International Journal of Advanced Biochemistry Research

ISSN Print: 2617-4693
ISSN Online: 2617-4707
NAAS Rating (2025): 5.29
IJABR 2025; SP-9(11): 1073-1081
www.biochemjournal.com
Received: 11-10-2025
Accepted: 14-11-2025

Sachin Prakash Nagre
Department of Plant Physiology, Agriculture, Jawaharlal Nehru Krishi Vishwa Vidyalaya (JNKVV), Jabalpur, Madhya Pradesh, India

Gyanendra Tiwari
Department of Plant Physiology, Agriculture, Jawaharlal Nehru Krishi Vishwa Vidyalaya (JNKVV), Jabalpur, Madhya Pradesh, India

Kumar Jai Anand
Department of Plant Breeding and Genetics, College of Agriculture, Jawaharlal Nehru Krishi Vishwa Vidyalaya (JNKVV), Jabalpur, Madhya Pradesh, India

Sunny Thakur
Department of Plant Breeding and Genetics, College of Agriculture, Jawaharlal Nehru Krishi Vishwa Vidyalaya (JNKVV), Jabalpur, Madhya Pradesh, India

Samiksha Hote
Department of Plant Physiology, Agriculture, Jawaharlal Nehru Krishi Vishwa Vidyalaya (JNKVV), Jabalpur, Madhya Pradesh, India

Corresponding Author:
Sachin Prakash Nagre
Department of Plant Physiology, Agriculture, Jawaharlal Nehru Krishi Vishwa Vidyalaya (JNKVV), Jabalpur, Madhya Pradesh, India

Mitigation of terminal heat stress in wheat through physiological and biochemical responses induced by salicylic acid and thiourea

Sachin Prakash Nagre, Gyanendra Tiwari, Kumar Jai Anand, Sunny Thakur and Samiksha Hote

DOI: https://www.doi.org/10.33545/26174693.2025.v9.i11Sn.6380

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 effects of salicylic acid (SA) and thiourea (TU) on biochemical stress tolerance, yield performance, and seed quality attributes of wheat (*Triticum aestivum* L.) under normal, and late sown conditions. Two wheat varieties, JW-3211 and JW-3382, were subjected to foliar application of SA (400 and 800 ppm) and TU (200 and 400 ppm) during critical growth stages. Significant variability was observed among varieties, sowing conditions, and treatments. Terminal heat stress in late sowing caused notable reductions in plant height (21.5%), spikelet number (7%), seed setting (10%), 1000-seed weight (23%), and seed yield (38%) compared with normal sowing. Foliar application of SA @ 800 ppm markedly improved biological yield (30.52%), seed yield (16%), and 1000-seed weight (21%) over the control, while TU @ 400 ppm enhanced seed setting (6%) and vigor index II (12%). JW-3211 exhibited superior performance, recording 15% higher biological yield, 9.4% more grains per ear, and 7% higher seed setting compared to JW-3382, indicating greater thermotolerance. SA treatments effectively maintained photosynthetic stability, antioxidant protection, and assimilate partitioning under stress, whereas TU improved reproductive efficiency and seedling vigor. The results clearly demonstrate that the use of bioregulators can substantially enhance wheat growth, productivity, and seed quality under high-temperature stress, providing a physiological basis for sustainable yield improvement in changing climatic conditions.

Keywords: *Triticum aestivum* L., salicylic acid, thiourea, terminal heat stress, seed quality, physiological efficiency

Introduction

Wheat (*Triticum aestivum* L.) remains one of the most important staple cereal crops globally, serving as a principal source of calories and protein for nearly two billion people about 36% of the global population. Recognized as the “King of Cereals,” it occupies a central position in global food systems due to its adaptability, wide geographical distribution, and significant contribution to human nutrition and international grain markets. Wheat contributes approximately 55% of total carbohydrate and 20-21% of global caloric intake, and provides about 13% protein, making it nutritionally superior to many other cereals (Khalid *et al.*, 2023; Erenstein, 2022; Shewry *et al.*, 2015; Alomari *et al.*, 2023) [23, 9, 42, 3].

India is the world’s second-largest wheat producer after China, with major production concentrated in the Indo-Gangetic Plains. In the 2024-25 season, India’s wheat production reached 115.3 million metric tonnes, marking a 2% increase from the previous year (India Data Map, 2025). This growth is attributed to improved seed technologies, irrigation management, and policy interventions such as the Minimum Support Price (MSP) scheme (Kumar *et al.*, 2023) [24]. Despite these advances, productivity remains below potential, averaging 3.5-4.0 tonnes per hectare compared to 7-8 tonnes per hectare in countries such as Germany and France (FAO, 2025). Madhya Pradesh ranks as the second-largest wheat-producing state, contributing approximately 20% of the national production, with yields averaging 3,150-3,300 kg ha^{-1} (India Data Map, 2025). However, terminal heat stress has emerged as a major threat to yield stability and grain quality in wheat, particularly under late and very late sown conditions in subtropical regions (Prasad *et al.*, 2022; Sharma *et al.*, 2024) [36, 41]. Elevated temperatures during reproductive and grain-filling stages accelerate phenological development, shorten the grain-filling duration, and affect assimilate partitioning, resulting in substantial yield reduction and deteriorated seed quality (Gurjar *et al.*, 2024; Abid *et al.*, 2024) [17, 2]. Heat stress induces the overproduction of reactive oxygen species (ROS), which cause oxidative damage to lipids, proteins, and nucleic acids, ultimately impairing cell membrane integrity and metabolic function (Farooq *et al.*, 2023) [12]. To mitigate these effects, plants activate antioxidant defence systems both enzymatic (superoxide dismutase, peroxidase, catalase, and ascorbate peroxidase) and non-enzymatic (ascorbate, glutathione, and phenolics) along with osmo-protective molecules such as proline and glycine betaine.

While genetic improvement for thermotolerance remains a long-term goal, recent approaches emphasize the use of exogenous protectants and signalling compounds to enhance physiological and biochemical resilience. Thiourea, a water-soluble organosulfur compound structurally analogous to urea, functions as a cytokinin-like growth regulator, enhancing photosynthetic activity, maintaining membrane stability, and improving dry matter partitioning under stress (Ishfaq *et al.*, 2024) [20]. Similarly, salicylic acid (SA), a phenolic phytohormone, plays a pivotal role in regulating plant responses to abiotic stresses by modulating antioxidant enzyme activities, osmolyte accumulation, and stress-responsive signalling pathways (Maqbool *et al.*, 2025; Choudhary *et al.*, 2024) [27, 7]. The combined use of these molecules has been reported to improve oxidative damage, improve biochemical defence mechanisms, and sustain grain yield under adverse conditions.

Given these physiological insights, understanding how thiourea and salicylic acid influence biochemical tolerance pathways and seed quality traits under varying sowing conditions is of great significance. Therefore, the present investigation aims to evaluate the effect of thiourea and salicylic acid on biochemical stress tolerance mechanisms and seed quality attributes of wheat under normal, and late sown environments.

Materials and Methods

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. The study aimed to assess the role of salicylic acid (SA) and thiourea (TU) in modulating physiological efficiency, biochemical tolerance, yield performance, and seed quality of wheat under both normal and late-sown (heat-stress) environments.

Experimental Site and Climate

The experimental site is situated at 23°09′ N latitude and 79°58′ E longitude, at an altitude of 411.78 m above mean sea level. The region is characterized by a subtropical climate, featuring hot, dry summers and cool winters. The mean annual rainfall is about 1,284 mm, of which nearly 90% is received between late June and September. The maximum and minimum temperatures range from 24 °C to 45 °C and 4 °C to 32 °C, respectively, while relative humidity varies between 80% and 90% during the monsoon, 60% to 70% in winter, and 30% to 40% in summer. The experimental field soil is classified as a Vertisol, characterized by a deep to medium depth, dark clay loam texture, and neutral reaction. The soil has a good moisture-retaining capacity but exhibits cracking during dry periods, a characteristic typical of Vertisol in central India.

Experimental Design and Treatments

The experiment was conducted in a factorial randomized block design (RBD) with three replications, comprising 20 treatment combinations formed by the interaction of three experimental factors two wheat varieties, five foliar spray treatments, and two sowing dates. The varieties used were JW-3211 (V_1) and JW-3382 (V_2), both obtained from the Department of Plant Breeding and Genetics, JNKVV, Jabalpur. The foliar treatments included T_1: Control (water spray), T_2: SA 800 ppm, T_3: SA 400 ppm, T_4: TU 400 ppm, and T_5: TU 800 ppm. The experiment was conducted under two sowing conditions, *viz*., normal sowing (S_1: 23 November 2019) and late sowing (S_2: 14 December 2019), to impose variable temperature regimes corresponding to normal and heat stress conditions.

Each treatment plot measured 2.1 × 2.0 m (gross area 4.20 m^2) with a net plot size of 1.5 × 1.4 m (2.10 m^2). 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: P_2O_5:K_2O, using urea, single super phosphate, and muriate of potash as nutrient sources. The experiment comprised 60 plots in total, laid out with proper spacing between plots and replications to ensure uniform crop management.

Crop Establishment and Management

Before sowing, well-decomposed farmyard manure (FYM) was incorporated into the soil in a 3:1 ratio with field soil to improve fertility and structure. A basal dose of half the nitrogen and full phosphorus and potassium was applied at sowing, while the remaining nitrogen was top-dressed at 25 days after sowing (DAS). Seeds of each variety were sown manually per pot. Thinning was carried out on 25 DAS to maintain a uniform stand, and hand-weeding was performed at 28 DAS. Intercultural operations such as light hoeing and removal of volunteer plants were performed as needed.

To simulate heat stress, irrigation was withheld for 15 days during the crown-root initiation, flowering, milking, and anthesis stages, while the control plots received irrigation according to the recommended schedule. Foliar sprays of SA and TU were applied twice, at the tillering (35 DAS) and anthesis (65 DAS) stages, using freshly prepared solutions and a hand-operated knapsack sprayer. Control plots were sprayed with distilled water to ensure uniform treatment.

Monitoring of Soil and Plant Water Status

Soil moisture content was estimated by the gravimetric method (Gardner, 1986). Soil samples were collected from different depths (0-15, 15-30, 30-45, 45-60, 60-90, and 90-120 cm) using a soil auger, sealed in pre-weighed aluminium boxes, and then oven-dried at 100-110 °C for 24 hours. The samples were reweighed after drying. Gravimetric soil moisture content (%) was calculated using the formula:

$$\text{Soil moisture (\%)} = (W1-W2) / (W2-C1) \times 100$$

Where W_1 = weight of moist soil + container, W_2 = oven-dried weight + container, and C_1 = weight of the empty container.

Yield and Yield Components

Yield and yield components were recorded at physiological maturity to assess the effects of the treatments. Plant height was measured in centimetres from the ground surface to the spike tip (excluding awns) from three randomly selected plants per plot. The number of tillers per plant and the number of productive tillers per plant were counted from three representative plants at maturity. Ear length was measured from the base to the tip of the main spike, excluding awns, from three plants per replication. The number of spikelets per ear and seeds per ear were obtained by counting spikelets and grains from three main spikes per treatment, and the means were recorded. The seed-set percentage was calculated as per Campbell *et al.* (1969) [6]:

$$\text{SEED SET (\%)} = \frac{\text{Number of grains}}{\text{Number of spikelets}} \times 100$$

(Campbell *et al.*, 1969) [6]

The 1000-seed weight was determined by weighing 1000 healthy seeds from each treatment using a precision electronic balance. The seed yield was measured by harvesting and threshing three randomly selected plants per plot, and yield was expressed on a per-plant, per-plot, and per-hectare basis. The biological yield was estimated by recording the total above-ground biomass (shoots + spikes) of three sun-dried plants, expressed in grams per plant. The harvest index (HI), representing the efficiency of translocation of assimilates into economic yield, was calculated following Synder and Carlson (1984) [46]:

$$\text{HI} = \frac{\text{Economic yield}}{\text{Biological yield}} \times 100$$

Only above-ground plant parts were considered for estimating biological yield and harvest index.

Seed Quality Parameters

Standard germination tests were performed according to ISTA (2013) guidelines using the between-paper method. One hundred seeds per treatment were germinated at 25-30 °C and 95±3% relative humidity for eight days, and the number of normal seedlings was counted to determine the germination percentage (Pradeep, 2018) [35]. On the eighth day, seedling length was measured from the tip of the primary leaf to the base of the hypocotyl from ten normal seedlings per treatment. The same seedlings were oven-dried at 50±1 °C for 24 h, and the dry weight was recorded. Vigour index I was computed following Abdul-Baki and Anderson (1973) [1]:

1. Vigour Index-I = (Root length (cm) +Shoot length (cm)) × Germination percentage

2. Vigour Index-II = Seedling dry weight (g) × Germination percentage

Results and Discussion

The availability of soil water is one of the major determinants of plant growth and physiological performance in field crops, particularly under variable temperature regimes. The forces acting on soil water determine its potential energy and, thus, its availability to roots. In wet soil, water is easily absorbed, whereas in dry soil, water is bound tightly to soil particles and is less accessible. In the present study, soil water content varied markedly across sowing environments. During the vegetative phase, the highest value (42.22%) was observed under normal sowing, while late-sown plots under high temperature showed a significant reduction. At the reproductive stage, soil water content decreased from 28.67% under normal conditions to 19.23% under late sowing a 49% decline and by maturity, a 34% reduction was recorded. These findings indicate that delayed planting accelerates evapotranspiration and reduces soil moisture retention under terminal heat, validating Martin *et al.*, who emphasized that water deficit substantially decreases plant growth and yield.

Table 1: Effect of Salicylic acid and Thiourea on Soil water content at different growth stages of wheat crop in different date of sowing.

Soil water content (%)				
Date of sowing	**Vegetative stage**	**Reproductive stage**	**Maturity stage**	**Mean**
Normal sowing	31.98	28.67	19.15	26.60
Late sowing	22.45	19.23	14.25	18.64

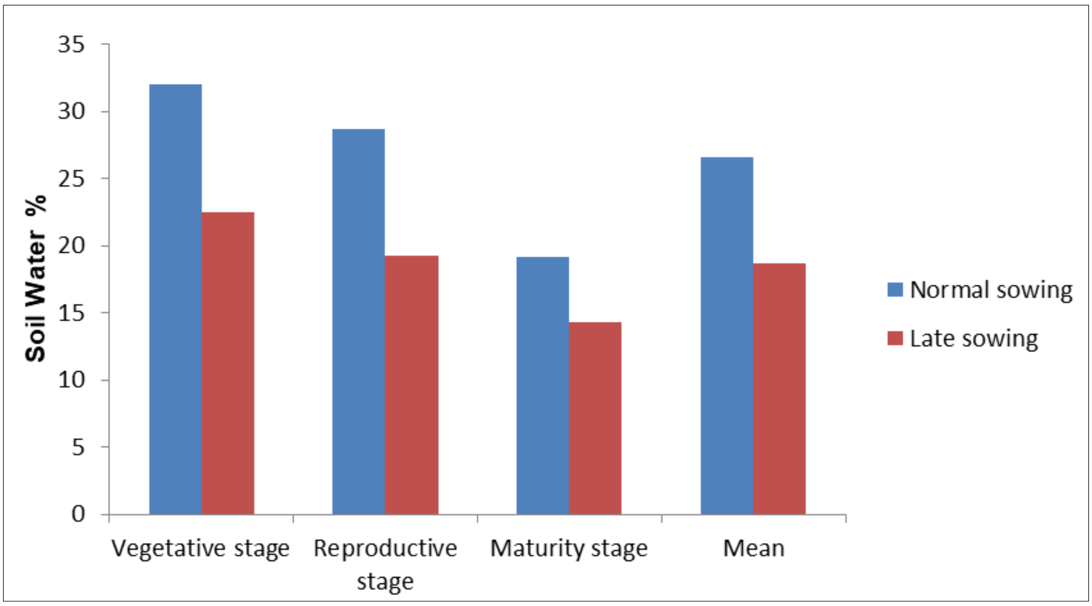

Fig 1: Soil water content

Plant height, a key indicator of vegetative growth and assimilate accumulation, exhibited noticeable variation under different treatments. Late sowing resulted in a reduction in height due to exposure to high temperatures, whereas the foliar application of salicylic acid (SA) at 400 ppm significantly improved plant height under stress. Similar findings were reported by Yadav *et al.* (2020) [24] and Meena *et al.* (2016) [29], who observed that SA and thiourea (TU) enhanced growth parameters under heat and drought stress. Sharma *et al.* and Khafi also recorded improved plant height following TU application. The increase in height under SA treatment may be attributed to its hormonal regulation, improved photosynthetic efficiency, and delayed senescence. The number of tillers per plant was moderately affected by temperature, showing a 21.5% reduction under late sowing compared to normal conditions. However, the foliar spray of SA @ 800 ppm resulted in a 29% increase over the control. These results align with Noreen *et al.* (2017), who reported that SA improved tiller formation and yield components under stress. The number of productive tillers followed a similar trend, with JW-3211 recording the highest number (8.15), showing an 11% reduction under heat stress, while SA @ 800 ppm increased productive tillers by 35%. Comparable findings by Dhikwal and Noreen *et al.* (2017) [32] confirm the role of SA in promoting dry matter accumulation and reproductive tiller formation through enhanced antioxidant activity and source-sink balance. Ear length also reflected varietal and treatment influences, with JW-3211 superior over JW-3382 by 5%. Late sowing reduced ear length by 2%, but foliar application of SA @ 800 ppm effectively enhanced spike elongation under both environments. These observations are consistent with those of Shakirova *et al.* (2003) [40] and Amin *et al.* (2016) [4], who demonstrated that SA and TU improved ear morphology and grain-bearing capacity under stress through hormonal regulation and enhanced assimilate translocation. Likewise, the number of spikelets per ear, a major determinant of spike fertility, was 12.6% higher in JW-3211 than in JW-3382. Heat stress caused a 7% reduction, whereas SA @ 800 ppm improved spikelet number by 9% over control, similar with Singh *et al.* (2015) [43] and Amin *et al.* (2016) [4], who reported SA-induced increases in spikelet formation in cereals.

The number of seeds per ear exhibited varietal variation, with JW-3211 producing 9.4% more seeds than JW-3382. High-temperature stress during late sowing resulted in a 5% reduction; however, SA at 800 ppm increased seed number by 4% relative to the control. These findings support the work of Prasad *et al.* (2011) [37] and Zamaninejad *et al.* (2013) [49], who reported that grain number per ear and yield are closely correlated, and that SA enhances pollen viability and assimilate flow under stress conditions. The seed setting percentage followed the same pattern, with JW-3211 recording a 7% higher seed set than JW-3382, while heat stress caused a 10% decline. Foliar spray of TU @ 400 ppm improved seed set by 6% over control, consistent with Sinha *et al.* (2018) [44] and Gitte *et al.* (2018) [16], who observed enhanced floret retention reduced with TU application. Similarly, Sumitra *et al.* (2019) [45] reported that early sowing improves pollen viability and seed set, indicating that TU helps mitigate the reproductive damage caused by late-season heat.

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

Treatments	Plant height(cm)	No. of Tillers/ Plant	No. of Productive tillers/Plant	No. of spikelet's /ear	Ear Length (cm)	SEED SET %
Varieties(V)						
V1	88.66	8.98	8.15	62.15	9.90	86.90
V2	87.65	8.54	7.34	55.12	9.38	81.05
Mean	88.16	8.76	7.75	58.63	9.64	83.98
SEm±	0.78	0.24	0.21	1.73	0.10	0.65
CD(0.05)	2.32	0.71	0.61	5.11	0.29	1.91
Date of sowing(D)						

D1	89.33	9.61	8.16	60.62	9.53	88.04
D2	86.99	7.91	7.34	56.65	9.75	79.91
Mean	88.16	8.76	7.75	58.63	9.64	83.98
SEm±	0.79	0.24	0.21	1.73	0.10	0.65
CD(0.05)	2.33	0.71	0.61	5.11	0.29	1.91
Treatments(T)						
T_1	91.00	8.14	7.22	52.33	9.60	81.90
T_2	88.80	10.53	9.76	67.75	10.09	83.53
T_3	88.62	8.47	7.58	56.58	9.43	85.04
T_4	87.83	8.50	7.56	57.00	9.38	87.44
T_5	84.54	8.18	6.63	59.50	9.71	81.97
Mean	88.16	8.76	7.75	58.63	9.64	83.98
SEm±	1.24	0.38	0.33	2.73	0.15	1.02
CD(0.05)	3.68	1.12	0.96	8.08	0.45	3.02
Interactions(DxVxT)						
$D1V1T_1$	94.17	8.498	8.00	56.50	9.65	89.93
$D1V1T_2$	92.50	11.83	10.87	65.50	10.53	88.33
$D1V1T_3$	86.33	10.665	9.15	68.00	9.67	92.03
$D1V1T_4$	93.17	9.165	8.50	54.00	9.98	95.51
$D1V1T_5$	90.17	9.17	7.00	65.00	9.84	92.49
$D1V2T_1$	91.17	9.165	6.50	57.84	9.05	79.25
$D1V2T_2$	91.67	11.33	10.165	65.00	9.17	87.25
$D1V2T_3$	89.00	8.33	6.835	58.34	9.54	90.04
$D1V2T_4$	86.17	9.325	6.885	53.50	9.04	84.58
$D1V2T_5$	79.00	8.63	7.665	62.50	8.87	81.00
$D2V1T_1$	88.83	7.83	7.50	54.00	9.36	79.38
$D2V1T_2$	82.84	9.965	9.665	73.00	10.95	83.41
$D2V1T_3$	89.50	7.2	7.835	66.50	9.71	83.40
$D2V1T_4$	85.83	7.335	7.17	68.50	9.50	84.43
$D2V1T_5$	83.34	8.15	5.835	50.50	9.87	80.10
$D2V2T_1$	89.835	7.06	6.87	41.00	10.345	79.05
$D2V2T_2$	88.215	9	8.33	67.50	9.695	75.14
$D2V2T_3$	89.665	7.665	6.50	33.50	8.815	74.70
$D2V2T_4$	86.165	8.17	7.67	52.00	9.015	85.23
$D2V2T_5$	85.665	6.75	6.00	60.00	10.285	74.29
Mean	88.16	8.76	7.75	58.63	9.64	83.98
SEm±	2.488	0.753	0.65	5.460	0.31	2.041
CD(0.05)	7.364	2.23	1.93	16.162	0.905	6.041
CV(%)	3.99	12.16	11.88	13.17	4.49	3.44

The 1000-seed weight, an indicator of grain-filling efficiency, was 2.3% higher in JW-3382 than in JW-3211 but declined by 23% under heat stress. Foliar spray of SA at 800 ppm increased test weight by 21% compared to the control. Bayat and Sepehri (2012) [5] and Shakirova *et al.* (2003) [40] similarly reported that SA enhances dry matter accumulation and prolongs grain filling by maintaining photosynthetic activity and delaying senescence. Seed yield per plot varied significantly between treatments, with JW-3211 yielding 2% more than JW-3382. Late sowing resulted in a 38% yield reduction, whereas SA at 800 ppm increased yield by 16% compared to the control. Similar findings were reported by Lakzayi *et al.* (2014) [26], Monjardino *et al.* (2005) [30], and Rani and Griffiths (2005) [38], who confirmed that high temperatures reduce yield by impairing endosperm development and the transfer of assimilates. Farooq *et al.* (2011) [12] further emphasized that integrating physiological and biochemical strategies with breeding can sustain yield under thermal stress by enhancing grain-filling rates. Biological yield, reflecting total biomass, differed significantly among treatments. JW-3211 produced 15% higher biological yield than JW-3382, while high temperature caused a 4% reduction. Foliar spray of SA @ 800 ppm increased biological yield by 30.52% over control, consistent with Bayat and Sepehri (2012) [5] and Noreen *et al.* (2017) [32], who reported that SA improved total dry weight and growth indices under stress by maintaining chlorophyll content and antioxidative efficiency.

The harvest index, which measures assimilate partitioning efficiency, was not significantly affected by variety but decreased by 22% under high temperatures. Application of SA at 800 ppm increased the harvest index by 11% compared to the control. Similar trends were observed by Meena *et al.* (2016) [29] and Amin *et al.* (2016) [4], who found that SA improved harvest index through enhanced source-sink coordination.

Devasirvatham *et al.* (2012) [8] explained that temperature stress affects both source and sink capacity, but SA mitigates this by maintaining assimilate transport to reproductive tissues.

Table 3: Effect of Salicylic acid and Thiourea on Yield and Yield Components in different date of sowing in wheat crop.

Treatments	No. of seeds/ear	1000 seeds weight(g)	Seed yield(gm/ plot)	Seed yield (gm/plant)	Biological yield(gm)	Harvest Index (%)
Varieties(V)						
V1	59.82	43.89	667.25	20.79	1747.50	38.03
V2	54.64	44.92	654.00	19.34	1526.00	37.68
Mean	57.23	44.41	660.63	20.06	1636.75	37.86
SEm±	0.73	1.15	10.87	0.62	32.08	0.38
CD(0.05)	2.17	3.39	32.19	1.82	94.96	1.13
Date of sowing(D)						
D1	58.68	48.97	767.25	21.75	1671.00	41.62
D2	55.79	39.85	554.00	18.38	1602.50	34.10
Mean	57.23	44.41	660.63	20.06	1636.75	37.86
SEm±	0.73	1.15	10.87	0.62	32.08	0.38
CD(0.05)	2.17	3.39	32.19	1.82	94.96	1.13
Treatments(T)						
T_1	53.50	41.56	605.63	18.77	1537.50	37.33
T_2	61.02	50.51	706.25	23.73	2006.25	41.56
T_3	57.19	45.55	676.25	19.60	1587.50	38.01
T_4	60.25	41.94	672.50	18.77	1468.75	38.35
T_5	54.21	42.49	642.50	19.46	1583.75	34.03
Mean	57.23	44.41	660.63	20.06	1636.75	37.86
SEm±	1.16	1.81	17.19	0.97	50.73	0.60
CD(0.05)	3.44	5.36	50.89	2.88	150.15	1.78
Interactions(DxVxT)						
$D1V1T_1$	58.59	40.775	657.50	19.69	1500.00	40.17
$D1V1T_2$	64.83	60.535	707.50	25.50	2475.00	46.97
$D1V1T_3$	62.92	50.88	857.50	24.82	1550.00	42.82
$D1V1T_4$	62.17	45.08	770.00	20.03	1575.00	39.85
$D1V1T_5$	59.50	45.76	745.00	21.41	1900.00	35.19
$D1V2T_1$	50.17	49.4	710.00	20.68	1450.00	40.75
$D1V2T_2$	63.24	59.635	797.50	24.91	1775.00	49.24
$D1V2T_3$	53.50	50.395	782.50	17.11	1450.00	40.67
$D1V2T_4$	62.37	41.415	870.00	20.68	1500.00	39.91
$D1V2T_5$	49.50	45.815	775.00	22.71	1535.00	40.60
$D2V1T_1$	52.59	35.39	565.00	16.15	1750.00	33.84
$D2V1T_2$	59.00	41.34	700.00	23.00	2050.00	33.92
$D2V1T_3$	62.33	40.45	550.00	22.00	1650.00	38.22
$D2V1T_4$	56.65	40.82	600.00	19.04	1350.00	38.84
$D2V1T_5$	59.67	37.91	520.00	16.25	1675.00	30.52
$D2V2T_1$	52.67	40.66	490.00	18.58	1450.00	34.56
$D2V2T_2$	57.00	40.51	620.00	21.50	1725.00	36.13
$D2V2T_3$	50.00	40.475	515.00	14.46	1700.00	30.35
$D2V2T_4$	59.84	40.455	450.00	15.33	1450.00	34.81
$D2V2T_5$	48.16	40.485	530.00	17.47	1225.00	29.82
Mean	57.23	44.41	660.63	20.06	1636.75	37.86
SEm±	2.322	3.624	34.388	1.947	101.454	1.204
CD(0.05)	6.873	10.728	101.79	5.764	300.3009	3.565
CV(%)	5.74	11.54	7.36	13.73	8.77	4.5

Seed quality parameters, such as germination percentage, seedling length, and vigour indices, provide valuable insights into the physiological health of seeds. Seed germination showed no significant varietal differences under heat stress. Foliar application of SA @ 400 ppm improved germination by 2% over control, consistent with Irfan *et al.* (2006) [19], who observed enhanced germination and seedling vigour in SA-primed wheat under saline stress. Seedling length was 6% higher in JW-3211 than in JW-3382 and showed no significant reduction under heat stress. TU at 400 ppm improved seedling length by 3% over the control, while SA at 400 ppm exhibited superior efficacy under both environments. These findings align with those of Shaheb *et al.* (2016) [39], Waseem *et al.* (2006) [48], and Kang *et al.* (2012) [22], who reported that SA enhances seedling growth, nutrient uptake, and stress-responsive protein expression. Vigor index I, which combines germination percentage and seedling length, was 15% higher in JW-3211 than JW-3382, while TU @ 400 ppm and SA @ 400 ppm improved the index by 3% over the control. Similar results were reported by Shaheb *et al.* (2016) [39] and Nayeem and Mahajan (1991) [31], who emphasized that seed vigour indices are highly sensitive to temperature and genotype. Vigor index II, based on seedling dry weight and germination percentage, was 8% higher in JW-3382 than in JW-3211 and 4% higher under late-sown conditions than normal. TU @ 400 ppm improved this parameter by 12% over control, consistent with Nayeem and Mahajan (1991) [31], who reported significant genotypic variation in seedling vigour and tolerance at elevated temperatures. The improvement in vigour indices with SA and TU treatments is attributed to their cytokinin-like and antioxidant effects, which stabilize membranes, enhance metabolic activity, and promote seedling establishment under high temperature.

Table 4: Effect of Salicylic acid and Thiourea on seed quality traits in different date of sowing in wheat crop.

Treatments (T)	Germination (%)	Seedling Length (CM)	Vigour Index I	Vigour Index II
Varieties (V)				
V1	94.20	24.60	2315.03	31.26
V2	95.10	21.15	2011.30	33.66
Mean	94.65	22.88	2163.17	32.46
SEm±	0.73	0.65	58.87	0.97
CD(0.05)	2.15	1.93	174.27	2.87
Date of sowing(D)				
D1	95.00	22.77	2163.16	31.87
D2	94.30	22.98	2163.17	33.05
Mean	94.65	22.88	2163.17	32.46
SEm±	0.73	0.65	58.87	0.97
CD(0.05)	2.15	1.93	174.27	2.87
Treatments(T)				
T_1	94.38	23.50	2214.90	31.34
T_2	93.25	22.50	2091.15	31.57
T_3	96.13	22.80	2191.58	31.72
T_4	94.13	24.23	2283.00	35.03
T_5	95.38	21.35	2035.20	32.66
Mean	94.65	22.88	2163.17	32.46
SEm±	1.15	1.03	93.09	1.54
CD(0.05)	3.40	3.06	275.54	4.54
Interactions(DxVxT)				
$D1V1T_1$	96.00	25.50	2448.00	28.80
$D1V1T_2$	91.00	23.70	2145.20	30.46
$D1V1T_3$	95.50	23.00	2197.00	32.50
$D1V1T_4$	96.50	28.30	2728.50	30.43
$D1V1T_5$	96.50	23.80	2297.00	31.42
$D1V2T_1$	94.00	20.20	1894.40	31.06
$D1V2T_2$	94.50	19.50	1847.50	32.18
$D1V2T_3$	96.00	23.10	2219.40	34.09
$D1V2T_4$	93.50	22.30	2087.90	33.19
$D1V2T_5$	96.50	18.30	1766.70	34.64
$D2V1T_1$	92.00	27.10	2490.50	31.10
$D2V1T_2$	92.00	23.80	2176.00	28.80
$D2V1T_3$	96.50	24.30	2344.60	28.93
$D2V1T_4$	93.00	23.60	2194.80	39.06
$D2V1T_5$	93.00	22.90	2128.70	31.15
$D2V2T_1$	95.50	21.20	2026.70	34.41
$D2V2T_2$	95.50	23.00	2195.90	34.85
$D2V2T_3$	96.50	20.80	2005.30	31.36
$D2V2T_4$	93.50	22.70	2120.80	37.46
$D2V2T_5$	95.50	20.40	1948.40	33.43
Mean	94.65	22.88	2163.17	32.46
SEm±	2.30	2.07	186.18	3.07
CD(0.05)	6.81	6.12	551.08	3.09
CV(%)	3.44	12.78	12.17	13.38

Overall, the results demonstrate that both salicylic acid and thiourea substantially mitigate the adverse impacts of terminal heat stress on wheat growth, yield, and seed quality. SA proved more effective in enhancing photosynthetic stability, antioxidant enzyme activity, grain filling, and seed physiology, whereas TU improved reproductive efficiency, seed set, and early seedling vigour. Among the genotypes, JW-3211 consistently performed better than JW-3382, suggesting higher inherent thermotolerance. The synergistic use of biochemical modulators, such as SA and TU, thus offers a practical and physiological approach to sustaining wheat productivity and seed quality under rising temperature regimes.

Conclusion

The study demonstrated that salicylic acid (SA) and thiourea (TU) both significantly reduced the negative impact of terminal heat stress on wheat. Foliar application of SA at 800 parts per million (ppm) increased biological yield by 30.52 percent, seed yield by 16 percent, and 1000-seed weight by 21 percent compared to the control. Application of TU at 400 ppm improved seed setting by 6 percent and vigour index II by 12 percent. The wheat variety JW-3211 exhibited 15 percent higher biological yield and 9.4 percent more grains per ear than JW-3382, indicating greater thermotolerance and productivity under late-sown conditions.

References

1. Abdul-Baki AA, Anderson JD. Vigor determination in *Glycine max* seed by multiple criteria. Crop Sci. 1973;13:630-633.
2. Abid M, Khan A, Nadeem F. Wheat response to heatwaves: Physiological disruption and mitigation strategies. Field Crops Res. 2024;310:109163.
3. Alomari DZ, Al-Rawashdeh IM, Al-Darawsheh JI, Al-Khasawneh NM, Al-Lataifeh FA, Al-Abed MA. Wheat grains as a sustainable source of protein for health. Front Nutr. 2023;10:10609835.
4. Amin A, Rasool S, Khan MA, Ahmad P. Physiological and biochemical responses of plants to salicylic acid

and thiourea under abiotic stress. Plant Growth Regul. 2016;69(3):271-280.
5. Bayat M, Sepehri A. Effects of salicylic acid and paclobutrazol on yield, growth and physiological parameters of *Triticum aestivum* under irrigation regimes. J Plant Physiol Breed. 2012;2(1):43-56.
6. Campbell CA, Davidson HR, Warder FG. Effects of temperature, nitrogen fertilization, and moisture stress on yield and protein content of Manitou *Triticum aestivum*. Can J Plant Sci. 1969;49:691-701.
7. Choudhary N, Singh S, Jha P. Salicylic acid-induced modulation of antioxidant metabolism and osmotic balance in heat-stressed *Triticum aestivum*. Physiol Mol Biol Plants. 2024;30(2):299-310.
8. Devasirvatham V, Tan DKY, Gaur PM, Raju TN, Trethowan RM. High-temperature tolerance in grain legumes. Euphytica. 2012;184(1):1-16.
9. Erenstein O. Global trends in wheat production, consumption and trade. In: Wheat Value Chains: Upgrading for Food Security and Livelihoods. Cham: Springer; 2022. p.55-77.
10. FAO. FAO Statistical Yearbook 2025 - World Food and Agriculture. Rome: Food and Agriculture Organization of the United Nations; 2025.
11. Farooq M, Bramley H, Palta JA, Siddique KHM. Heat stress in *Triticum aestivum* during reproductive and grain-filling phases. Crit Rev Plant Sci. 2011;30(6):491-507.
12. Farooq M, Rehman A, Wahid A, Siddique KHM. Heat stress in wheat: Effects and management strategies. Agron Sustain Dev. 2023;43(1):14.
13. Fischer RA. The importance of grain or kernel number in wheat. Field Crops Res. 2008;105(1-2):15-21.
14. Fisher RA. Statistical Methods for Research Workers. 14th ed. Edinburgh: Oliver & Boyd; 1967.
15. Gardner WH. Water content. In: Klute A, editor. Methods of Soil Analysis, Part 1: Physical and Mineralogical Methods. 2nd ed. Madison (WI): ASA & SSSA; 1986. p.493-544.
16. Gitte AN, Patil RH, Pawar RD. Influence of thiourea and NAA on seed set and yield attributes in *Sesamum indicum*. J Oilseeds Res. 2018;35(3):145-151.
17. Gurjar G, Jain S, Meena RS. Effect of high temperature on physiological and yield traits in wheat genotypes under late-sown conditions. J Cereal Sci. 2024;117:104513.
18. India Data Map. Agricultural production statistics for 2024-25. Ministry of Agriculture & Farmers Welfare, Government of India; 2025.
19. Irfan M, Ahmad A, Hayat S. Effect of hormonal priming on germination and seedling growth of *Triticum aestivum* under saline conditions. Pak J Bot. 2006;38(3):1127-1136.
20. Ishfaq M, Ali A, Ahmad S, Hussain M. Thiourea-mediated improvement in physiological efficiency and yield stability of wheat under terminal heat stress. Plant Physiol Rep. 2024;29(1):112-123.
21. ISTA. International Rules for Seed Testing. Bassersdorf (Switzerland): International Seed Testing Association; 2013.
22. Kang G, Li G, Liu G, Xu W, Peng X, Wang C, *et al*. Exogenous salicylic acid enhances salt tolerance in wheat seedlings by regulating energy metabolism and stress defense proteins. Plant Growth Regul. 2012;68(1):87-95.
23. Khalid A, Hussain A, Qamar S, Yaseen M, Noor R. Wheat quality: A review on chemical composition, nutritional quality, processing, and health implications. Front Nutr. 2023;10:1053196.
24. Kumar R, Singh D, Sharma P, Tripathi S. Heat stress mitigation and yield stability in wheat through integrated agronomic management. Indian J Plant Physiol. 2023;28(4):789-801.
25. Kumar S, Singh M, Yadav P, Sharma D. Effect of thiourea and irrigation regimes on growth, yield and water-use efficiency in wheat. J Agrometeorol. 2018;20(2):170-176.
26. Lakzayi M, Khourgami A, Tavakoli A. Effect of salicylic acid on antioxidant enzyme activity, flowering and yield of wheat under drought stress. Ann Biol Res. 2014;5(1):65-70.
27. Maqbool R, Khan MMA, Alam M. Role of salicylic acid in enhancing heat stress tolerance and antioxidant defense in *Triticum aestivum*. Plant Stress. 2025;5:100128.
28. Marcos-Filho J. Physiological seed quality evaluation. Seed Sci Technol. 1998;26(3):625-636.
29. Meena HR, Kumar D, Singh P. Salicylic acid and brassinosteroid-mediated growth responses in wheat under abiotic stress. J Appl Nat Sci. 2016;8(4):2143-2149.
30. Monjardino P, Smith P, Sadras VO. Relationship between radiation interception and biomass and grain yield in *Zea mays* under heat stress. Field Crops Res. 2005;93(2-3):153-163.
31. Nayeem KA, Mahajan V. Genetic variation for seedling vigor and high-temperature tolerance in *Triticum aestivum*. Indian J Genet Plant Breed. 1991;51(3):262-266.
32. Noreen S, Ashraf M, Akram NA. Salicylic acid-induced improvement in yield and biochemical attributes of wheat under heat stress. J Plant Growth Regul. 2017;36(3):785-795.
33. Panse VG, Sukhatme PV. Statistical Methods for Agricultural Workers. 2nd ed. New Delhi: ICAR; 1985.
34. Pinthus MJ, Millet E. Interrelationships among yield components in wheat. Euphytica. 1978;27:211-221.
35. Pradeep T. Seed quality evaluation under stress environments in cereals. J Seed Sci Technol. 2018;47(2):125-131.
36. Prasad PVV, Sharma DK, Joshi AK. Physiological basis of heat tolerance in *Triticum aestivum*: Current understanding and future prospects. Plant Stress. 2022;4:100092.
37. Prasad PVV, Staggenborg SA, Ristic Z. Impacts of drought and high temperature stress on physiological, growth and yield processes of crop plants. Field Crops Res. 2011;133(1):1-12.
38. Rani A, Griffiths H. Physiological consequences of heat stress on legume crops. Plant Physiol Biochem. 2005;43(10-11):1075-1085.
39. Shaheb MR, Kabir MH, Rahman MM. Effect of sowing time on seed quality of *Triticum aestivum*. Bangladesh Agron J. 2016;19(1):1-8.
40. Shakirova FM, Sakhabutdinova AR, Bezrukova MV, Fatkhutdinova RA, Fatkhutdinova DR. Changes in the

hormonal status of wheat seedlings induced by salicylic acid and salinity. Plant Sci. 2003;164(3):317-322.
41. Sharma R, Singh M, Kaur S. Impact of terminal heat stress on wheat growth and productivity under changing climate scenarios. Environ Exp Bot. 2024;218:105678.
42. Shewry PR, Hawkesford MJ, Piironen V, Lampi AM, Gebruers K, Boros D, *et al*. The contribution of wheat to human diet and health. Food Energy Secur. 2015;4(3):178-202.
43. Singh R, Kaur G, Bhullar GS. Effect of salicylic acid on spikelet development and yield in *Oryza sativa* under stress. Oryza. 2015;52(1):68-74.
44. Sinha S, Patel JR, Gami RA. Effect of thiourea on physiological traits, seed set and yield of *Sesamum indicum* under stress. J Pharmacogn Phytochem. 2018;7(2):1805-1810.
45. Sumitra P, Kumari M, Sharma R. Effect of sowing time on pollen viability and seed set in *Sesamum indicum*. Int J Curr Microbiol Appl Sci. 2019;8(5):1258-1267.
46. Synder FW, Carlson GE. Selecting for high harvest index in grain crops. Euphytica. 1984;33:573-578.
47. Tekrony DM, Egli DB. Relationship of seed vigor to crop yield: A review. Crop Sci. 1977;17(5):865-872.
48. Waseem M, Ali A, Tahir M, Iqbal RM. Role of salicylic acid in improving growth and nutrient uptake in wheat under water stress. Pak J Agric Sci. 2006;43(3-4):156-160.
49. Zamaninejad M, Khajehpour MR, Fathi G. Correlation and path analysis of yield and yield components in wheat genotypes. Int J Agron Plant Prod. 2013;4(2):333-342.