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Physiological and phenological responses of wheat to terminal heat stress under foliar application of salicylic acid and thiourea

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Abstract

The present investigation was conducted during the *rabi* season of 2019-2020 at the Seed Technology Research Farm, Jawaharlal Nehru Krishi Vishwa Vidyalaya (JNKVV), Jabalpur, Madhya Pradesh, India to evaluate the influence of terminal heat stress and foliar application of bioregulators on pheno-physiological traits of wheat (*Triticum aestivum* L.). Two varieties, JW-3211 and JW-3382, were evaluated under normal and late-sown conditions with foliar sprays of thiourea (TU) and salicylic acid (SA) at 400 and 800 ppm concentrations. Significant variations were recorded among varieties, sowing dates, and treatments for all phenophases and physiological parameters. Late sowing accelerated phenological development, with earlier ear emergence (48.55 DAS), shorter grain filling duration (40.81 DAS), and reduced field maturity (108.24 DAS) compared to normal sowing (58.70, 44.14, and 118.19 DAS, respectively). Heat stress reduced grain filling duration by 7.57% and maturity period by 17% over normal conditions. Among genotypes, JW-3211 exhibited superior adaptability, showing earlier ear emergence (55.00 DAS), shorter maturity (109.76 DAS), and higher physiological efficiency. Foliar application of SA @ 800 ppm and TU @ 800 ppm enhanced leaf area index (4.27), leaf area duration (7344.28), and chlorophyll content index, thereby improving photosynthetic activity and delaying leaf senescence under heat stress. The interaction effects indicated that JW-3211 under late sowing with SA @ 800 ppm maintained higher LAI and chlorophyll stability, reflecting better heat tolerance. Overall, foliar application of bioregulators, particularly SA and TU at 800 ppm, effectively mitigated the adverse impact of high temperature by stabilizing physiological processes and extending photosynthetic duration, contributing to sustained wheat performance under terminal heat stress conditions.

Keywords: Wheat, terminal heat stress, salicylic acid, thiourea, phenology, LAI, LAD, CCI

1. Introduction

Wheat (*Triticum aestivum* L.) is one of the most extensively cultivated cereal crops, serving as a staple food for nearly two billion people worldwide and providing a major source of energy and nutrition for approximately 36% of the global population. Often referred to as the “King of Cereals,” wheat occupies a premier position in global agriculture due to its huge land, adaptability, and substantial contribution to the international grain market. It contributes around 55% of the total carbohydrates and about 20-21% of the total caloric intake consumed globally (Khalid *et al.*, 2023; Erenstein, 2022) ^[20, 11]. Furthermore, wheat accounts for nearly one-fifth of the global dietary protein intake, with an average protein content of about 13%, which is higher than that of most other major cereals, thereby playing a crucial role in global nutritional security (Shewry *et al.*, 2015; Alomari *et al.*, 2023) ^[37, 4].

In India, wheat ranks second only to rice among staple food crops and is used extensively in the preparation of diverse food products, including various types of bread, pasta, bakery items, and fermented products such as beer. India is currently the second-largest producer of wheat in the world, following China. In India, wheat cultivation is concentrated in the Indo-Gangetic Plains. During the 2024-25 season, production reached approximately 115.3 million metric tonnes, representing a 2% increase over the 113.3 million metric tonnes harvested in 2023-24 (India Data Map, 2025) ^[17]. This increase is attributed to advancements in seed technology, improved

irrigation infrastructure, and government support mechanisms such as the Minimum Support Price (MSP) (Kumar *et al.*, 2023)^[23]. Despite these improvements, wheat productivity in India remains heterogeneous. The national average yield is 3.5 to 4.0 tonnes per hectare, which is lower than yields in Germany and France, where technological interventions enable yields of 7 to 8 tonnes per hectare (India Data Map, 2025; FAO, 2025)^[17].

Madhya Pradesh is a main contributor to India's wheat sector. In 2024-25, the state produced 23.03 million metric tonnes, ranking second after Uttar Pradesh (India Data Map, 2025)^[17]. This output accounted for approximately 20% of national wheat production, with yields typically ranging from 3,150 to 3,300 kilograms per hectare. The region's black soils, consistent rainfall, and widespread implementation of modern agronomic practices have significantly supported these production levels (Kumar *et al.*, 2023)^[23].

Despite these advancements, emerging challenges continue to threaten yield stability and grain quality. Terminal heat stress during the reproductive and grain-filling stages is a primary constraint on wheat productivity in subtropical regions, including Madhya Pradesh (Prasad *et al.*, 2022; Sharma *et al.*, 2024)^[34, 36]. The early onset of high temperatures shortens the grain-filling period, reduces assimilate translocation, and results in substantial yield losses (Gurjar *et al.*, 2024)^[14]. Heatwaves have been shown to decrease grain weight and cause yield reductions of up to 20 to 30 percent during extreme years (Abid *et al.*, 2024)^[1].

Heat stress primarily affects wheat by inducing excessive production of reactive oxygen species (ROS), which damage cellular membranes and macromolecules and disrupt cellular homeostasis (Farooq *et al.*, 2023)^[12]. Wheat plants counteract these effects through enzymatic and non-enzymatic antioxidant defence systems and by accumulating osmolytes (Kumar *et al.*, 2023)^[23]. While breeding heat-tolerant cultivars remains a long-term strategy, there is increasing interest in the exogenous application of bio-regulators to improve crop resilience.

Recent studies indicate that foliar application of thiourea, a water-soluble organosulfur compound with cytokinin-like properties, enhances photosynthetic efficiency, sink strength, and dry matter partitioning. These effects contribute to increased grain yield under late-sowing and stress conditions (Ishfaq *et al.*, 2024)^[18]. Similarly, salicylic acid (SA), an important signalling molecule in thermotolerance, regulates antioxidant enzyme activity and physiological processes, resulting in improved heat stress management and higher productivity (Maqbool *et al.*, 2025; Choudhary *et al.*, 2024)^[25, 8].

In response to the critical need for stable and increased wheat production in vulnerable regions such as Madhya Pradesh, this study systematically evaluates the effects of exogenous thiourea and salicylic acid application on wheat phenology, physiology, and productivity under both normal and late-sown conditions.

2. Material and Methods

The present investigation was carried out during the *rabi* season of 2019-2020 at the Seed Technology Research Farm, Department of Plant Breeding and Genetics, Jawaharlal Nehru Krishi Vishwa Vidyalaya (JNKVV), Jabalpur, Madhya Pradesh, India. The study aimed to evaluate the effectiveness of salicylic acid (SA) and thiourea (TU) in modulating physiological efficiency, biochemical tolerance, yield performance, and seed quality of wheat (*Triticum aestivum* L.) under normal and late-sown (heat-stress) environments.

2.1 Experimental Site and Climate

The experimental site is located at 23°09' N latitude and 79°58' E longitude, at an altitude of 411.78 m above mean sea level. The region experiences a subtropical climate with hot, dry summers and cool winters. The mean annual rainfall is approximately 1,284 mm, of which nearly 90% is received from late June to September. During the cropping period, the maximum and minimum temperatures ranged between 24-45 °C and 4-32 °C, respectively, with relative humidity varying from 30-90% depending on the season. The experimental soil was classified as a Vertisol, deep to medium in depth, dark clay loam in texture, neutral in reaction, and with high moisture-retention capacity but prone to cracking during dry periods—typical of the central Indian agro-ecological zone.

2.2 Experimental Design and Treatments

The experiment was laid out in a factorial randomized block design (RBD) with three replications, comprising 20 treatment combinations derived from three experimental factors two wheat varieties, five foliar spray treatments, and two sowing dates. The varieties used were JW-3211 (V₁) and JW-3382 (V₂), both obtained from the Department of Plant Breeding and Genetics, JNKVV, Jabalpur. The foliar spray treatments included: T₁ - Control (water spray), T₂ - SA 800 ppm, T₃ - SA 400 ppm, T₄ - TU 400 ppm, and T₅ - TU 800 ppm. Sowing was carried out under two environments -normal sowing (S₁: 23 November 2019) and late sowing (S₂: 14 December 2019) to expose the crop to differential thermal regimes, thereby simulating normal and terminal heat-stress conditions.

Each plot measured 2.1 × 2.0 m (4.20 m² gross area) with a net plot size of 1.5 × 1.4 m (2.10 m²). The row spacing was maintained at 30 cm, and a seed rate of 100 kg ha⁻¹ was used. Fertilizer was applied at a recommended dose of 120:60:40 kg ha⁻¹ N: P₂O₅:K₂O using urea, single super phosphate, and muriate of potash as nutrient sources. In total, 60 plots were established with adequate spacing between replications and plots to ensure uniform field conditions and minimize border effects.

2.3 Crop Establishment and Management

Before sowing, the field was prepared by incorporating well-decomposed farmyard manure (FYM) at a 3:1 ratio with soil to enhance fertility and improve soil structure. Half of the nitrogen and the full dose of phosphorus and potassium were applied as a basal application at sowing, while the remaining nitrogen was top-dressed at 25 days after sowing (DAS). Each variety were manually sown per plot and thinning was performed at 25 DAS to maintain a uniform stand, and hand-weeding was carried out at 28 DAS. Light hoeing and removal of volunteer plants were done as needed to ensure healthy crop growth.

To simulate heat-stress conditions, irrigation was withheld for 15 days during the crown-root initiation, flowering, milking, and anthesis stages, while control plots received irrigation as per standard recommendations. Foliar sprays of SA and TU were applied twice, at the tillering (35 DAS) and anthesis (65 DAS) stages, using freshly prepared aqueous solutions and a hand-operated knapsack sprayer to ensure fine and uniform coverage. Control plots were sprayed with distilled water to maintain experimental consistency. All other agronomic and plant protection measures were followed as per standard practices recommended for wheat cultivation in the region.

Phenological observations were recorded from three tagged plants in each plot through daily visual monitoring from sowing to harvest. The traits observed included days to ear emergence, days to 50% flowering, grain filling duration, days to

physiological maturity, and days to field maturity. Days to ear emergence were recorded when approximately 50% of the plants in each plot had visible spikes, while days to 50% flowering were noted when half of the spikelet's showed anthesis. Grain filling duration was computed as the interval between flowering and physiological maturity. Physiological maturity was determined when the flag leaf and spikes turned yellow, whereas field maturity was recorded when the grains attained harvestable dryness.

Physiological parameters were recorded at defined growth stages to quantify differences among treatments. Leaf area index (LAI), representing the ratio of total leaf surface area (one side) to the ground area occupied by the plant canopy, was calculated following the method of Gardner *et al.* (1985) using the formula:

LAI =	Total leaf area	LAI =	$(LA_2 + LA_1)/2$
	Land area		p

Where LA_1 and LA_2 are leaf areas measured at two consecutive intervals and P represents the ground area per plant. Leaf area duration (LAD), expressing the magnitude and persistence of leaf area over time, was estimated using the formula of Watson (1952):

LAD =	$(LA_2 + LA_1)$	$\times (t_2 - t_1) \text{ (cm}^2 \cdot \text{days)}$
	2	

Where t_1 and t_2 denote two successive time intervals corresponding to leaf area measurements.

The chlorophyll content index (CCI), an indicator of leaf greenness, was measured non-destructively on the fourth fully expanded leaf of five-week-old plants using a portable chlorophyll meter (Model: CCM-200, USA). The readings were expressed in SPAD units.

3. Result and Discussion

Phenological development and physiological behaviour of wheat are vital indicators of its adaptability to environmental fluctuations, particularly under terminal heat stress conditions associated with late sowing. Phenology governs the duration available for each growth stage, influencing assimilate partitioning and ultimately determining yield potential. The present investigation revealed significant variation among wheat varieties, sowing environments, and foliar bio regulator treatments for all recorded traits.

The progress of phenophases such as ear emergence, flowering, grain filling, physiological maturity, and field maturity showed a clear influence of temperature and growth regulator application. The variety JW-3211 exhibited later ear emergence (55.00 DAS) compared to JW-3382 (52.25 DAS), while the earliest ear emergence (48.55 DAS) occurred under late-sown conditions, indicating acceleration of developmental stages due to high temperature. The application of thiourea at 800 ppm resulted in the maximum delay in ear emergence, whereas the no-spray (control) treatments promoted earlier spike initiation. The interaction among variety, treatment, and sowing date revealed that JW-3382, when sown late without a growth regulator, recorded the earliest ear emergence. These results align with the observations of Boese (1987)^[7] and Kavita *et al.*, who reported that heat stress accelerates heading, reducing the period available for assimilate accumulation. In contrast, Tewolde *et al.* (2006)^[41] highlighted that early heading is an effective adaptive trait under high-temperature stress.

Days to 50% flowering also varied significantly among

treatments. The variety JW-3211 recorded the maximum duration (58.6 days after sowing, DAS), whereas JW-3382 required the minimum (41.8 DAS). Normal-sown wheat took more days (62.1) to reach 50% flowering compared to late-sown wheat (52.65), showing a 17.94% reduction under heat stress. Among treatments, thiourea at 800 ppm delayed flowering, while salicylic acid (SA) advanced it slightly, indicating its role in enhancing metabolic activity and promoting early reproductive transition. Similar results were reported by Sahu and Singh (1995)^[35], who observed yield enhancement with thiourea sprays, and Metwally *et al.* (2003)^[28], who found that SA induces flowering and delays senescence by stimulating enzyme activities. The interaction effect revealed that JW-3211, sown under normal conditions with thiourea at 800 ppm, recorded the greatest delay in flowering, suggesting varietal differences in sensitivity to bioregulators.

Grain-filling duration was markedly affected by heat stress. The variety JW-3382 exhibited the longest grain-filling period (43.14 DAS), while JW-3211 recorded the shortest (41.80 DAS). Normal-sown wheat recorded a longer grain-filling duration (44.14 DAS) compared to late-sown wheat (40.81 DAS), corresponding to a 7.57% reduction under elevated temperature. None of the bioregulator treatments could completely compensate for this reduction; however, SA at 800 ppm maintained a slightly longer grain-filling duration under normal conditions. The shortest grain-filling period (38.75 days after sowing, DAS) was observed in JW-3211 under late-sown conditions, indicating accelerated maturation due to heat stress. Tewolde *et al.* (2006)^[41] reported that temperatures exceeding 22°C at anthesis drastically reduce yield, and Pandey *et al.* (2013)^[33] confirmed that delayed sowing reduces grain-filling duration due to exposure to high temperatures. The beneficial effects of SA and TU on prolonging grain filling and enhancing assimilate translocation have been demonstrated by Bakhtavar *et al.* (2015)^[6], Pandey *et al.* (2013)^[33], and Hernández *et al.* (1983)^[16].

The variation in days to physiological maturity followed a similar trend. The earliest physiological maturity (99.06 DAS) was recorded in JW-3211, while JW-3382 reached maturity later (104.80 DAS). Late-sown wheat matured earlier (96.80 DAS) than normal-sown wheat (107.06 DAS), suggesting that heat stress accelerated reproductive development. Among treatments, SA @ 400 ppm resulted in the shortest duration (101.50 DAS), whereas SA @ 800 ppm delayed maturity slightly (102.16 DAS). The interaction among variety, treatment, and sowing date revealed that JW-3211, under late sowing without bioregulator spray, attained the earliest maturity (92.75 DAS), whereas JW-3382, under normal sowing without spray, required the longest duration (110.75 DAS). Advancement of maturity under heat stress reflects the crop's tendency to escape unfavourable temperatures by shortening its life cycle. These results align with those of Saini and Aspinall and Dias *et al.*, who reported that high temperatures (>30 °C) during floret development accelerate maturity and reduce grain weight.

Similarly, days to field maturity were influenced by both varietal and environmental factors. The earliest field maturity (109.76 DAS) was recorded in JW-3211, while JW-3382 took the longest time (116.66 DAS). Late-sown wheat matured earlier (108.24 DAS) compared to normal-sown wheat (118.19 DAS), with a mean reduction of 17% under heat stress. Among foliar treatments, thiourea at 400 ppm promoted early maturity (112.75 days after sowing, DAS), whereas SA at 800 ppm delayed it slightly (113.78 DAS). The interaction revealed that JW-3211, sown late without bioregulator spray, achieved the earliest

maturity (103.75 DAS), while JW-3382, sown under normal conditions with water spray, reached the latest maturity (122.75 DAS). Similar findings were reported by Ahmed *et al.* (2013)^[2], Nahar *et al.* (2010)^[32], and Hakim *et al.* (2012)^[15], who all observed that heat stress accelerates plant development and

shortens the duration of growth phases. Although Kumar *et al.* (2004)^[24] found a positive correlation between days to maturity and yield, Mondal *et al.* (2016)^[31] emphasized that early-maturing genotypes may perform better under terminal heat stress due to their heat escape mechanism.

Table 1: Effect of Salicylic acid and Thiourea on phenological observations in different date of sowing in wheat crop.

Treatments	Days to ear emergence	Days to 50% flowering	Grain filling duration	Days to physiological maturity	Days to field maturity
Varieties (V)					
V1	55.00	58.6	41.80	99.06	109.76
V2	52.25	56.15	43.14	104.80	116.66
Mean	53.63	57.375	42.47	101.93	113.21
SEM	0.17	0.18	0.11	0.22	0.41
CD(0.05)	0.49	0.54	0.33	0.64	1.23
Date of sowing (D)					
D1	58.70	62.1	44.13	107.06	118.19
D2	48.55	52.65	40.81	96.80	108.24
Mean	53.63	57.375	42.47	101.93	113.21
SEm±	0.17	0.18	0.11	0.22	0.41
CD(0.05)	0.49	0.54	0.33	0.64	1.23
Treatments (T)					
T1	53.38	57.13	43.25	102.06	113.13
T2	53.63	57.25	42.84	102.16	113.78
T3	53.50	57.38	42.38	101.50	113.00
T4	53.63	57.38	42.06	101.84	112.75
T5	54.00	57.75	41.81	102.09	113.41
Mean	53.63	57.38	42.47	101.93	113.21
SEm±	0.26	0.29	0.17	0.34	0.66
CD(0.05)	0.78	0.86	0.51	1.02	1.94
Interactions (DxVxT)					
D1V1T1	60.5	64	44.75	104.75	114.5
D1V1T2	59.5	62.5	44.25	105.25	115.25
D1V1T3	60	63	43.25	103.75	113.75
D1V1T4	60	63	44.00	104.25	115
D1V1T5	60.5	64	43.25	104.38	114.375
D1V2T1	55.5	59	45.75	110.75	122.75
D1V2T2	58	61.5	45.25	109.75	122
D1V2T3	57.5	61	43.75	109.00	121.25
D1V2T4	57.5	61.5	43.25	109.50	121
D1V2T5	58	61.5	43.75	109.25	122
D2V1T1	50.5	54.5	40.25	92.75	103.75
D2V1T2	49.5	53.5	40.00	93.63	106.5
D2V1T3	49	53	40.25	94.25	105.25
D2V1T4	50	54	39.25	93.88	104.5
D2V1T5	50.5	54.5	38.75	93.75	104.75
D2V2T1	47	51	42.25	100.00	111.5
D2V2T2	47.5	51.5	41.88	100.00	111.38
D2V2T3	47.5	52.5	42.25	99.00	111.75
D2V2T4	47	51	41.75	99.75	110.5
D2V2T5	47	51	41.50	101.00	112.5
Mean	53.63	57.38	42.47	101.93	113.21
SEm±	0.53	0.58	0.35	0.69	1.311
CD(0.05)	1.55	1.72	1.03	2.03	3.881
CV (%)	1.38	1.43	1.16	0.95	1.64

Physiological parameters such as leaf area index (LAI), leaf area duration (LAD), and chlorophyll content index (CCI) also exhibited significant variability and were closely associated with phenological responses. The variety JW-3211 showed a higher LAI (3.19) than JW-3382 (2.91), indicating superior canopy development. Normal-sown wheat exhibited a higher LAI (3.42) than late-sown wheat (2.67), reflecting the adverse effect of heat on leaf expansion and longevity. Among foliar treatments, SA @ 800 ppm recorded the highest LAI (3.49), while TU @ 400 ppm recorded the lowest (2.76). The interaction of factors showed that JW-3211 under normal sowing with SA @ 800 ppm

attained the highest LAI (4.27), while JW-3382 under late sowing with TU @ 400 ppm had the lowest (1.72). At 60 DAS, a similar pattern was observed, with normal-sown wheat maintaining a higher LAI (3.50) than late-sown wheat (2.51). The reduction in LAI under high temperatures can be attributed to premature senescence and reduced leaf expansion. The enhancement of LAI by SA suggests its role in maintaining turgor and photosynthetic surface area under stress. Similar trends have been reported by Amin *et al.* (2013)^[5], Suryavanshi *et al.* (2016)^[40], and Meena *et al.* (2016)^[27], who found significant improvement in LAI following foliar application of

SA and TU in wheat (Karmnath Kumar *et al.*, 2024) [43].

Leaf area duration (LAD), which reflects the magnitude and persistence of photosynthetically active leaf area, also varied significantly. The maximum LAD (7344.28) was recorded for JW-3211, while the minimum (6439.56) was observed for JW-3382. High temperature under late-sown conditions reduced LAD by 26.33% compared to normal sowing. The application of thiourea at 800 ppm resulted in a 6.2% increase in LAD over the control, indicating its role in delaying senescence and maintaining prolonged photosynthetic activity. These findings agree with those of Yadav (2005) [45], Waqas *et al.* (2017) [44], and Kumar *et al.* (2020) [22], who reported improved LAD with thiourea application.

The chlorophyll content index (CCI), an indicator of leaf greenness and photosynthetic efficiency, was higher in JW-3211 than in JW-3211, but decreased considerably under late-sown conditions due to heat-induced degradation of pigments and disruption of chloroplast structure. The application of thiourea at 800 ppm enhanced CCI in both varieties, attributed to its cytokinin-like properties that delay chlorophyll breakdown and leaf senescence. Korat *et al.* (2020) [21] and Kumar *et al.* (2020) [22] reported similar improvements in SPAD values with thiourea foliar spray. Although Moharekar *et al.* (2003) [30] found that SA may reduce chlorophyll by inducing oxidative stress, the present study found that SA treatments maintained higher CCI than the control, suggesting a partial protective effect under stress.

Table 2: Effect of Salicylic acid and Thiourea on physiological observations in different date of sowing in wheat crop.

Treatments (T)	LAI (30 DAYS)	LAI (60DAYS)	LAD	CCI
Varieties (V)				
V1	3.19	3.01	7344.28	47.60
V2	2.91	3.00	6439.56	48.86
Mean	3.05	3.00	6891.92	48.23
SEm±	0.10	0.08	6.76	0.55
CD(0.05)	0.29	0.24	20.00	1.64
Date of sowing (D)				
D1	3.42	3.50	7936.84	48.81
D2	2.67	2.51	5847.01	47.66
Mean	3.05	3.00	6891.92	48.23
SEm±	0.10	0.08	6.76	0.55
CD(0.05)	0.29	0.24	20.00	1.64
Treatments (T)				
T1	3.05	2.73	7831.66	45.60
T2	3.49	3.48	6328.23	49.34
T3	2.87	2.88	6184.45	47.83
T4	2.76	2.86	6587.67	47.79
T5	3.06	3.08	7527.58	50.61
Mean	3.05	3.00	6891.92	48.23
SEm±	0.16	0.13	10.68	0.88
CD(0.05)	0.46	0.38	31.62	2.59
Interactions (DxVxT)				
D1V1T1	3.19	3.16	9224.00	45.05
D1V1T2	4.27	3.96	7528.56	51.10
D1V1T3	3.59	3.38	7836.50	46.48
D1V1T4	3.01	3.82	8789.99	45.42
D1V1T5	4.06	3.17	9803.75	54.70
D1V2T1	3.16	3.33	7059.89	47.36
D1V2T2	3.43	3.90	6244.74	47.57
D1V2T3	2.78	3.27	6246.04	50.03
D1V2T4	3.52	3.09	7499.19	50.76
D1V2T5	3.23	3.93	9135.70	49.65
D2V1T1	3.18	2.23	7205.76	42.61
D2V1T2	3.00	3.14	6474.51	49.32
D2V1T3	2.40	2.32	5305.76	46.10
D2V1T4	2.79	2.36	5793.26	46.90
D2V1T5	2.35	2.53	5480.76	48.38
D2V2T1	2.69	2.22	7837.01	47.38
D2V2T2	3.24	2.91	5065.13	49.40
D2V2T3	2.73	2.53	5349.51	48.70
D2V2T4	1.72	2.19	4268.26	48.08
D2V2T5	2.58	2.69	5690.13	49.72
Mean	3.05	3.00	6891.92	48.23
SEm±	0.31	0.26	21.37	1.75
CD(0.05)	0.92	0.76	63.24	5.18
CV(%)	14.47	12.06	0.44	5.13

4. Conclusion

The study revealed that late-sown wheat experienced accelerated phenophases and reduced physiological efficiency due to

terminal heat stress. Variety JW-3211 exhibited better adaptability, with earlier ear emergence (55.00 DAS), shorter grain filling (41.80 DAS), and earlier maturity (109.76 DAS)

compared to JW-3382. Heat stress reduced grain filling duration by 7.57% and field maturity by 17%, while SA @ 800 ppm and TU @ 800 ppm improved LAI (4.27), LAD (7344.28), and CCI, enhancing photosynthetic activity and delaying senescence. These treatments effectively mitigated heat effects and sustained crop productivity under stress conditions.

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