kg/ha^{-1})	No spray	0.06	0.05	0.06	0.05	0.05	0.05
		Tap water	0.07	0.07	0.07	0.06	0.06	0.06
		K at 1.25%	0.08	0.07	0.08	0.08	0.07	0.07
		B at 0.2%	0.09	0.08	0.09	0.09	0.07	0.08
		K + B	0.10	0.08	0.09	0.10	0.08	0.09
	RDF + Co at 4 kg/ha^{-1}	No spray	0.07	0.06	0.07	0.06	0.06	0.06
		Tap water	0.08	0.08	0.08	0.08	0.07	0.07
		K at 1.25%	0.09	0.09	0.09	0.09	0.07	0.08
		B at 0.2%	0.11	0.09	0.10	0.09	0.08	0.08
		K + B	0.12	0.10	0.11	0.10	0.09	0.10
		Mean	0.09	0.07	0.08	0.08	0.07	0.07

Every time, the later sown crop was exposed to higher temperatures because of a larger duration of bright sunshine. This higher temperature during the pod development stage in the later sowing condition led to lower biomass and seed yield along with more heat units' accumulation. However, the TUE for both dry matter production and seed yield also differed due to the application of plant nutrients either through soil or foliar application. The mean values of TUE for both parameters reached the maximum when the crop was provided with soil application of Co at the time of sowing and combined foliar spray with K and B at the flower initiation stage (for dry matter accumulation: 0.24 and 0.20 $g/m^{-2}/°C/day^{-1}$; for seed yield: 0.11 and 0.10 $g/m^{-2}/°C/day^{-1}$).

Previously, numerous research efforts separately revealed the effectiveness of different macro-and micronutrients in boosting biomass production and seed yield in many field crops. In a developing country like India, summer-grown pulse crops are generally taken up by marginal farmers with minimal care and cannot reach their optimum yield potentials [32]. The unique combination of beneficial (Co), macro- (K) and micronutrients (B) under study is definitely a new economical potent area to intensify the overall development and production of summer-grown pulse crops like black gram with lower dosages of these nutrients. Together with boosting up the production, this combined nutrient schedule apparently aided in a greater increment in heat use efficiency under the normal and later sowing situation. Greater use efficiency of thermal energy suggested better utilization of heat energy, i.e., higher production of dry matter or seed yield with a lower accumulation of heat units. The results agree with the observations of Mane et al. [52] and Rana et al. [58] in black gram.

4. Conclusions

This experiment came to a conclusion that appropriate time of sowing along with nutrient application has a great potential to achieve higher yield in black gram. The study found that the crop experienced a continuous increment in air temperature starting right from the vegetative phase to the reproductive phase. This stress was apparently more predominant during the reproductive stage of the later sown crop (third week of March), which consecutively compelled it to complete the phenophases to some extent earlier than the normally sown one (first week of March). Soil application of Co at 4 kg/ha^{-1} and foliar sprays of K at 1.25% and B at 0.2% mitigated the adversities of excess heat. Sowing in the first week of March along with soil application of Co and combined foliar sprays of K and B proved to be more proficient in producing satisfactory biomass and seed yield of the black gram crop along with less stringent heat requirements and better thermal use efficiency under the spring–summer season in Indian subtropics. The information from the study will be helpful for the sustainability of black gram production in subtropical regions in the modern era of climate change. Though separately these nutrients have proved to be effective for improving the production of various pulse crops, further research on different summer season pulse crops is necessary to explore the huge potential of this combined nutrient schedule under normal as well as under stressed situations to attain their optimum yield potentials through mitigation of abiotic stresses.

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