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RESEARCH ARTICLE

# Influence of sowing dates and nutrient management on growth and yield of spring green gram (*Vigna radiata* L.) under heat and moisture stress conditions in Punjab

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## Abstract

This study was carried out in the spring of 2025 at the agricultural farms of Lovely Professional University, Phagwara, Punjab, to assess the impact of sowing dates and nutrient management on the growth and yield of spring green gram (*Vigna radiata* L.) under conditions of heat and moisture stress. The experiment utilized a factorial randomized block design including two sowing dates (24 March and 08 April 2025) and nine nutrient management treatments, each replicated three times. The results indicated that growth characteristics, including plant height, leaf number, leaf area, fresh weight, dry weight, branch number plant$^{-1}$ and chlorophyll content, were strongly affected by nutrient management, whereas sowing dates had comparatively slight but significant effects. The combination of sugarcane bagasse biochar at 5 t ha$^{-1}$ with soil applications of cobalt (1 kg ha$^{-1}$) and molybdenum (1.5 kg ha$^{-1}$), combined with 100 % RDF (N7), yielded the highest growth parameters, yield attributes and seed yield (1450.65 kg ha$^{-1}$). Early sowing (24 March) resulted in a comparatively higher seed yield (1313.38 kg ha$^{-1}$) than late sowing (1278.50 kg ha$^{-1}$), demonstrating the benefit of mitigating late-season temperature stress. Correlation studies revealed strong positive relationships among temperature, soil moisture and crop growth traits; however excessive humidity and wind speed negatively influenced yield. The results highlight that the combination of biochar with micronutrient application and timely sowing can significantly reduce heat and moisture stress, thereby improving the production of spring green gram in subtropical environments.

**Keywords:** biochar; cobalt; green gram; heat stress; molybdenum; sowing dates; yield

## Introduction

Weather conditions significantly determine the success or failure of crops, as they significantly impact both physiological expression and genetic potential. The yield of any crop or variety is dependent upon the availability of optimal rainfall, solar radiation, temperature, soil moisture and heat units at various phases of growth. Abiotic stressors such as high temperature and moisture levels, significantly limit the growth and yield of crops. Climate change continues to create unfavorable conditions for crops, leading to substantial economic losses in agriculture and horticulture (1). Increased temperatures and moisture stress can induce a range of morpho-anatomical, physiological, reproductive and biochemical changes in plants, adversely affecting growth and development and ultimately resulting in diminished economic yield (2). High temperatures frequently correlate with diminished water availability. In this context, global food security in the 21st century has been compromised by increasing heat and drought stress caused by climate change, especially in tropical and subtropical regions. Exposure to increased air temperatures significantly above the optimal range from late February to mid-June is highly detrimental to crop growth. This season consistently suffers from depleted soil moisture reserves due to ongoing evapotranspiration and inadequate, irregular rainfall. Abiotic stress effects, particularly during the reproductive phase of plants, are increasingly recognized as a significant threat to the productivity of leguminous crops, as they reduce pollen viability, fertilization and pod formation (3). The incidence of moisture stress combined with heat stress is expected to increase in the next few years. This situation necessitates the adoption of more efficient and cost-effective agronomic solutions in crop management to mitigate climate-related challenges. Sowing time is a critical management factor for achieving higher yields. The timing of sowing significantly affects the growth and yield of green gram (4). Optimal sowing time primarily relies on the prevailing agro-climatic conditions of a region, in addition to the cultivated variety. Planting during the optimal period enhances compatibility between the plant and climatic conditions, ultimately leading to increased agricultural yields. After the harvest of wheat, Indian farmers leave their fields fallow. Incorporating spring pulse crops such as green grams into this cropping sequence may effectively help soil fertility while also providing economic returns at the end of season. Green gram is a significant short-duration pulse crop commonly cultivated during the kharif season in India. The primary disadvantage of selecting the spring-summer season for green gram cultivation is the occurrence of higher temperatures and reduced soil moisture from the onset of flowering, which significantly affect nutrient uptake and yield potential (5).

This crop can withstand temperatures of up to 42 °C (6). It favours cooler temperatures during the vegetative phase and warmer temperatures during the later growth stages, with the optimal growth temperature ranging from 18 to 30 °C, specifically 22 to 28 °C. Therefore, timely seeding of green gram is crucial for achieving an appropriate balance between its vegetative and reproductive stages, ultimately influencing the crop's maximum yield potential. Additionally, green gram, being a leguminous crop with an indeterminate growth habit, experiences ongoing conflict about the allocation of assimilates between vegetative and reproductive sinks. The translocation of assimilates to developing vegetative sinks following the initiation of the reproductive phase significantly reduces the crop's production potential due to significant source challenges (7). A significant physiological limitation of green gram is the occurrence of flower and fruit drop due to substantial intra-plant competition. Therefore, enhancing assimilate production and delaying the senescence of reproductive structures are primary goals in green gram cultivation (7). Micronutrients are crucial for plant growth and development, serving as cofactors in many enzymes and participating in several redox processes. To enhance crop yield and quality, adequate fertilization with macro and micronutrients must be applied in plant nutrition (8). Micronutrient deficiencies constrain crop productivity in numerous regions globally. Deficiencies of these nutrients can significantly diminish crop output and may even stop plant growth. Legume production has been constrained by deficiencies in both macronutrients and micronutrients, including molybdenum and cobalt. Moreover, molybdenum is a crucial micronutrient for plant development and is a component of several enzymes that facilitate a range of oxidation–reduction events in plants (9). Due to its involvement in nitrate assimilation, nitrogen fixation and the transport of nitrogenous compounds in plants, molybdenum is essential for nitrogen metabolism (10). Cobalt plays a crucial role in essential physiological and biochemical processes in plants, particularly in the synthesis of leghemoglobin, which is necessary for rhizobial activity in legumes and subsequent nitrogen fixation, thereby significantly influencing enzyme systems. Cobalt enhances the levels of amino acids and antioxidant enzymes, including superoxide dismutase (SOD). The simultaneous enhancement of drought resistance and suppression of ethylene production in legume crops through cobalt treatment has also been documented (11). The foliar application of micronutrients facilitates quicker translocation compared to soil treatment, which is crucial for reducing stress in plants. Biochar is a carbon-rich substance derived from the pyrolysis of biomass such as wood, dung, or foliage, under oxygen-limited conditions (12). The impact of biochar on soil water balance, nitrogen cycling, soil fertility, soil ecology and other associated beneficial properties is continually being explored. The physicochemical characteristics of biochar enhance its function as a tool for ecological management. Incorporation of biochar into the soil modifies soil texture, structure, porosity and consistency by altering its physicochemical properties. Consequently, it was hypothesized that the application of biochar, cobalt and molybdenum would constitute an effective agronomic strategy for enhancing green gram yield by reducing stress during the spring-summer period. In this context, an experiment was undertaken to determine the optimal planting date and fertilizer management for maximizing the growth and yield of green gram by mitigating prevailing high temperature and moisture stress during the spring season.

## Materials and Methods

### Details of the experimental site

The experimental trial was conducted at the agricultural farm of Lovely Professional University, Phagwara, Punjab, during the spring season of 2025. The agricultural farm is located at latitude 31.242108° N and longitude 75.696344° E (Fig. 1). The selected experimental site is situated at an altitude of 272 m above mean sea level. The soil at the experimental site was classified as coarse sandy loam according to USDA classification. The initial soil status indicated medium levels of organic carbon and available phosphorus, while available nitrogen was low.

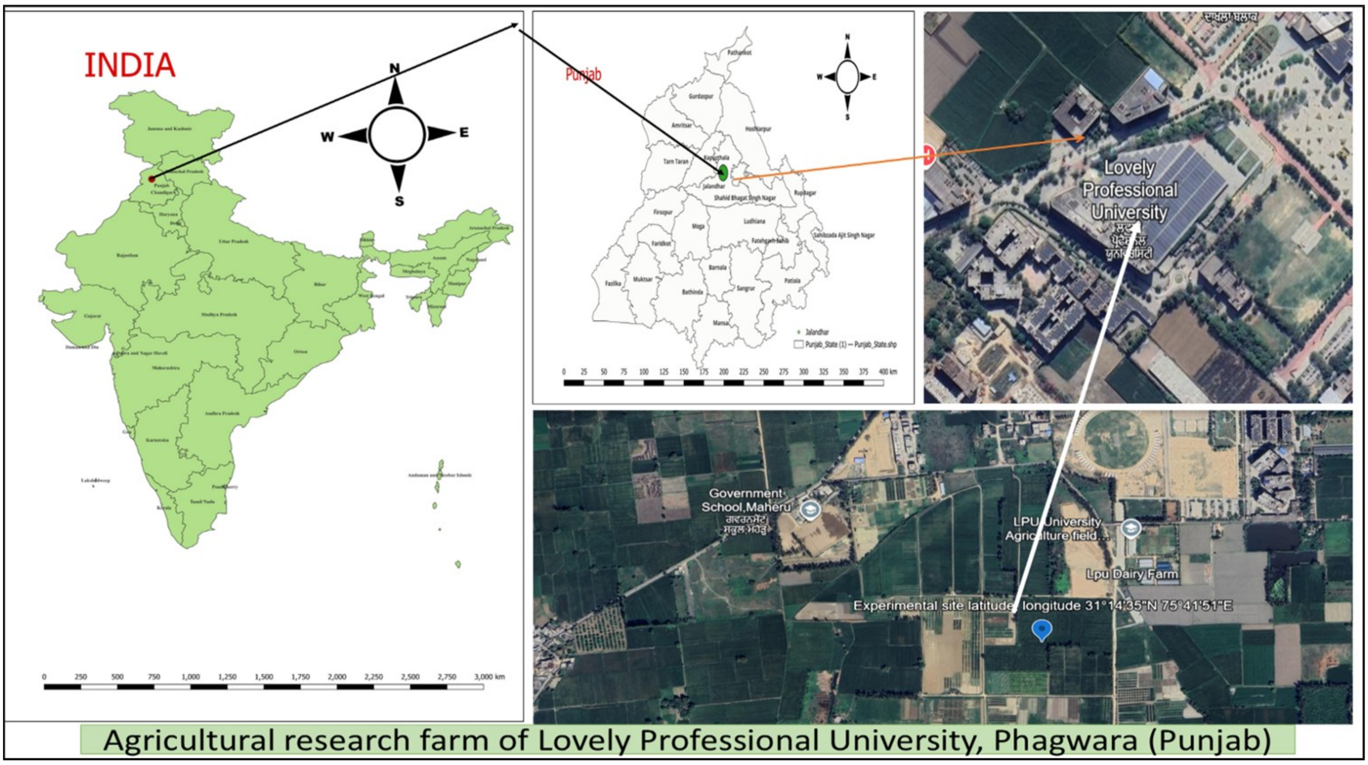



**Fig. 1.** Geographical location of experimental site.

## Treatment details

The field experiment was replicated thrice in a factorial RBD design. The main factor (A) comprised two dates of sowing and factor (B) consisted of nine nutrient management treatments. Detailed descriptions of the treatments are provided in Table 1. The total number of plots was 54. The net plot size was 5 × 3 m ($15 m^2$). The SML 1827 variety of green gram was used for the experiment and was procured from PAU, Ludhiana. Line sowing (kera) method was adopted with a spacing of 22.5 cm between rows and 7 cm between plants at a sowing depth of 5 cm. Seeds were inoculated with Rhizobium culture at the time of sowing at 10 g $kg^{-1}$ seed to enhance germination and yield. The seeds were sown on 24-03-2025 for the first date of sowing and on 08-04-2025 for the second date of sowing. A total of five irrigations were provided to the crop as per weather conditions. The last irrigation was stopped about 55 days after sowing (DAS) to obtain higher yields and synchronous maturity. A total of 12.5 kg N from urea and 40 kg $P_2O_5$ from Single Super Phosphate (SSP) were applied to the crop at the time of sowing. Sugarcane bagasse biochar was applied @ 5 tonnes $ha^{-1}$ and incorporated into the soil during land preparation. Soil application of cobalt and molybdenum was performed after emergence by drenching method, whereas foliar application of cobalt and molybdenum was done at 30 and 45 DAS. The crop was harvested when 80 % of the pods turned brown and threshing was done manually. All intercultural operations were done as per the package and practices of PAU, Ludhiana, to ensure normal crop growth.

## Weather parameters and observation methodology

Weather parameters were recorded three times daily (Morning - 8:30 AM, Afternoon - 2:00 PM and Evening - 5:30 PM) to observe microclimatic variations and their impact on crop growth and development. The particulars of the parameters, instruments used and timing of observations are as follows: Minimum and maximum temperatures (°C) were measured using a standard thermometer. Relative humidity (%) was determined using a wet- and dry-bulb thermometer. Soil temperature (°C) was measured with a soil thermometer. Canopy temperature (°C) was measured using an infrared thermometer. Precipitation (mm) was measured using a rain gauge. Wind velocity (km/hr) was measured with an anemometer. Soil moisture was assessed using a soil moisture meter. Solar intensity ($Wm^{-2}$) was measured using a solar power meter, whereas cloud cover percentage data were sourced from the Indian Meteorological Department rather than recorded manually.

## Data recording of crops

Plant height was determined as the average of five randomly selected plants from the inner rows of each plot. The plant height was measured from the base (above ground) to the apex. The number of branches per plant was counted for five randomly selected plants from each plot and a mean value was computed. Plant data, including leaf count, leaf area ($cm^2$), fresh weight (g) and dry weight (g) were recorded according to the protocol outlined in a previous study (13). The chlorophyll content of leaves (mg $g^{-1}$) was quantified by measuring absorbance at 645 and 663 nm using a blank consisting of 80 % acetone and a digital spectrophotometer (Systronics Model 105) with high accuracy and reliability (wavelength range: 340-960 nm, 4-digit 7-segment LED display). Total chlorophyll was calculated using the methodology provided by an earlier study (14). Green leaf segments were detached from the stems to assess the average leaf area per plant. All yield parameters (number of pods per plant, pod length, pod weight, number of seeds per pod, test weight, seed yield and stalk yield) were recorded based on the net plot at harvest and subsequently converted to a per-hectare basis. Data related to yield attributes were collected following established protocols reported in previous studies (15).

## Statistical analysis

The recorded data were tabulated treatment-wise under three replications. Differences between mean values were estimated using two-way ANOVA (analysis of variance) with the OPSTAT software. Correlation studies between weather parameters, growth parameters and yield parameters were analyzed using GRAPES software (General R-based Analysis Platform Empowered by Statistics), launched in 2020. Significant differences among the means were calculated on the basis of LSD (least significant difference) at the 5 % level of significance.

**Table 1.** Treatment details

| Treatments |
|---|
| **Factor A : Date of sowing** |
| D1 : Third week of March (24-03-2025) |
| D2 : First week of April (08-04-2025) |
| **Factor B : Nutrient management** |
| N0 : Control (100 % RDF) |
| N1 : Soil application of cobalt @ 1kg $ha^{-1}$ + 100 % RDF |
| N2 : Foliar application of cobalt @ 50 ppm + 100 % RDF |
| N3 : Soil application of molybdenum @ 1.5 kg $ha^{-1}$ + 100 % RDF |
| N4 : Foliar application of molybdenum @ 30 ppm + 100 % RDF |
| N5 : Sugarcane bagasse biochar @ 5 tonnes $ha^{-1}$ +100 % RDF |
| N6 : Sugarcane bagasse biochar @ 5 tonnes $ha^{-1}$ + foliar application of cobalt @ 50 ppm + foliar application of molybdenum @ 30 ppm + 100 % RDF |
| N7 : Sugarcane bagasse biochar @ 5 tonnes $ha^{-1}$ + soil application of cobalt @ 1kg $ha^{-1}$ + soil application of molybdenum @ 1.5 kg $ha^{-1}$ + 100 % RDF |
| N8 : Foliar application of molybdenum @ 30 ppm+ foliar application of cobalt @ 50 ppm + 100 % RDF |

## Results and Discussion

### Thermal regime and weather parameters pattern during green gram growth

Fig. 2 indicates the trends in maximum, minimum and diurnal air temperatures (morning, afternoon and evening) recorded during Standard Meteorological Weeks (SMW 13-23). The maximum temperature varied from 30 to 35 °C, with a gradual increase during the later weeks (SMW 21-23), while the minimum temperature ranged between 14 and 20 °C, similarly indicating a steady rise with the maturity of the crop. Diurnal observations indicate that afternoon air temperatures consistently exceeded those of the morning (24-27 °C) and evening (26-30 °C), with afternoon temperatures ranging from 32 to 36 °C and the lowest values observed in the morning. This daily variation reflects the temperature stress conditions experienced by the crop, particularly during the reproductive growth phase. Fig. 3 depicts variations in soil temperature at both surface and subsurface levels (morning, afternoon and evening) over SMW 13-23. The afternoon soil surface temperature was the highest, ranging from 28 to 34 °C, followed by evening values of 26 to 32 °C and morning values of 16 to 20 °C. Subsurface soil temperature showed relatively constant values, fluctuating between 11 and 23 °C throughout the day, with afternoon readings slightly exceeding those of the morning and evening. A gradual increase in both surface and subsurface soil temperatures was noted during SMW 21-23, correlating with maximum atmospheric temperatures. The higher afternoon soil surface temperature compared to subsurface levels signifies increased solar radiation exposure; however, subsurface temperatures remained moderated, offering a more stable thermal environment for root activity. Fig. 4 illustrates the weekly trend of canopy temperature (°C) measured during morning, afternoon and evening hours, along with soil moisture (%) recorded during the same periods over SMW 13-23. Canopy temperature showed a stable diurnal pattern, with afternoon values usually being the highest (20-27 °C), followed by evening and morning readings. A progressive increase in canopy temperature was noticed from SMW 13, reaching its highest point between SMW 18 and 22, corresponding with higher solar radiation levels. Conversely, soil moisture content showed a relatively stable pattern during the study period, with minor variations at different times of the day. Afternoon soil moisture levels were the highest (~8.0-8.2 %), followed by morning (7.8 %) and evening (7.0-7.2 %). A slight reduction in evening soil moisture was observed after SMW 17, possibly due to increased evaporative demand resulting from higher temperatures and solar radiation. These data highlight an inverse correlation between canopy temperature and soil moisture dynamics, demonstrating the influence of atmospheric evaporative demand on crop water utilization. Fig. 5 shows the weekly variations in solar intensity (W $m^{2}$) during morning, afternoon and evening periods, alongside the associated cloud cover (%). Solar intensity demonstrated a distinct diurnal pattern, with afternoon measurements frequently exceeding over 1000 W $m^{-2}$, followed by morning values ranging from 800 to 900 W $m^{-2}$ and evening readings between 700 and 800 W $m^{-2}$. Peak solar radiation occurred between SMW 16 and 18, corresponding with increased canopy temperatures. Conversely, cloud cover percentage exhibited an inverse trend, with maximum observed during SMW 15, 19 and 21, where afternoon values exceeded 20-25 %. Enhanced cloud cover correlated with a decrease in solar intensity during these weeks, especially in SMW 20, where decreased radiation was associated with high relative humidity and precipitation events. Fig. 6 depicts the weekly variations in wind speed (km/hr) during morning, afternoon and evening hours, along with the associated precipitation (mm) recorded between SMW 13 and 23. Wind speed demonstrated significant diurnal fluctuation, with afternoon readings typically exceeding those of the morning and evening. The maximum wind speed occurred during SMW 16-18, exceeding 14 km/hr, while comparatively lower wind speeds were noted during SMW 21-23. Precipitation events were irregular, with the highest levels recorded in SMW 15, 19, 20 and 23. The highest level of precipitation (5 mm) occurred in SMW 19, which also exhibited increased wind speed, indicating the effect of convective events during this timeframe. In general, wind speed exhibited relative consistency throughout the weeks, whereas precipitation displayed erratic and irregular events. Fig. 7 illustrates the weekly distribution of relative humidity (RH, %) during morning, afternoon and evening hours for the identical period (SMW 13-23). Morning relative humidity levels regularly ranged from 60-75 %, followed by

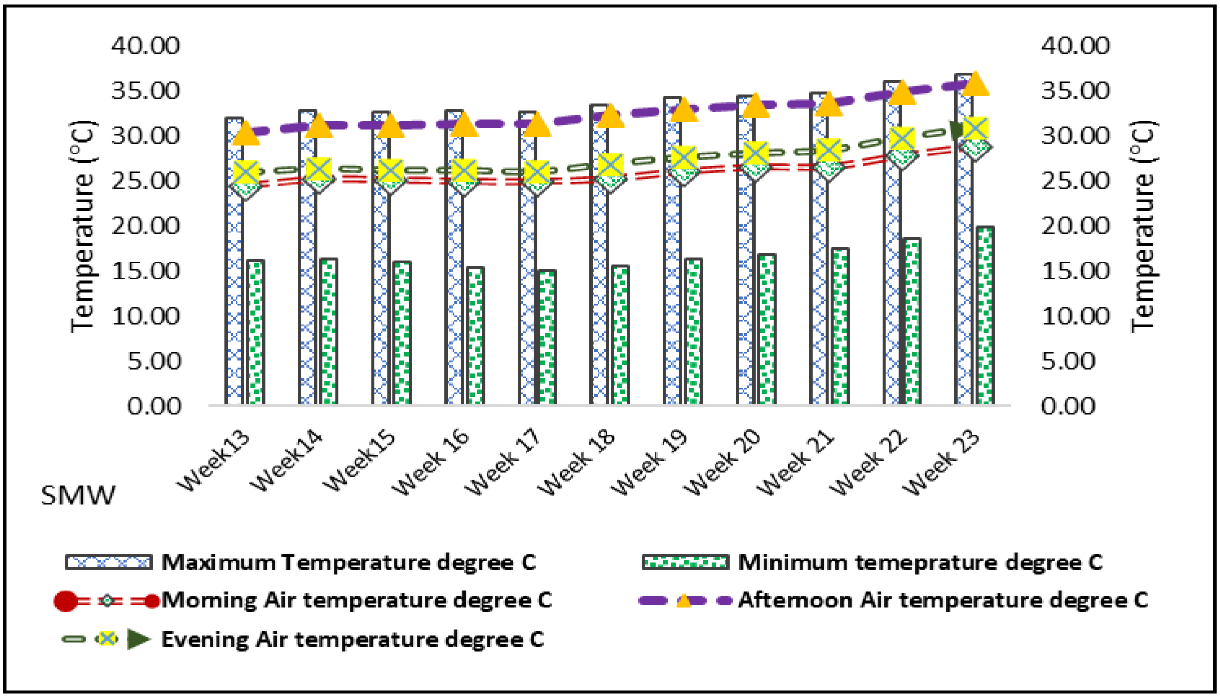



**Fig. 2.** Air temperature (maximum, minimum and during morning, afternoon and evening).

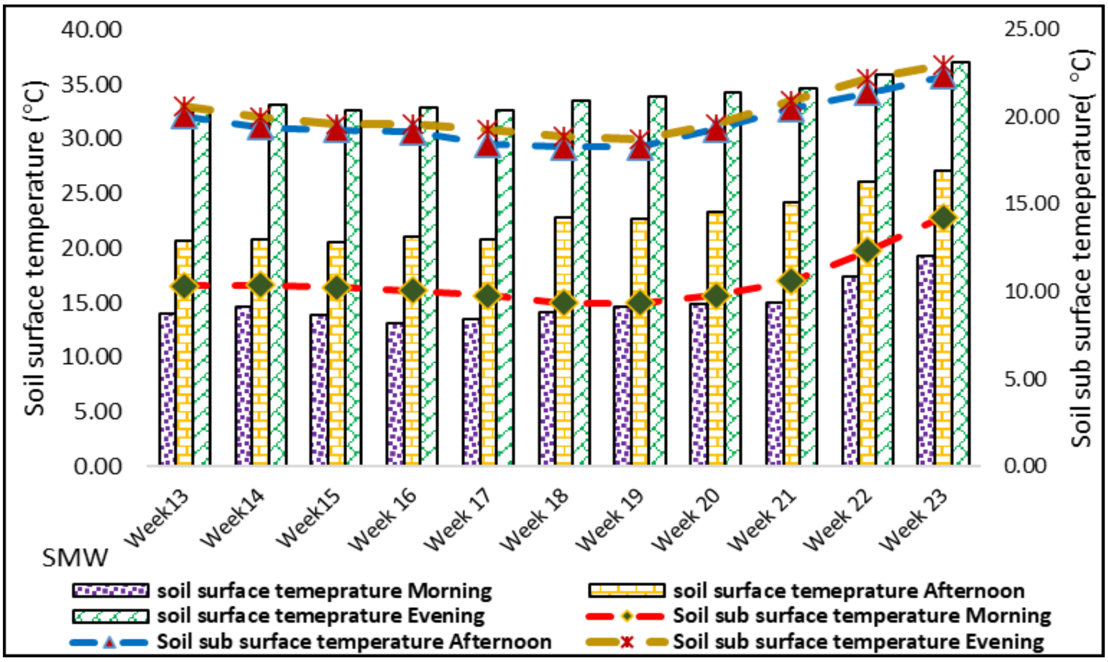



**Fig. 3.** Soil surface and subsurface temperature during morning, afternoon and evening.

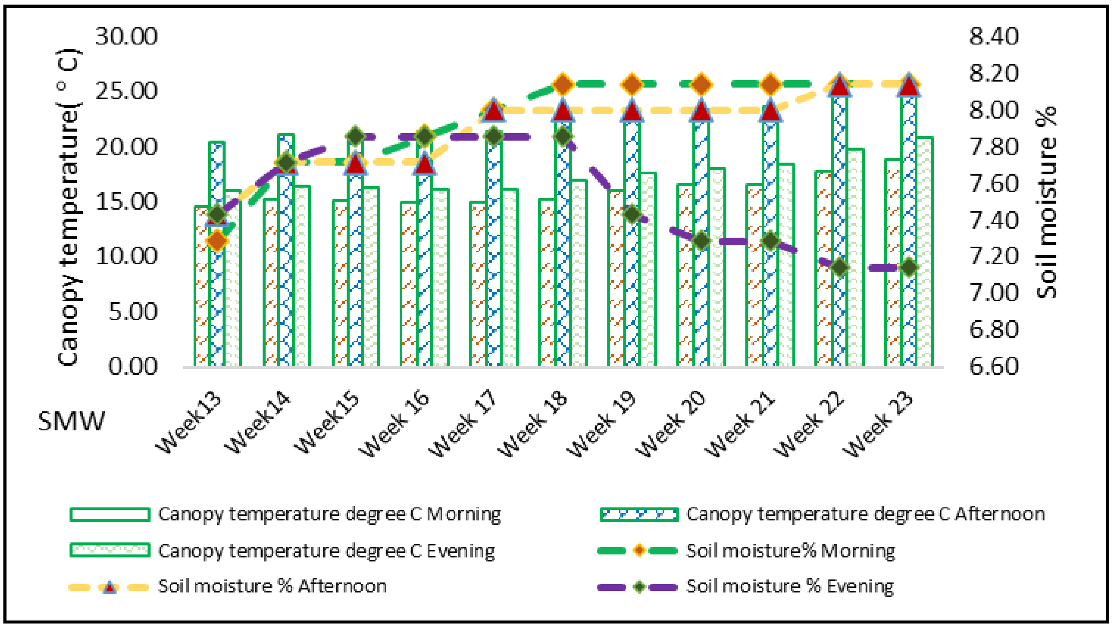



**Fig. 4.** Canopy temperature (°C) and soil moisture (%) during morning, afternoon and evening.

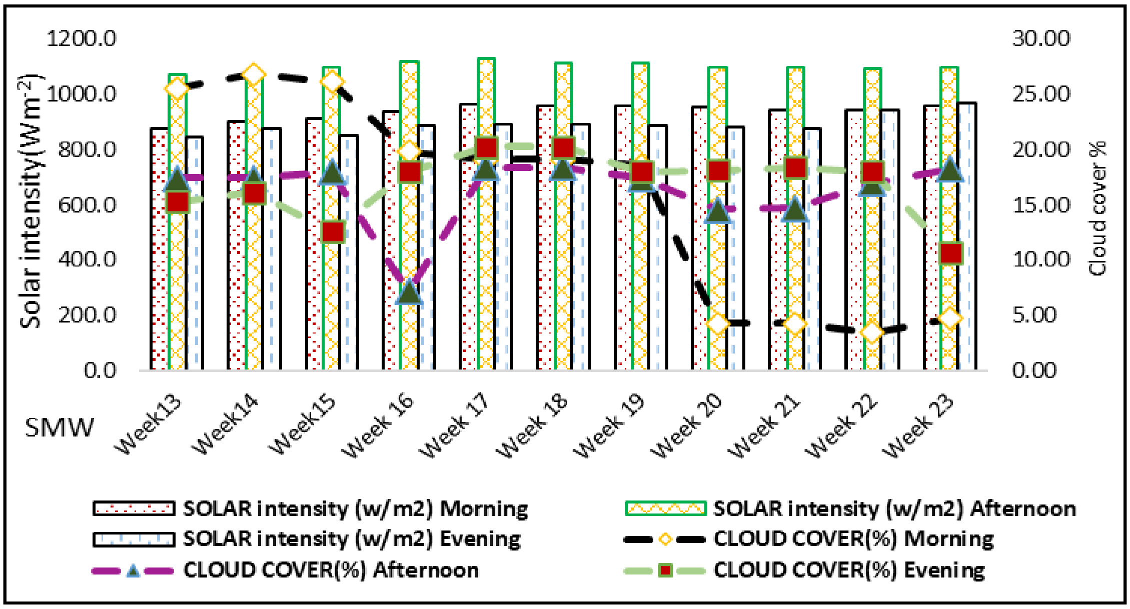



**Fig. 5.** Solar intensity ($Wm^{-2}$) and Cloud cover (%) during morning, afternoon and evening.

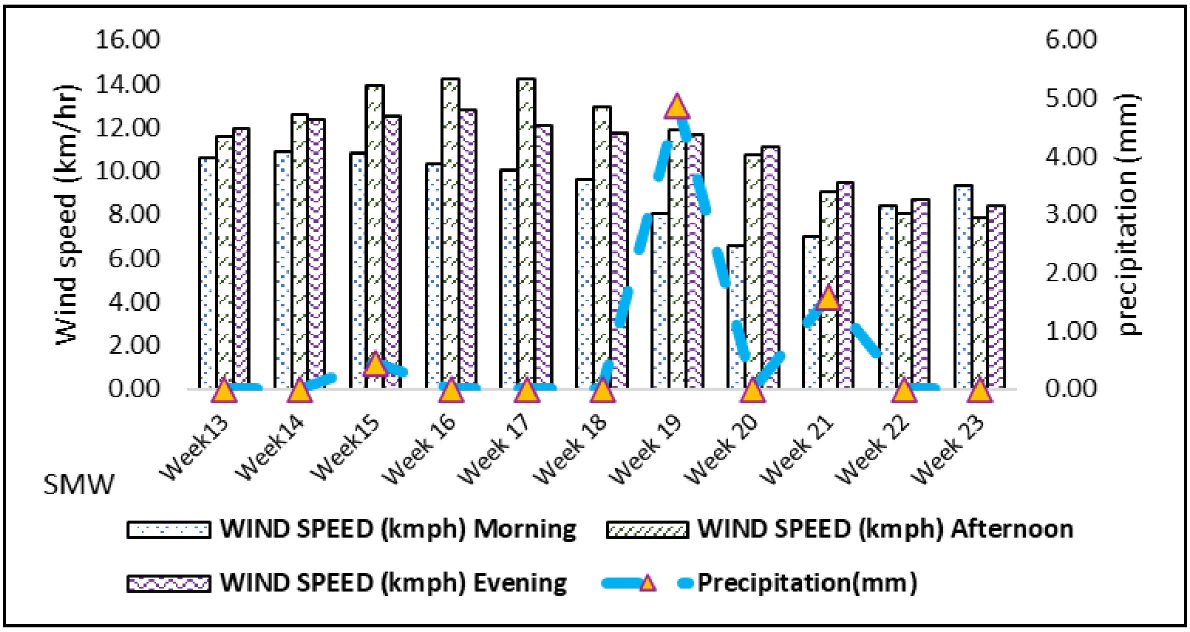



**Fig. 6.** Wind speed (km/hr) and precipitation (mm) across SMWs.

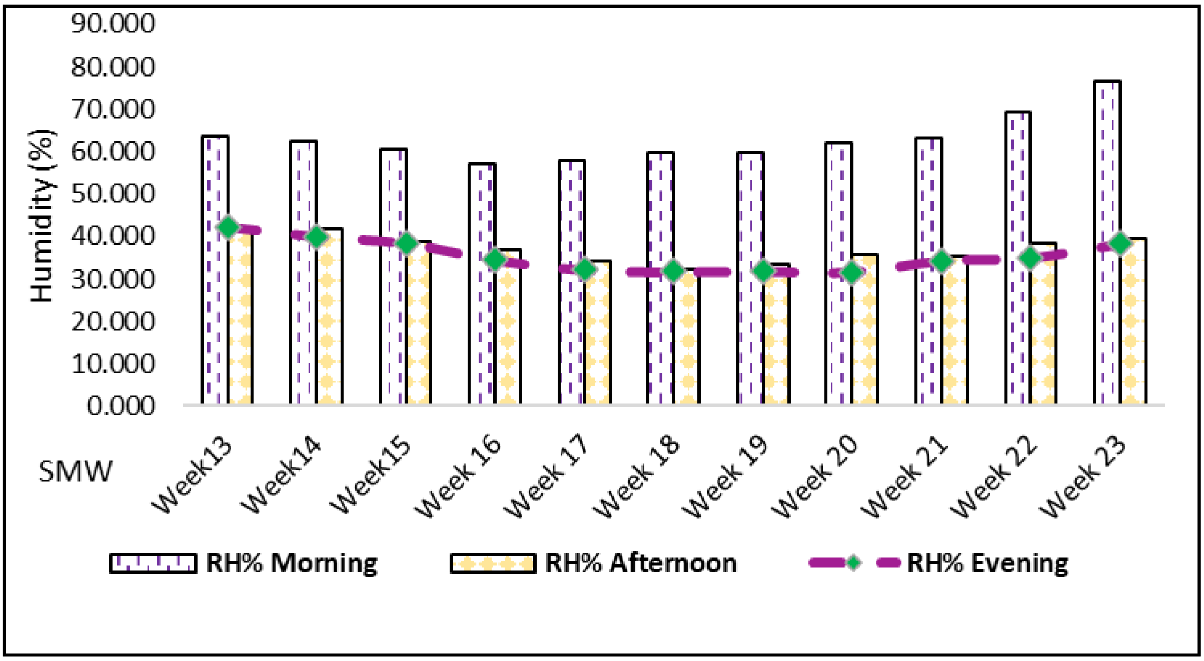



**Fig. 7.** Relative humidity (%) during morning, afternoon and evening across different SMWs during the experimental period.

evening values of 30-40 % and afternoon values of 25-35 %, illustrating the typical diurnal variation affected by daily temperature increases. A gradual rise in morning relative humidity was noted from SMW 21, reaching a maximum of approximately 80 % in SMW 23. Afternoon relative humidity consistently recorded the lowest levels throughout the study period, signifying heightened evaporative demand during midday. Evening relative humidity showed an intermediate trend, characterized by minor changes between 30-40 %. The observed pattern indicates a predominance of elevated morning humidity that decreases over the day, significantly influenced by air temperature and precipitation events.

### Influence of sowing dates and nutrient management on growth attributes of spring green gram

Plant height, number of leaves, leaf area, fresh and dry weight, number of branches and chlorophyll content were significantly influenced by nutrient management, while the sowing date exerted a relatively lesser effect, as indicated in Table 2.

#### Plant height (cm)

Plant height was significantly affected by nutrient management, whereas sowing dates had negligible effects. The tallest plants, measuring 56.61 cm, were recorded in treatment N7 (sugarcane bagasse biochar combined with soil application of cobalt and molybdenum and 100 % RDF), followed by N6 at 55.13 cm, demonstrating the synergistic effect of biochar with micronutrients. Biochar likely improved soil structure, moisture retention and nutrient availability, whereas cobalt and molybdenum improved nodulation and nitrogen assimilation, thereby increasing stem elongation. The shortest plants were observed under N1 (42.09 cm), indicating that the application of cobalt alone to the soil was inadequate to promote growth. Between planting dates, D2 (first week of April) yielded slightly taller plants (48.97 cm) compared to D1 (48.37 cm), likely attributable to higher temperatures during vegetative growth that promote stem elongation. These findings align with previous reports indicating that the synergy between biochar and micronutrients promotes vegetative growth in legumes (1, 16).

**Table 2.** Influence of sowing dates and nutrient management on growth of spring green gram

| Treatments | Plant height (cm) | No. of leaves plant$^{-1}$ | Leaf area (cm$^2$) | Fresh weight plant$^{-1}$(g) | Dry weight plant$^{-1}$ (g) | No. of branches plant $^{-1}$ | Chlorophyll content (mg) |
|---|---|---|---|---|---|---|---|
| Factor A: Date of sowing | | | | | | | |
| D1 | 48.37 | 41.88 | 28.04 | 68.43 | 16.80 | 4.6 | 18.24 |
| D2 | 48.97 | 41.01 | 28.08 | 64.74 | 14.65 | 4.3 | 16.38 |
| SE(m)± | 0.11 | 0.22 | 0.12 | 0.29 | 0.09 | 0.03 | 0.068 |
| CD (p<0.05) | 0.31 | 0.63 | NS | 0.84 | 0.20 | 0.067 | 0.19 |
| Factor B: Nutrient management | | | | | | | |
| $N_0$ | 43.14 | 36 | 23.14 | 46.25 | 15.35 | 3.25 | 14.36 |
| $N_1$ | 42.09 | 40.02 | 28.22 | 59.38 | 13.34 | 4.7 | 19.32 |
| $N_2$ | 50.16 | 43.48 | 25.04 | 63.28 | 15.15 | 3.8 | 17.33 |
| $N_3$ | 48.29 | 42.48 | 26.91 | 64.85 | 13.95 | 4.05 | 16.06 |
| N4 | 43.97 | 38.98 | 26.07 | 52.32 | 12.29 | 3.25 | 18.04 |
| $N_5$ | 51.51 | 45.01 | 27.93 | 74.93 | 16.45 | 4.6 | 16.08 |
| $N_6$ | 55.13 | 45.02 | 31.42 | 93.85 | 21.60 | 5.85 | 18.08 |
| $N_7$ | 56.61 | 46.52 | 35.07 | 74.50 | 19.4 | 6.3 | 19.01 |
| $N_8$ | 47.16 | 35.50 | 28.72 | 69.93 | 14.02 | 4.2 | 17.52 |
| SE(m)± | 0.23 | 0.46 | 0.24 | 0.62 | 0.15 | 0.05 | 0.14 |
| CD (p<0.05) | 0.65 | 1.33 | 0.72 | 1.78 | 0.43 | 0.143 | 0.415 |
| D×N | | | | | | | |
| Factor A×B (C.D) | 0.93 | 1.88 | 1.01 | 2.52 | 0.61 | 0.20 | 0.59 |

(D1- 1st date of sowing; D2- 2nd date of sowing; N0 - Control (100 % RDF); N1- Soil application of cobalt @ 1 kg ha$^{-1}$ + 100 % RDF; N2 - Foliar application of cobalt @ 50 ppm + 100 % RDF; N3 - Soil application of molybdenum @ 1.5 kg ha$^{-1}$ + 100 % RDF; N4 - Foliar application of molybdenum @ 30 ppm + 100 % RDF; N5 - Sugarcane bagasse biochar @ 5 tonnes ha$^{-1}$ +100 % RDF; N6 - Sugarcane bagasse biochar @ 5 tonnes ha$^{-1}$ + foliar application of cobalt @ 50 ppm + foliar application of molybdenum @ 30 ppm +100 % RDF; N7 - Sugarcane bagasse biochar @ 5 tonnes ha$^{-1}$ + soil application of cobalt @ 1 kg ha$^{-1}$ + soil application of molybdenum @ 1.5 kg ha$^{-1}$+100 % RDF; N8 - Foliar application of molybdenum @ 30 ppm+ foliar application of cobalt @ 50 ppm + 100 % RDF)

**Number of leaves plant$^{-1}$**

The number of leaves per plant varied between 36.00 (N0) and 46.52 (N7). Treatments that included biochar (N6 and N7) demonstrated the highest leaf counts, indicating enhanced nutrient absorption and canopy development. The application of cobalt encouraged leaf initiation, whereas molybdenum contributed to nitrogen fixation, leading to vigorous vegetative growth, as indicated by earlier studies (2). The control treatment (N0) showed the lowest leaf number, highlighting the importance of additional nutrient sources. Comparison of the sowing dates D1(41.88) and D2 (41.01), revealed minimal differences, indicating that sowing time had a limited impact on leaf production under the prevailing environmental conditions. Leaf proliferation exhibited a positive correlation with morning humidity and soil moisture availability during the early stages of crop development, as reported in similar findings by previous researchers (17).

**Leaf area (cm$^2$)**

One significant factor influencing photosynthetic capability is leaf area. Treatment N7 recorded the largest leaf area (35.07 cm$^2$), followed by N6 (31.42 cm$^2$). Supplementation with cobalt and molybdenum improved nitrogen metabolism and chlorophyll synthesis, while biochar-amended soils enhanced water and nutrient availability, as indicated by the increased leaf area under these treatments. These results are in conformity with the findings of earlier studies in black gram (18, 19). The control treatment (N0), which had no micronutrient or biochar addition, recorded the smallest leaf area (23.14 cm$^2$). Differences between sowing dates were not statistically significant; however, D2 exhibited slightly higher leaf area. Higher morning RH was associated with larger leaf area under integrated nutrient management, limiting excessive leaf desiccation and permitting optimal canopy growth.

**Fresh and dry weight of plant (g)**

The fresh weight of plants varied between 46.25 g (N0) and 93.85 g (N6), while dry weight ranged from 12.29 g (N4) and 21.60 g (N6). Biochar, when combined with foliar and soil micronutrient application, enhanced biomass accumulation, as evidenced by the superior performance of treatments N6 and N7. Biochar increased biomass production by improving cation exchange capacity, increasing soil organic carbon and reducing soil moisture variations. On the other hand, biomass accumulation was lower under the control and single-nutrient applications. Compared to D2, the first planting date (D1) showed slightly greater dry matter accumulation, indicating that early sowing provided favourable canopy temperature and soil moisture during the critical growth phase. These findings are consistent with previous research demonstrating that biochar increased plant biomass by controlling the root-zone microenvironment and nutrient availability (4, 20).

**Number of branches plant$^{-1}$**

Branching exhibited a trend comparable to biomass accumulation. Treatment N7 recorded the highest number of branches (6.3), followed by N6 (5.85) and N4 and the control (N0) recorded the lowest (3.25). Enhanced branching under biochar treatments may be attributed to improved root proliferation, optimal nutrition availability and a favourable canopy microclimate. A greater number of branches directly enhanced pod bearing thereby influencing yield. Between sowing dates, D1 (4.6) outperformed D2 (4.3), indicating that earlier sowing enhanced vegetative branching under relatively mild weather conditions. These results agree with findings reported in wheat and black gram crop (5, 21).

**Chlorophyll content (mg g$^{-1}$ FW)**

The chlorophyll content varied from 14.36 mg (N0) to 19.32 mg (N1). It is noteworthy that foliar and soil application of cobalt (N1) resulted in a significant increase in chlorophyll content, which indicates its role as a cofactor in nitrogen metabolism and chlorophyll biosynthesis. In addition, the use of biochar in treatments resulted in the maintenance of high chlorophyll levels (N6: 18.08 mg g-1 FW; N7: 19.01 mg g-1 FW), thereby ensuring sustained photosynthetic efficiency, as reported by an earlier study (6). The control treatment showed the lowest chlorophyll content, suggesting nutrient deficiency. Between the sowing dates, D1 (18.24) exhibited higher chlorophyll content than D2 (16.38), indicating that the temperature –humidity balance was more favorable for chlorophyll stability under early sowing conditions, as documented by earlier researchers (22).

## Effect of sowing dates and nutrient management on the yield attributes

### Number of pods plant$^{-1}$

The number of pods exhibited considerable variation in relation to nutrition management, ranging from 21.15 (N0) to 29.26 (N7). Biochar in combination with micronutrients (N6 and N7) resulted in a significant increase in pod production due to enhanced branching, increased leaf area and improved photosynthetic efficiency. The control plots produced the least number of pods, highlighting the importance of balanced nutrient supply. Similar results have been reported in previous studies (7, 23). Between the sowing dates, D2 (26.93) recorded a slightly higher number of pods than D1 (26.14); however, the difference was non-significant, as indicated in Table 3.

### Pod weight (g) and pod length (cm)

Pod length showed a comparable pattern, with a slight increase under early sowing (6.84 cm) compared to late sowing (6.65 cm). The longest pods were observed in N6 (7.60 cm) and N7 (7.55 cm) among the nutrient treatments, indicating enhanced sink development and assimilate supply. The smallest pods were observed in N3 (6.15 cm) and N0 (6.20 cm), where restricted nutrient availability limited pod growth. Earlier findings indicated that integrated nutrient management significantly improved pod development compared to control (8, 24). Pod weight was marginally higher under early sowing (7.71 g) compared to late sowing (7.27 g). Nutrient management significantly improved pod weight, with the heaviest pods recorded in N7 (9.75 g), followed by N6 (8.75 g). These treatments likely improved photosynthetic activity and assimilate translocation, resulting in well-filled pods. The lightest pods were observed in N5 (6.35 g) and N8 (6.55 g), indicating that biochar or foliar feeding alone could not maximize pod filling.

### Number of seeds pod$^{-1}$

The number of seeds per pod was significantly influenced by nutrient management, while sowing dates had a relatively less effect. Early sowing (D1) yielded significantly more seeds per pod (11.12) compared to late sowing (D2: 10.81), probably due to advantageous microclimatic conditions during blooming and pod development. The highest number of seeds per pod was observed in N6 (12.26) and N7(12.15), highlighting the synergistic effect of biochar combined with cobalt and molybdenum in improving reproductive efficiency, pollen viability and seed development (25). The minimum values were recorded in N5 (9.39) and N0 (9.85), indicating that biochar or RDF alone was insufficient to support reproductive growth under heat stress.

### Test weight (g)

Test weight, an important indicator of seed quality and grain filling, was significantly influenced by nutrient management but not by sowing dates. Early sowing (D1: 45.27 g) maintained a slight advantage over late sowing (D2: 44.48 g). Among the nutrient treatments, the highest test weight was observed in N7(47.72 g), followed by N6 (46.88 g) and N5 (46.26 g), reflecting the positive effect of biochar and micronutrients in prolonging the seed-filling duration and ensuring proper translocation of assimilates. Similar results are in support of previous research findings (1, 2). The lowest test weight was recorded in N0 (40.67 g), indicating nutrient deficiency stress.

### Seed yield (kg ha$^{-1}$)

Seed yield of green gram was significantly influenced by nutrient management, while sowing dates showed a relatively minor effect. Early sowing on 24 March (D1) resulted in a slightly higher seed yield (1313.38 kg ha$^{-1}$) than late sowing on 08 April (D2: 1278.50 kg ha$^{-1}$).

**Table 3.** Influence of sowing dates and nutrient management on yield of spring green gram

| Treatments | No. of pods plant$^{-1}$ | Pod weight (g) | Pod length (cm) | No. of seeds per pod | Test weight (g) | Seed yield (Kg ha$^{-1}$) | Stalk yield (Kg ha$^{-1}$) | Harvest index (%) |
|---|---|---|---|---|---|---|---|---|
| **Factor A: Date of sowing** | | | | | | | | |
| D1 | 26.14 | 7.71 | 6.84 | 11.12 | 45.27 | 1313.38 | 2645.99 | 33.38 |
| D2 | 26.93 | 7.27 | 6.65 | 10.81 | 44.48 | 1278.5 | 2605.60 | 33.49 |
| SE(m)± | 0.09 | 0.039 | 0.04 | 0.06 | 0.15 | 6.02 | 12.57 | NS |
| CD (p<0.05) | 0.29 | 0.114 | 0.11 | 0.17 | 0.44 | 21.23 | 36.29 | 0.21 |
| **Factor B: Nutrient management** | | | | | | | | |
| N0 | 21.15 | 6.7 | 6.2 | 9.85 | 40.67 | 1167.62 | 2300.95 | 33.85 |
| N1 | 24.42 | 7.98 | 6.65 | 10.97 | 44.12 | 1290.12 | 2691.82 | 32.41 |
| N2 | 25.28 | 7.40 | 7.102 | 11.72 | 44.19 | 1305.09 | 2823.45 | 31.59 |
| N3 | 23.09 | 6.90 | 6.15 | 10.37 | 45.02 | 1280.48 | 2352.42 | 32.6 |
| N4 | 25.12 | 7.04 | 6.9 | 10.96 | 44.25 | 1324.04 | 2591.81 | 32.39 |
| N5 | 24.37 | 6.35 | 6.4 | 9.39 | 46.26 | 1335.15 | 2162.36 | 32.02 |
| N6 | 27.91 | 8.75 | 7.60 | 12.26 | 46.88 | 1382.10 | 2823.10 | 36.71 |
| N7 | 29.26 | 9.75 | 7.55 | 12.15 | 47.72 | 1450.65 | 3273.40 | 37.31 |
| N8 | 24.71 | 6.55 | 6.2 | 10.95 | 44.73 | 1231.85 | 2613.41 | 32.06 |
| SE(m)± | 0.21 | 0.084 | 0.08 | 0.12 | 0.32 | 12.78 | 26.67 | 0.91 |
| CD (p<0.05) | 0.60 | 0.24 | 0.225 | 0.36 | 0.93 | 36.91 | 76.99 | 0.44 |
| | | | D× N | | | | | |
| Factor A×B (C.D) | 0.85 | 0.34 | 0.32 | 0.51 | 1.32 | 52.2 | 108.8 | 1.28 |

(D1- 1st date of sowing (third week of March); D2- 2nd date of sowing (first week of April); N0 - Control (100 % RDF); N1- Soil application of cobalt @ 1 kg ha$^{-1}$ + 100 % RDF; N2- Foliar application of cobalt @ 50 ppm + 100 % RDF; N3- Soil application of molybdenum @ 1.5 kg ha$^{-1}$ + 100 % RDF; N4- Foliar application of molybdenum @ 30 ppm + 100 % RDF; N5- Sugarcane bagasse biochar @ 5 tonnes ha$^{-1}$ +100 % RDF; N6- Sugarcane bagasse biochar @ 5 tonnes ha$^{-1}$ + foliar application of cobalt @ 50 ppm + foliar application of molybdenum @ 30 ppm +100 % RDF; N7- Sugarcane bagasse biochar @ 5 tonnes ha$^{-1}$ + soil application of cobalt @ 1 kg ha$^{-1}$ + soil application of molybdenum @ 1.5 kg ha$^{-1}$ + 100 % RDF; N8- Foliar application of molybdenum @ 30 ppm+ foliar application of cobalt @ 50 ppm + 100 % RDF)

The incremental effect of early sowing can be attributed to comparatively favourable canopy temperature and soil moisture conditions throughout the reproductive phase, which encouraged better pod set and seed filling. However, the difference between sowing dates was statistically significant. The highest seed yield among nutrient management treatments was recorded in N7 (1450.65 kg ha$^{-1}$), followed by N6 (1382.10 kg ha$^{-1}$), both involving biochar and micronutrient supplementation. The increased yield in these treatments could be due to improvements in plant growth parameters (height, leaf area and number of branches), enhanced photosynthetic efficiency and improved assimilate allocation to reproductive sinks, as reported in previous studies (9, 22). The control treatment (N0: 1167.62 kg ha$^{-1}$), which lacked biochar and nutrients application, recorded the lowest seed yield. Treatments that received only single applications of cobalt or molybdenum (N1, N2, N3, N4) had average yields (1280-1324 kg ha$^{-1}$), whereas biochar applied alone with reduced RDF (N5: 1335.15 kg ha$^{-1}$) showed a yield advantage over the control. This indicates that the combined effect of biochar and micronutrients was more effective than their individual treatments.

**Stalk yield (kg ha$^{-1}$)**

Stalk yield was significantly influenced by nutrient management, while sowing dates had less effect. Stalk yield varied from 2645.99 kg ha$^{-1}$ (D1) to 2605.60 kg ha$^{-1}$ (D2), indicating that biomass accumulation was comparable across sowing periods. Nutrient management strategies have shown more variation. The highest stalk yield was recorded in N7 (3273.40 kg ha$^{-1}$), followed by N6 (2823.10 kg ha$^{-1}$) and N2 (2823.45 kg ha$^{-1}$), indicating the beneficial impact of biochar and micronutrients on biomass production. These treatments enhanced soil moisture retention, nutrient utilization efficiency and photosynthetic performance, resulting in increased vegetative growth and dry matter accumulation as reported in earlier studies (10, 17). The minimum stalk yield was observed under N5 (2162.36 kg ha$^{-1}$), indicating that biochar with 100 % RDF alone was inadequate to support increased vegetative biomass and indicating that the addition of micronutrients is necessary for the best possible results.

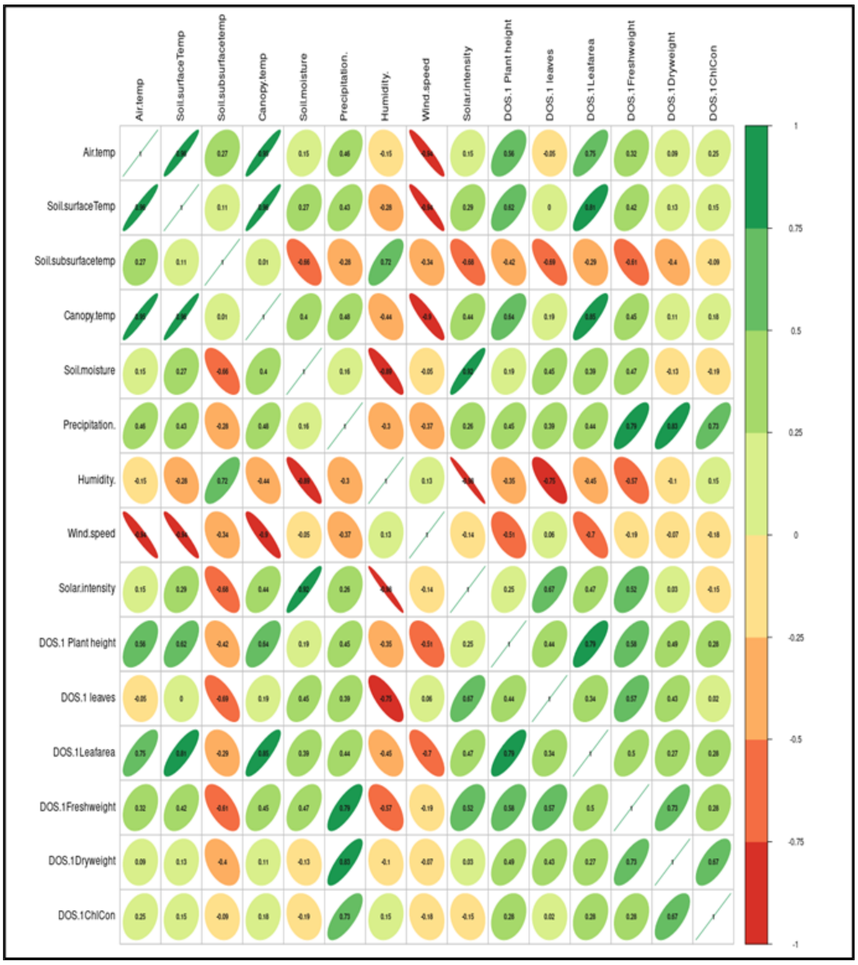
**Harvest index (%)**

The harvest index (HI), reflecting the efficiency of assimilate allocation to economic yield, was significantly affected by nutrient management practices, whereas the impact of sowing dates was not significant. HI values across sowing dates were nearly identical, ranging from 33.38 % for the 24 March sowing (D1) to 33.49 % for the 08 April sowing (D2). This indicates that sowing time had minimal impact on biomass partitioning under the prevailing thermal and moisture stress conditions. Although seed yield showed a slight increase with early sowing, the corresponding rise in stalk yield offset the HI values, resulting in statistically non-significant differences. Nutrient management treatments exhibited distinct variations. The highest HI was observed in N7 (37.31 %), which involved the application of sugarcane bagasse biochar at 5 t ha$^{-1}$, soil-applied cobalt at 1 kg ha$^{-1}$, molybdenum at 1.5 kg ha$^{-1}$ and 100 % RDF. This was followed by N6 (36.71 %), which combined biochar with foliar application of cobalt and molybdenum along with 100 % RDF. The enhancement in HI resulting from these treatments is linked to increased nodulation and nitrogen fixation, improved soil moisture retention due to biochar and a better source-sink balance, which facilitates greater allocation of assimilates to seeds rather than vegetative biomass. Similar results have been reported in earlier studies (1, 21). The lowest HI values were recorded in N2 (31.59 %) and N5 (32.02 %), suggesting ineffective biomass partitioning when either single-nutrient foliar feeding or biochar with reduced RDF was applied alone. Although N5 exhibited a higher test weight (46.26 g), its lower seed yield relative to vegetative biomass accumulation resulted in a reduced HI. Similarly, N2 produced a significantly higher stalk yield; however, this did not correspond to a proportional increase in seed yield. These findings support previous studies indicating that the combined use of biochar and micronutrients improves dry matter allocation to reproductive sinks in legumes. Overall, the results indicate that the combination of biochar with cobalt and molybdenum enhanced vegetative growth and yield attributes while also increasing HI, thereby demonstrating improved reproductive efficiency under spring-season stress conditions.

### Correlation of growth, yield attributes with weather parameters as per date of sowing

The correlogram displays the pairwise correlation coefficients among environmental variables (air temperature, soil surface temperature, soil subsurface temperature, canopy temperature, soil moisture, precipitation, humidity, wind speed and solar intensity) and crop growth parameters (plant height, number of leaves, leaf area, fresh weight, dry weight and chlorophyll content) across various stages of crop development (DOS-1 and DOS-2), as indicated in Fig. 8-11. Positive correlations are depicted in green, whereas negative correlations are shown in red. The intensity of the colour and the shape of the ellipses illustrate the strength and direction of the correlations. The results indicate significant positive correlations among growth parameters, including plant height, leaf area and fresh weight, demonstrating their interdependence in biomass accumulation. Environmental variables such as air temperature, canopy temperature and soil moisture showed moderate to strong positive correlations with leaf area and plant height, highlighting their essential influence on crop development.

On the other hand, wind speed and humidity exhibited negative correlations with various growth traits, suggesting potential stress impacts on crop physiology. Solar intensity exhibited positive correlations with chlorophyll content and leaf area, indicating its role in promoting photosynthetic activity. A significant positive correlation was identified among yield components, particularly pod length, pod weight, seeds per pod, test weight and seed yield, demonstrating their combined contribution to overall productivity. Air temperature, canopy temperature and soil moisture exhibited moderate to strong positive correlations with pod number, pod length and seed yield, indicating that optimal thermal and soil moisture conditions promote yield formation. In contrast, wind speed and humidity showed negative correlations with most yield parameters, suggesting their possible inhibitory effects on pod development and seed filling. Solar intensity displayed a positive correlation with test weight and seed yield, indicating its influence on assimilate partitioning and grain filling. Overall, the correlogram indicates that crop growth traits are significantly affected by temperature and soil moisture dynamics, while wind speed and humidity exert negative impacts, highlighting the critical role of environmental factors in crop performance. Similarly, yield attributes were interdependent and significantly affected by environmental conditions with temperature and soil moisture exerting positive influences, whereas excessive humidity and wind speed serve as limiting factors for yield attainment.



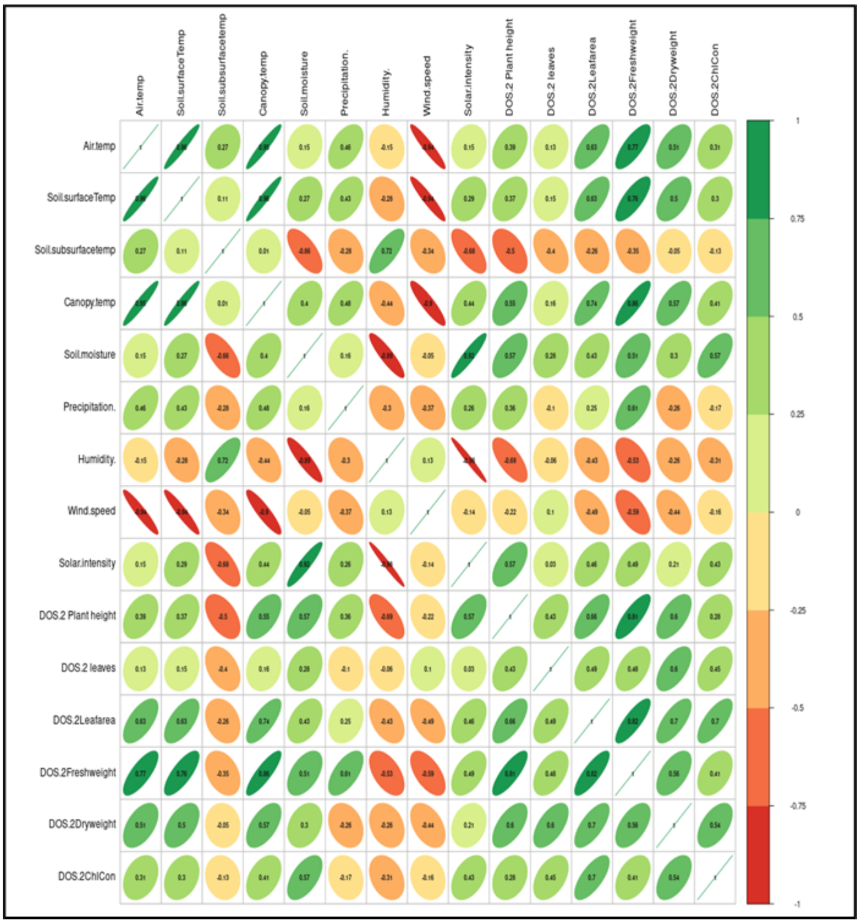
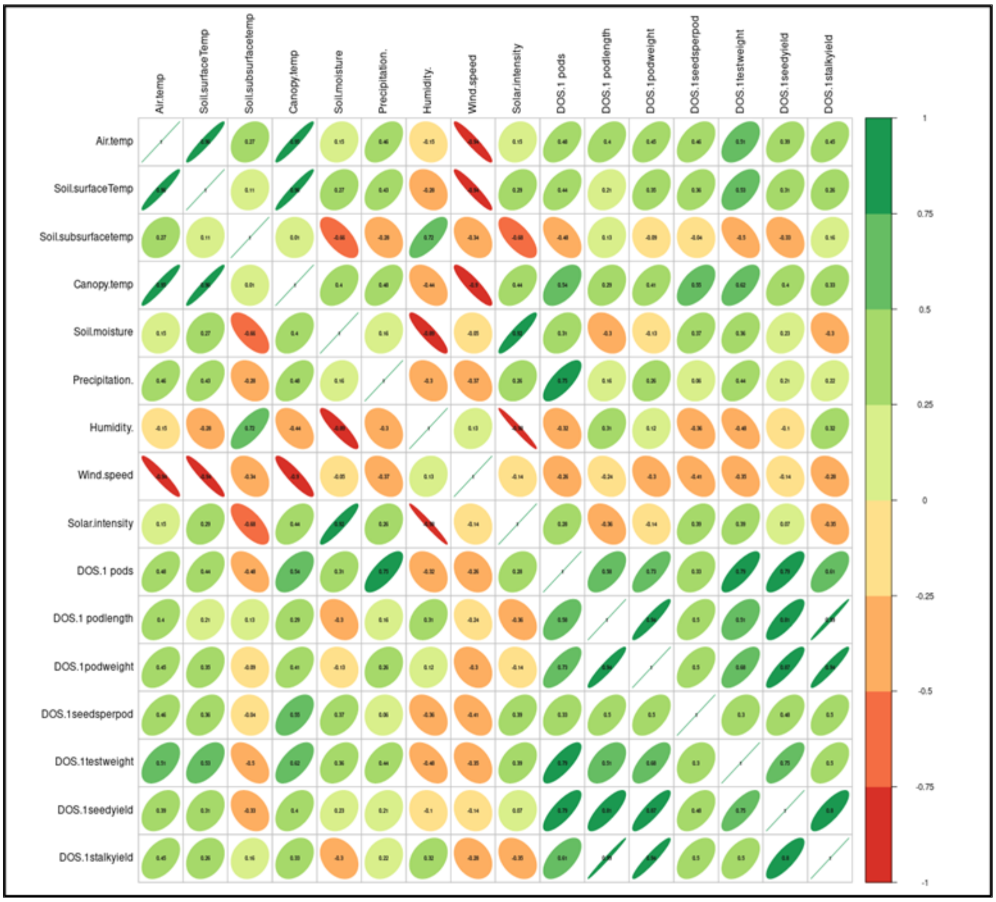




**Fig. 8, 9.** Correlation matrix showing the relationships between environmental factors (air temperature, soil temperature, canopy temperature, soil moisture, precipitation, humidity, wind speed and solar intensity) and green gram growth attributes (plant height, number of leaves, leaf area, fresh weight, dry weight and chlorophyll content) at different dates of sowing (DOS). Positive correlations are indicated in green and negative correlations in red, with colour intensity and ellipse shape denoting the strength of the correlations.



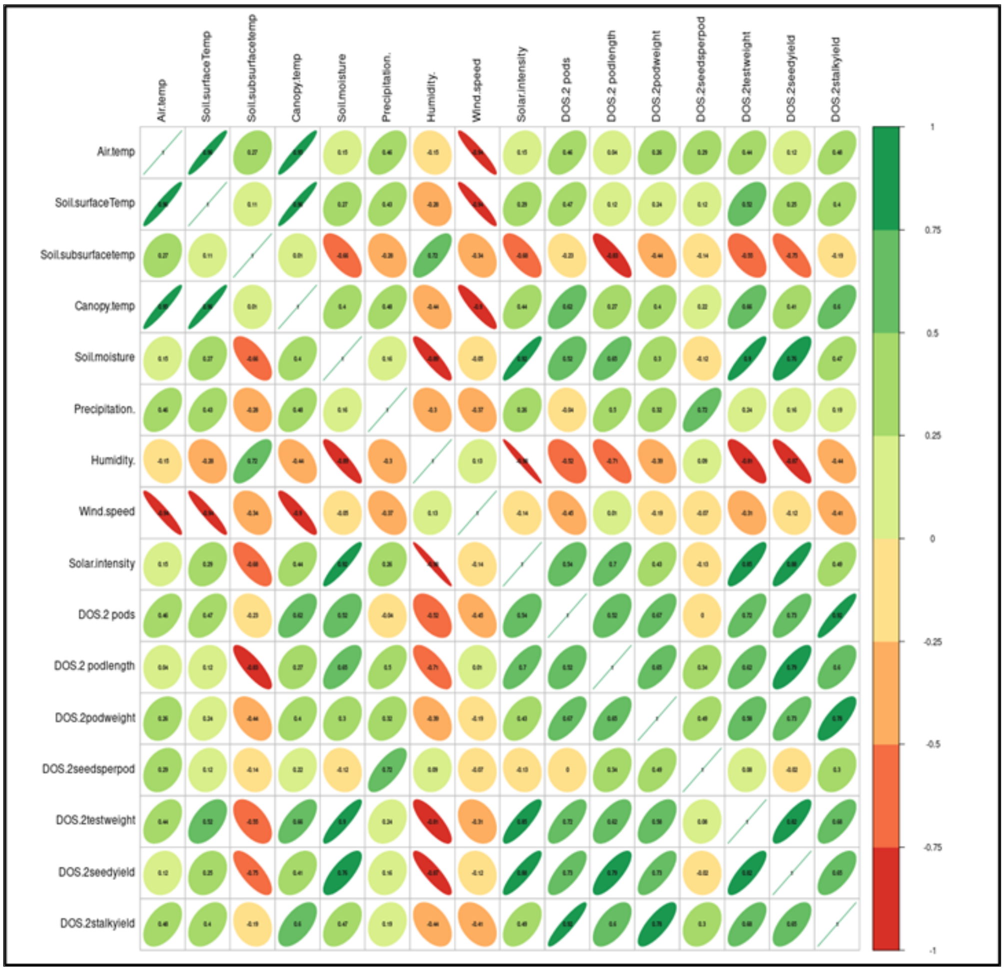




**Fig. 10, 11.** Correlation matrix depicting the relationships between weather parameters (air temperature, soil temperature, canopy temperature, soil moisture, precipitation, humidity, wind speed and solar intensity) and yield attributes of green gram (number of pods, pod length, pod weight, seeds per pod, test weight, seed yield and stalk yield) at different dates of sowing. Positive correlations are indicated in green and negative correlations in red, with ellipse orientation and colour intensity representing the strength of the correlations.

## Conclusion

The research indicated that sowing date and nutrient management are essential factors influencing the growth and yield of spring green gram under conditions of heat and moisture stress. The impact of sowing date was less significant; however, early sowing in the third week of March was beneficial, as it mitigated late-season high canopy temperatures and resulted in increased seed yield. Nutrient management had a significant impact, with the integrated application of sugarcane bagasse biochar, cobalt and molybdenum along with reduced RDF (N7) identified as the most effective treatment for enhancing plant growth, biomass accumulation, yield attributes and final seed yield. Biochar improved soil physical properties and nutrient retention, while cobalt and molybdenum enhanced nodulation, nitrogen metabolism and reproductive efficiency. The findings indicate that adopting a favorable sowing time in combination with integrated nutrient management using biochar and micronutrients provides a sustainable agronomic approach to address climatic challenges and improve green gram productivity in subtropical areas.

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## Authors' contributions

SM prepared the research plan, conducted the analysis, contributed to manuscript writing and participated in proofreading. AJ provided guidance throughout the research and supported the development of the methodology. SSH assisted in writing and proofreading the manuscript. All authors have read and approved the final version of the manuscript.

## Compliance with ethical standards

**Conflict of interest:** The authors declare that they have no conflict of interest.

**Ethical issues:** None

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