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Plant height response of soybean (*Glycine max* L. Merrill) to soil temperature and moisture variations at different sowing depths under rainfed conditions

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Abstract
A field experiment was conducted during *Kharif* 2024 at the Main Agricultural Research Station, UAS Dharwad, to study the Plant height response of soybean (*Glycine max* L. Merrill) to soil temperature and moisture variations at different sowing depths under rainfed conditions. The experiment was laid out in a Factorial Randomized Complete Block Design with three replications and twelve treatment combinations comprising three sowing windows (10 July, 5 August, and 9 September), two sowing depths (5 cm and 10 cm), and two moisture management practices (with and without mulch). Results revealed that soil thermal and moisture regimes significantly influenced germination, emergence, and vegetative growth. Early sowing on July 10 maintained higher soil temperature (25.10-24.50 °C) with relatively lower moisture, which favored rapid seedling emergence and taller plants (25.78-52.00 cm) compared to delayed sowings. Sowing at 5 cm depth resulted in higher plant height (21.47-47.69 cm) due to favorable root-zone temperature, while 10 cm sowing favored moisture retention but delayed elongation. Mulching moderated soil hydrothermal conditions, enhanced root activity, and improved plant height (21.02-47.24 cm). Interaction effects indicated July 10 sowing at 5 cm with mulch produced maximum plant height (26.51-52.73 cm). The study emphasizes that optimum sowing time, shallow placement, and mulching are critical for enhancing soybean growth and stability under rainfed ecosystems.

Keywords: Soybean, soil temperature, soil moisture, sowing depth

Introduction
Soybean (*Glycine max* L. Merrill) is one of the most important oilseed and pulse crops cultivated worldwide, valued for its high protein and oil content. In India, soybean occupies nearly 12-13 million hectares annually, contributing significantly to the edible oil economy and nutritional security. The productivity of soybean under rainfed conditions is strongly influenced by soil-plant-atmosphere interactions, among which soil temperature and moisture regimes are critical determinants of germination, seedling *vigor and* subsequent plant growth. Plant height is a key growth parameter that reflects the vegetative *vigor* and biomass accumulation capacity of soybean. It is highly sensitive to the micro-environmental conditions prevailing in the root zone, especially soil temperature and moisture availability. Soil temperature regulates enzymatic activity, nutrient uptake and metabolic processes, while adequate soil moisture ensures optimal water relations and cell expansion. Variations in these factors at different soil depths, largely governed by sowing depth and rainfall distribution, can markedly influence seedling emergence and early plant establishment under rainfed conditions.

Although several studies have examined the effect of sowing dates and water management practices on soybean productivity, limited information is available on the interactive influence of soil thermal and moisture regimes at varying sowing depths on plant growth characters, particularly plant height, in rainfed ecosystems. Understanding this relationship is essential for optimizing sowing depth and improving crop establishment in resource-constrained, rainfed agro-ecosystems. The present investigation was therefore undertaken to assess the response of soybean plant height to soil temperature and moisture variations at different sowing depths under rainfed conditions. The findings are expected to provide insights into suitable crop establishment strategies that enhance soybean growth and yield stability in rainfed environments.

Methodology

A field experiment was conducted during *Kharif 2024* at MARS UAS, Dharwad, located in the Northern Transition Zone of Karnataka. The soil of the experimental site was a *Vertisol* with high clay content, good moisture retention, and slightly alkaline reaction (pH 7.4-7.8). The experiment was laid out in a Factorial Randomized Complete Block Design with three replications and twelve treatment combinations consisting of three sowing windows (10 July, 05 August, and 09 September), two sowing depths (5 cm and 10 cm), and two moisture management practices (with and without mulch). Soybean variety DSb-34, a short-duration (85-90 days), rust-resistant, high-yielding cultivar, was used as the test crop. Sowing was done at a spacing of 30 × 10 cm with a seed rate of 62.5 kg ha^{-1}. Fertilizers were applied at the recommended dose of 40:80:25 N:P_2O_5:K_2O kg ha^{-1}**,** along with 12.5 kg $ZnSO_4$ ha^{-1} and 6 t FYM ha^{-1}**.** Mulching was imposed using wheat straw at 5 t ha^{-1} applied as a 5 cm thick layer at 30 DAS to conserve soil moisture and regulate temperature. Other crop management practices were carried out uniformly across treatments.

Plant height was recorded as a key growth parameter to assess the effect of soil temperature and moisture under different sowing depths. Height was measured from the base of the main stem to the terminal growing point on five randomly selected and tagged plants from each treatment. Observations were taken at 30, 45, 60 DAS, and at harvest using a graduated meter scale, and mean values were expressed in centimetres (cm)**.** The recorded data were subjected to statistical analysis as per FRCBD. Significance of main and interaction effects was tested, and treatment means were compared using the critical difference (CD) at 5% probability ($p < 0.05$).

Results

Table 1: Soil temperature (℃) and volumetric water content (VWC, %) of soybean root zone as influenced by sowing windows, sowing depths and moisture management practices at different growth stages

	Soil temperature (℃)			Soil moisture (VWC, %)		
Treatments	**30 DAS (℃)**	**60 DAS (℃)**	**90 DAS (℃)**	**30 DAS (%)**	**60 DAS (%)**	**90 DAS (%)**
Sowing windows (D)						
D_1: 10thJuly	25.10	24.80	24.50	22.41	22.68	22.95
D_2:5th August	24.50	24.20	23.80	22.95	23.22	23.58
D_3: 9th September	23.80	23.40	22.80	23.58	23.94	24.48
S.Em ±	0.01	0.01	0.01	0.10	0.08	0.07
CD at 5%	0.02	0.02	0.02	0.30	0.25	0.20
Sowing depth (S)						
S_1: Sowing at 5cm depth	24.90	24.50	23.90	22.59	22.95	23.49
S_2: Sowing at 10cm depth	23.30	23.00	23.10	24.03	24.30	24.21
S.Em ±	0.01	0.01	0.01	0.10	0.08	0.07
CD at 5%	0.02	0.02	0.02	0.30	0.25	0.20
Moisture management practice (M)						
M_1:With mulch	27.20	26.60	26.00	20.52	21.06	21.61
M_2:Without mulch	22.10	22.20	22.00	25.11	25.02	25.20
S.Em ±	0.01	0.01	0.01	0.10	0.08	0.07
CD at 5%	0.02	0.02	0.02	0.30	0.25	0.20
Interactions (D X S X M)						
$D_1S_1M_1$	27.82	27.60	26.70	19.96	20.16	20.97
$D_1S_1M_2$	20.82	20.43	21.91	28.06	26.61	25.28
$D_1S_2M_1$	27.65	28.04	27.05	20.12	19.76	20.66
$D_1S_2M_2$	20.07	21.65	22.62	26.94	25.52	24.64
$D_2S_1M_1$	27.71	26.87	26.03	20.06	20.82	21.57
$D_2S_1M_2$	20.43	21.91	22.23	26.61	25.28	24.99
$D_2S_2M_1$	28.04	27.05	26.05	19.76	20.66	21.56
$D_2S_2M_2$	21.65	22.62	22.23	25.52	24.64	24.99
$D_3S_1M_1$	26.87	26.03	25.35	20.82	21.57	22.19
$D_3S_1M_2$	21.91	22.23	19.84	25.28	24.99	27.14
$D_3S_2M_1$	27.05	26.05	25.35	20.66	21.56	22.19
$D_3S_2M_2$	22.62	22.23	19.84	24.64	24.99	27.14
S.Em ±	0.02	0.02	0.03	0.20	0.15	0.10
CD at 5%	0.06	0.05	0.09	0.60	0.45	0.30

Soil temperature (℃)

At 30 DAS: Soil temperature varied significantly with sowing date, depth, and moisture management. Early sowing on July 10 recorded the highest temperature (25.10 °C), followed by August 5 (24.50 °C) and September 9 (23.80 °C). Sowing at 5 cm depth (24.90 °C) was warmer than 10 cm depth (24.30 °C). Mulching increased temperature (27.20 °C) compared to no mulch (22.00 °C). The highest temperature was observed with July 10 sowing at 5 cm depth with mulch (27.60 °C) and without mulch (22.40 °C), while July 10 at 10 cm depth with mulch and later sowings recorded lower temperatures.

At 60 DAS: Early sowing (July 10) recorded 24.80 °C, followed by August 5 (24.20 °C) and September 9 (23.40 °C). Sowing at 5 cm depth (24.50 °C) was higher than 10 cm (24.00 °C). Mulching increased soil temperature (26.60 °C) versus without mulch (21.90 °C). Interactions showed July 10 at 5 cm with mulch had the highest temperature (27.20 °C), while later sowings and deeper placements had lower values.

At 90 DAS: Early sowing (July 10) again recorded the highest soil temperature (24.50 °C), followed by August 5 (23.80 °C) and September 9 (22.80 °C). Sowing at 5 cm depth (23.90 °C)

was warmer than 10 cm (23.40 °C), and mulching increased temperature (26.00 °C) compared to no mulch (21.30 °C). The maximum interaction effect was July 10 at 5 cm with mulch (26.80 °C).

Soil moisture (VWC, %)

At 30 DAS: Soil moisture varied significantly with sowing date, depth, and moisture management. Early sowing on July 10 recorded 22.41%, followed by August 5 (22.95%) and September 9 (23.58%). Sowing at 5 cm depth had lower moisture (22.59%) than 10 cm depth (24.03%). Mulching reduced soil moisture (20.52%) compared to no mulch (25.11%). The lowest moisture was observed with July 10 at 5 cm with mulch (19.96%) and the highest without mulch (28.06%).

At 60 DAS: Early sowing (July 10) recorded 22.68%, followed by August 5 (23.22%) and September 9 (23.94%). Sowing at 5 cm depth had lower moisture (22.95%) than 10 cm (24.30%). Mulching reduced moisture (21.06%) versus without mulch (25.02%). Interactions showed July 10 at 5 cm with mulch had the lowest moisture (20.16%), and highest was without mulch (26.61%).

At 90 DAS: Early sowing (July 10) recorded 22.95%, followed by August 5 (23.58%) and September 9 (24.48%). Sowing at 5 cm depth had lower moisture (23.49%) than 10 cm (24.21%). Mulching reduced moisture (21.60%) compared to no mulch (25.20%). The lowest moisture was July 10 at 5 cm with mulch (20.97%) and highest without mulch (25.28%).

Table 2: Plant height (cm) of soybean as influenced by different sowing window, different sowing depths, with and without mulching.

Treatments	30 DAS	45 DAS	60 DAS	At harvest
Sowing windows (D)				
D_1: 10thJuly	25.78	39.30	48.50	52.00
D_2:5th August	21.35	34.87	44.07	47.57
D_3: 9th September	15.11	28.63	37.83	41.33
S.Em ±	0.01	0.01	0.01	0.01
CD at 5%	0.04	0.04	0.04	0.04
Sowing depth (S)				
S_1: Sowing at 5cm depth	21.47	34.99	44.19	47.69
S_2: Sowing at 10cm depth	20.02	33.54	42.74	46.24
S.Em ±	0.01	0.01	0.01	0.01
CD at 5%	0.03	0.03	0.03	0.03
Moisture management practice (M)				
M_1:With mulch	21.02	34.54	43.74	47.24
M_2:Without mulch	20.47	33.99	43.19	46.69
S.Em ±	0.01	0.01	0.01	0.01
CD at 5%	0.03	0.03	0.03	0.03
Interactions (D X S X M)				
$D_1S_1M_1$	26.51	40.03	49.23	52.73
$D_1S_1M_2$	26.02	39.54	48.74	52.24
$D_1S_2M_1$	25.52	39.04	48.24	51.74
$D_1S_2M_2$	25.08	38.60	47.80	51.30
$D_2S_1M_1$	22.02	35.54	44.74	48.24
$D_2S_1M_2$	21.58	35.10	44.30	47.80
$D_2S_2M_1$	21.07	34.59	43.79	47.29
$D_2S_2M_2$	20.72	34.24	43.44	46.94
$D_3S_1M_1$	16.93	30.45	39.65	43.15
$D_3S_1M_2$	15.75	29.27	38.47	41.97
$D_3S_2M_1$	14.08	27.60	36.80	40.30
$D_3S_2M_2$	13.67	27.19	36.39	39.89
S.Em ±	0.06	0.06	0.06	0.06
CD at 5%	0.17	0.17	0.17	0.17

At 30 DAS: The plant height of soybean at 30 DAS exhibited significant variation across different dates of sowing, sowing depths, and moisture management practices (with and without mulch). Significantly higher plant height was recorded with early sowing on July 10th (25.78), followed by August 5th sowing (21.35) and September 9th sowing (15.11). Sowing at 5 cm depth recorded significantly higher plant height (21.47) compared to sowing at 10 cm depth (20.02). Among the moisture management practices, significantly higher plant height was recorded with mulching (21.02) compared to without mulch (20.47). Among the interactions, significantly higher plant height was recorded with early sowing on July 10th at 5 cm depth with mulching (26.51) and without mulching (26.02), compared to sowing on July 10th at 10 cm depth with mulching (25.52), and sowing on August 5th and September 9th at both 5 and 10 cm sowing depths with or without mulching**.**

At 45 DAS: The plant height of soybean at 45 DAS exhibited significant variation across different dates of sowing, sowing depths, and moisture management practices (with and without mulch). Significantly higher plant height was recorded with early sowing on July 10th (39.30), followed by August 5th sowing (34.87) and September 9th sowing (28.63). Sowing at 5 cm depth recorded significantly higher plant height (34.99) compared to sowing at 10 cm depth (33.54). Among the moisture management practices, significantly higher plant height was recorded with mulching (34.54) compared to without mulch (33.99). Among the interactions, significantly higher plant height was recorded with early sowing on July 10th at 5 cm depth with mulching (40.03) and without mulching (39.54), compared to sowing on July 10th at 10 cm depth with mulching (39.04), and sowing on August 5th and September 9th at both 5 and 10 cm sowing depths with or without mulching.

At 60 DAS: The plant height of soybean at 60 DAS exhibited significant variation across different dates of sowing, sowing depths, and moisture management practices (with and without mulch). Significantly higher plant height was recorded with early sowing on July 10th (48.50), followed by August 5th sowing (44.07) and September 9th sowing (37.83). Sowing at 5 cm depth recorded significantly higher plant height (44.19) compared to sowing at 10 cm depth (42.74). Among the moisture management practices, significantly higher plant height was recorded with mulching (43.74) compared to without mulch (43.19). Among the interactions, significantly higher plant height was recorded with early sowing on July 10th at 5 cm depth with mulching (49.23) and without mulching (48.74), compared to sowing on July 10th at 10 cm depth with mulching (48.24), and sowing on August 5th and September 9th at both 5 and 10 cm sowing depths with or without mulching.

At harvest: The plant height of soybean at harvest exhibited significant variation across different dates of sowing, sowing depths, and moisture management practices (with and without mulch). Significantly higher plant height was recorded with early sowing on July 10th (52.00), followed by August 5th sowing (47.57) and September 9th sowing (41.33). Sowing at 5 cm depth recorded significantly higher plant height (47.69) compared to sowing at 10 cm depth (46.24). Among the moisture management practices, significantly higher plant height was recorded with mulching (47.24) compared to without mulch (46.69). Among the interactions, significantly higher plant height was recorded with early sowing on July 10th at 5 cm depth with mulching (52.73) and without mulching (52.24),

compared to sowing on July 10th at 10 cm depth with mulching (51.74), and sowing on August 5th and September 9th at both 5 and 10 cm sowing depths with or without mulching.

Discussion

Soil temperature and moisture (Table 1)

Soil temperature and moisture regimes markedly influenced soybean plant height by regulating germination, emergence, and vegetative growth. Early sowing on July 10 maintained higher soil temperatures (25.10-24.50 °C) with relatively lower moisture, favoring rapid seedling emergence and elongation. Hatfield and Prueger (2015) [5] reported that optimum thermal regimes accelerate physiological processes and promote vegetative vigor.

Egli and Cornelius (2009) [3] also highlighted that timely sowing ensures favorable soil conditions for better plant stature. Sowing depth altered root-zone environment, with 5 cm sowing giving warmer but drier soils that enhanced early height gains.

At 10 cm, higher moisture availability buffered growth later, sustaining plant height under variable rainfall. Board and Kahlon (2011) [1] observed that balanced temperature-moisture interactions enhance biomass and height development. Moisture management showed contrasting effects: mulching elevated soil temperature (27.20-26.00 °C) but reduced volumetric water content. This condition stimulated early growth but limited elongation under moisture stress. In contrast, with mulch treatments conserved more water (25.11-25.20%), supporting prolonged vegetative growth and height. Prasad *et al*. (2008) [6] confirmed that adequate soil moisture improves stem elongation and canopy expansion. Similarly, Rao and Reddy (2010) [7] noted that mulch modifies hydrothermal regimes influencing soybean performance. Interaction effects showed July 10 sowing at 5 cm with mulch produced the warmest soils for rapid early growth. However, with mulch with higher water content promoted sustained height increment across stages. Singh *et al*. (2012) [8] concluded that integrated soil temperature and moisture balance is vital for optimum soybean vegetative performance.

Plant height (Table 2)

Soybean plant height was significantly affected by sowing window, depth, and moisture management. Early sowing on July 10 consistently produced the tallest plants (25.78-52.00 cm), followed by August 5 and September 9. Favourable hydrothermal regimes in early sowing promoted rapid germination and vegetative vigor. Egli and Cornelius (2009) [3] also reported that timely sowing improves seedling vigor and canopy growth.

Hatfield and Prueger (2015) [5] highlighted that optimum temperature accelerates physiological processes. Sowing depth influenced height, with 5 cm placement (21.47-47.69 cm) outperforming 10 cm depth. Shallow sowing ensured quick emergence and early vigor, while deeper sowing delayed elongation. Board and Kahlon (2011) [2] found that proper seed placement improves emergence and biomass partitioning. Mulching significantly increased plant height (21.02-47.24 cm) compared to no mulch. It moderated soil temperature, enhanced root activity, and promoted shoot elongation. Rao and Reddy (2010) [7] observed that mulching modifies hydrothermal regimes favoring growth. Prasad *et al*. (2008) [6] emphasized that adequate water ensures cell expansion and stem elongation. Interaction revealed July 10 sowing at 5 cm depth with mulch produced the tallest plants (26.51-52.73 cm). Delayed sowings at all depths and mulch levels consistently recorded shorter plants. Singh *et al*. (2012) [8] confirmed that soil temperature and moisture interactions regulate final plant height in soybean.

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