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Effect of Plant Growth Regulators on Phenology and Heat Unit of Wheat (*Triticum aestivum* L.)

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Authors' contributions

This work was carried out in collaboration among all authors. All authors read and approved the final manuscript.

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Abstract

Wheat (*Triticum aestivum* L.) productivity is strongly influenced by crop phenology and thermal accumulation during different growth stages. Plant growth regulators may modify phenological development and heat-unit accumulation, thereby affecting crop adaptation under varying environmental conditions. An experiment was conducted during the *rabi* seasons at the Zonal Agricultural Research Station, Powarkheda, JNKVV, Narmadapuram, to evaluate the influence of plant growth regulators on the phenology and heat indices of wheat varieties**.** The experiment comprised twenty treatment combinations, with four wheat varieties (GW 322, Sujata, C 306, and MP 1202) as the main-plot treatments and five plant growth regulator treatments (CCC @ 1000 and 1500 ppm, ethephon @ 10 and 30 ppm, and a control) as the sub-plot

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treatments, arranged in a split-plot design with three replications. Observations were recorded at the following phenological stages: emergence, crown root initiation, tillering, jointing, booting, heading, anthesis, milking, dough, and physiological maturity. Accumulated growing degree days, helio-thermal units, and photo-thermal units were also calculated at the specified phenological stages. Among the varieties, C 306 required the longest duration (123 days) to attain physiological maturity and recorded the highest accumulated growing degree days (1659.27 ˚C day), helio-thermal units (11299.30 ˚C day hour), and photo-thermal units (19525.89 ˚C day hour) at physiological maturity. Regarding plant growth regulators, CCC @ 1500 ppm resulted in the longest duration (119 days) to reach physiological maturity. The highest accumulated growing degree days (1513.75 ˚C day) were recorded with CCC @ 1500 ppm; the corresponding helio-thermal units (10134.42 ˚C day hour) and photo-thermal units (19112.46 ˚C day hour) were statistically at par with ethephon @ 30 ppm.

Keywords: Wheat variety; plant growth regulators; phenology; growing degree days; helio-thermal unit; photo-thermal unit.

1. Introduction

Wheat (*Triticum aestivum* L.) is one of the most important cereal crops in the world, contributing around 20% of the calories and protein in the human diet. Wheat is essential for food security and agricultural sustainability in India. However, rising temperatures and variable weather conditions pose major challenges to sustaining wheat yields because of climate-change-related concerns. Phenological stages are primary determinants of grain yield because they influence the duration of biomass accumulation and the partitioning of assimilates. In wheat, phenology is principally regulated by genotype, temperature, photoperiod, and vernalisation requirements. Matching growth stages with favourable environmental conditions improves resource-use efficiency and reduces vulnerability to terminal heat stress. Early flowering reduces biomass accumulation, whereas late flowering exposes reproductive tissues to excessive temperatures during grain filling, resulting in poor grain set and reduced grain weight. Thus, crop phenology is important for improving wheat productivity under changing climatic conditions. Temperature is the most important environmental factor affecting crop growth. Growing degree days (GDD) are often used to quantify phenological development in wheat. Other agrometeorological indices include helio-thermal units (HTU) and photo-thermal units (PTU), which combine temperature with solar radiation or day length and provide a better description of crop growth. Hyles et al. (2020) reported that these indices are useful for understanding crop adaptation, assessing varietal performance, and anticipating developmental stages under diverse conditions. Generally, early-maturing varieties use fewer heat units and escape terminal heat stress, whereas late-maturing varieties require greater thermal accumulation but often produce more biomass and yield under favourable conditions. Hence, selecting an appropriate variety with optimum thermal requirements is important for achieving higher production under diverse agroclimatic conditions.

Recent evidence indicates that wheat development is governed by interacting thermal, photoperiod, and vernalisation responses, and that warmer conditions generally accelerate flowering and maturity, thereby shortening the duration available for canopy development and grain filling (Alipour & Abdi, 2021; Aslam et al., 2017; Craufurd & Wheeler, 2009; Sadras & Monzon, 2006). Consequently, thermal indices should be interpreted together with genotype and photoperiod because identical accumulated heat units may not represent equivalent developmental responses across cultivars or environments (Aslam et al., 2017; Sadras & Monzon, 2006).

Plant growth regulators (PGRs) have been recognised as effective agronomic tools for modulating crop growth and development. They influence endogenous hormonal balance, alter cell division and elongation, promote assimilate translocation, retard senescence, and increase stress tolerance. Growth retardants such as chlormequat chloride (CCC) and ethephon limit excessive stem elongation by reducing gibberellin production, thereby enhancing lodging resistance and assimilate partitioning to reproductive organs. CCC usually delays heading and maturity by prolonging the vegetative period, which may lead to greater biomass production and grain filling. Conversely, ethephon can accelerate reproductive growth and also improve lodging resistance (Singh et al., 2008).

Plant growth regulator responses also depend on the compound, dose, application stage, genotype, and prevailing lodging risk. Studies in cereals have shown that chlormequat chloride and ethephon can reduce stem elongation and modify canopy architecture, but their effects on development and yield are context-specific rather than uniformly beneficial (Ghuman & Ram, 2021; Rajala & Peltonen-Sainio, 2001; Ramburan & Greenfield, 2007). This variability supports the joint evaluation of PGR treatments with varietal phenology and local thermal conditions.

However, current research indicates that improved wheat varieties combined with appropriate plant growth regulator management may modify crop phenology, improve heat-use efficiency, and stabilise grain production under climatic variability. Nevertheless, knowledge of the combined effects of different wheat genotypes and plant growth regulators on phenological development and thermal indices under Indian conditions remains limited. Therefore, plant growth regulators need to be systematically evaluated across wheat varieties to identify suitable combinations for improving crop adaptation, resource-use efficiency, and production under changing climatic conditions.

2. Materials and Methods

The experiment was conducted at the Zonal Agricultural Research Station, Powarkheda Centre, located in the Central Narmada Valley agroclimatic zone of Madhya Pradesh at 22°40' N latitude, 77°42' E longitude, and an altitude of 299 m above mean sea level. The region has cool winters and hot summers. The average maximum temperature ranged from 18.63 to 41.4 °C, while the average minimum temperature ranged from 6.06 to 21.83 °C during both experimental years. The soil at the experimental site contained 49.26% sand, 24.24% silt, and 26.50% clay and had a deep black texture with a neutral pH. The organic carbon content was 0.63%. The soil was low in available N (238.25 kg ha^{-1}), medium in available P (10.75 kg ha^{-1}), and high in available K (597.96 kg ha^{-1}). The experiment was conducted in a split-plot design with four wheat varieties, namely GW 322, Sujata, C 306, and MP 1202, as the main-plot factor and five plant growth regulator treatments (CCC @ 1000 ppm, CCC @ 1500 ppm, ethephon @ 10 ppm, ethephon @ 30 ppm, and control) as the sub-plot factor, with three replications. The growth regulators were sprayed at the first-node and booting stages of the crop using a knapsack sprayer. The recommended N: P: K dose (120:60:40 kg ha^{-1}) was applied, with half of the nitrogen and the full doses of phosphorus and potassium applied initially; the remaining nitrogen was applied during the first and second irrigations. The crop was sown on 10 November 2020 and 11 November 2021. Data on phenological duration, growing degree days, helio-thermal units, and photo-thermal units were recorded and calculated using the following formulae.

Heat indices were calculated as described below.

2.1 Growing Degree Days

The growing degree days (GDD) were determined according to Nuttonson (1955).

$$GDD = \frac{T_{max} + T_{min}}{2} - T_t$$

where T_{max} and T_{min} are the daily maximum and minimum temperatures (°C), respectively, and T_t is the base temperature. The base temperature for wheat is generally taken as 5 °C.

2.2 Helio-thermal Unit

The helio-thermal unit is the product of a heat unit (HU) and the daily hours of bright sunshine. HTU was calculated using the formula given by Rajput (1980).

$$HTU = \sum_{i=1}^{n} GDD \times SSH$$

where

GDD = growing degree days; SSH = bright sunshine hours

2.3 Photo-thermal Unit

The photo-thermal unit was calculated using the equation given by Wilsie (1962)**:**

PTU = GDD x L

where GDD = growing degree days and L = maximum day length

3. Results and Discussion

3.1 Effect on Phenological Days

Data in Table 1 on phenological stages revealed differences among the varieties and plant growth regulator treatments. Among the wheat varieties, C 306 required the maximum number of days to attain physiological maturity (123 days), followed by Sujata (119 days), whereas MP 1202 (111 days) and GW 322 (110 days) matured earliest. C 306 also required the longest duration for each intermediate phenophase, particularly from jointing to physiological maturity. This genotypic variation in phenological duration is consistent with the well-established fact that wheat varieties differ widely in their thermo-photoperiodic sensitivity. Among the plant growth regulator treatments, CCC @ 1500 ppm delayed physiological maturity to 119 days, six days later than the control (113 days), while ethephon @ 30 ppm extended maturity to 117 days. These delays in phenological progression under the plant growth regulator treatments are consistent with the known modes of action of these compounds. CCC inhibits ent-kaurene synthase in the gibberellin biosynthetic pathway, thereby restricting cell elongation, while ethephon-released ethylene may similarly retard transitions through successive growth stages. These responses are consistent with previous observations of PGR effects on wheat development (Rajala & Peltonen-Sainio, 2001; Ramburan & Greenfield, 2007).

The longer duration of C 306 is therefore plausibly associated with greater genetic sensitivity to photoperiod and/or vernalisation and with differences in earliness per se, although these mechanisms were not measured directly in the present experiment (Alipour & Abdi, 2021; Aslam et al., 2017). The contrast between C 306 and the earlier varieties also agrees with reports that cultivar-specific phenological responses can substantially alter the timing of anthesis and maturity under the same field environment (Craufurd & Wheeler, 2009; Sadras & Monzon, 2006). For the PGR treatments, the delayed phenophases should be interpreted as a treatment-associated extension of crop duration rather than direct evidence of improved heat tolerance. Previous field studies indicate that chlormequat chloride and ethephon responses vary with cultivar and application timing, which may explain the different magnitudes of delay observed among treatments (Ghuman & Ram, 2021; Ramburan & Greenfield, 2007).

3.2 Effect on Growing Degree Days

Among the varieties, C 306 accumulated the highest number of growing degree days at physiological maturity (1659.27 °C day), followed by Sujata (1569.53 °C day), while MP 1202 (1402.00 °C day) and GW 322 (1387.23 °C day) accumulated fewer growing degree days (Table 2). Regarding plant growth regulators, the highest accumulated growing degree days at maturity (1513.75 °C day) were recorded with CCC @ 1500 ppm, followed by ethephon @ 30 ppm (1509.29 °C day). The higher accumulated growing degree days under CCC @ 1500 ppm and ethephon @ 30 ppm were attributable to the additional days required to reach each phenophase, particularly during the reproductive and grain-filling stages, when the crop was exposed to progressively rising temperatures. Similar relationships between crop duration and heat-unit accumulation in wheat have been reported by Bisht et al. (2019).

Because GDD is accumulated until a specified phenological stage, the higher values recorded for C 306 and CCC at 1500 ppm primarily reflect their longer calendar duration under the temperature regime experienced during the experiment. This interpretation is consistent with the use of thermal time as an integrative measure of developmental progress, provided that the base temperature and calculation procedure are clearly defined (McMaster & Wilhelm, 1997; Wang & Engel, 1998). However, thermal time alone may not fully represent wheat development because photoperiod and vernalisation can modify the rate at which accumulated temperature is translated into phenological advancement (Aslam et al., 2017; Wang & Engel, 1998). Therefore, the higher GDD requirement should not be considered intrinsically superior; its agronomic value depends on whether the extended duration coincides with favourable conditions during anthesis and grain filling.

Table 1. Effect of plant growth regulators on phenological stages (Mean of 2 year)

Treatment	Emergence	CRI	Tillering	Jointing	Booting	Heading	Anthesis	Milking	Dough	Physiological maturity
Main plot -Variety										
GW 322	5	20	30	44	53	66	77	85	94	110
Sujata	6	21	31	47	58	69	92	103	111	119
C 306	5	21	31	50	61	73	96	105	116	123
MP 1202	6	20	26	43	52	63	77	87	97	111
Sub plot - Plant growth regulators										
Control	5	20	30	44	53	64	80	91	100	113
CCC @ 1000 ppm	5	20	29	44	54	66	84	93	102	114
CCC @ 1500 ppm	5	21	30	49	60	71	90	99	110	119
Ethephon @ 10 ppm	5	20	29	45	55	67	85	94	103	114
Ethephon @ 30 ppm	5	21	29	48	59	70	89	98	109	117

Table 2. Effect of plant growth regulators on accumulated growing degree days (Mean of 2 year)

Treatment	Emergence	CRI	Tillering	Jointing	Booting	Heading	Anthesis	Milking	Dough	Physiological Maturity
Main plot-Variety										
GW 322	82.63	312.67	448.00	614.60	742.67	899.87	977.77	1016.77	1122.83	1387.23
Sujata	92.50	339.40	463.27	665.03	786.87	923.67	1064.33	1211.23	1353.03	1569.53
C 306	89.13	354.10	457.50	707.30	838.17	971.23	1165.63	1281.17	1471.30	1659.27
MP 1202	92.50	317.80	448.83	580.97	719.03	874.47	984.43	1034.20	1137.47	1402.00
SEm±	2.53	9.77	19.18	1.16	1.05	2.18	2.29	1.42	0.73	2.53
CD (p=0.05)	8.94	34.44	67.61	4.10	3.71	7.69	8.07	5.01	2.58	8.92
Sub plot - Plant growth regulators										
Control	89.75	331.29	462.13	637.33	766.88	902.25	1041.67	1130.38	1266.13	1498.75
CCC @ 1000 ppm	89.42	330.13	461.17	638.00	767.88	903.25	1043.79	1131.38	1267.13	1499.75
CCC @ 1500 ppm	89.04	331.96	459.25	649.75	779.71	942.08	1060.17	1145.50	1279.54	1513.75
Ethephon @ 10 ppm	89.25	332.46	437.46	639.00	768.88	904.25	1043.63	1132.63	1268.38	1501.00
Ethephon @ 30 ppm	88.50	329.13	452.00	645.79	775.08	934.71	1050.96	1139.33	1274.63	1509.29
SEm±	0.43	1.50	8.30	1.54	2.15	2.08	2.76	2.66	2.13	2.24
CD (p=0.05)	1.25	4.34	24.01	4.46	6.22	6.02	8.00	7.71	6.17	6.49

Table 3. Effect of plant growth regulators on helio-thermal unit (Mean of 2 year)

Treatment	Emergence	CRI	Tillering	Jointing	Booting	Heading	Anthesis	Milking	Dough	Physiological Maturity
Main plot – Variety										
GW 322	703.96	2181.73	2958.13	4177.27	5109.50	6328.33	7093.60	7372.83	8346.20	9079.73
Sujata	766.47	2243.10	3030.83	4596.03	5539.83	6626.53	7794.83	9164.53	10249.27	10510.57
C 306	764.11	2290.70	2960.13	4898.57	6029.27	7036.90	8774.60	9683.50	11072.07	11299.30
MP 1202	701.44	2029.00	2793.00	3906.87	5014.40	6096.37	7143.30	7522.03	8487.63	8913.57
SEm±	30.05	59.12	62.28	2.22	7.57	2.40	9.99	8.85	33.72	41.82
CD (p=0.05)	105.93	208.42	219.57	7.83	26.70	8.46	35.22	31.20	118.90	147.46
Sub plot - Plant growth regulators										
Control	731.10	2192.50	2941.58	4388.13	5379.92	6515.88	7688.00	8426.50	9467.00	9823.54
CCC @ 1000 ppm	731.48	2189.38	2959.71	4389.50	5389.08	6517.00	7690.00	8427.63	9492.25	9865.96
CCC @ 1500 ppm	734.90	2176.25	2944.92	4405.92	5492.75	6532.75	7728.67	8461.21	9679.67	10134.42
Ethephon @ 10 ppm	731.56	2193.13	2911.58	4390.63	5400.83	6518.00	7690.00	8429.13	9506.17	9879.04
Ethephon @ 30 ppm	740.94	2179.42	2919.83	4399.25	5453.67	6526.54	7711.25	8434.17	9548.88	10051.00
SEm±	4.22	7.69	20.82	2.74	14.03	2.96	12.82	9.59	52.87	40.87
CD (p=0.05)	12.20	22.25	60.23	7.93	40.60	8.57	37.10	27.74	152.97	118.26

Table 4. Effect of plant growth regulators on photo-thermal unit (Mean of 2 year)

Treatment	Emergence	CRI	Tillering	Jointing	Booting	Heading	Anthesis	Milking	Dough	Physiological Maturity
Main plot – Variety										
GW 322	817.87	3275.33	4682.57	6419.90	7420.10	9659.37	11166.94	11590.86	13076.51	16979.22
Sujata	908.60	3507.70	4866.21	6970.88	8230.05	9776.20	12455.70	14433.07	15265.44	18560.44
C 306	852.83	3593.20	4809.37	7406.49	8646.72	10798.74	13787.74	15368.57	16763.65	19525.89
MP 1202	913.10	3243.30	4470.70	6062.43	7629.16	8353.43	11587.69	12052.06	14149.49	17257.27
SEm±	31.84	83.42	115.64	9.38	20.54	146.98	163.33	158.80	158.62	320.71
CD (p=0.05)	112.24	294.12	407.71	33.08	72.42	518.19	575.85	559.89	559.23	1130.71
Sub plot - Plant growth regulators										
Control	872.17	3415.00	4721.71	6684.04	7801.79	9288.60	11742.76	12855.50	13096.07	17102.11
CCC @ 1000 ppm	876.92	3414.13	4721.50	6695.00	7863.92	9438.88	11986.33	13233.08	14346.79	17910.17
CCC @ 1500 ppm	876.04	3413.25	4721.04	6772.92	8200.17	10009.04	12969.33	14041.25	16535.42	19112.46
Ethephon @ 10 ppm	876.21	3412.38	4720.71	6696.25	7961.75	9696.88	11987.58	13254.25	14607.38	17911.25
Ethephon @ 30 ppm	864.17	3369.67	4651.11	6726.42	8079.92	9801.29	12561.58	13421.63	15483.21	18367.54
SEm±	5.52	14.56	31.04	21.88	68.59	123.07	229.75	220.05	436.97	327.50
CD (p=0.05)	15.98	42.12	89.82	63.32	198.46	356.09	664.78	636.70	1264.36	947.62

3.3 Effect on Helio-thermal Unit and Photo-thermal Unit

The data on helio-thermal and photo-thermal units are presented in Tables 3 and 4. Among the wheat varieties, C 306 accumulated the highest helio-thermal units (11299.30 °C day hour) and photo-thermal units (19525.89 °C day hour) at maturity, whereas MP 1202 and GW 322 accumulated the lowest values. Among the plant growth regulator treatments, CCC @ 1500 ppm recorded the highest helio-thermal units (10134.42 °C day hour) and photo-thermal units (19112.46 °C day hour), representing increases of approximately 3.2% and 11.7%, respectively, over the control. Treatments that delayed crop phenophases accumulated more photo-thermal units, which is consistent with earlier reports that foliar applications of growth retardants such as CCC and ethephon can modify wheat phasic development and, consequently, crop heat-unit requirements (Rodrigues et al., 2003).

The higher HTU and PTU values under C 306 and CCC at 1500 ppm are consistent with the additional days required to reach maturity, which increased cumulative exposure to temperature together with sunshine duration or day length. Studies combining thermal time with photoperiod have shown that joint consideration of these variables can improve the description of wheat phenological development across contrasting environments (Aslam et al., 2017; Wang & Engel, 1998). The present differences in HTU and PTU should therefore be interpreted mainly as consequences of altered phenological duration, not as direct measures of physiological efficiency. Moreover, field evidence shows that the agronomic response to chlormequat chloride and ethephon depends on genotype, application stage, and lodging pressure (Ghuman & Ram, 2021; Ramburan & Greenfield, 2007), emphasising the need to validate the observed thermal-index shifts against grain yield, lodging, and heat-use efficiency before recommending a specific PGR treatment.

4. Conclusion

Among the varieties, C 306 exhibited the longest crop duration and the highest thermal-unit requirements, whereas GW 322 and MP 1202 matured earliest and accumulated the fewest heat units. Among the plant growth regulator treatments, CCC @ 1500 ppm and ethephon @ 30 ppm delayed successive phenophases, particularly anthesis and physiological maturity, and correspondingly increased accumulated growing degree days, helio-thermal units, and photo-thermal units compared with the control. These results indicate that plant growth regulators can modify the phenological development and thermal-unit accumulation of wheat under the conditions of this experiment.

5. Limitations

The experiment was conducted at a single location over two rabi seasons; therefore, the observed varietal and treatment responses may vary under other soils, climates, and management conditions. Grain yield, lodging, and heat-use efficiency were not reported alongside the thermal indices. Consequently, the agronomic value of the delayed phenophases and greater heat-unit accumulation requires validation through multi-location experiments that include yield and lodging assessments.

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Declaration of AI Use

This manuscript was prepared through the combined contributions of all author(s), including contributions to the study design, data, content development, results, interpretation, and related scholarly work. The author(s) acknowledge the use of Grammarly and ChatGPT to assist with grammar checking, language refinement, reference formatting. These AI-assisted tools were not used as authors and did not replace the intellectual contributions or scholarly judgment of the author(s). All AI-assisted outputs, including content, references, and interpretations, were carefully reviewed, revised, verified, and approved by the author(s). The author(s) accept full responsibility for the accuracy, integrity, and final content of the manuscript.

Competing Interests

Authors have declared that no competing interests exist.

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