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Physiology and Grain Yield of Summer Maize as Influenced by Sowing Methods, Straw Mulching, and Irrigation Scheduling in Northwestern India

Mohitesh Singh

mohitbhullar46@gmail.com

Punjab Agricultural University

Satpal Singh

Punjab Agricultural University

Ajmer Singh Brar

Punjab Agricultural University

K. B. Singh

Punjab Agricultural University

R. S. Grewal

Director extension education GADVASU

Norah Johal

Punjab Agricultural University

Shashi Pathania

Punjab Agricultural University

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Abstract

Water scarcity is a major constraint for summer maize production in semi-arid regions, necessitating efficient irrigation and soil management strategies. A two-year field study was conducted to evaluate the synergistic effects of planting methods (pneumatic bed planter, S1; PAU bed planter, S2), mulching (paddy straw mulch, M1; no mulch, M2), and irrigation schedules (I1: 20% DASM (depletion from available soil moisture), I2: 30% DASM, I3: 40% DASM, I4: PAU recommended irrigation schedule) on physiological parameters and grain yield of summer maize. The experiment was laid out in a split-plot design with three replications. Results revealed that the combination of paddy straw mulch with irrigation at 20% DASM (I1) significantly enhanced photosynthetic rate, stomatal conductance, transpiration rate, chlorophyll content, and photosystem II efficiency (Fv/Fm) compared to no-mulch and deficit irrigation treatments. The highest grain yields were recorded under combination of pneumatic bed planter + paddy straw mulch and irrigation at 20% DASM with treatment representing as S1M1I1 (80.63 q ha^{-1}) and PAU bed planter + paddy straw mulch + irrigation at 20% DASM S2M1I1 (80.30 q ha^{-1}), which were statistically at par and significantly higher than the conventional flood irrigation control. Straw mulch with 20% DASM (I1) improved soil moisture retention, moderated soil temperature, and sustained physiological activity, leading to higher yield. In contrast, irrigation at 40% DASM and PAU recommended irrigation without mulch severely reduced photosynthetic efficiency and grain yield. The two bed planters performed similarly, indicating their comparable suitability for conservation agriculture. The study concludes that integrating paddy straw mulch with irrigation scheduling at 20% DASM offers a viable water-smart strategy to enhance physiological performance and productivity of summer maize in semi-arid environments, achieving higher yield with efficient water use.

Introduction

Maize (*Zea mays* L.) is one of the most important cereal crops in the world, used for food, animal feed, and industrial products such as ethanol and starch (Chaudhary et al., 2024; Singh et al., 2023). It is grown in more than 160 countries under different climatic conditions and contributes significantly to global grain production. Due to its high yield potential, it is often called the “queen of cereals.” In India, maize is cultivated on about 10.8 million hectares with a production of nearly 38 million tonnes (USDA, 2024). Its adaptability allows it to be grown in kharif, rabi, spring and summer seasons.

Summer maize is gaining importance in northwestern India, but its production is limited by high temperature and low water availability. During April to June, the Indo-Gangetic plains experience high evapotranspiration (above 10 mm day^{-1}), very low rainfall, and temperatures often exceeding 40°C during grain filling (Kaur and Arora, 2018; Singh and Vashist, 2016). These conditions negatively affect plant growth, physiological processes, and yield. At the same time, the increasing demand for maize grain and silage, especially for the dairy sector, has led to expansion of summer maize cultivation in Punjab, Haryana, and western Uttar Pradesh (Dhanda et al., 2022; Singh et al., 2025). However, this expansion is placing additional pressure on already declining groundwater resources.

Sowing method is another important factor influencing crop performance. It affects plant establishment, root development, and water distribution in the soil (Kaur and Vashist, 2015; Singh and Vashist, 2016). Raised bed and ridge planting systems have shown better results than flat sowing due to improved soil aeration, drainage, and water use efficiency (Bakker et al., 2005; Li et al., 2023). The pneumatic broad-bed planting system further improves plant spacing and reduces water loss by limiting the wetted soil surface area (Singh et al., 2025; Munmun et al., 2024).

Mulching, especially with paddy straw, is an effective practice for conserving soil moisture and improving soil conditions. It reduces evaporation losses by 25–35%, moderates soil temperature, suppresses weeds, and improves soil structure and microbial activity (Jalota and Arora, 2002; Zhang et al., 2019). In summer maize, mulching helps reduce heat stress and supports better crop growth and grain filling (Li et al., 2022).

Irrigation scheduling based on soil moisture is an effective approach to improve water use efficiency. The concept of depletion of available soil moisture (DASM) allows irrigation to be applied according to the crop's actual water requirement (Pramanik et al., 2022; Asimwe et al., 2022). Available soil moisture is the water held between field capacity and permanent wilting point. Maintaining soil moisture within optimal limits helps avoid stress conditions that reduce photosynthesis, accelerate leaf senescence, and limit grain development (Farooq et al., 2009; Aslam et al., 2013).

Agriculture consumes about 78–80% of India's freshwater, and in Punjab, this share is nearly 95%, mainly for irrigation (CGWB, 2024). Continuous groundwater extraction has resulted in a serious water deficit in the region. Conventional flood irrigation, which is widely used, has low efficiency (30–40%) and leads to significant water losses through evaporation, runoff, and deep percolation (Liang et al., 2016; Sandhu et al., 2019). It also results in nutrient leaching and higher energy use for pumping water (Brar et al., 2022). Therefore, improving irrigation efficiency is essential for sustainable maize production.

Maize is highly sensitive to water stress, particularly during flowering and grain filling stages. Water deficit during these stages reduces photosynthesis, limits nutrient uptake, and decreases grain yield (Cakir, 2004; Payero et al., 2008). Physiological parameters such as photosynthetic rate, transpiration rate, chlorophyll content, stomatal conductance and photosystem II efficiency (Fv/Fm) are closely related to crop productivity and can indicate the plant's response to water availability (Weisany et al., 2023; Sandhu and Irmak, 2019). Proper irrigation management helps maintain these parameters at optimal levels.

The combined use of improved sowing methods, mulching, and efficient irrigation scheduling can provide better results than using these practices separately. Bed planting improves water distribution, mulching conserves moisture, and proper irrigation scheduling ensures timely water supply. Together, these practices can increase water productivity and maintain crop yield.

However, limited research is available on the combined effects of these practices on summer maize under conventional flood irrigation in northwestern India with respect to physiological studies on

summer maize.

The present study was conducted with the following objectives:

1. To study the response to sowing methods, mulching and irrigation scheduling on physiological aspects of summer maize.
2. To study the effect of sowing methods, mulching and irrigation scheduling on grain yield of summer maize.

Material and methods

Experimental Site and Climate

The study was conducted over two consecutive summer seasons in 2023 and 2024 at the research farm of Punjab Agricultural University, Ludhiana, India (30°54'N, 75°48'E, 247 m above mean sea level). The soil of the experimental site is a well-drained sandy loam (Typic Ustochrept) with a pH of 7.5, organic carbon content of 0.31%, and available N, P, and K of 167.8, 15.2, and 156.3 kg ha^{-1}, respectively. The climate is semi-arid, characterized by hot, dry springs and summers. Detailed meteorological data for both growing seasons, including maximum and minimum temperature, sunshine hours, wind speed, relative humidity, rainfall, and pan evaporation, are provided in Supplementary Data Table S1 and S2. The treatments consisted of main plot having four treatment combinations having two methods of sowing *viz.*, Pneumatic bed planter and PAU bed planter and two mulches comprising of paddy straw mulch and no-mulch. Sub-plots in the study consisted of four irrigation schedules following soil moisture depletion approach *viz.*, 20%, 30%, 40% depletion from available soil moisture (DASM) and PAU recommended irrigation schedule. This resulted in 10 treatment combinations (2 methods of sowing × 2 mulching levels × 4 irrigation schedules). The gross area of plot for Pneumatic bed planter was 5.5 x 3.6 m and of PAU bed planter was 5.50 x 3.37 m. The net plot area for grain purpose for Pneumatic bed planter was 3.0 x 2.4 m and of PAU bed planter was 3.00 x 2.02 m. The buffer area of 1.0 m was maintained to avoid interflow of water between plots.

Crop Management

Maize (*Zea mays* L.) hybrid 'PMH 10' was sown on 5th May 2023 and 27th April 2024. The sowing was done by two methods *viz*., broad bed and furrow using the Pneumatic bed planter with spacing of 60 x 20 cm, and bed planting made by PAU bed planter keeping the spacing of 67.5 x 18 cm. The broad beds were made in east-west direction by using the Pneumatic bed planter and simultaneous sowing in a single operation with seed rate of 25 kg ha^{-1}. The broad beds were prepared having bed top of 90 cm and furrow of 30 cm. Two rows of maize were sown on bed at row to row spacing of 60 cm. On the bed top of 90 cm, two rows of crop are adjusted in such a way that 15 cm space remains vacated from both the edges of bed top. In overall look of field, the row to row spacing was 60 cm. The bed preparation, fertilizer placement and sowing were done in a single operation. In PAU bed planter, 37.5 cm bed top was

made with furrows of 30 cm and one row was sown in centre of bed top, in east-west direction. In both of experiments, sowing was done by keeping a seed rate of 25 kg ha^{-1}. 100% of recommended dose of fertilizers, RDF, (N: P_2O_5: K_2O- 130:63:0 kg ha^{-1}) was applied. Nitrogen (130 kg ha^{-1}) was applied in three equal splits- at sowing, knee- high, and pre-tasseling stages (43.33 kg N each). The phosphorus was applied as basal dose with application of 137 kg DAP ha^{-1}, which gave 24.66 kg of N ha^{-1}. The remaining N (18.67 kg) was compensated by urea at sowing. The other splits of N at knee high and pre-tasseling were applied by using 94.20 kg urea at each growth stage. the irrigation was scheduled on the basis of depletion from available soil moisture (DASM) at 20%, 30% and 40% DASM and at PAU recommended irrigation schedule. The effective root zone length was considered while noting the moisture levels of soil profile which was set at 0–10 cm at 25 DAS, 0–20 cm between 25 and 50 DAS and 0–30 cm after 50 DAS. The frequency domain refractometer (FDR) based soil moisture sensors were permanently installed in field to record soil moisture content on volumetric basis. Irrigations were given treatment when 20, 30 and 40% depletion from available soil moisture (field capacity minus permanent wilting point) in the root zone. In PAU recommended irrigation schedule, irrigation was applied as per the package of practices of PAU. In Pneumatic bed planter, the irrigation depth was fixed at 4 cm and in PAU bed planter, the irrigation depth was fixed at 5.5 cm.

Physiological attributes

At the tasseling and silking stages, the following parameters were recorded between 10:30 and 11:30 AM on clear, sunny days from the youngest fully expanded leaf of five randomly selected and tagged plants per plot. Gas Exchange parameters *viz.*, photosynthetic rate (Pn, µmol CO_2 m^{-2} s^{-1}), transpiration rate (E, mmol H_2O m^{-2} s^{-1}), and stomatal conductance (gs, mol H_2O m^{-2} s^{-1}) were measured using a portable photosynthesis system (LCi, ADC BioScientific Ltd., UK). Measurements were taken under ambient CO_2 conditions (nearly 380 ppm). Chlorophyll Content was measured as SPAD values using a chlorophyll content meter (CCM-300, Opti-Sciences Inc., Hudson, USA). Chlorophyll Fluorescence which is the maximum quantum efficiency of Photosystem II (Fv/Fm) was determined on dark-adapted leaves (30 min) using a portable fluorometer (OS-30p+, Opti-Sciences Inc., Hudson, USA).

Grain yield

The crop was harvested at physiological maturity, which occurred on 18 August 2023 and 9 August 2024, corresponding to approximately 105 after sowing (DAS) in both the years respectively. The entire plot of pneumatic bed planter 3.0 x 2.4 m and of PAU bed planter 3.00 x 2.02m was manually harvested. Plants were cut at ground level, and ears were separated from stover. Grain yield (q/ha) was determined after shelling and adjusting the moisture content to 14% using a digital moisture meter.

Weather conditions

During 2023 (from sowing till harvesting; 105 days), the mean weekly minimum and maximum air temperatures varied from 17.4 to 34.6C and 25.5 to 43.2C, respectively, with the respective means of 26.1 and 35.3C. The mean weekly relative humidity ranged from 28.0% to 92.0% with average of 60.3%. The total amount of rainfall and pan evaporation was 360.2 and 683.3 mm, respectively. During 2024 (from sowing till harvesting; 105 days), the mean weekly minimum and maximum temperatures varied from 14.4 to 32.4 and 26.4 to 45.6C, respectively, with the respective means of 26.6 and 38.0C. The mean weekly relative humidity ranged from 17.0 to 83.5% with average of 50.8%. The total amount of rainfall and pan evaporation was 189.0 and 828.3 mm, respectively.

Statistical analysis

The experiment was laid out in a split-plot design with three replications. Main plots comprised four treatment combinations of two sowing methods (pneumatic bed planter and PAU bed planter) and two mulching levels (paddy straw mulch and no mulch). Sub-plots consisted of four irrigation schedules (20%, 30%, and 40% depletion of available soil moisture, and the PAU-recommended schedule), resulting in a total of 16 treatment combinations. Data were subjected to analysis of variance (ANOVA) using the general linear model appropriate for a split-plot design. The significance of treatment effects was tested at $p \leq 0.05$, and means were compared using the least significant difference (LSD) test when the *F*-test was significant. All statistical analyses were performed using R software (version 4.3, R Core Team, 2023) with the 'agricolae' package for mean separation. Principal component analysis (PCA) was conducted on the standardized means of physiological traits to visualize treatment relationships and trait associations, using the 'factoextra' and 'FactoMineR' packages.

Results

The results revealed that the combination of planting technique, mulch, and irrigation worked together to drive a cascade of physiological benefits that ultimately determined grain yield. At tasseling, the highest photosynthetic rate of 43.72 μ mol CO_2 m^{-2} s^{-1} was recorded in the treatment with the pneumatic planter, mulch, and irrigation at 20% DASM (S1M1I1). This was statistically at par with the PAU bed planter under the same mulch and irrigation (S2M1I1, 43.02). The same pattern was observed at silking, where S1M1I1 again recorded the highest (47.43), followed closely by S2M1I1 (46.14). At the other end, the lowest rates at both stages were consistently seen where there was no mulch and water was limited to 40% DASM (S1M2I3 and S2M2I3), highlighting how water stress and the absence of mulch severely restrict photosynthesis.

Transpiration followed a similar pattern with well-watered, mulched conditions, transpiration rates were high with treatment S1M1I1 reached 5.70 at tasseling, and at silking the highest values were in S2M1I1 (5.72) and S1M1I2 (5.78). In contrast, the stressed, no-mulch treatment S2M2I3 had the lowest transpiration at both stages (4.25 and 4.47). Stomatal conductance, which directly reflects how open the stomata are, followed the exact same trend. S1M1I1 had the highest conductance at tasseling (0.38)

and silking (0.42), while the I3 treatments without mulch (S1M2I3 and S2M2I3) dropped to as low as 0.23 and 0.27, respectively.

Chlorophyll content, measured as SPAD values, was also highest where mulch and frequent irrigation were combined. S1M1I1 maintained the highest SPAD at tasseling (182.45) and silking (194.15), and S2M1I1 performed nearly as well (182.14 at tasseling, 192.40 at silking). Under the stressed, no-mulch treatments, chlorophyll content was lowest, indicating accelerated chlorophyll degradation due to water deficit. The efficiency of the photosynthetic system, captured by the Fv/Fm ratio, followed the same pattern. The highest value (0.91) was recorded in S1M1I1 at silking, but under the I3 regime without mulch, Fv/Fm dropped well below the healthy threshold of 0.75 down to 0.64 in S1M2I3 and 0.67 in S2M2I3 at tasseling which shows a clear sign of photoinhibition and stress.

All these physiological advantages translated directly into grain yield. The highest yield came from S1M1I1 (80.63 q ha^{-1}), statistically similar to S2M1I1 (80.30 q ha^{-1}). This confirms that bed planters combined with mulch and irrigation at 20% DASM delivered the best results. Yields fell steadily as irrigation became less frequent (I2, I3, I4), and the lowest yields were recorded in the no-mulch, severely water-stressed treatments—S1M2I3 (60.08 q ha^{-1}) and S2M2I3 (60.00 q ha^{-1}). This shows that physiological functions under optimal mulch and irrigation leads to superior productivity.

To better understand how the treatments and traits related to each other, we carried out a principal component analysis (PCA). The first two components captured 97.2% of the total variation PC1 accounted for 95.1% and PC2 for 2.1%. The analysis showed that all measured traits SPAD at silking, SPAD at tasseling, and transpiration rate at silking clustered tightly together, which shows that they responded in a highly coordinated way across treatments. The two bed planter types (S1 and S2) also plotted close to each other, suggesting that the choice of planter had little influence on the overall physiological response compared to the larger effects of mulch and irrigation. In essence, the PCA confirms what the main results showed: irrigation and mulch were the dominant drivers, and the two planters performed similarly.

Discussion

The results show a clear chain of cause and effect when mulch is combined with bed planting and frequent irrigation, the crop benefits through a series of linked physiological improvements that ultimately lead to higher grain yield. The highest rates of photosynthesis, stomatal conductance, and transpiration were always found in treatments where mulch was used and irrigation was applied at 20% DASM (I1). This was true for both types of bed planters. The reason is that paddy straw mulch acts as a protective cover on the soil surface. It reduces water loss by evaporation and helps the soil hold more moisture (Zhang et al., 2025). With a steady supply of water in the root zone, the plants keep their stomata open, allowing CO_2 to enter freely and photosynthesis to proceed efficiently (Li et al., 2023). When water becomes scarce as in treatments with irrigation at 40% DASM (I3) or less the plants close their stomata to save water. This is a normal survival response, but it also cuts down photosynthesis

(Sandhu & Irmak, 2019). The sharp drop in these physiological traits under the no-mulch, I3 treatments reflects exactly that. The fact that the two bed planters (S1 and S2) performed similarly confirms that both provide comparable benefits for soil structure and water distribution, which is consistent with earlier studies on permanent beds with residue retention (Sandhu et al., 2017; Singh et al., 2025).

The same pattern was seen for chlorophyll content and the efficiency of photosystem II (Fv/Fm). Both are good indicators of how much stress the plant is under. When mulch and regular irrigation were combined, chlorophyll levels stayed high. This is likely because the mulch helped keep soil temperature and moisture more stable, which delayed leaf aging and reduced stress (Li et al., 2023; Zhang et al., 2025). Straw mulch also promotes better root growth and nutrient uptake, which helps maintain chlorophyll (Singh et al., 2025). On the other hand, in treatments with no mulch and irrigation at 40% DASM, chlorophyll broke down faster which shows water stress. The Fv/Fm ratio tells us how well the photosynthetic system is working. In all well-watered, mulched treatments, Fv/Fm stayed above 0.80, meaning the plants were healthy. But under I3 with no mulch, it dropped below 0.70, showing that the plants were suffering from photoinhibition and their photosynthetic machinery was damaged (Sandhu & Irmak, 2019). Similar declines in Fv/Fm under water stress have been widely reported and are known to lead to lower grain yields (Li et al., 2023). The fact that S1M1I1 and S2M1I1 kept high Fv/Fm values matches findings from other studies showing that ridge-furrow mulching systems improve photosynthesis by helping the plant use resources more efficiently (Li et al., 2023).

Grain yield followed the same pattern as the physiological traits. The highest yields were recorded in S1M1I1 (80.63 q ha^{-1}) and S2M1I1 (80.30 q ha^{-1}), and these two were statistically similar. This shows that combining mulch with irrigation at 20% DASM creates soil and water conditions that keep photosynthesis active and help the plant move more nutrients to the grain. Earlier research by Sandhu et al. (2017) supports this: they found that bed planting combined with residue retention and drip irrigation increased wheat yield by 13.7% and maize yield by 23.1% compared to furrow irrigation without residue. They attributed this to frequent, targeted applications of water and nutrients that improve soil moisture and nutrient availability (Sandhu et al., 2017; Singh et al., 2025). Yields went down steadily as irrigation became less frequent (I2, I3, I4). This is because ongoing water shortage causes stomata to close, speeds up leaf aging, and reduces the amount of biomass the plant can build (Sandhu & Irmak, 2019). Interestingly, the PAU-recommended schedule (I4) did not give higher yields than the more frequent I1 schedule. This suggests that irrigating based on soil moisture (20% DASM) is a better approach for achieving maximum yields in these conditions. This idea is supported by Singh et al. (2025), who found that irrigating at 30% DASM together with straw mulch and subsurface drip irrigation greatly improved both grain yield and water productivity. The lowest yields were seen in the no-mulch, deficit-irrigation treatments (S1M2I3 and S2M2I3). This highlights how damaging water stress can be when the soil is not protected; the combination of high soil temperature and low moisture severely hurt plant health and limited yield (Li et al., 2023; Singh et al., 2025).

The principal component analysis (PCA) adds a clear visual summary of these findings. It confirms that irrigation frequency and mulch were the main factors driving physiological performance, while the type

of bed planter made little difference. All the physiological traits chlorophyll content (SPAD) and transpiration rate clustered closely together, showing that they responded as a single, coordinated system to the treatments. The first principal component (PC1) explained 95.1% of the variation, meaning the biggest difference among treatments was between those with favorable conditions (mulch plus adequate irrigation) and those under stress (no mulch with deficit irrigation). This matches the earlier observations: in well-watered, mulched treatments, plants had higher stomatal conductance, transpiration, and chlorophyll retention; in stressed, no-mulch treatments, all these traits declined together. The two bed planters (S1 and S2) plotted near each other on the PCA, confirming that both created similar soil environments, likely because they both improve soil structure and water distribution in comparable ways. Overall, the PCA provides a concise visual confirmation that the physiological traits behaved as an integrated whole, with irrigation and mulch being the overriding influences—regardless of which bed planter was used.

Declarations

Author Contribution

M.S.: Conceptualization, methodology, formal analysis, data curation, writing original draft, review & editing; S.S.: Conceptualization, methodology, investigation, supervision, review & editing; A.S.B.: Validation, supervision, investigation, formal analysis, data curation, resources, review & editing; K.B.S.: Validation, supervision, investigation, formal analysis, data curation; R.S.G.: Validation, supervision, methodology, formal analysis, data curation; N.J.: Data analysis, data curation, supervision, review & editing; S.P.: Data analysis, data curation, supervision, review & editing.

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Tables

Table 1: Grain yield (mean ± SE) of wheat as influenced by different treatment combinations of sowing date (S), mulching (M), and irrigation level (I).

Treatments	Grain yield
S1M1I1	80.63±1.83^{a}
S1M1I2	77.14±2.70^{ab}
S1M1I3	67.90±3.32^{cdef}
S1M1I4	70.04±3.30^{bcde}
S1M2I1	74.17±2.85^{abc}
S1M2I2	72.21±1.73^{bcd}
S1M2I3	60.08±2.80^{g}
S1M2I4	64.41±2.32^{efg}
S2M1I1	80.30±2.25^{a}
S2M1I2	77.42±1.45^{ab}
S2M1I3	65.36±3.34^{defg}
S2M1I4	68.14±4.90^{cdef}
S2M2I1	73.66±2.68^{abc}
S2M2I2	71.14±1.49^{bcde}
S2M2I3	60.90±3.40^{fg}
S2M2I4	63.65±3.49^{efg}

Figures

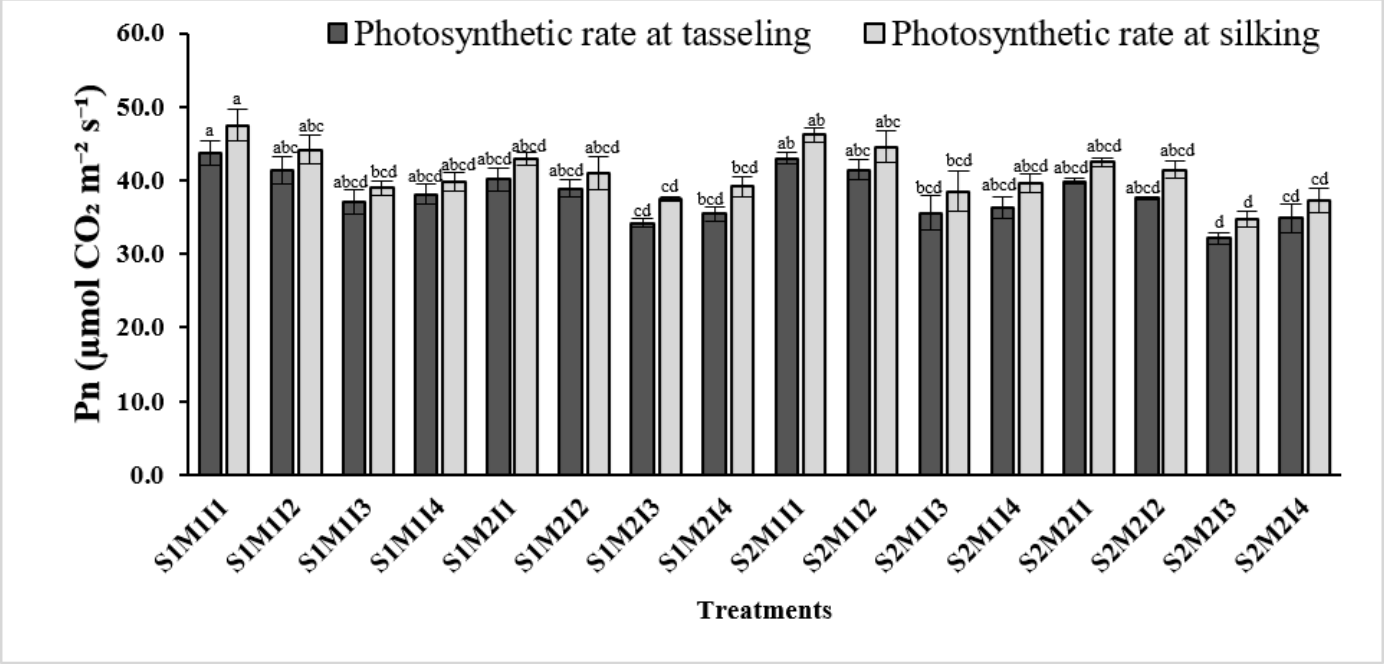


Figure 1

Fig. 1 Photosynthetic rate (µ mol CO_2 m^{-2} s^{-1}) at tasseling and silking stages as influenced by different treatment combinations of sowing method (S), mulching (M), and irrigation level (I).

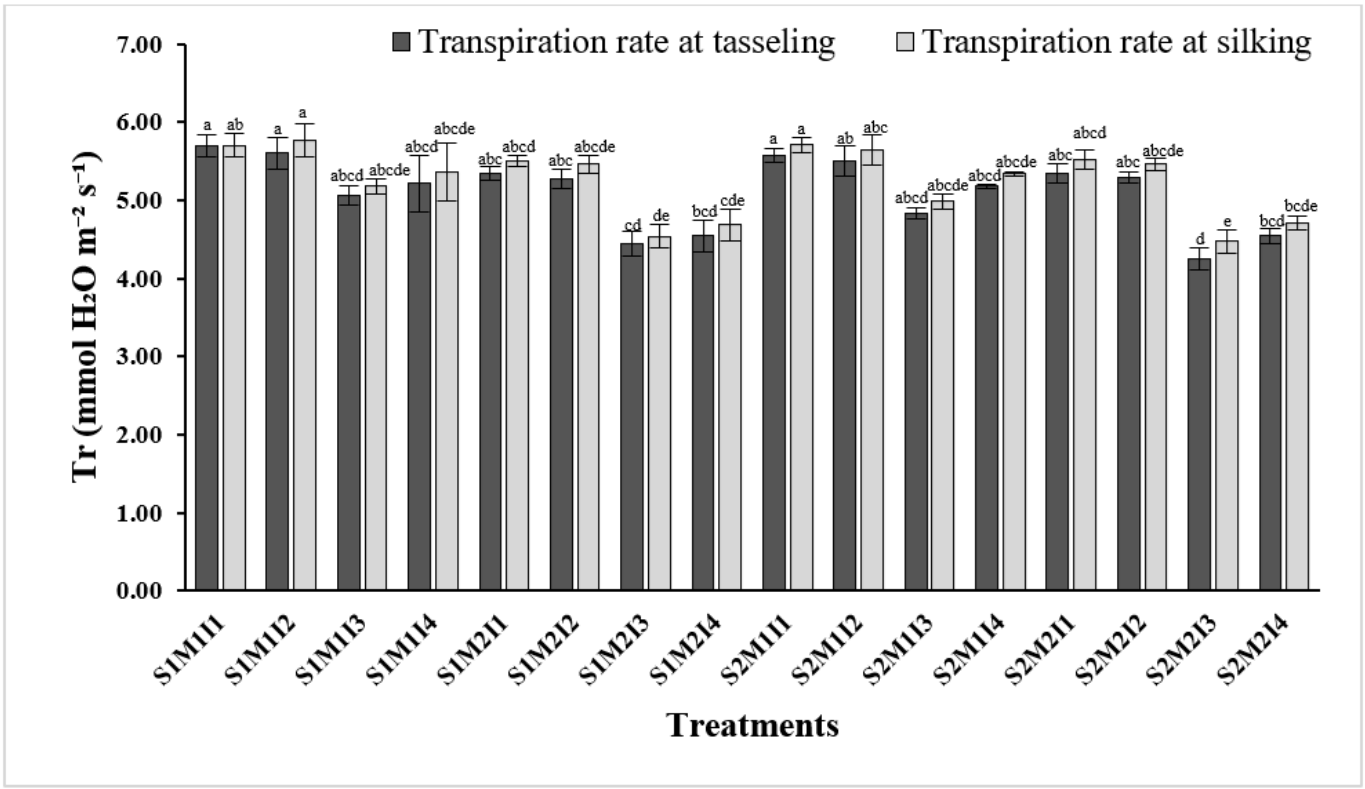


Figure 2

Fig. 2 Transpiration rate (m mol m^{-2} s^{-1}) at tasseling and silking stages as influenced by different treatment combinations of sowing method (S), mulching (M), and irrigation level (I).

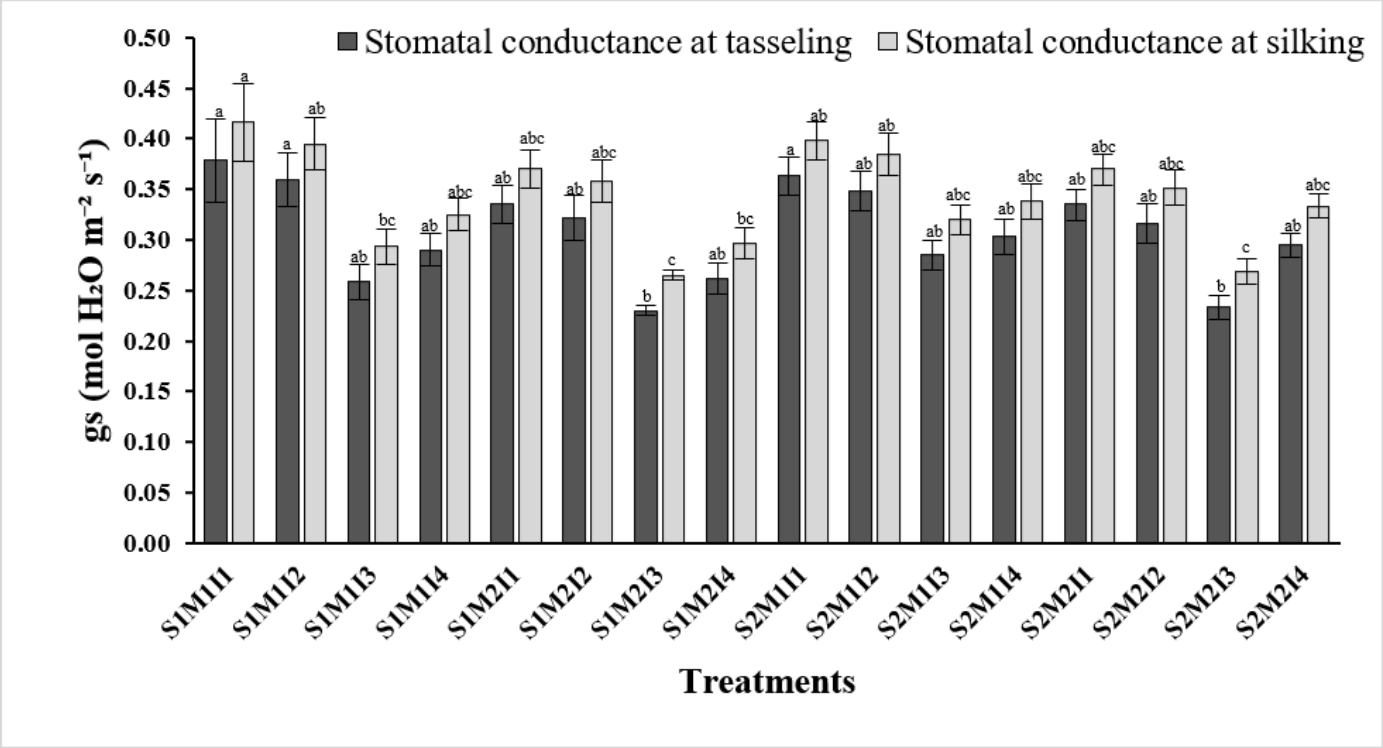


Figure 3

Fig. 3 Stomatal conductance (mol m^{-2} s^{-1}) at tasseling and silking stages as influenced by different treatment combinations of sowing method (S), mulching (M), and irrigation level (I).

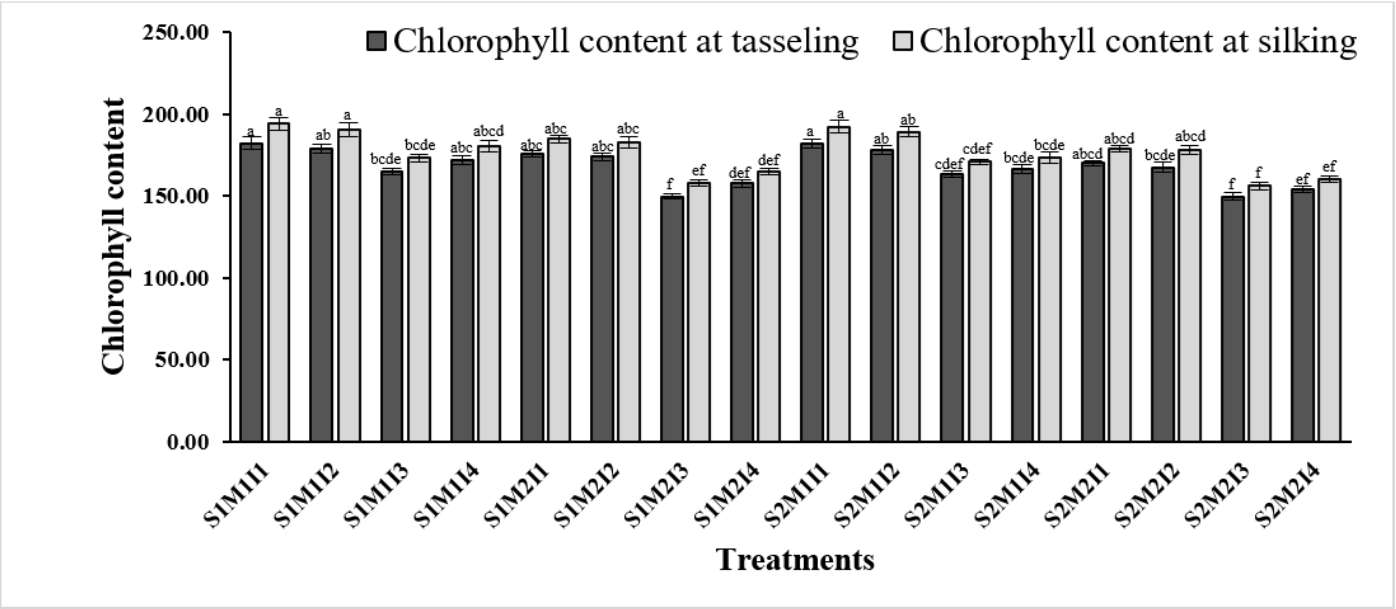


Figure 4

Fig. 4 Chlorophyll content (mg m^{-2}) at tasseling and silking stages as influenced by different treatment combinations of sowing method (S), mulching (M), and irrigation level (I).

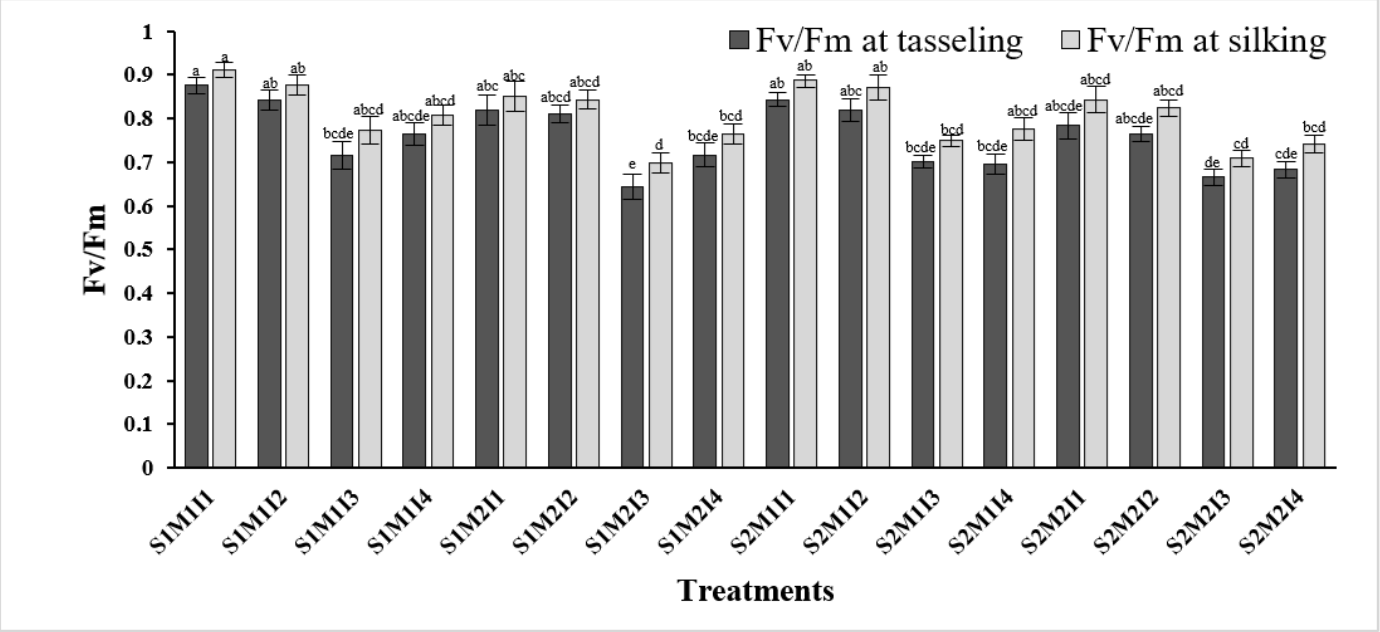


Figure 5

Fig. 5 Fv/Fm at tasseling and silking stages as influenced by different treatment combinations of sowing method (S), mulching (M), and irrigation level (I).

Supplementary Files

This is a list of supplementary files associated with this preprint. Click to download.

- Supplementarydata.doc