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Evaluating water stress through stress degree days and phenology of summer maize under silicon and irrigation management strategies

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Abstract
A two-year field experiment was conducted during the summer seasons of 2023 and 2024 at Visva-Bharati, Sriniketan, West Bengal, to assess the effects of irrigation scheduling, irrigation methods, and silicon application on stress degree days (SDD) and phenological traits in summer maize (*Zea mays* L.). The study followed a split-plot design with three irrigation regimes based on cumulative pan evaporation (CPE: 40 mm, 50 mm, and 60 mm), three irrigation methods (border strip, every furrow, and alternate furrow) in main plot, and two silicon levels (control and foliar application @ 2 mM L^{-1}) in sub plot. Results showed that frequent irrigation at 40 mm CPE and every furrow irrigation significantly reduced canopy stress (SDD:-0.311) and delayed tasseling (59.44 days) and silking (62.61 days), while wider irrigation intervals (60 mm CPE) advanced reproductive stages due to stress (SDD: 0.200). Every furrow irrigation proved most effective in minimizing stress and promoting phenological stability. Silicon application marginally lowered SDD (-0.015) but had no significant effect on tasseling and silking timing. Regression analysis indicated strong negative correlations between SDD and phenology (R^2 = 0.46 for tasseling; R^2 = 0.49 for silking), suggesting that increased stress accelerates flowering. The findings emphasize the importance of frequent irrigation, efficient water application methods, and supportive silicon use in managing water stress in summer maize.

Keywords: Summer maize, stress degree days, tasselling, silking

Introduction
Maize (Zea mays L.) is a globally significant cereal crop known for its high productivity and versatile uses in food, feed, and industry (Malhotra, 2017) [7]. In India, maize is cultivated during the *kharif*, *rabi*, and *summer* seasons, with summer maize gaining attention due to its high yield potential under assured irrigation (Jaidka *et al.*, 2019) [6]. Among the various maize cultivation systems, summer maize stands out, occupying 7.37 lakh hectares and yielding an average of 4.6 tonnes per hectare (Department of Agriculture & Farmers Welfare, Government of India, 2024). However, water stress, especially during the reproductive phase, severely hampers yield by disrupting physiological processes, particularly tasseling and silking synchrony (Chen, 2024) [2]. Timely tasseling and silking are crucial for effective pollination and kernel development, and these phenological stages are highly sensitive to environmental and water stress (Vennam *et al.*, 2023) [11].
Water stress leads to an increase in canopy temperature due to reduced transpiration, which can be quantitatively assessed using Stress Degree Days (SDD). SDD, calculated as the difference between canopy temperature (Tc) and air temperature (Ta), is a reliable physiological indicator to measure crop stress response, particularly under water-deficient conditions (Sakshi *et al.*, 2025) [8]. Elevated SDD values are often correlated with disrupted phenological development, delayed or asynchronous tasseling and silking, reduced photosynthesis, and ultimately, yield loss. Therefore, studying SDD in relation to phenological stages such as days to 50% tasseling and silking provides insight into the crop's adaptive response and performance under stress.
To mitigate the impact of water stress, judicious water management and ameliorative treatments like silicon application have shown promise (Ahsan *et al.*, 2023) [1]. Silicon (Si), though not considered an essential nutrient, plays a pivotal role in enhancing plant tolerance

to abiotic stresses (Tripathi *et al.*, 2014; Singhal *et al.*, 2023) [10, 9]. It improves water use efficiency, reduces canopy temperature, maintains turgor pressure, and stabilizes membranes under stress. These effects of Si can potentially lower SDD and improve the synchrony of tasseling and silking even under suboptimal irrigation.

Moreover, the method and scheduling of irrigation significantly influence soil moisture dynamics and crop microclimate. In surface irrigation systems, border strip irrigation, every furrow irrigation, and alternate furrow irrigation offer different water distribution patterns that affect plant water availability. Among these, alternate furrow irrigation is gaining attention for its ability to save water while maintaining yield by promoting partial root-zone drying and hormonal regulation (Iqbal *et al.*, 2020) [5]. In addition, cumulative pan evaporation (CPE)-based irrigation scheduling, particularly at intervals like 40 mm, 50 mm, and 60 mm CPE, enables precise irrigation timing that matches crop evapotranspiration demands, thereby improving water productivity.

Despite these advancements, there is limited literature exploring the interactive effects of silicon nutrition, irrigation methods, and CPE-based irrigation scheduling on SDD and phenological behaviour (50% tasseling and silking) of summer maize. Understanding these interactions is critical for developing integrated management strategies aimed at improving maize productivity under water-limited environments.

Materials and Methods

A two-year field experiment was conducted on sandy loam soil during the summer months (February to June) of 2023 and 2024 at the Agriculture Farm, Palli Siksha Bhavana (Institute of Agriculture), Visva-Bharati, Sriniketan, located in the Red and Lateritic zone of West Bengal, India. The farm is situated at a latitude of about 23° 39’ N and longitude 87° 42’ E, with an elevation of 58.9 meters above sea level. In 2023, the total rainfall received during the growing season was 189.9 mm, while in 2024, it was 109.0 mm. The experiment followed a split-plot design with three replications. The main plots consisted of two factors: irrigation methods (M) [border strip irrigation (M_1), every furrow irrigation (M_2), and alternate furrow irrigation (M_3)], and irrigation regimes (I) [40 mm CPE (I_1), 50 mm CPE (I_2), and 60 mm CPE (I_3)]. The subplots included two silicon treatments (S): control (water spray) (S_0) and foliar silicon application (S_1). Silicon was applied as a foliar spray at 2 mM per liter of water (using monosodium silicate, Na_2SiO_3) at a rate of 500 liters of water per hectare, at 40 and 60 days after sowing (DAS). The maize crop was fertilized with 150:75:60 kg N, P_2O5, and K_2O per hectare. One-third of nitrogen (N), along with full phosphorus (P_2O_5) and potassium (K_2O), was applied as basal fertilizer, while the remaining one-third of nitrogen was applied at the knee-high stage and pre-tasseling stage. The maize hybrid P-3536 was sown at a rate of 20 kg per hectare, with rows spaced 60 cm apart and plants spaced 25 cm within the rows. The crop was harvested during 95-97 DAS.

Stress Degree Days (SDD) is calculated as the difference between canopy temperature (Tc) and air temperature (Ta), expressed by the equation:

$$SDD = Tc - Ta.$$

This index serves as an effective tool for assessing plant growth responses under stress conditions. The concept of SDD was first introduced by Idso *et al.* (1981) [4] as a foundation for developing a Crop Water Stress Index (CWSI), enabling researchers to quantify crop water stress based on thermal imaging techniques. Here, canopy temperature (°C) was measured using an infrared thermometer, which detects long-wave infrared radiation emitted by the plant canopy. The sensor converts this radiation into an electrical signal that is displayed as temperature. In this study, canopy temperature readings were taken at midday (1300-1400 h), and the air temperature (°C) data were collected from the local weather station, Sriniketan, Birbhum, WB, India.

Days to 50% Tasseling: Observations were regularly made to count the number of plants in the central row that had produced tassels following the appearance of the first tassel. The date on which 50% of the plants displayed tasseling was noted. The number of days required to reach 50% tasseling was then determined by calculating the interval between the date of sowing and the date when half of the plants had tassels.

Days to 50% Silking: Similarly, routine monitoring was carried out to record the number of plants showing silk emergence in the middle row of each plot, starting from the first observed silk. The date when 50% of the plants had produced silks was documented. The duration to reach 50% silking was computed by subtracting the sowing date from the date when 50% silking was observed.

The data were analyzed using the method outlined by Gomez and Gomez (1984) [3]. The significance of the variations was tested at a 0.05 probability level. The standard error of the mean (SEm±) and the critical difference (CD) values were provided in the tables to compare the mean values of the different treatments.

Results and Discussion

During the early vegetative phase (15-30 DAS), the lowest Stress Degree Days (SDD) was recorded under the 40 mm CPE irrigation regime (I_1:-0.364), indicating minimal water stress due to more frequent irrigation, followed by 50 mm CPE (I_2:-0.228), while the highest and positive SDD was observed under 60 mm CPE (I_3: 0.704), reflecting considerable stress. Among the irrigation methods, every furrow irrigation (M_2:-0.095) showed the lowest SDD, suggesting more effective moisture distribution, whereas alternate furrow (M_3: 0.137) exhibited the highest stress. Border strip irrigation (M_1) was intermediate (0.070). Silicon application had only a slight effect in this stage, with SDD under control (S_0) and silicon spray @ 2 mM L^{-1} (S_1) being 0.042 and 0.032 respectively, with no significant difference. In the next phase (31-60 DAS), the trend persisted with the lowest SDD under I_1 (-0.327), while I_2 (0.091) and I_3 (0.152) showed increasing stress as irrigation intervals widened. Every furrow irrigation again proved superior (M_2:-0.085), followed by border strip (M_1:-0.040) and alternate furrow (M_3: 0.041). Silicon-treated plants (S_1:-0.029) recorded slightly lower SDD than control (S_0:-0.027), though the difference remained statistically non-significant. However, in the reproductive phase (61-90 DAS), the stress response became more pronounced. The lowest SDD continued to be under 40 mm CPE (I_1:-0.311), while moderate to high stress was observed under I_2 (0.132) and I_3 (0.200). Every furrow irrigation again minimized stress (M_2:-0.039), whereas alternate furrow (M_3: 0.034) and border strip (M_1: 0.026) showed higher values. Importantly, silicon application showed a statistically significant effect at this stage, with S_1 recording a lower SDD (-0.015) compared to control (S_0: 0.029), suggesting its effectiveness in mitigating water stress during critical reproductive development (Table 1).

Table 1: Effect of silicon and methods of irrigation on stress degree days of summer maize under different irrigation regimes (pooled data of 2023 & 2024)

Treatments	Stress degree days		
	15-30 DAS	**31-60 DAS**	**61-90 DAS**
Irrigation regimes (I)			
I_1: 40 mm CPE	-0.364	-0.327	-0.311
I_2: 50 mm CPE	-0.228	0.091	0.132
I_3: 60 mm CPE	0.704	0.152	0.200
S.Em (±)	0.011	0.003	0.008
CD (5%)	0.033	0.009	0.023
Methods of irrigation (M)			
M_1: Border strip	0.070	-0.040	0.026
M_2: Every furrow	-0.095	-0.085	-0.039
M_3: Alternate furrow	0.137	0.041	0.034
S.Em (±)	0.011	0.003	0.008
CD (5%)	0.033	0.009	0.023
Silicon application (S)			
S_0: Control (water spray)	0.042	-0.027	0.029
S_1: Si spray @ 2 mM L^{-1}	0.032	-0.029	-0.015
S.Em (±)	0.009	0.002	0.008
CD (5%)	NS	NS	0.022
Interactions			
I×M	NS	S	S
I×S	NS	NS	NS
M×S	NS	NS	NS
I×M×S	NS	NS	NS

During the period of 31-60 DAS, the interaction between irrigation regimes and irrigation methods (I × M) showed a significant effect on Stress Degree Days (SDD), with an S.Em (±) of 0.01 and a critical difference (CD) at 5% of 0.02. Among the combinations, the lowest SDD was recorded under the combination of 40 mm CPE with every furrow irrigation (I_1M_2:-0.46), indicating the most effective stress reduction due to frequent irrigation and uniform water distribution. This was followed by 40 mm CPE with border strip (I_1M_1:-0.35) and alternate furrow irrigation (I_1M_3:-0.17), both of which exhibited higher canopy temperatures and thus relatively more stress. In contrast, under the 50 mm CPE regime, SDD values were comparatively moderate with every furrow irrigation (I_2M_2: 0.07), border strip (I_2M_1: 0.09), and alternate furrow (I_2M_3: 0.11). The 60 mm CPE treatment showed the highest SDD values across all irrigation methods, indicating greater water stress: every furrow (I_3M_2: 0.13), border strip (I_3M_1: 0.14), and alternate furrow (I_3M_3: 0.18) (Table 2). This interaction clearly demonstrates that every furrow irrigation under 40 mm CPE was the most effective in minimizing stress during this critical developmental phase, while wider irrigation intervals and less efficient irrigation methods significantly increased canopy temperature and crop stress.

In the reproductive stage of maize (61-90 DAS), the interaction between irrigation regimes and irrigation methods (I × M) exhibited a significant influence on Stress Degree Days (SDD), as indicated by the standard error (±0.02) and a critical difference (CD) at 5% level of 0.06. Among the treatment combinations, the lowest SDD value was observed under 40 mm CPE combined with every furrow irrigation (I_1M_2:-0.38), highlighting its effectiveness in minimizing plant stress through consistent moisture availability and better root-zone hydration. This was followed by 40 mm CPE with alternate furrow (I_1M_3:-0.34) and border strip (I_1M_1:-0.21), both of which also helped reduce stress compared to wider irrigation intervals. On the other hand, under 50 mm CPE, all methods recorded positive SDD values, with every furrow (I_2M_2: 0.11), border strip (I_2M_1: 0.13), and alternate furrow (I_2M_3: 0.15) reflecting moderate stress levels. The highest stress intensity occurred under the 60 mm CPE with alternate furrow irrigation (I_3M_3: 0.29), suggesting a strong build-up of canopy heat and reduced transpiration efficiency under prolonged irrigation intervals. Other combinations under 60 mm CPE also showed higher SDD values, such as every furrow (I_3M_2: 0.16) and border strip (I_3M_1: 0.15) (Table 2). Overall, the results confirm that frequent irrigation (40 mm CPE) combined with every furrow irrigation method significantly reduced stress during this crucial phase, while wider irrigation intervals—particularly with alternate furrow irrigation—intensified canopy temperature and stress accumulation.

Table 2: Interaction effect of methods of irrigation and irrigation regimes on stress degree days (31-60 DAS & 61-90 DAS) of summer maize (pooled data of 2023 & 2024)

Stress degree days							
31-60 DAS				**61-90 DAS**			
	M_1	**M_2**	**M_3**		**M_1**	**M_2**	**M_3**
I_1	-0.35	-0.46	-0.17	I_1	-0.21	-0.38	-0.34
I_2	0.09	0.07	0.11	I_2	0.13	0.11	0.15
I_3	0.14	0.13	0.18	I_3	0.15	0.16	0.29
I×M	S.Em (±)	CD (5%)		I×M	S.Em (±)	CD (5%)	
	0.01	0.02			0.02	0.06	

I_1: 40 mm CPE, I_2: 50 mm CPE, I_3: 60 mm CPE & M_1: Border strip, M_2: Every furrow, M_3: Alternate furrow

The phenological development of summer maize, particularly days to 50% tasseling and silking, was significantly influenced by irrigation regimes and methods of irrigation, while silicon application and interaction effects showed no significant impact (Table 3).

Among the irrigation regimes, the longest duration to 50% tasseling (59.44 days) and silking (62.61 days) was observed under the most frequent irrigation treatment, I_1 (40 mm CPE). This was followed by I_2 (50 mm CPE) with 58.78 days to tasseling and 61.75 days to silking. The shortest phenological durations were recorded under I_3 (60 mm CPE) with 57.83 days to tasseling and 60.81 days to silking. These differences were statistically significant (CD at 5%: 0.82 for tasseling and 0.88 for silking), suggesting that wider irrigation intervals led to earlier flowering, likely as a stress escape mechanism under moisture-limiting conditions (Table 3).

Regarding irrigation methods, every furrow irrigation method (M_2) recorded the maximum days to tasseling (59.67) and silking (62.78), indicating better water availability delayed the onset of reproductive stages, allowing more vegetative growth. In contrast, the alternate furrow method (M_3) led to the earliest tasseling (57.86 days) and silking (60.78 days), possibly due to moderate water stress accelerating reproductive development. Border strip irrigation (M_1) was intermediate in both cases (58.53 and 61.61 days). The differences were statistically significant, with CD values of 0.82 and 0.88 for tasseling and silking, respectively (Table 3).

In the case of silicon application, the differences were minimal and non-significant (NS). Days to 50% tasseling under control (S_0) and silicon spray (S_1) were 58.57 and 58.80 days, respectively. Similarly, days to silking were 61.70 (S_0) and 61.74 (S_1), showing that silicon had no significant influence on the timing of flowering in this case, although slight improvements were noted numerically (Table 3).

All interaction effects (I × M, I × S, M × S, I × M × S) were non-significant, indicating that the main effects of irrigation regime and method independently influenced phenological development, but their combinations did not produce synergistic or antagonistic effects on tasseling and silking (Table 3).

Table 3: Effect of silicon and methods of irrigation on days to 50% tasseling and silking of summer maize under different irrigation regimes (pooled data of 2023 & 2024)

Treatments	Days to 50% tasseling	Days to 50% silking
Irrigation regimes (I)		
I_1: 40 mm CPE	59.44	62.61
I_2: 50 mm CPE	58.78	61.75
I_3: 60 mm CPE	57.83	60.81
S.Em (±)	0.29	0.31
CD (5%)	0.82	0.88
Methods of irrigation (M)		
M_1: Border strip	58.53	61.61
M_2: Every furrow	59.67	62.78
M_3: Alternate furrow	57.86	60.78
S.Em (±)	0.29	0.31
CD (5%)	0.82	0.88
Silicon application (S)		
S_0: Control (water spray)	58.57	61.70
S_1: Si spray @ 2 mM L^{-1}	58.80	61.74
S.Em (±)	0.23	0.24
CD (5%)	NS	NS
Interactions		
I×M	NS	NS
I×S	NS	NS
M×S	NS	NS
I×M×S	NS	NS

Fig 1: Combined regression plot of SDD vs 50% tasselling and silking

The combined regression plot illustrates a clear negative relationship between Stress Degree Days (SDD) during 61-90 DAS and the timing of 50% tasseling and silking in summer maize (Graph plotted using Python-based regression analysis) (Fig. 1). As SDD increases—indicating greater canopy temperature and water stress—both tasseling and silking occur earlier, reflecting a stress-induced acceleration of reproductive development. The regression equations, y= −2.96x + 58.71 for tasseling and y= −3.36x + 61.75 for silking, along with R^2 values of 0.46 and 0.49

respectively, confirm that nearly half of the variability in these phenological traits can be explained by changes in SDD. Treatments with negative SDD values, such as those under frequent irrigation or every furrow method, are associated with delayed flowering and reduced stress, while high SDD values from wider irrigation intervals lead to earlier tasseling and silking, characteristic of a drought escape response. This plot effectively captures the physiological link between canopy stress and crop phenology under varying water management practices (Fig. 1).

Summary

The study comprehensively evaluated the influence of irrigation scheduling (based on CPE levels), irrigation methods, and foliar silicon application on stress degree days (SDD) and phenological development (50% tasseling and silking) of summer maize.

Across all growth stages, SDD values increased with wider irrigation intervals, reflecting higher canopy temperatures and more intense water stress. The lowest SDD values were consistently recorded under 40 mm CPE (I_1), particularly during 15-30 DAS (-0.364), 31-60 DAS (-0.327), and 61-90 DAS (-0.311), signifying lower crop stress due to frequent irrigation. Conversely, 60 mm CPE (I_3) exhibited the highest SDD values (0.704, 0.152, and 0.200 across the same stages), indicating substantial stress build-up under longer irrigation gaps.

Among irrigation methods, every furrow irrigation (M_2) effectively reduced SDD values throughout all stages (e.g.,-0.095 at 15-30 DAS and-0.085 at 31-60 DAS), suggesting superior water distribution and stress mitigation compared to border strip (M_1) and alternate furrow (M_3) methods. Silicon application (@ 2 mM L^{-1}) also showed a consistent reduction in SDD, especially during 61-90 DAS (from 0.029 in control to-0.015 in treated), indicating its significant role in reducing stress during the reproductive stage.

Phenologically, frequent irrigation (I_1: 40 mm CPE) delayed tasseling (59.44 days) and silking (62.61 days), while 60 mm CPE (I_3) advanced both (57.83 and 60.81 days, respectively), showing a typical drought-escape response under limited moisture. Similarly, every furrow irrigation (M_2) led to longer duration to 50% tasseling (59.67 days) and silking (62.78 days), reflecting improved water availability. On the other hand, alternate furrow irrigation (M_3) resulted in earlier tasseling (57.86 days) and silking (60.78 days), possibly due to stress-induced acceleration of reproductive phases. Silicon application had a negligible but consistent non-significant increase in tasseling and silking days, indicating minor influence on phenology compared to irrigation factors.

Conclusion

The integration of stress degree days and phenological responses clearly demonstrates that irrigation frequency and method are the most crucial determinants of stress intensity and reproductive timing in summer maize. The combination of 40 mm CPE with every furrow irrigation consistently minimized SDD and extended the duration to tasseling and silking, thereby improving the chances of tassel-silk synchrony and successful pollination. Wider irrigation intervals (60 mm CPE), especially under alternate furrow irrigation, significantly increased canopy stress and induced earlier flowering, potentially compromising reproductive success. While silicon application did not significantly influence tasseling or silking timelines, it notably reduced canopy stress during the reproductive phase, reinforcing its role as a supplementary stress alleviation strategy under sub-optimal water conditions.

In conclusion, to enhance maize performance under water-limited environments, an integrated approach involving frequent irrigation (40 mm CPE), uniform water distribution (every furrow method), and supportive use of foliar silicon offers an effective strategy to minimize stress, synchronize phenological events, and optimize grain yield potential.

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