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Effect of gibberellic acid (GA_3) levels on growth, yield and economics of different varieties of palak (*Beta vulgaris* var. *bengalensis*)

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Abstract
The experiment investigates the effect of different concentrations of gibberellic acid (GA_3) and varietal differences on the growth, yield, and economic returns of palak (*Beta vulgaris* var. *bengalensis*). Growth parameters evaluated included plant height, number of leaves, leaf width, length, leaf area, and leaf area index. Yield parameters such as fresh and dry leaf yield, along with economic indicators like gross and net returns and benefit-cost ratio, were also studied. Results showed that 200 ppm GA_3 significantly enhanced growth traits, with plant height reaching 24.22 cm and leaf area 85.06 cm^2, outperforming other concentrations. Yield was highest at 200 ppm with 18.15 t/ha fresh leaf yield and 2.18 t/ha dry leaf yield. Although 300 ppm also improved parameters compared to control, its effect was less than 200 ppm, indicating possible negative effects at higher concentrations. Among varieties, Pusa Bharti had superior growth, yield, and economic outcomes compared to All Green and Jobner Green. The findings demonstrate that 200 ppm GA_3 optimizes palak growth and productivity, while varietal selection further influences results. Economic analysis confirms that this treatment is cost-effective, offering the best return on investment. This study highlights the importance of appropriate GA_3 dosing and selecting responsive varieties to maximize palak production.

Keywords: Palak, gibberellic acid, PGRs, varietal performance

Introduction
Palak or spinach beet (*Beta vulgaris* var. *bengalensis*), commonly known as Indian spinach, belongs to the family Chenopodiaceae and represents one of the most important leafy vegetables cultivated throughout India (Krishna *et al.*, 2022) [6]. This versatile crop has gained significant attention due to its exceptional nutritional profile, adaptability to diverse climatic conditions, and potential for multiple harvests within a single growing season. Palak stands distinguished as a nutritional powerhouse, earning the title "Mines of Minerals" due to its remarkable mineral content. The crop serves as an affordable source of essential vitamins including A, K, E, D, and C, along with crucial minerals such as calcium, iron, thiamine, folic acid, nicotinic acid, riboflavin, and pyridoxine (Maurya *et al.*, 2019; Tripathy *et al.*, 2021) [8, 12]. Per 100 grams of edible portion, palak provides 268.60 mg nitrogen, 49.68 mg phosphorus, 141.68 mg potash, 368.00 mg calcium, 42.32 mg iron, 50.24 mg ascorbic acid, and 52.00 µg carotene (Krishna *et al.*, 2022) [6]. In India, leafy vegetables occupy approximately 9.205 million hectares with an annual production of 162.187 million tonnes (Kumar *et al.*, 2022) [7]. Palak cultivation offers farmers multiple cutting opportunities, typically yielding 6-8 harvests at 15-18-day intervals, making it an economically viable crop for smallholder farmers.

Several improved varieties of palak have been developed to meet diverse agroclimatic requirements across India. All Green variety represents an early-maturing cultivar suitable for September sowing, characterized by uniformly green, tender leaves and typically matures in 40 days yielding approximately 125 q/ha through 6-7 cuttings. Pusa Bharati stands out as a superior variety developed through hybridization, featuring dark green, succulent leaves with enhanced nutritional content and late bolting characteristics, recording maximum fresh weight of 21.96-24.11 g per plant across multiple cuttings. Jobner Green variety, evolved through spontaneous mutation, exhibits tolerance to alkaline soils (pH 7.0-10.5) and produces long, thick, succulent leaves with strong flavor.

Plant growth regulators (PGRs) have emerged as crucial tools in modern agriculture for enhancing crop productivity, quality, and stress tolerance. Among various PGRs, gibberellic acid (GA_3) represents one of the most extensively studied and commercially utilized phytohormones (Shah *et al.*, 2023) [9]. GA_3, chemically known as gibberellin A_3 with the molecular formula $C_{19}H_{22}O_6$, functions as a tetracyclic diterpene compound that regulates numerous developmental processes in plants. GA_3 exerts its influence through complex molecular mechanisms involving gene expression regulation and protein synthesis modulation (Tang *et al.*, 2025) [11]. At the cellular level, GA_3 overcomes growth restraint mediated by DELLA proteins, thereby facilitating stem elongation, leaf expansion, and overall plant development. Research demonstrates that GA_3 applications significantly enhance various physiological processes including seed germination, stem elongation, flowering induction, and fruit development. In leafy vegetables, GA_3 treatment has been shown to increase plant height, leaf area, biomass accumulation, and overall yield parameters. Studies on lettuce revealed that GA_3 concentrations of 10^{-8} to 10^{-6} M promoted growth and enhanced yield, with optimal responses observed at 10^{-6} M concentration.

The application of GA_3 in vegetable production has yielded promising results across various crops. In spinach cultivation, GA_3 treatments have demonstrated significant improvements in germination percentage, seedling vigor, and growth parameters. Studies on various leafy vegetables confirm GA_3's effectiveness in enhancing nutritional quality alongside yield improvements. In kale, GA_3 application at 100 ppm increased total phenolic content by 17% and vitamin C content significantly compared to control treatments. Similarly, research on chili plants showed that GA_3 at 150 ppm produced superior results in plant height (141.58 cm), fruit yield (25.70 t/ha), and vitamin C content (98.49 mg/100 g).

Determining optimal GA_3 concentrations remains crucial for maximizing benefits while avoiding potential adverse effects. Research indicates that GA_3 effectiveness follows a concentration-dependent response, with optimal ranges typically falling between 50-200 ppm for most vegetable crops. Lower concentrations (50-100 ppm) generally promote vegetative growth parameters, while higher concentrations (150-200 ppm) may enhance reproductive development and quality attributes. Application timing and methods significantly influence GA_3 effectiveness, with foliar applications during active growth phases typically yielding superior results compared to soil applications.

Despite extensive research on GA_3 applications in various crops, specific studies examining GA_3 effects on different palak varieties remain limited. The interaction between GA_3 concentrations and varietal characteristics requires systematic investigation to develop variety-specific recommendations. Furthermore, the optimization of GA_3 application for enhancing quality parameters such as oxalic acid content, mineral composition, and antioxidant activity in palak needs comprehensive evaluation. Understanding GA_3's role in stress mitigation, particularly under challenging environmental conditions, could significantly enhance palak cultivation in marginal areas.

Materials and methods

The experiment was conducted during the *Rabi* season of 2024-25 at the School of Agricultural Sciences, Jaipur National University, Jaipur, Rajasthan. The experimental design was a factorial randomized block design (FRBD) with 12 treatment combinations (four GA_3 levels and three palak varieties: All Green, Pusa Bharti, and Jobner Green) replicated thrice, giving a total of 36 plots. Plants were spaced 20 cm × 5 cm. The field was prepared by thorough ploughing, weed removal, and application of 15-20 t/ha farmyard manure. Fungicide-treated seeds were sown in rows at a depth of 2-3 cm. All farming practices were implemented during the crop grown period. Thinning was performed at 15-20 DAS to ensure an optimal plant-to-plant distance of 5-10 cm. Weeding was done first at 20-25 DAS and as necessary thereafter. Irrigation was given immediately after sowing and then at 7-10 day intervals, while fertilizer was applied at recommended doses, with nitrogen split half at sowing and remainder after the first cutting. GA_3 was applied as foliar spray at 25 DAS during the active vegetative growth stage. Pest and disease control involved neem products or Dimethoate for insect pests and Mancozeb for fungal diseases as per requirements. Irrigation was managed using a sprinkler system to ensure uniform water distribution throughout the growing period. Only one cutting was done at 45 DAS to assess the treatment effects on growth, yield, and quality parameters. Statistical analysis was carried out using analysis of variance (ANOVA), and means were separated using the least significant difference (LSD) test at a 5% level of significance. The interactions between both factors were analyzed to assess their combined effect on palak growth.

Results

Effect of GA_3 levels

Application of GA_3 significantly influenced the growth parameters of palak, with the magnitude of effects varying among GA_3 levels and varieties. Among the GA3 treatments, plants treated with 200 ppm GA_3 (G2) exhibited the highest values for all growth parameters, recording a plant height of 24.22 cm, 10.42 leaves per plant, a leaf width of 10.45 cm, a leaf length of 16.12 cm, a maximum leaf area of 85.06 cm², and a leaf area index of 0.85. The next best performance was observed in the 300 ppm GA_3 level (G3), which also manifested substantial enhancement in all growth metrics compared to control but was slightly inferior to 200 ppm. The 100 ppm GA_3 (G1) also showed a significant improvement over control (G0) across all studied parameters. The control treatment consistently recorded the lowest values, indicating the positive role of GA_3 application in palak growth.

Application of GA_3 had a significant impact on the yield parameters of palak. Among the GA_3 levels, treatment with 200 ppm (G2) resulted in the highest fresh leaf yield (18.15 t/ha) and dry leaf yield (2.18 t/ha), followed closely by the 300 ppm level (G3), which produced fresh and dry yields of 17.18 t/ha and 1.99 t/ha, respectively. Application at 100 ppm (G1) also enhanced both fresh (14.90 t/ha) and dry leaf yields (1.63 t/ha) compared to the control, whereas the control (G0) recorded the lowest yields (12.23 t/ha fresh, 1.14 t/ha dry).

Among GA_3 treatments, the highest gross return (Rs. 453,850/ha), net return (Rs. 325,866/ha), and benefit-cost (B:C) ratio of 2.55 were recorded for the 200 ppm GA_3 treatment (G2). The 300 ppm level (G3) also showed substantial returns with a gross return of Rs. 429,434/ha, net return of Rs. 299,451/ha, and a B:C ratio of 2.30. The 100 ppm GA_3 treatment (G1) produced a gross return of Rs.

372,513/ha, net return of Rs. 246,530/ha, and B:C ratio of 1.96, all significantly higher than the control (G0), which showed the lowest returns and a B:C ratio of 1.48.

Effect of varieties

- Regarding varietal performance, Pusa Bharti (V2) outperformed All Green (V1) and Jobner Green (V3) in all growth attributes, registering the tallest plants (22.40 cm), highest leaf count (9.52), maximum leaf width (9.50 cm), longest leaves (17.39 cm), largest mean leaf area (83.59 cm²), and the highest leaf area index (0.84). Jobner Green (V3) was next in performance, followed by All Green (V1), which showed the lowest values among varieties but still benefited from GA_3 treatments.
- For varietal effects, Pusa Bharti (V2) significantly outperformed the other varieties, achieving the highest fresh leaf yield (18.70 t/ha) and dry leaf yield (2.17 t/ha). This was followed by Jobner Green (V3) and All Green (V1), with All Green recording the lowest yield values among the varieties evaluated.
- Regarding varietal performance, Pusa Bharti (V2) yielded the highest gross return (Rs. 467,477/ha), net return (Rs. 340,602/ha), and B:C ratio (2.68), outperforming Jobner Green (V3) and All Green (V1). Jobner Green showed intermediate values, with a gross return of Rs. 369,469/ha, net return Rs. 242,444/ha, and B:C ratio 1.90, while All Green exhibited the lowest profitability metrics.

Summary

The study demonstrated that application of gibberellic acid (GA_3) significantly enhanced growth, yield, and economic returns of palak (*Beta vulgaris* var. *bengalensis*). Among GA_3 levels, 200 ppm consistently showed the most pronounced improvement in growth parameters such as plant height, number of leaves, leaf dimensions, leaf area, and leaf area index. This treatment also yielded the highest fresh and dry leaf production, surpassing both lower and higher GA_3 concentrations. In terms of economics, 200 ppm GA_3 resulted in the maximum gross and net returns and the best benefit-cost ratio, confirming its cost-effectiveness despite a modest increase in cultivation cost. Regarding varietal performance, Pusa Bharti outperformed All Green and Jobner Green in all growth and yield parameters, including plant height, leaf size, leaf area, fresh and dry yield, and substantially higher economic returns with the best B:C ratio. Jobner Green ranked second, while All Green recorded the lowest values, though still responsive to GA_3 treatment.

Discussion

The pronounced improvement in growth parameters at 200 ppm GA_3 is primarily due to the hormone's pivotal role in promoting cell elongation, division, and overall leaf expansion, processes that directly increase leaf area and leaf area index critical indicators of the plant's photosynthetic capacity. GA_3 functions by stimulating the biosynthesis of essential growth-related enzymes and the upregulation of gene expression involved in cell wall loosening and expansion, which leads to increased cell size and number (Singh *et al.*, 2025) [10]. This enzymatic activity facilitates greater biomass accumulation, manifested as taller plants, increased leaf number, and enlarged leaf surfaces, which directly enhance photosynthetic area and, consequently, biomass productivity (Aftab *et al.*, 2011) [1].

However, the diminished performance observed at 300 ppm compared to 200 ppm suggests that supraphysiological concentrations of GA_3 may induce hormonal imbalance or phytotoxic effects, inhibiting optimum growth. This response aligns with findings by El-Shazoly (2024) [3], who reported that excessive GA_3 can disrupt the endogenous hormonal balance, leading to reduced cell elongation and overall plant vigor. The concentration-dependent nature of GA_3's effects was further detailed by Han *et al.*, (2025) [5], who noted that while low to moderate doses enhance plant growth, surpassing the threshold concentration causes metabolic toxicity or overstimulation, triggering stress responses and growth retardation in leafy vegetables. Therefore, the observed drop in growth parameters at 300 ppm reflects this threshold phenomenon, marking 200 ppm as the optimum concentration that balances growth promotion without adverse hormonal disruption.

The superior response exhibited by the Pusa Bharti variety underscores the critical role of genetic potential and varietal sensitivity in modulating responsiveness to plant growth regulators. Pusa Bharti's enhanced leaf morphology, characterized by larger and thicker leaves, coupled with its physiological efficiency, such as higher chlorophyll content and nutrient uptake efficiency, contributes to its increased photosynthetic capacity (Khedkar *et al.*, 2023) [13]. Enhanced photosynthesis directly results in higher biomass accumulation and yield, outperforming All Green and Jobner Green varieties under identical GA_3 treatments. This finding is supported by studies from Filimon *et al.* (2023) [4], who emphasized the interaction effects of genotype and plant growth regulators, highlighting that cultivar-specific traits influence the magnitude of response to GA_3 foliar application.

Economically, the significant increases in both growth and yield parameters under optimal GA_3 application translate directly into enhanced gross and net returns, as well as improved benefit-cost (B:C) ratios, validating the practical and economic viability of GA_3 use in palak cultivation. Despite a marginal increase in input costs associated with hormone application, the proportional boost in crop productivity justifies these expenditures. These economic benefits align with observations by Ali *et al.*, (2024) [2], who demonstrated that judicious use of GA_3 in leafy vegetables optimizes resource use efficiency and profitability by maximizing biomass and marketable yield. Moreover, the balance achieved between biological efficacy and economic returns at 200 ppm GA_3 highlights this concentration as both agronomically and commercially optimal for palak production systems.

In summary, the integration of physiological, biochemical, and economic factors, supported by the literature, confirms that 200 ppm GA_3 efficiently enhances palak growth and yield through molecular and cellular growth stimulation while avoiding the deleterious effects observed at higher concentrations. Concurrently, varietal genetic attributes play a decisive role in defining the magnitude of growth regulator responsiveness, with Pusa Bharti exhibiting superior performance. Collectively, these findings coalesce to recommend the targeted use of 200 ppm GA_3, particularly in high-potential varieties like Pusa Bharti, to maximize sustainable production and profitability in palak cultivation.

Table 1: Effect of GA_3 levels and varieties on growth, yield and economics of palak

Treatments	Growth parameters						Yield parameters		Economics		
	Plant height (cm)	Number of leaves per plant	Leaf width (cm)	Leaf length (cm)	Leaf area (cm^2)	Leaf area index	Fresh leaf yield (t/ha)	Dry leaf yield (t/ha)	Gross return (Rs/ha)	Net return (Rs/ha)	B:C ratio (Net return basis)
Effect of GA_3 levels											
G_0-Control	18.58	6.84	6.38	13.25	42.85	0.43	12.23	1.14	305842	182358	1.48
G_1-100 ppm	20.38	8.49	8.55	15.38	66.75	0.67	14.90	1.63	372513	246530	1.96
G_2-200 ppm	24.22	10.42	10.45	16.12	85.06	0.85	18.15	2.18	453850	325866	2.55
G_3-300 ppm	22.14	9.31	9.54	15.30	73.97	0.74	17.18	1.99	429434	299451	2.30
SEm±	0.35	0.34	0.41	0.67	5.14	0.05	0.88	0.10	21989	21989	0.17
CD @ 5%	1.01	1.01	1.19	1.97	15.06	0.15	2.58	0.30	64490	64490	0.51
Effect of varieties											
V_1-All Green	20.57	8.19	8.20	13.07	54.65	0.55	13.37	1.43	334282	207607	1.63
V_2-Pusa Bharti	22.40	9.52	9.50	17.39	83.59	0.84	18.70	2.17	467477	340602	2.68
V_3-Jobner Green	21.01	8.59	8.50	14.57	63.24	0.63	14.78	1.61	369469	242444	1.90
SEm±	0.30	0.30	0.35	0.58	4.45	0.04	0.76	0.09	19043	19043	0.15
CD @ 5%	0.88	0.88	1.03	1.71	13.05	0.13	2.23	0.26	55850	55850	0.44

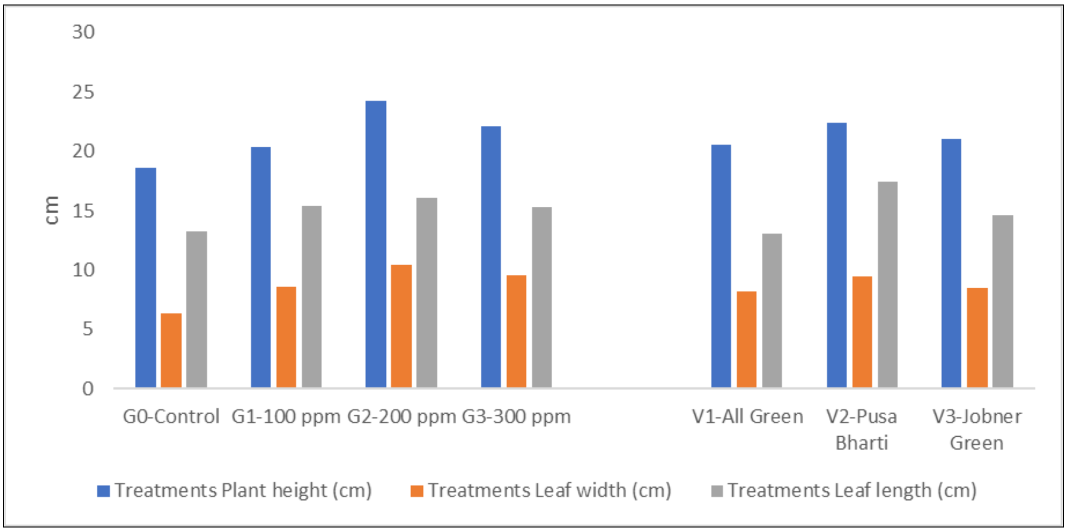

Fig 1: Effect of GA_3 levels and varieties on growth parameters of palak

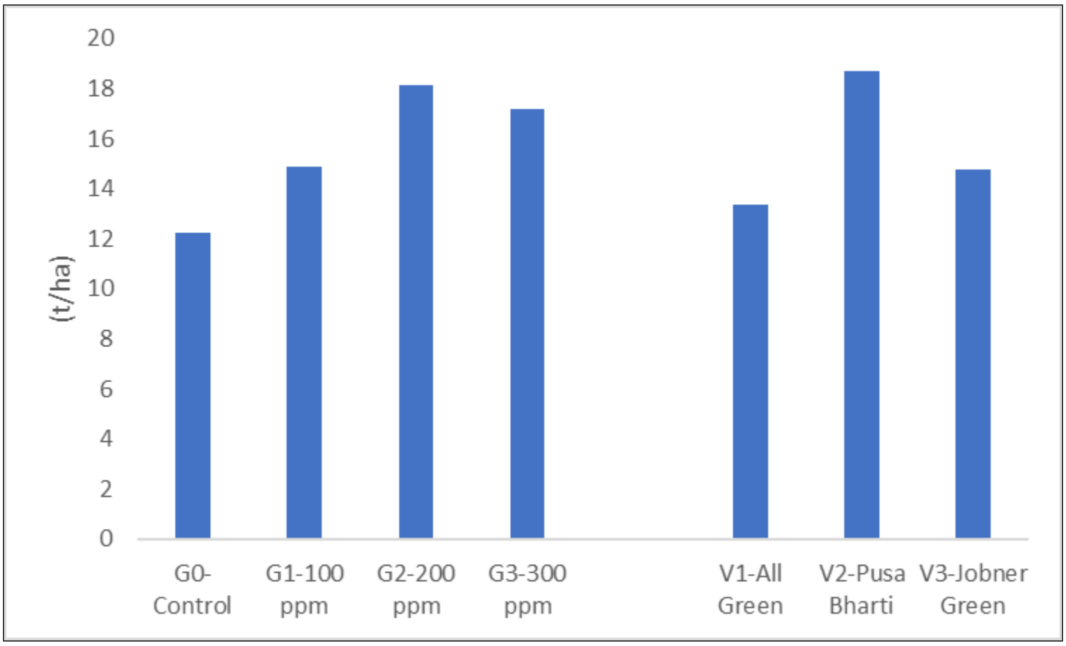

Fig 2: Effect of GA_3 levels and varieties on green leaf yield (t/ha) of palak

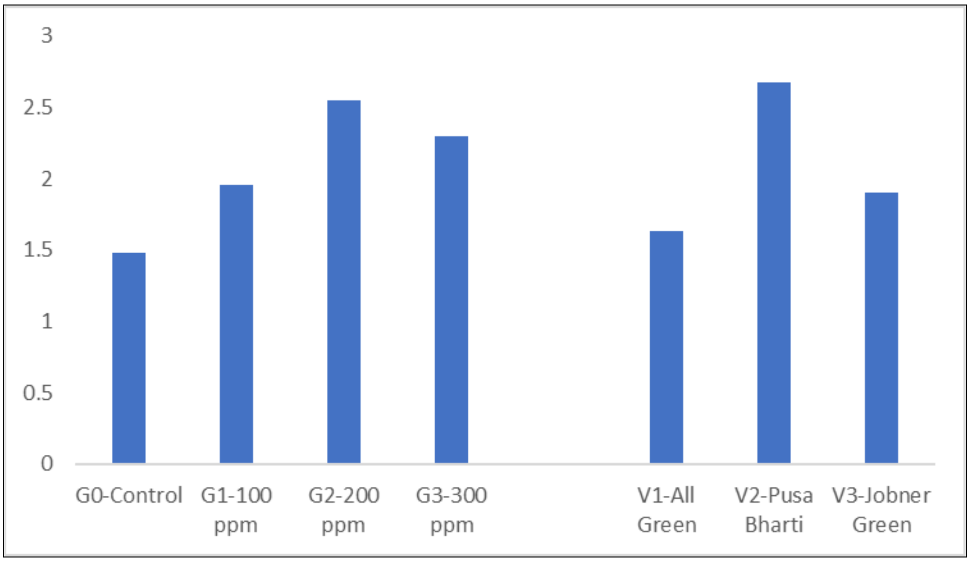

Fig 3: Effect of GA_3 levels and varieties on B:C ratio of the treatment

Conclusion

The application of GA_3 significantly improved the growth, yield, and economic returns of palak. The 200 ppm GA_3 treatment showed the highest plant height, leaf number, leaf dimensions, leaf area, and leaf area index, indicating optimal vegetative growth stimulation. Though the 300-ppm level also enhanced growth and yield compared to control, its effectiveness was slightly lower than 200 ppm, suggesting a threshold beyond which GA_3 may negatively affect growth. Control plants exhibited the lowest growth and yield parameters.

In yield terms, 200 ppm GA_3 produced the highest fresh and dry leaf yields. Among varieties, Pusa Bharti consistently outperformed All Green and Jobner Green, showing greater biomass and higher yield. Economically, 200 ppm GA_3 resulted in the best gross and net returns and benefit-cost ratio, with Pusa Bharti also proving the most profitable cultivar.

Overall, GA_3 at 200 ppm is the most effective concentration for maximizing palak growth, yield, and profitability. Increased GA_3 levels beyond this point reduce benefits, highlighting the importance of optimizing hormone dosage. Selecting a responsive variety like Pusa Bharti further enhances productivity and economic gains.

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