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Improving Rice (*Oryza sativa* L.) Growth Through Exogenous Application of Gibberellic Acid and Cytokinin under Varying Zinc Levels

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ABSTRACT

Background: Poor translocation of micronutrients especially zinc (Zn) within plants poses a significant constraint on the growth of cereal crops. The present study investigated the effect of various Zn application methods and plant growth regulators (gibberellic acid (GA) and cytokinin) on the growth of rice crop.

Methods: The experiment was carried out using a split-split plot design with three replications to assess two rice varieties (SAVA 127 and PR 126) under three Zn application methods: no Zn application (Zn0), soil Zn application (Zn1) and soil + foliar Zn application (Zn2) along with four PGR levels: no PGR application (H0), 10 mg L^{-1} GA (H1), 10 mg L^{-1} cytokinin (H2) and 5 mg L^{-1} GA + 5 mg L^{-1} cytokinin (H3).

Result: Plant height was increased by 14.4% in variety SAVA 127 with foliar spray of 10 mg L^{-1} GA along with soil + foliar Zn application method. Application of 10 mg L^{-1} cytokinin in combination with soil + foliar Zn application method significantly enhanced growth parameters, where number of leaves per plant, leaf area index (LAI) and dry matter accumulation (DMA) were increased by 18.7, 36.0 and 41.6% respectively as compared to control in the variety SAVA 127. On the other hand, the maximum number of tillers per square meter (6.7% higher than control) was noted in variety PR 126. Overall, combined approach of soil + foliar Zn application along with 10 mg L^{-1} cytokinin was found as a superior option in improving various growth parameters of rice varieties.

Key words: Growth parameters, Plant growth regulators, Rice varieties, Zinc application methods.

INTRODUCTION

Zinc deficiency is a significant global health concern, affecting nearly 25% of the world's population (Ganeshamurthy *et al.,* 2019). It also poses significant challenges in agriculture, affecting the growth and yield of cereal crops like rice. Rice is a staple food for nearly half of the global population, supplying 35-60% of daily caloric intake for over three billion individuals (Fageria *et al.,* 2003). Populations that consume rice as a primary dietary component are at a higher risk of Zn deficiency, especially when the rice is cultivated in Zn-deficient soils (Shen *et al.,* 2023). This deficiency can impair the function of the immune system, hinder cognitive development and lead to other health issues associated with inadequate Zn intake (Wessels *et al.,* 2017). Zinc is a vital micronutrient involved in numerous physiological and biochemical processes in crops (Kambe *et al.,* 2015) which influence their growth, development and productivity. It is essential for enzyme activation (Mrudula *et al.,* 2022), chlorophyll formation, improving photosynthesis, protein synthesis and nutrient uptake (Ariraman *et al.,* 2022; Hamzah Saleem *et al.,* 2022) and production of growth hormones like auxins, which contribute to overall plant vigour. Zinc deficiency in plants leads to stunted growth, chlorosis and reduced grain yield, highlighting its importance in crop production and nutritional quality (Cakmak, 2008; Hafeez *et al.,* 2013).

Application of Zn through various methods plays a vital role in improving the growth characteristics of rice. Soil application of Zn provides a continuous Zn supply for root uptake, supporting the early growth of the crop. However, soil + foliar application ensures Zn translocation through both xylem and phloem for better redistribution, improving Zn mobility to shoot meristems and young leaves (Mathpal *et al.,* 2023). The synergistic effect of soil and foliar Zn application ultimately leads to more robust plant architecture, higher biomass accumulation and greater productivity. Zinc is required for the biosynthesis of auxins, which promote internodal elongation and its translocation from roots to shoots enhances cell expansion, resulting in taller plants (Cakmak, 2008). It plays a role in protein

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synthesis and carbohydrate metabolism, both of which contribute to rapid leaf development (Alloway, 2008). Adequate Zn supply prevents early chlorosis, maintaining active photosynthetic tissue and increasing the total number of functional leaves per plant (Hafeez *et al.,* 2013; Batra and Sharma, 2022). Zinc also enhance cytokinin activity, which stimulates axillary bud development, leading to increased tiller production (Singh *et al.,* 2024). Soil Zn enhances root proliferation (Noor *et al.,* 2024), supporting tiller emergence, while foliar Zn application at tillering stage further strengthens tiller survival (Chattha *et al.,* 2023). Zinc regulates the synthesis of growth hormones that promote cell division and expansion, leading to a greater LAI (Teale *et al.,* 2006), whereas its direct role in chlorophyll biosynthesis and enzyme activation lead to increased dry matter production (Rehman *et al.,* 2012). Soil + foliar Zn application ensures efficient translocation of Zn to actively growing tissues, improving total plant biomass (Singh *et al.,* 2024).

Gibberellic acid and cytokinin are key plant growth regulators (PGRs) that significantly influence the growth (Wavhale and Salve, 2024) and development of rice by regulating cell division, elongation and differentiation. Gibberellic acid primarily promotes plant height by stimulating internode elongation (Shan *et al.,* 2021), while cytokinin supports shoot meristem activity and encourages tiller formation (Koprna *et al.,* 2021; Zha *et al.,* 2022). Gibberellic acid promotes rapid cell elongation in emerging leaves, resulting in larger leaves and a greater LAI (Sprangers *et al.,* 2020), whereas cytokinin induces new leaf primordia at the shoot apex, leading to more leaf production (Wu *et al.,* 2021). Moreover, cytokinin prevents chlorophyll degradation, thereby prolonging leaf lifespan and maintaining a higher LAI (Mayta *et al.,* 2019). Gibberellic acid increases the efficiency of photosynthesis and carbohydrate metabolism (Fu *et al.,* 2023), leading to greater biomass production. Cytokinin significantly influence DMA by enhancing photosynthetic activity, delaying leaf senescence and improving nutrient translocation (Sosnowski *et al.,* 2023; Zhang *et al.,* 2024). The study hypothesizes that foliar application of PGRs (GA and cytokinin) will significantly enhance the growth characteristics of rice by promoting better nutrient uptake, tiller formation, leaf expansion and DMA, ultimately improving overall plant vigour and productivity. This study aims to investigate the role of GA and cytokinin in improving key growth parameters under different Zn application methods, thereby optimizing rice growth and yield potential.

MATERIALS AND METHODS

The field experiment was conducted at the agriculture farm, School of Agriculture, Lovely Professional University, Phagwara, Punjab, during the *kharif* season of the years 2022 and 2023. The research site is geographically located at 31.25°N latitude and 75.0°E longitude, with an elevation of 232 meters above mean sea level. The study was carried out under subtropical climatic conditions. The experimental soil had a sandy loam texture with a pH of 7.8, electrical conductivity (EC) of 0.29 dS m^{-1} and an organic carbon content of 0.34%. The soil Zn content was 2.5 mg kg^{-1}, while available nutrient levels included 328 kg ha^{-1} nitrogen (N), 18 kg ha^{-1} phosphorus (P) and 260 kg ha^{-1} potassium (K).

The study was conducted in a split-split plot design with three replications. The main plots comprised of two rice varieties: SAVA 127 (V1) and PR 126 (V2) while the subplots were having three Zn application methods: Zn0, Zn1 and Zn2. The sub-sub plots consisted of four PGR levels: H0, H1, H2 and H3. The rice varieties were first raised separately on nursery beds having a size of 3 m × 3 m. After 26 days, the seedlings were transplanted into the main field (17 m × 43 m) during the kharif seasons of 2022 and 2023. A planting distance of 20 cm × 15 cm was maintained, with one seedling per hill. Urea (NH_2CONH_2), diammonium phosphate $(NH_4)_2HPO_4$) and muriate of potash (KCl) were applied across all plots to supply N, P and K, respectively. Nitrogen was applied in three splits: half of the recommended dose at transplanting, followed by two equal applications at the tillering stage (30 DAT) and the panicle initiation stage (50 DAT). In contrast, the entire dose of P and K was applied at the time of transplanting. Zinc sulphate heptahydrate ($ZnSO_4 .7H_2O$) was used for both soil and foliar Zn applications. Zinc was applied using three different methods: control (Zn0), soil application (Zn1) and combined soil + foliar application (Zn2), where application rates under each method were: 0% Zn, 100% soil application of the recommended dose (*i.e.* 62.5 kg ha^{-1} of zinc sulphate) and 50% soil application of the recommended dose (*i.e.* 31.25 kg ha^{-1} of zinc sulphate) + foliar spray of 0.5% $ZnSO_4.7H_2O$ solution. Soil-applied Zn was incorporated at the time of transplanting, whereas foliar Zn application was sprayed at 30, 60 and 90 days after transplanting. Additionally, four different levels of PGRs were tested: 0 mg L^{-1} of PGR (H0), 10 mg L^{-1} GA (H1), 10 mg L^{-1} cytokinin (H2) and a combination of 5 mg L^{-1} GA + 5 mg L^{-1} cytokinin (H3). Gibberellic acid (GA_3) and kinetin served as sources of GA and cytokinin, respectively. The PGR solutions were sprayed one day after the foliar application of Zn.

Five plants were randomly selected and tagged from different rows in each plot, excluding border and destructive rows for the assessment of growth parameters. Plant height was recorded at maturity using a meter scale, with the average height calculated from five randomly selected plants in centimeters (cm). The height of selected plants was recorded from the base to the tip of the tallest leaf or panicle. The total number of leaves per plant was counted manually at maturity from selected plants and the average was determined. The number of tillers per square meter was recorded at maturity by counting the total tillers within one square meter area and the average was calculated. For precise measurements of LAI, leaves were detached from the plant and placed inside the leaf area meter.

The recorded values of leaf area were then used to calculate the LAI based on the per unit land area.

$$\text{Leaf area index} = \frac{\text{Leaf area (cm}^2\text{)}}{\text{Ground area (cm}^2\text{)}}$$

To determine dry matter accumulation (DMA), plant samples were harvested, cleaned and dried in a preheated oven at 60-80°C until a constant weight was achieved. After cooling in a desiccator to prevent moisture absorption, the final dry weight was recorded as a measure of accumulated dry matter.

Statistical analysis

The collected data was analyzed statistically by using ANOVA in OPSTAT and Duncan's multiple range test (DMRT) was used for multiple comparisons at $p \leq 0.05$.

RESULTS AND DISCUSSION

Plant height

Effect of various treatments on plant height in both the rice varieties is presented in Table 1. Variety SAVA 127 exhibited greater plant height (108.6 cm) as compared to PR 126 (108.0 cm) across both years. Regarding Zn application methods, Zn2 (109.5 cm) was found most effective in enhancing plant height, outperforming both Zn1 (108.1 cm) and Zn0 (107.3 cm). All PGR levels contributed positively to plant height as compared to H0 (103.1 cm) and foliar application of H1 (112.6 cm) resulted the tallest plant height in both the varieties. Notably, a combination of Zn2 (soil application of 31.25 kg ha^{-1} $ZnSO_4.7H_2O$ + foliar spray of 0.5% $ZnSO_4.7H_2O$ solution) along with H2 (10 mg L^{-1} cytokinin) level of PGR resulted in the most significant increase in plant height, marking a substantial 14.4% improvement over the Zn0 + H0 in variety SAVA 127. Increase in plant height by the application of Zn might be linked to its role in auxin synthesis. Our findings align with those of Ali and Subhani (2021), who reported the maximum plant height with the combined application of soil-applied Zn at 50 kg ha^{-1} and 1% foliar spray, compared to no Zn application. Susilawati *et al.* (2014) further reinforced this finding, highlighting that the application of GA3 significantly enhanced plant height by cell enlargement and cell elongation. These processes contribute to the overall increase in internode length, resulting in taller plants with improved structural development.

Number of leaves per plant

The influence of various treatments on number of leaves per plant in both the rice varieties is presented in Table 2. Variety SAVA 127 showed the highest number of leaves per plant (49.7) compared to PR 126 (47.9). Among the different Zn application methods, Zn2 resulted in the maximum number of leaves per plant (50.0) followed by Zn1 (49.3) and Zn0 (47.1). Among various levels of PGRs, application of H2 (50.6) level showed the greatest improvement over the H3, H1 and H0. Overall, a combination of Zn2 (soil application of 31.25 kg ha^{-1} $ZnSO_4.7H_2O$ + foliar spray of 0.5% $ZnSO_4.7H_2O$ solution) along with H2 (10 mg L^{-1} cytokinin) was found most effective in increasing the number of leaves per plant in SAVA 127 and led to a 18.7% increase as compared to Zn0 + H0. The increase in the number of leaves could be attributed to the fact that sufficient Zn availability promotes cell proliferation, thereby facilitating the development of more number of leaves. The findings of our experiment are consistent with the results reported by Narayan *et al.* (2020). Cytokinins stimulate cell division in the shoot apical meristem, directly contributing to leaf formation and increasing leaf numbers. Moreover, they play a role in leaf expansion and delay senescence, indirectly influencing leaf count by extending the vegetative growth phase (Wu *et al.,* 2021).

Number of tillers m^{-2}

The impact of various treatments on number of tillers m^{-2} in both the rice varieties is illustrated in Table 3. Variety PR

Table 1: Effect of various Zn application methods along with foliar spray of gibberellic acid and cytokinin on plant height of two rice varieties during 2022 and 2023.

		Plant height (cm)					
		Zn0		Zn1		Zn2	
		2022	2023	2022	2023	2022	2023
SAVA 127	H0	100.0±.02^{m}	103.5±0.1^{n}	101.9±.01^{kl}	105.8±0.3^{l}	101.7±0.1^{kl}	106.0±0.1^{l}
	H1	110.5±0.3^{def}	109.5±0.1^{fg}	112.8±.0.4^{c}	113.5±0.1^{c}	115.7±0.2^{a}	116.9±0.3^{a}
	H2	107.0±.02^{h}	108.9±0.2^{gh}	104.6±.0.3^{j}	108.0±0.2^{ijk}	106.9±0.2^{hi}	110.6±0.3^{de}
	H3	109.0±.02^{g}	110.0±0.2^{ef}	109.2±0.4^{g}	110.8±0.2^{d}	111.3±0.1^{d}	113.0±0.3^{c}
PR 126	H0	101.0±0.2^{lm}	102.3±0.1^{o}	102.6±0.3^{k}	104.0±0.3^{mn}	103.9±0.9^{j}	104.3±0.2^{m}
	H1	110.1±0.3^{efg}	110.4±0.2^{de}	110.9±0.4^{de}	110.9±0.4^{d}	114.1±1.1^{b}	116.2±0.7^{b}
	H2	107.9±0.2^{h}	107.7±0.2^{jk}	105.9±0.2^{i}	107.3±0.1^{k}	107.7±.04^{h}	108.3±0.1^{hij}
	H3	109.6±0.3^{fg}	109.4±0.3^{fg}	111.1±0.5^{de}	110.9±0.1^{d}	107.1±0.6^{h}	108.6±0.3^{hi}

Mean values with distinct superscript letters represent significant differences at $p \leq 0.05$.

Treatment details: Zn0: No Zn application, Zn1: Soil Zn application, Zn2: Soil + foliar Zn application, H0: No PGR application, H1: 10 mg L^{-1} GA, H2: 10 mg L^{-1} cytokinin, H3: 5 mg L^{-1} GA + 5 mg L^{-1} cytokinin.

126 produced the highest number of tillers m^{-2} (777.1) followed by SAVA 127 (765.1). The mean number of tillers m^{-2} across both varieties increased significantly with the application of Zn2 (794.1), making it most effective Zn application method over Zn1 (776.0) and Zn0 (743.3). Pertaining to the effect of various PGR levels, all the levels significantly increased the tiller number, with the highest improvement recorded under H2 (855.9) as compared to H0 (682.2). Overall, maximum number of tillers m^{-2} was noted under the combination of Zn2 (soil application of 31.25 kg ha^{-1} $ZnSO_4.7H_2O$ + foliar spray of 0.5% $ZnSO_4.7H_2O$ solution) and H2 (10 mg L^{-1} cytokinin) in variety PR 126, which showed an increment of 36.0% over Zn0 + H0. The increase in tillering could be linked to the role of Zn in enhancing enzymatic activity and stimulating auxin biosynthesis within the plants (Khan and Qasim, 2007). Cytokinins are well known for their ability to stimulate cell division in plants (Panda *et al.,* 2018). When applied to leaves, they can potentially enhance cell division in axillary buds, leading to increased tiller initiation and improved tiller development (Koprna *et al.,* 2021). Our findings were supported by Singh *et al.* (2024), who also found an increased number of tillers m^{-2} by the combined application of Zn through soil + foliar spray along with foliar spray of 10 mg L^{-1} cytokinin.

Leaf area index

Influence of various treatments on LAI in both the rice varieties is presented in Table 4. Variety SAVA 127 exhibited the highest LAI (7.18) as compared to PR 126 (7.14). Regarding the various Zn application methods, Zn2 (7.80) proved to be the most effective in enhancing the LAI, surpassing Zn1 (7.20) and Zn0 (6.47). In context to various PGR levels, all significantly contributed to enhance the LAI, with the highest value recorded under H2 (7.54), followed by H3 (7.21), H1 (7.14) and H0 (6.75). Overall, the maximum

Table 2: Effect of various Zn application methods along with foliar spray of gibberellic acid and cytokinin on number of leaves per plant of two rice varieties during 2022 and 2023.

		Number of leaves per plant					
		Zn0		Zn1		Zn2	
		2022	2023	2022	2023	2022	2023
SAVA 127	H0	44.9±0.5^{i}	45.1±0.4^{i}	48.0±0.4^{defg}	49.0±0.4^{def}	45.1±0.9^{i}	49.7±2.3^{cde}
	H1	47.1±0.4^{g}	47.0±0.5^{gh}	48.6±0.4^{cde}	49.9±0.3^{cd}	51.8±0.5^{a}	52.1±0.8^{b}
	H2	49.6±0.4^{b}	49.8±0.4^{cde}	52.1±0.6^{a}	51.7±0.6^{b}	52.0±0.6^{a}	54.9±0.3^{a}
	H3	48.0±0.6^{defg}	49.2±0.3^{def}	51.5±0.8^{a}	51.2±0.6^{cbc}	51.9±0.4^{a}	52.3±0.4^{b}
PR 126	H0	44.8±0.8^{i}	43.3±0.8^{j}	47.3±1.1^{g}	47.2±0.1^{gh}	46.0±1.1^{h}	47.7±1.5^{fgh}
	H1	45.7±0.7^{hi}	46.8±0.3^{h}	47.7±1.0^{efg}	48.2±0.4^{efgh}	48.3±.0.7^{def}	48.6±1.1^{defg}
	H2	48.4±0.6^{de}	48.6±1.1^{defg}	49.6±0.4^{b}	49.9±0.3^{cd}	49.3±0.6^{bc}	51.7±0.7^{b}
	H3	47.4±0.9^{fg}	47.7±0.5^{fgh}	47.8±1.1^{efg}	49.1±0.7^{def}	48.9±0.8^{bcd}	50.1±0.4^{cd}

Mean values with distinct superscript letters represent significant differences at p≤0.05.

Treatment details: Zn0: No Zn application, Zn1: Soil Zn application, Zn2: Soil + foliar Zn application, H0: No PGR application, H1: 10 mg L^{-1} GA, H2: 10 mg L^{-1} cytokinin, H3: 5 mg L^{-1} GA + 5 mg L^{-1} cytokinin.

Table 3: Effect of various Zn application methods along with foliar spray of gibberellic acid and cytokinin on number of tillers m^{-2} of two rice varieties during 2022 and 2023.

		Number of tillers m^{-2}					
		Zn0		Zn1		Zn2	
		2022	2023	2022	2023	2022	2023
SAVA 127	H0	631.6±21.5^{u}	652.6±13.0^{p}	706.3±10.9^{p}	706.3±10.7^{m}	676.1±11.2^{s}	720.9±13.3^{l}
	H1	739.6±10.9^{n}	739.6±10.7^{k}	781.5±13.6^{i}	781.5±3.4^{g}	747.0±13.2^{m}	747.0±13.7^{j}
	H2	805.2±17.2^{g}	805.2±4.9^{f}	842.6±11.2^{d}	842.6±13.3^{c}	866.3±14.5^{c}	866.3±11.3^{b}
	H3	752.5±15.9^{l}	752.5±6.7^{i}	767.4±9.9^{k}	783.2±16.0^{g}	824.4±10.9^{f}	824.4±15.6^{e}
PR 126	H0	702.0±11.0^{q}	681.1±19.8^{n}	668.7±11.0^{t}	668.7±14.6^{o}	685.9±15.9^{r}	685.9±2.9^{n}
	H1	735.3±11.0^{o}	735.3±14.6^{k}	796.6±12.9^{h}	774.4±18.9^{h}	806.2±10.9^{g}	806.2±10.7^{f}
	H2	835.2±11.0^{e}	835.2±14.6^{d}	870.6±17.1^{b}	870.6±10.9^{b}	912.4±7.3^{a}	918.8±10.1^{a}
	H3	735.3±11.0o	753.8±11.7i	771.9±17.2j	783.0±14.3g	808.7±12.9g	808.7±12.7^{f}

Mean values with distinct superscript letters represent significant differences at p≤0.05.

Treatment details: Zn0: No Zn application, Zn1: Soil Zn application, Zn2: Soil + foliar Zn application, H0: No PGR application, H1: 10 mg L^{-1} GA, H2: 10 mg L^{-1} cytokinin, H3: 5 mg L^{-1} GA + 5 mg L^{-1} cytokinin.

increase in LAI was recorded in variety PR 126 under the treatment combination of Zn2 (soil application of 31.25 kg ha^{-1} $ZnSO_4.7H_2O$ + foliar spray of 0.5% $ZnSO_4.7H_2O$ solution) + H2 (10 mg L^{-1} cytokinin), with a percent increment of 41.6% as compared to Zn0 + H0. The increase in LAI due to Zn application may be attributed to its essential role in enzyme functions responsible for chlorophyll biosynthesis (Bhantana *et al.,* 2020), which led to increased photosynthetic activity and leaf development, ultimately influencing LAI. Cytokinin promoted leaf expansion and delayed senescence, ultimately led to an increase in leaf area (Zaheer *et al.,* 2019). Singh *et al.* (2024) also supported the findings of our study.

Dry matter accumulation (DMA) m^{-2}

The effect of various treatments on DMA m^{-2} in both the rice varieties is illustrated in Table 5. Among the two rice varieties, SAVA 127 showed the highest DMA (2.77 kg m^{-2}) as compared to PR 126 (2.74 kg m^{-2}). Among different Zn application methods, Zn2 significantly enhanced the DMA (2.82 kg m^{-2}) in both varieties, surpassing Zn1 (2.77 kg m^{-2}) and Zn0 (2.67 kg m^{-2}). In context to various PGR levels, the highest DMA was recorded under H2 (2.77 kg m^{-2}), which was notably greater than H0 (2.74 kg m^{-2}). Overall, a combination of Zn2 (soil application of 31.25 kg ha^{-1} $ZnSO_4.7H_2O$ + foliar spray of 0.5% $ZnSO_4.7H_2O$ solution) + H2 (10 mg L^{-1} cytokinin) resulted in the highest DMA m^{-2} across both varieties, with an increase of 6.7% over Zn0 + H0 in variety SAVA 127. A larger LAI improved light interception, which consequently increased dry matter production at various growth stages of the plant. Similarly, foliar application of cytokinin significantly enhanced DMA, possibly because cytokinins delay leaf senescence (Biswal and Rout, 2020), thereby prolonging the photosynthetically active phase and leading to increased DMA accumulation over time. Kushwaha *et al.* (2021) also validated the beneficial effects of PGRs on DMA, reporting that foliar application of plant hormones significantly enhanced the total DMA as compared to control.

Table 4: Effect of various Zn application methods along with foliar spray of gibberellic acid and cytokinin on leaf area index of two rice varieties during 2022 and 2023.

		Leaf area index					
		Zn0		Zn1		Zn2	
		2022	2023	2022	2023	2022	2023
SAVA 127	H0	6.16±0.1^{k}	6.00±0.1^{k}	6.82±0.1^{fghijk}	6.80±0.1^{fghij}	7.06±0.2^{defghij}	7.77±0.4^{cd}
	H1	6.40±0.3^{ijk}	6.53±0.1^{hijk}	6.96±0.3^{efghijk}	6.82±0.03^{fghij}	8.18±0.4^{ab}	8.29±0.2^{bc}
	H2	6.82±0.5^{fghijk}	6.18±0.1^{jk}	7.59±0.3^{abcdef}	7.65±0.1^{de}	8.29±0.3^{a}	8.92±0.2^{a}
	H3	6.47±0.2^{hijk}	6.29±0.01^{ijk}	7.11±0.1^{defghi}	7.00±0.2^{fgh}	7.81±0.3^{abcd}	8.37±0.1^{abc}
PR 126	H0	6.29±0.3^{jk}	6.05±0.1^{k}	7.17±0.3^{defghi}	6.88±0.05^{fghi}	6.92±0.3^{efghijk}	7.08±0.2^{efgh}
	H1	6.74±0.2^{ghijk}	6.76±0.1^{fghij}	7.42±0.1^{bcdefg}	6.94±0.1^{fghi}	7.27±0.1^{cdefgh}	7.36±0.1^{def}
	H2	6.91±0.3^{efghijk}	6.32±0.1^{ijk}	7.64±0.3^{abcde}	7.67±0.04^{de}	8.05±0.1^{abc}	8.40±0.1^{ab}
	H3	7.00±0.3^{efghij}	6.65±0.1^{ghijk}	7.48±0.2^{bcdefg}	7.28±0.1^{defg}	7.59±0.2^{abcdef}	7.42±0.1^{def}

Mean values with distinct superscript letters represent significant differences at p≤0.05.

Treatment details: Zn0: No Zn application, Zn1: Soil Zn application, Zn2: Soil + foliar Zn application, H0: No PGR application, H1: 10 mg L^{-1} GA, H2: 10 mg L^{-1} cytokinin, H3: 5 mg L^{-1} GA + 5 mg L^{-1} cytokinin.

Table 5: Effect of various Zn application methods along with foliar spray of gibberellic acid and cytokinin on dry matter accumulation m^{-2} of two rice varieties during 2022 and 2023.

		Dry matter accumulation m^{-2} (kg m^{-2})					
		Zn0		Zn1		Zn2	
		2022	2023	2022	2023	2022	2023
SAVA 127	H0	2.66±0.01^{fg}	2.70±0.01^{abc}	2.75±0.01^{abcdefg}	2.77±0.01^{abc}	2.82±0.01^{ab}	2.83±0.01^{abc}
	H1	2.67±0.005^{efg}	2.70±0.004^{abc}	2.79±0.01^{abcde}	2.80±0.004^{abc}	2.83±0.004^{ab}	2.84±0.01^{abc}
	H2	2.69±0.01^{cdefg}	2.71±0.01^{abc}	2.80±0.01^{abcd}	2.82±0.005^{abc}	2.85±0.01^{a}	2.87±0.01^{a}
	H3	2.68±0.01^{defg}	2.69±0.005^{abc}	2.79±0.003^{abcde}	2.82±0.01^{abc}	2.83±0.003^{ab}	2.86±0.01^{ab}
PR 126	H0	2.64±0.01^{g}	2.65±0.01^{c}	2.72±0.004^{bcdefg}	2.73±0.004^{abc}	2.78±0.004^{abcdef}	2.78±0.01^{abc}
	H1	2.64±0.005^{g}	2.66±0.01^{c}	2.75±0.004^{abcdefg}	2.74±0.02^{abc}	2.79±0.005^{abcde}	2.80±0.01^{abc}
	H2	2.66±0.01^{fg}	2.68±0.01^{abc}	2.76±0.01^{abcdefg}	2.77±0.01^{abc}	2.82±0.01^{ab}	2.83±0.01^{abc}
	H3	2.65±0.01^{g}	2.67±0.01^{bc}	2.76±0.01^{abcdefg}	2.76±0.01^{abc}	2.81±0.01^{abc}	2.82±0.01^{abc}

Mean values with distinct superscript letters represent significant differences at p≤0.05.

Treatment details: Zn0: No Zn application, Zn1: Soil Zn application, Zn2: Soil + foliar Zn application, H0: No PGR application, H1: 10 mg L^{-1} GA, H2: 10 mg L^{-1} cytokinin, H3: 5 mg L^{-1} GA + 5 mg L^{-1} cytokinin.

CONCLUSION

The findings of this study revealed that combined approach of Zn application through soil + foliar spray significantly improved the growth parameters of rice varieties during both the years. Foliar application of GA and cytokinin effectively enhanced rice growth when sprayed at various intervals. The results further confirmed that the application of Zn through combined approach of soil + foliar spray and PGRs led to a substantial increase in various growth parameters. Maximum increase in plant height was found under foliar spray of 10 mg L^{-1} GA along with soil + foliar application of Zn, whereas a combination of 10 mg L^{-1} cytokinin and soil + foliar Zn application method resulted significant improvement in the number of leaves, number of tillers, LAI and DMA. This study suggested that the integration of PGRs can enhance rice growth by promoting cell division, elongation and nutrient mobilization, which contribute to increased biomass accumulation and overall plant development.

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Conflict of interest

The authors declare that there is no conflict of interest regarding the publication of this article.

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