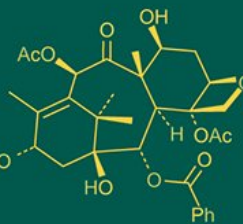
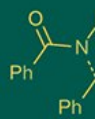


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Effect of sowing dates and heat stress Mitigators on growth responses of wheat (*Triticum Aestivum* L) under terminal heat stress

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Abstract

A field experiment evaluated the effects of three sowing dates (D1-D3) and five heat stress mitigating treatments (H0-H4) on wheat growth and physiological traits under terminal heat stress using a split-plot design. Sowing date significantly affected plant population, plant height, leaf area, plant dry weight and chlorophyll content throughout the crop season. D1 (15 November) consistently recorded the highest values, while D3 (25 December) recorded the lowest values. At harvest, D1 recorded 76.32 plants m⁻¹ row length, 104.50 cm plant height, 749.39 cm² plant⁻¹ leaf area and 34.18 g plant⁻¹ dry weight, compared with 50.83 plants m⁻¹ row length, 80.37 cm plant height, 672.61 cm² plant⁻¹ leaf area and 23.83 g plant⁻¹ dry weight under D3. Chlorophyll content under D1 was 23.05, 38.47 and 31.33 at 30, 60 and 90 DAS, respectively, compared with 16.99, 27.55 and 19.32 under D3. Heat stress mitigating treatments did not significantly affect plant population at initial and harvest stages, while their effects on plant height, leaf area and dry weight were more pronounced during the later growth stages. Progesterone 1 µM (H4) performed best at 90 DAS and harvest, recording the highest plant height (92.46 and 97.68 cm), leaf area (773.06 and 756.31 cm² plant⁻¹) and dry weight (22.83 and 30.99 g plant⁻¹), respectively. Chlorophyll content was significantly influenced by the treatments only at 90 DAS, with H4 recording the highest value (27.44). Overall, timely sowing on 15 November (D1) ensured better crop establishment, growth and physiological performance, while progesterone 1 µM (H4) showed the greatest potential for improving growth and physiological performance under terminal heat stress.

Keywords: Wheat, Terminal heat stress, Heat stress mitigators,

1. Introduction

Wheat (*Triticum aestivum* L.) is one of the most important cereal crops of the world and plays a pivotal role in ensuring food and nutritional security. In India, wheat is predominantly grown during the rabi season, when crop productivity depends strongly on the prevailing temperature during different phenological stages. However, the increasing frequency of temperature extremes associated with climate variability and climate change has emerged as a major constraint to stable wheat production. Among the different climatic stresses, terminal heat stress is particularly important in wheat-growing regions of Madhya Pradesh especially in the gird region (Gwalior) because the crop frequently encounters high temperatures during the reproductive and grain-filling stages.

Sowing date also influences the duration and rate of crop growth, canopy development, biomass accumulation and partitioning of assimilates. A suitable sowing window allows the crop to utilize favourable temperature conditions during vegetative growth and maintain a comparatively longer grain-filling period. In contrast, delayed sowing generally accelerates phenological development and reduces the duration available for biomass accumulation and grain development. A recent study in the Indo-Gangetic Plains reported that appropriate adjustment of planting time can help reduce exposure to post-heading heat stress and improve wheat productivity. Similarly, a systematic review of South Asian wheat research found that advancing sowing by approximately 7-10 days was an effective adaptation option under heat-stress conditions. Growth responses provide an important basis for evaluating the

effectiveness of these strategies. Parameters such as plant height, dry matter accumulation, leaf area, crop growth rate, relative growth rate and other growth attributes integrate the effects of environmental conditions and management practices over the crop cycle. Heat stress can alter these parameters through accelerated phenological development, reduced photosynthetic efficiency, premature leaf senescence and impaired assimilate production. Consequently, studying growth responses under different sowing dates and heat stress mitigation treatments can provide valuable insight into how wheat adapts to terminal high-temperature conditions.

Recent research emphasizes that adaptation to terminal heat stress should not rely on a single intervention but should integrate agronomic and physiological approaches. Meta-analysis of South Asian studies indicated that early sowing, heat-tolerant cultivars and conservation-oriented management can substantially reduce heat-associated yield losses. In particular, early sowing has demonstrated considerable potential because it allows the crop to escape the period of severe terminal heat during grain filling. However, the effectiveness of sowing-time adjustment is dependent on the local thermal regime, genotype and crop management conditions. Therefore, there is a need to evaluate the interaction between sowing dates and heat stress mitigation strategies under field conditions, particularly for wheat grown in the semi-arid environment of central India. A systematic assessment of growth responses under contrasting sowing environments can help identify the sowing window that minimizes exposure to terminal heat, while evaluation of exogenous mitigators can provide information on their capacity to sustain crop growth under high-temperature conditions. Such an integrated approach is particularly relevant in the context of climate change, where increasing temperature variability may reduce the reliability of conventional sowing windows.

Keeping these considerations in view, the present investigation entitled “Effect of Sowing Dates and Heat Stress Mitigators on Growth Responses of Wheat under Terminal Heat Stress” was undertaken to assess the influence of different sowing dates and exogenous heat stress mitigation treatments on the growth behaviour of wheat. The study aims to understand whether appropriate adjustment of sowing time, either alone or in combination with physiological mitigation strategies, can maintain favourable crop growth and improve the adaptation of wheat to terminal heat stress. The findings are expected to contribute towards developing practical agronomic strategies for sustaining wheat productivity under warming and increasingly variable climatic conditions.

2. Materials and Methods

A field experiment was conducted during the rabi seasons of 2024-25 and 2025-26 at the Research Farm of KVK, Gwalior, Madhya Pradesh, under RVSKVV, Gwalior, representing the semi-arid agro-climatic conditions of the Gird region. The experiment was laid out in a split-plot design with three replications, comprising three sowing dates as main-plot treatments: D₁ (15 November), D₂ (5 December) and D₃ (25 December), and five heat stress mitigation treatments as sub-plot treatments: H₀ (water

spray), H₁ (KNO₃ @ 2.0%), H₂ (melatonin @ 100 µM), H₃ (sodium nitroprusside @ 100 µM) and H₄ (progesterone @ 1 µM). Thus, 15 treatment combinations were evaluated. Wheat was sown manually on the respective dates, and all plots received uniform recommended agronomic practices, including fertilization, irrigation, weed and pest management. Heat stress mitigation treatments were applied as foliar sprays at the booting and anthesis stages, which are critical periods for terminal heat stress. Meteorological observations were recorded to characterize the prevailing weather conditions. The heat stress mitigation treatments were applied as foliar sprays at the booting and anthesis stages of wheat, which are critical developmental stages associated with increasing sensitivity to high temperature and terminal heat stress as detailed below:

Table 1: Heat stress mitigation treatments and concentrations used in the experiment

Treatment	Heat stress mitigator	Concentration
H ₀	Control (water spray)	—
H ₁	Potassium nitrate (KNO ₃)	2.0% (20 g L ⁻¹)
H ₂	Melatonin	100 µM (23.23 mg L ⁻¹)
H ₃	Sodium nitroprusside (SNP)	100 µM (26.19 mg L ⁻¹)
H ₄	Progesterone	1 µM (0.314 mg L ⁻¹)

Potassium nitrate (KNO₃) was applied at a concentration of 2.0%, equivalent to 20 g L⁻¹. Melatonin and sodium nitroprusside (SNP) were applied at concentrations of 100 µM, corresponding to 23.23 and 26.19 mg L⁻¹, respectively. Progesterone was applied at 1 µM, corresponding to 0.314 mg L⁻¹. The prepared solutions were applied uniformly over the crop canopy at the booting and anthesis stages using a suitable knapsack or hand-operated sprayer, however the control plots received an equivalent volume of water spray. Care was taken to ensure uniform spray coverage of the foliage and minimize spray drift between adjacent plots. The foliar applications were performed under suitable weather conditions to facilitate effective absorption and minimize losses due to evaporation or rainfall immediately after application.

Growth parameters were recorded at 30, 60 and 90 DAS and at harvest following standard agronomic procedures. Plant population was counted per metre row length, plant height measured in cm, leaf area recorded in cm² plant⁻¹, and plant dry weight determined after oven drying to constant weight. Chlorophyll content was measured using a SPAD meter. Terminal heat stress was assessed based on prevailing temperatures during anthesis and grain filling across different sowing dates. Data were analyzed using ANOVA appropriate for split-plot design, with significance tested by F-test and treatment means compared using CD at 5% probability. CV was calculated to assess experimental variability, while pooled analysis across years considered year effects and their interactions with treatments. Particular emphasis was given to sowing date × heat stress mitigation interaction to identify effective treatments under late-sown conditions.

Results and Discussion

Plant population

Table 2: Plant population per metre row length at initial and harvest stage as influenced by different heat mitigation treatments

Treatment	Plant population per m row length (Pooled data of 2 years)	
	Initial	At harvest
Date of sowing		
D ₁ (15 November)	74.93	76.32
D ₂ (05 December)	61.82	61.52
D ₃ (25 December)	50.86	50.83
SE(m) ±	0.99	0.33
CD (P=0.05)	3.23	1.08
Heat Stress treatment		
H ₀ (control)	62.92	62.56
H ₁ (KNO ₃)	62.11	63.01
H ₂ (Melatonin)	62.89	62.89
H ₃ (SNP)	61.68	63.09
H ₄ (Progesterone)	63.08	62.91
SE(m) ±	1.25	0.76
CD (P=0.05)	NS	NS

Date of sowing significantly affected plant population at 30 DAS and harvest. The highest pooled plant population was recorded under D₁ (15 November), with 74.93 and 76.32 plants m⁻², followed by D₂ (5 December) with 61.82 and 61.52 plants m⁻², while D₃ (25 December) recorded the lowest values of 50.86 and 50.83 plants m⁻², respectively (Table 1). Delayed sowing reduced plant population, likely

due to unfavorable temperatures during crop establishment, consistent with findings of Sattar *et al.* (2010) [5], and Lakhani *et al.* (2025) [4]. Foliar application of KNO₃, melatonin, SNP and progesterone had no significant effect on plant population due to their application at later growth stages.

Table 3: Plant height under different treatment at various crop growth stages

Treatment	Plant height (cm) (Pooled data of 2 years)			
	30 DAS	60 DAS	90 DAS	At harvest
Date of sowing				
D ₁ (15 November)	31.01	71.01	98.47	104.50
D ₂ (05 December)	27.47	59.22	88.03	89.13
D ₃ (25 December)	26.84	56.88	75.62	80.37
SE(m) ±	0.41	0.55	1.51	0.81
CD (P=0.05)	1.34	1.80	4.19	2.65
Heat Stress treatment				
H ₀ (control)	27.36	62.26	82.58	83.98
H ₁ (KNO ₃)	28.66	62.23	85.36	88.91
H ₂ (Melatonin)	29.31	62.43	88.78	89.80
H ₃ (SNP)	28.61	62.46	87.69	96.30
H ₄ (Progesterone)	28.26	62.48	92.46	97.68
SE(m) ±	0.52	1.09	1.28	1.30
CD (P=0.05)	NS	NS	3.65	3.68

Plant height (CM)

Plant height was significantly influenced by sowing date at all growth stages. D₁ (15 November) recorded the tallest plants (31.01, 71.01, 98.47 and 104.50 cm at 30, 60, 90 DAS and harvest), whereas D₃ (25 December) recorded the shortest (26.84, 56.88, 75.62 and 80.37 cm, respectively). Delayed sowing reduced plant height, likely due to a shortened vegetative period and unfavorable temperatures, in agreement with Jat *et al.* (2003) [3]. Heat stress mitigation treatments had no significant effect at 30 and 60 DAS but significantly influenced plant height at 90 DAS and harvest. At 90 DAS, H₄ (progesterone 1 µM) recorded the highest height (92.46 cm), followed by H₂ (melatonin), H₃ (SNP), H₁ (KNO₃) and H₀ (control); a similar trend occurred at harvest, with H₄ recording the maximum height (97.68 cm).

The positive effects of SNP and KNO₃ under heat stress were also reported by Suryavanshi *et al.* (2016) [7], and Zhang *et al.* (2023) [8,9].

Leaf area

Leaf area was significantly influenced by sowing date at all stages. D₁ (15 November) recorded the maximum pooled leaf area (104.00, 476.47, 750.24 and 749.39 cm² plant⁻¹ at 30, 60, 90 DAS and harvest), whereas D₃ (25 December) recorded the minimum (79.36, 411.81, 687.39 and 672.61 cm² plant⁻¹, respectively). Delayed sowing reduced leaf area, likely due to a shorter vegetative period and higher temperatures causing restricted leaf expansion and early senescence, as reported by Pradhan *et al.* (2021).

Table 4: Leaf area under different treatment at various crop growth stages

Treatment	Leaf area (cm ²) (Pooled data of 2 years)			
	30 DAS	60 DAS	90 DAS	At harvest
Date of sowing				
D ₁ (15 November)	104.00	476.47	750.24	749.39
D ₂ (05 December)	90.61	446.24	702.06	698.09
D ₃ (25 December)	79.36	411.81	687.39	672.61
SE(m) ±	0.94	3.96	4.40	4.56
CD (P=0.05)	3.07	12.92	14.35	14.88
Heat Stress treatment				
H ₀ (control)	89.05	446.65	663.78	636.87
H ₁ (KNO ₃)	90.50	446.37	683.89	696.03
H ₂ (Melatonin)	91.11	442.36	706.94	698.53
H ₃ (SNP)	92.15	445.68	738.48	745.76
H ₄ (Progesterone)	93.82	443.13	773.06	756.31
SE(m) ±	1.13	5.67	6.61	10.30
CD (P=0.05)	NS	NS	18.80	29.29

Heat stress mitigation treatments were non-significant at 30 and 60 DAS but significantly influenced leaf area at 90 DAS and at harvest. At harvest, H₄ (progesterone 1 µM) recorded the highest pooled leaf area (756.31 cm² plant⁻¹), followed by H₃ (SNP) (745.76 cm² plant⁻¹), H₂ (melatonin) (698.53 cm² plant⁻¹), H₁ (KNO₃) (696.03 cm² plant⁻¹) and H₀ (control) (636.87 cm² plant⁻¹). A similar trend was observed at 90 DAS, where H₄ recorded the highest leaf area (773.06 cm² plant⁻¹), followed by H₃ (738.48 cm² plant⁻¹), H₂ (706.94 cm² plant⁻¹), H₁ (683.89 cm² plant⁻¹) and H₀ (663.78 cm² plant⁻¹). The increased leaf area under mitigation treatments may be attributed to improved stress tolerance, maintenance of photosynthetic stability and reduced oxidative damage. Melatonin and SNP are also known to enhance antioxidant defence and photosynthetic performance (Buttar *et al.*, 2020; Khan *et al.*, 2024) ^[1].

Plant dry weight

Plant dry weight was significantly influenced by sowing date at 30, 60, 90 DAS and harvest. The highest pooled dry weight was recorded under D₁ (15 November), with 1.75, 8.99, 25.44 and 34.18 g plant⁻¹, at 30, 60, 90 DAS and at harvest respectively, whereas D₃ (25 December) recorded the lowest values of 1.35, 7.15, 17.27 and 23.83 g plant⁻¹. D₂ (5 December) showed intermediate values of 1.54, 8.37, 20.40 and 28.27 g plant⁻¹ respectively. The decline in dry matter accumulation with delayed sowing may be attributed to a shortened growth period and greater exposure to high temperature, which adversely affects leaf development, photosynthesis and assimilate accumulation. Similar findings were reported by Pradhan *et al.* (2012) and Laghari *et al.* (2023).

Table 5: Plant dry weight under different treatment at various crop growth stages

Treatment	Plant dry weight (g) (Pooled data of 2 years)			
	30 DAS	60 DAS	90 DAS	At harvest
Date of sowing				
D ₁ (15 November)	1.75	8.99	25.44	34.18
D ₂ (05 December)	1.54	8.37	20.40	28.27
D ₃ (25 December)	1.35	7.15	17.27	23.83
SE(m) ±	0.01	0.09	0.29	0.42
CD (P=0.05)	0.05	0.30	0.95	1.38
Heat Stress treatment				
H ₀ (control)	1.56	8.09	19.08	26.56
H ₁ (KNO ₃)	1.56	8.23	20.53	28.10
H ₂ (Melatonin)	1.55	8.20	21.18	28.87
H ₃ (SNP)	1.52	8.10	21.57	29.28
H ₄ (Progesterone)	1.54	8.22	22.83	30.99
SE(m) ±	0.03	0.13	0.38	0.50
CD (P=0.05)	NS	NS	1.09	1.42

Heat stress mitigation treatments had no significant effect on dry weight at 30 and 60 DAS but significantly influenced it at 90 DAS and harvest. At harvest, H₄ (progesterone 1 µM) recorded the highest pooled dry weight (30.99 g plant⁻¹), followed by H₃ (SNP; 29.28 g plant⁻¹), H₂ (melatonin; 28.87 g plant⁻¹), H₁ (KNO₃; 28.10 g plant⁻¹) and H₀ (control; 26.56 g plant⁻¹). A similar trend was observed at 90 DAS, where H₄ recorded the highest dry weight (22.83 g plant⁻¹), followed by H₃ (21.57 g plant⁻¹), H₂ (21.18 g plant⁻¹), H₁ (20.53 g plant⁻¹) and H₀ (19.08 g plant⁻¹). The enhanced dry matter accumulation under mitigation treatments may be

attributed to improved photosynthetic efficiency, antioxidant defence and maintenance of cellular metabolism under heat stress, with progesterone showing the most pronounced effect.

Chlorophyll content

Chlorophyll content was significantly influenced by sowing date at 30, 60 and 90 DAS. D₁ (15 November) recorded the highest pooled values of 23.05, 38.47 and 31.33 at 30, 60 and 90 DAS, respectively, whereas D₃ (25 December) recorded the lowest values of 16.99, 27.55 and 19.32. The

decline in chlorophyll with delayed sowing may be attributed to increased exposure to high temperature, resulting in accelerated chlorophyll degradation and

impaired chloroplast activity. Similar findings were reported by Lavkush *et al.* (2022).

Table 6: Chlorophyll content at different crop growth stages as influenced by the heat mitigation treatments

Treatment	Chlorophyll content (Pooled data of 2 years)		
	30 DAS	60 DAS	90 DAS
Date of sowing			
D ₁ (15 November)	23.05	38.47	31.33
D ₂ (05 December)	19.87	31.88	25.05
D ₃ (25 December)	16.99	27.55	19.32
SE(m) ±	0.19	0.21	0.22
CD (P=0.05)	0.62	0.68	0.70
Heat Stress treatment			
H ₀ (control)	19.78	32.22	22.75
H ₁ (KNO ₃)	19.89	32.20	24.53
H ₂ (Melatonin)	20	32.47	25.13
H ₃ (SNP)	19.94	33.16	26.34
H ₄ (Progesterone)	20.26	33.11	27.44
SE(m) ±	0.16	0.34	0.30
CD (P=0.05)	NS	NS	0.85

Heat stress mitigation treatments were non-significant at 30 and 60 DAS but significantly affected chlorophyll content at 90 DAS. H₄ (progesterone 1 µM) recorded the highest pooled chlorophyll content (27.44), followed by H₃ (SNP; 26.34), H₂ (melatonin; 25.13), H₁ (KNO₃; 24.53) and H₀ (control; 22.75). The higher chlorophyll content under mitigation treatments may be attributed to better protection of the photosynthetic apparatus and reduced oxidative damage under heat stress. Similar protective effects of melatonin and potassium on chlorophyll and photosynthetic performance under heat stress have been reported by Buttar *et al.* (2020) [1], and Zhang *et al.* (2023) [8, 9].

Summary

Pooled analysis of two years revealed that sowing date significantly influenced all growth parameters. D₁ (15 November) consistently recorded superior plant height, leaf area, dry weight, chlorophyll content and plant population, with plant height (104.50 cm), leaf area (749.39 cm² plant⁻¹), dry weight (34.18 g plant⁻¹) and plant population (76.32 plants m⁻¹ row length) at harvest. In contrast, D₃ (25 December) recorded the lowest values, indicating that delayed sowing adversely affected crop growth due to shortened growth duration and greater exposure to terminal heat stress.

Heat-stress mitigation treatments showed stage- and parameter-specific effects. At later growth stages, H₄ (progesterone 1 µM) recorded the highest plant height (97.68 cm), leaf area (756.31 cm² plant⁻¹), dry weight (30.99 g plant⁻¹) and chlorophyll content (27.44), followed by H₃ (SNP 100 µM) and H₂ (melatonin 100 µM). Plant population remained unaffected by the mitigation treatments, confirming their limited influence on crop establishment. Overall, D₁ was the most favourable sowing date, while D₃ adversely affected growth. Among the mitigators, H₄ showed the most consistent improvement in growth and physiological attributes under terminal heat stress, likely through better maintenance of photosynthetic activity, antioxidant defence and cellular metabolism.

Conclusion

Pooled analysis over two years revealed that sowing date significantly influenced crop establishment, growth and

physiological performance. D₁ (15 November) recorded the highest plant population, plant height, leaf area, dry weight and chlorophyll content, indicating favourable crop establishment and growth under timely sowing. In contrast, delayed sowing, particularly D₃ (25 December), consistently reduced these parameters due to shortened growth duration and greater exposure to terminal heat stress. Heat-stress mitigation treatments had a more pronounced effect during later growth stages. H₄ (progesterone 1 µM) consistently recorded higher plant height, leaf area, dry weight and chlorophyll content at 90 DAS and harvest, followed by H₃ (SNP 100 µM) and H₂ (melatonin 100 µM). However, these treatments did not significantly influence plant population, indicating their primary role in maintaining growth and physiological activity rather than crop establishment. Overall, D₁ (15 November) was the most suitable sowing date, whereas D₃ (25 December) adversely affected crop performance. Among the mitigators, progesterone 1 µM emerged as the most promising treatment for sustaining growth and physiological performance under terminal heat stress, followed by SNP and melatonin.

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