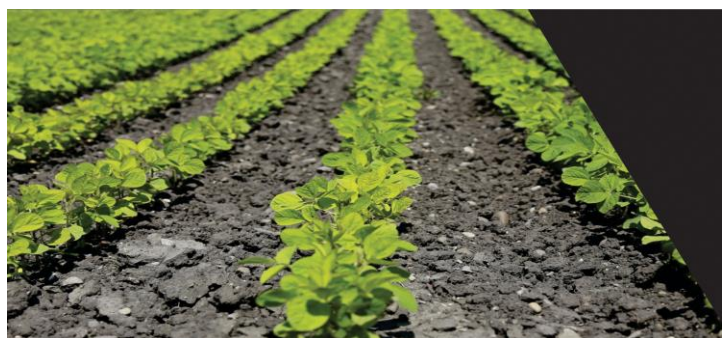




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Impact of silicon on growth, biomass and yield of different rice (*Oryza sativa* L.) under drought stress

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Abstract

Drought is a major constraint for rice production as it affects biomass accumulation, partitioning of assimilates and grain yield. The present investigation was carried out during kharif season of 2023 and 2024 to evaluate the efficacy of foliar spray of silicon on performance of eight rice genotypes under irrigated and drought conditions during reproductive stage. The experiment was conducted in split plot design with four treatments irrigated control (T₁), irrigated + silicon (T₂), drought + silicon (T₃) and drought without silicon (T₄). Silixol, 80 ppm was used as silicon in each case. Plants treated with silicon (Silixol, 80 ppm) showed significantly higher plant height, total dry matter at flowering and harvest, grain yield, test weight, and harvest index compared with drought-stressed plants that did not receive silicon. Silicon had a higher positive effect under drought condition, suggesting its usage to reduce water-deficit stress by producing biomass and efficiently allocating biomass to grain production. The reaction amplitude was found to vary widely across genotypes. Genotypes 28P67, 27P37 and HRI-174 performed considerably better for growth and yield measures. Correlation study showed that biomass accumulation and grain yield & harvest index were positively associated. The findings suggested that foliar application of silicon may be a potential agronomic method to improve the productivity and drought tolerance of rice and underscore the relevance of genotype-specific responses in improving crop performance under water stress conditions.

Keywords: *Oryza sativa*, foliar silicon, drought stress, biomass accumulation, grain yield, harvest index, correlation analysis

Introduction

Rice (*Oryza sativa* L.) is the most significant staple cereal grain for more than 50% of the global population and an important source of dietary energy, especially in Asia, where it plays a crucial role in food and nutritional security (Rahman and Zhang, 2016) [2]. In the past several decades the global output of rice has drastically expanded due to genetic advancements and improved management of crops. However, the changing environment is making gains in future production harder and more difficult (Dhankher and Foyer, 2018) [6]. Rice is the most sensitive crop to abiotic stresses especially susceptible to drought stress at all the stages starting from seedling to grain filling, since it demands large amount of water throughout the development cycle (FAO, 2014). However, drought stress during panicle development, blooming and early grain filling is particularly harmful due to the loss of canopy photosynthesis, rapid senescence, disruption of nutrient supply and increased spikelet sterility. The extent of damage is determined by the intensity and duration of stress, stage of crop, genotype and recovery after re-watering (Farooq *et al.*, 2009; Pandey and Shukla, 2015) [1, 18]. The impacts include decreased plant height, poor biomass buildup, poor grain filling, loss of grain volume and reduced harvest index. The development of drought resistance is a priority for sustainable rice production systems owing to the expected rise in global rice consumption to triple by 2050 (Samal *et al.*, 2022) [19].

India is the second largest rice producer in the world and accounts for more than one-fifth of the world's rice output. The crop is usually planted in the monsoon season. Rice crop depends on seasonal rainfall, making it vulnerable to the lack of rainfall and protracted dry periods (Maiti *et al.*, 2024) [14]. Almost 68 per cent of the country's agricultural land is drought sensitive and roughly one third of this area is chronically drought prone.

This issue is particularly common in eastern India where much of the upland and rainfed lowland rice is often under water stress (Dar *et al.*, 2020) [5]. Long-term records of rice production (Maiti *et al.*, 2024) [14] suggest that sub-optimal rainfall may cause a significant drop in productivity of monsoon rice with losses of up to 19% under acute drought circumstances. The extent of this issue was shown in the 2022 drought in Bihar when water stress resulted in delayed transplanting, decrease in rice acreage and an estimated loss of productivity by roughly 0.94 t ha⁻¹, almost 23% in the afflicted fields (Mkondiwa *et al.*, 2025) [17]. Water deficit conditions also retard the agricultural revenue and raise the livelihood risk in rainfed farming systems additionally in respect of its effect on crop yield, with further impacts on household food consumption and nutritional security (Carpena, 2019; Samuel *et al.*, 2024) [3, 20].

Silicon is not often regarded as a necessary nutrient for plants. Rice is especially effective in collecting silicon and a substantial supply is typically of great utility. Roots take up Si preferentially in the form of neutral monosilicic acid via influx and efflux transporters, translocate it via xylem, and deposit it as hydrated silica in transpiring tissues (Ma & Yamaji, 2008; Mitani-Ueno & Ma, 2021) [13, 16]. These deposits participate in the control of water relations of plants, alter epidermal and cuticular characteristics and reinforce leaves and culms. But silicon is a building block, and more. It has been related with improved plant water status, higher stability of photosynthetic pigments, better osmotic adjustment, stronger antioxidant defense, balanced nutrient absorption, and prolonged biomass production under drought circumstances (Etesami & Jeong, 2018; Malik *et al.*, 2021) [9, 15]. Based on these principles, controlled and field experiments revealed increased growth, dry matter buildup and grain yield of rice under drought stress following silicon application (Chen *et al.*, 2011; Elshayb *et al.*, 2021; El-Okkiah *et al.*, 2022; Abd-El-Aty *et al.*, 2024) [4, 8, 7, 1]. The size of this reaction depends on genotype, silicon availability, manner of administration and ambient circumstances. Further field investigations in additional rice genotypes are needed.

2. Material and method

The field experiment was conducted in kharif season of 2023 and 2024 at N E. Borlaug CRC, GBPUA&T, Pantnagar, Uttarakhand, India. The site is located in Tarai area of the Himalayan foothills with humid subtropical climate, suitable to irrigated rice farming. Eight rice genotypes viz., 27P37, 27P63, 28P67, HRI-174, US-312, US-314, AZ8433DT and Sahbhagi Dhanwere obtained from ICAR-IIRR, Hyderabad. The genotypes were assessed under four treatments including T₁: control irrigated; T₂: irrigated + silixol, 80 ppm; T₃: drought + silixol, 80 ppm; T₄: drought without silicon. Silicon was used as foliar sprays at 15, 30, 45 and 60 days after transplanting (DAT). In treatments T₃ and T₄, drought stress at reproductive stage was imposed by withholding irrigation for 12 days before flowering and 10 days after anthesis. Irrigated treatments were normally irrigated throughout the crop period.

2.1 Measurement of plant height, total dry matter, grain yield, test weight and harvest index

Plant height was recorded at flowering using a measuring tape from the base at soil level to the highest point of the plant on a representative sample in centimetres. Total dry matter was determined at flowering and at physiological maturity after oven drying sampled plant material at 65°C to constant mass and was expressed as g m⁻². Grain yield was recorded from the harvested plot area and expressed as g m⁻². A sample of 1000 grains was counted and weighed to determine 1000-grain. The harvest index

was computed as the ratio of yield of economic interest (grain yield) and biological yield and was calculated by using the formula:

$$\text{Harvest Index} = \frac{\text{Grain Yield}}{\text{Biological Yield}} \times 100$$

2.2 Statistical Analysis

Data were analysed using analysis of variance (ANOVA) appropriate for a split-plot design, and treatment means were compared at the 5% level of significance (p=0.05) using the critical difference (CD) test. Data processing and preliminary analyses were carried out in Microsoft Excel, Graphical representation was done by using OriginPro software, while Pearson's correlation analysis among measured traits were performed using R-software.

3. Results

The relative response of individual genotypes in the four treatment comparisons was studied by pooled means of Kharif 2023 and 2024. Percentage changes were interpreted as T₂ over T₁ for the effect of silicon under irrigation, T₃ over T₄ for the effect of silicon under drought, T₁ over T₄ for the reduction associated with drought in the absence of silicon, and T₂ over T₃ for the difference between irrigated and drought-stressed plants receiving silicon. The pooled percentage-change responses are presented in Figures 1 and 2. The pooled results show an overall response throughout the two seasons.

3.1 Effect of silicon plant height and TDM at flowering

Plant height (cm)

When considering the two seasons combined, the plant height revealed a mild response to silicon and water deprivation. Fig. 1A shows the percent change according to genotype. Application of silicon (T₂ over T₁) increased the plant height ranging from 1.09% in SB DHAN to 6.49% in 27P63 under irrigated circumstances. Under drought, the response of T₃ was 0.64-3.40% higher than T₄ with the maximum response again in 27P63. The comparatively small T₃overT₄ values show that silicon gave a moderate increase in plant stature under water deprivation. The impact of water deficit condition was more pronounced in the T₁overT₄ comparison where the variation in the plant height across genotypes was 1.99% in 28P67 and 5.27% in SB DHAN. Similarly, T₂ was 1.59–8.02% higher than T₃, and the largest difference was seen in 27P63. The very narrow range of percent change shows that plant height was less sensitive to drought and silicon than dry matter and yield related characteristics.

TDM (g/m²)

The use of silicon under irrigation conditions (T₂ over T₁) increased the TDM at the flowering stage by 0.80–14.59% across genotypes (Fig. 1B). The greatest T₂ over T₁ response was for US-314 (14.59%), whereas AZ8433DT showed a very less increase of 0.80%. Silicon increased TDM by 3.11-12.69% in T₃ over T₄ during flowering stage under drought, with highest response in HRI-174 (12.69%) followed by US-312(10.37%) and AZ8433DT (10.33%). This suggests that the ability of silicon to support biomass under water stress was genotype specific. The T₁ over T₄ comparison ranged from 8.08% in US-314 to 19.98% in AZ8433DT, indicating a higher influence of dryness on biomass accumulation than on plant height. T₂ was 8.60-20.32% greater than T₃, with the maximum difference in 27P37. The higher percent change in TDM at flowering suggest that the effect of silicon was more clearly shown via the preservation of dry matter production rather than in changes in plant height.

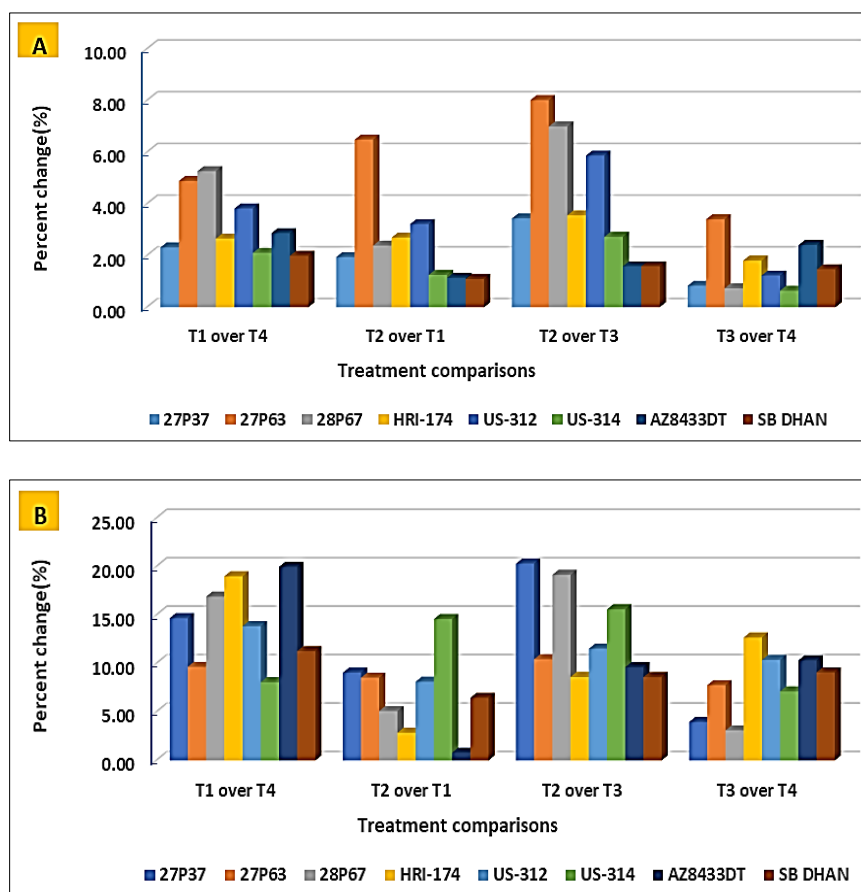


Fig 1: Graphical representation illustrating the comparative effect of silicon on pooled mean percent change (A) Plant height and (B) TDM at the flowering stage in different rice genotypes.

3.2 Effect of silicon on TDM, grain yield, 1000 grain weight and harvest index at harvest

TDM (g/m^2): The genotype-wise percent changes are shown in Fig. 2A. Under irrigated conditions T_2 was superior to T_1 by the range 2.32–18.71% with highest rise in SB DHAN (18.71%) followed by US-312 (18.18%). Under drought, T_3 over T_4 response varied from 2.13 to 13.73% with the largest rise in AZ8433DT. The positive T_3 over T_4 response in all genotypes indicated a superior maintenance of harvest biomass when silicon was provided under water shortage. The difference between T_1 and T_4 was 4.93% in 28P67 and 23.34% in 27P63. Thus, the impact of drought on final biomass varied greatly depending on the genotype. T_2 was 10.06–36.59% higher than T_3 with the highest variance in SB DHAN. These data suggest that silicon partially preserved biomass during drought, although the amount of the response was very variable across genotypes.

3.2.2 Grain yield (g/m^2)

Silicon had good response on grain yield. Figure 2B shows the pattern of % change and shows clear differences across genotypes. Under irrigated condition T_2 increased grain production over T_1 by 1.82–7.42% with 27P63 showed best response. More importantly, T_3 was 3.76–14.15% greater than T_4 under drought. The highest increase was observed in 28P67 (14.15%) then US-312 and 27P63, showing relatively high yield response to silicon under water deficiency. The differences between T_1 and T_4 ranged from 5.89 to 24.73%, with the most drought related change in 28P67. The T_2 over T_3 comparison was 7.32 to 16.15% with again 28P67 with the greatest outcome. Therefore, 28P67 showed a high effect of drought and a very favorable response to silicon under drought, being one of the most sensitive genotypes for grain yield.

3.2.3 1000 grain weight (g)

The T_2 over T_1 response (Figure 2C) was between 0.12% for US-314 and 9.43% for 27P37, suggesting considerable differences in the response of grain weight to silicon under irrigated normal conditions. T_3 was found 1.99–13.00% greater than T_4 during drought with maximum response in US-314 (13%) followed by 28P67 (11%). The T_1 over T_4 comparison ranged from 2.74% to 21.38%. The largest percent change was seen for US-314, which indicated that the drought had a large effect on grain weight in this genotype. T_2 exceeded T_3 by 1.52–13.74% with the highest value in 28P67. For all genotypes, T_3 values were substantially higher than T_4 , showing that silicon contributed to sustain grain filling under water scarcity conditions during reproductive stage although the effect varied for each genotype.

3.2.4 Harvest index (%)

The harvest index showed greatest relative response among the studied traits. In the genotype wise responses shown in Fig. 2D, T_2 was greater than T_1 by 0.67–18.34%. The maximum reaction was seen in US-312. The harvest index increased in T_3 over T_4 during drought from 5.06 to 21.47%. The maximum response was seen in 28P67 (21.47%) followed by US-312 (20.47%) and 27P63 (20.11%) indicating substantially superior biomass partitioning to grain by these genotypes under silicon supply during drought. The T_1 over T_4 comparison revealed a broad range of 8.63–47.70% with 28P67 having the highest difference, which indicated a substantial loss in partitioning efficiency during drought without silicon. Similarly, T_2 was greater than T_3 by 4.09–27.21% and the highest response observed in 28P67. The very substantial percent change for harvest index indicate that drought affected not only total biomass output but also, its partitioning to grain and silicon partially alleviated this negative impact.

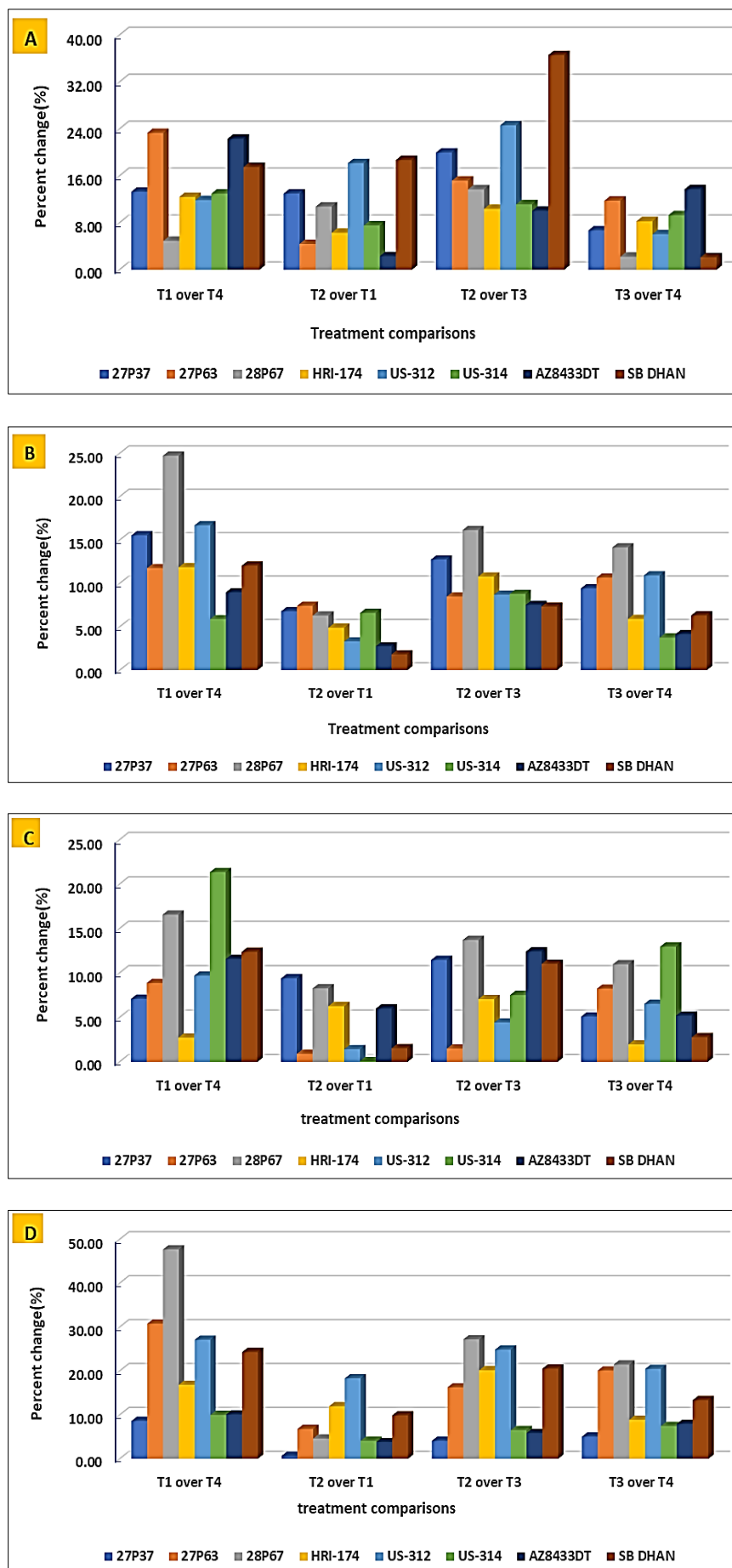


Fig 2: Graphical representation illustrating the comparative effect of silicon on pooled mean percent change (A) TDM and (B) Grain yield (C) 1000 grain weight (D) HI at the harvest in different rice genotypes.

3.3 Relationship among growth, biomass and yield traits

The overall pooled correlation heatmap depicting the association between plant height, total dry matter during flowering, total dry matter at harvest, grain yield, test weight and harvest index (Figure 3). Total dry matter at flowering ($r = 0.85$) and total dry matter at harvest ($r = 0.84$) were significantly and positively correlated with plant height indicating that tall plant height is more likely to accumulate more biomass. Similarly, total dry matter at flowering and total dry matter at harvest were both significantly and positively correlated ($r = 0.85$), which means that genotypes with higher biomass at flowering tended to

maintain this advantage until harvest. However, grain yield showed weak positive associations with plant height ($r = 0.15$), TDM at flowering ($r = 0.24$) and TDM at harvest ($r = 0.03$). Thus, increased vegetative growth or biomass was not always related with greater grain yield in the present investigation. However, grain yield was more strongly positively correlated with test weight ($r = 0.48$) and even more strongly positively correlated with harvest index ($r = 0.63$), indicating that yield improvement was more strongly related with grain filling and partitioning efficiency than total biomass production.

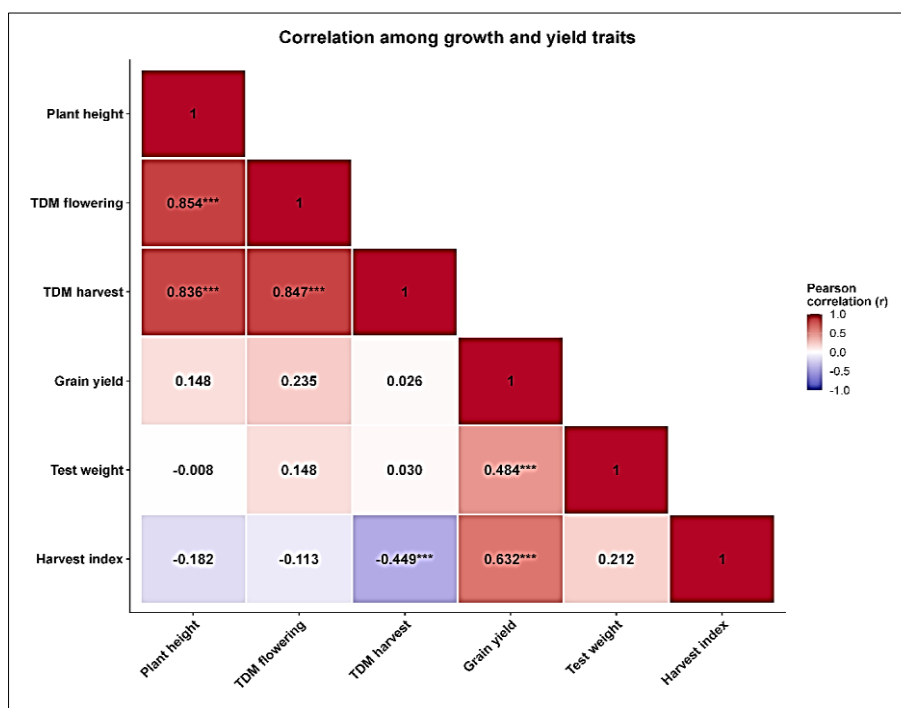


Fig 3: Pearson correlation heat map among plant height, total dry matter at flowering, total dry matter at harvest, grain yield, test weight and harvest index in rice based on pooled data of Kharif 2023 and 2024 (***) indicates significance at $P < 0.001$).

Test weight (1000 grain weight) was very faintly inversely correlated with plant height (-0.01) and weakly positively correlated with TDM at flowering ($r = 0.15$) and TDM at harvest ($r = 0.03$). The positive correlation of grain yield with grain filling indicated that better grain filling was directly responsible for the final productivity. However, harvest index demonstrated weakly negative association with plant height (-0.18), TDM during flowering (-0.11) and considerable negative association with TDM during harvest (-0.45). Thus, increasing total biomass, particularly at harvest, was not necessarily related with successful partitioning of assimilates to grain. The positive association of harvest index with grain yield further demonstrates importance of dry matter translocation and reproductive efficiency in determining final output. The heatmap also supports these linkages, with dark red shades indicating larger positive correlations, blue colors indicating negative correlations and lighter shades indicating weaker associations. The correlation investigation revealed that measures of growth and biomass were highly correlated although rice yield performance is more impacted by harvest index and test weight than plant height or total dry matter alone.

4. Discussion

Silicon boosted the crop output in all seasons under irrigated and dry environment but the magnitude of reaction was variable for the qualities. The plant height was only 1.99-5.27% higher in T_1

than T_4 under drought whereas TDM at flowering was 8.08-19.01% and TDM at harvest was 4.93-23.34% higher in T_1 than T_4 . The principal agronomic benefit of silicon was seen in the trend for increased retention of dry matter accumulation rather than in a considerable change in plant height. Application of Si has been shown to improve rice growth and biomass under water deficit conditions (Chen *et al.*, 2011; Elshayb *et al.*, 2021) [4, 8]. Silicon also had a beneficial effect on reproductive performance. Under drought situation, Silicon (T_3 over T_4) boosted the plant height by 3.40% in 27P63, TDM at flowering and harvest by 12.69% in HRI-174 and 13.73% in AZ8433DT respectively, grain yield by 10.92% in US-312, 1000-grain weight by 13% in US-314, and harvest index by 21.47% in 28P67. The higher grain weight and harvest index under T_3 suggest that silicon helped maintain grain filling and the allocation of assimilates towards grain under water deficit. Yield response showed that the degree of benefit from silicon was varying seasonally but showed positive interaction in both years. Silicon was also shown to boost grain filling and yield in drought challenged rice (Flores *et al.*, 2022; Abd-El-Aty *et al.*, 2024) [12, 1]. Percent change analyzed across genotypes demonstrated significant genotype dependent variance in response to silicon and drought. 28P67 showed relatively higher percent gain in grain yield and harvest index, whereas 27P37 also showed favorable yield response and US-312 showed a positive response for harvest index. These differences suggest that the advantage of silicon was not evenly shown in all

genotypes. Previous studies have also shown that the response of rice to silicon under stress varies among genotypes (Wongla *et al.*, 2023; Abd-El-Aty *et al.*, 2024)^[22, 1]. The correlations analysis validated this response as grain yield was more closely related to 1000-grain weight and harvest index than to total biomass, while the negative relationship between TDM at harvest and harvest index showed that greater biomass accumulation did not necessarily relates to more efficient partitioning toward grain. A positive interaction of grain yield with 1000-grain weight and harvest index has also been reported in rice, supporting the importance of grain filling and biomass partitioning in assessing final yield (Tiruneh *et al.*, 2021)^[21].

5. Conclusion

The pooled analysis grouped the primary growth, biomass and yield characteristics and indicated substantial differences across the genotypes and treatments. Foliar silicon generally improved rice performance during reproductive-stage drought stress by promoting dry matter accumulation, grain filling, grain yield and harvest index. Genotypes 28P67 and 27P37 performed comparably better, however the magnitude of improvement varied across the attributes and between the seasons. The correlation analysis further indicated that grain yield was more closely associated with 1000-grain weight and harvest index than with total biomass. Results show that silicon may alleviate the negative effects of water deprivation in rice. However, the response is strongly genotype-dependent.

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