

ORIGINAL ARTICLE

Crop Ecology and Physiology

Efficacy evaluation of novel actives Carrabiitol on growth and yield of soybean in different agro-ecological zones

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Abstract

As soybean (*Glycine max* L.) demand continues to rise amid growing climate uncertainty, enhancing the crop's resilience to water scarcity and flooding has become vital for sustainable production. The present study investigated impact of foliar applications of Carrabiitol, a patented oligosaccharide polyol, on soybean growth and yield across the diverse agro-ecological zones of Himachal Pradesh, India. The study encompassed three ecological zones: Zone I (Akrot), a sub-montane low-hill subtropical zone; Zone II (Palampur), a mid-hill sub humid zone and Zone III (Awarana), high-hill temperate wet zone. Treatments consisted of four Carrabiitol application rates: T1 (50 g ha⁻¹), T2 (75 g ha⁻¹), T3 (125 g ha⁻¹), and T4, the control (0 g ha⁻¹). Soybean growth and yield responses were evaluated based on plant height, number of branches per plant, number of pods per plant, number of seeds per pod, seed weight, seed yield, straw yield, and harvest index. Notably, soybean response to the application of 75 and 125 g Carrabiitol ha⁻¹ outperformed the untreated control treatment in all climate zones. The soybean response to Carrabiitol was in the sub-montane low-hill subtropical zone (Zone II), and the most effective treatment was Carrabiitol at 125 g ha⁻¹. In Zone I, where temperatures were higher and rainfall was lower compared to Zone II, this treatment increased soybean seed yield by 54.3%. These findings suggest that Carrabiitol can help mitigate the adverse impact of unfavorable climatic conditions.

Plain Language Summary

This study explored how Carrabiitol, a patented sugar-based plant formulation, affects soybean growth and yield in different regions of Himachal Pradesh, India. Trials were conducted in three zones with varying climates: low hills (Zone I), mid hills (Zone II), and high hills (Zone III). Soybean crops were treated with different Carrabiitol doses—50, 75, and 125 grams per hectare—compared to a

Abbreviations: DAS, days after sowing; LSD, least significant difference; SEM, standard error of mean.

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control group without the spray. Researchers measured plant height, number of branches, pods, seeds, and overall yield. Results showed that the 75 and 125 g/ha doses significantly boosted plant growth and yield across all zones. The best overall growth was observed in the mid hills (Zone II), likely due to favorable weather. However, the highest seed yield increase (54.27%) occurred in the low hills (Zone I), where conditions were hotter and drier. The study concludes that Carrabiitol helps soybeans cope with climate stress and improves productivity.

1 | INTRODUCTION

Soybean (*Glycine max* L.) is an important leguminous oilseed crop that is cultivated using an array of cropping systems under a wide range of agro-ecological conditions (Kaur et al., 2020). India ranks fifth in soybean cultivation after Brazil, United States, Argentina, and China (Agarwal et al., 2013). In India, the production of soybean for the year 2020–2021 is projected at around 12.9 metric tons from an area of 12.8 million ha. India is divided into six agro-climatic zones, namely, northern plain zone, northern hill zone, eastern zone, northeastern hill zone, southern zone, and central zone, for cultivation of soybean (Dupare, 2023). Each of these zones has different limiting factors ranging from high temperatures to erratic rainfall (Agarwal et al., 2013; Kaur et al., 2020). For small farms, techniques to reduce these yield barriers are needed.

Soybean contains from 32% to 42% of protein and from 18% to 20% of oil contents. These values are higher than many other legumes or pulses (Cheng et al., 2019). In addition, it fixes atmospheric nitrogen through a symbiotic association with rhizobia (Adjei-Nsiah et al., 2022). Soybean crops are cultivated in environments ranging from frigid to thermic. However, it grows best in warm temperate climates with adequate water (Coleman et al., 2021).

In many areas soybean yields have been increasing (Joshi et al., 2025). In central United States, yield increases are attributed to better genetics and improved soil health. In India, soybean yield increases due to the increased use of chemical fertilizers and the use of high-yielding varieties. However, this increased use of chemical fertilizers has the potential to have a detrimental impact on environmental health. Therefore, it is crucial to seek out and implement sustainable solutions that do not have a negative impact on the environment.

Soybeans are extremely vulnerable to moisture-deficient conditions during the blooming, legume formation, and seed development stages. Water stress is a major abiotic issue that limits the growth of soybeans and can reduce yields by up to 40% or more (El Sabagh et al., 2015). Similarly, waterlogging is a widespread phenomenon drastically reducing the growth and production of soybean in many regions of the

world, mostly due to the occurrence of flat topography, high water tables, and poor drainage in clay-like soils (Jitsuyama, 2017). Oxidative stress is one of the major consequences in plants exposed to water-deficit or waterlogging conditions, resulting from massive generation of reactive oxygen species in different forms and in different subcellular compartments (Hasanuzzaman et al., 2022). This oxidative stress can be overcome by application of different osmo-protectants.

Generally, plants release low molecular weight biomolecules to combat oxidative stress, known as osmolytes, such as sugar, sugar alcohols, proline, and betaines, among others. These compounds have the potential to help plants tolerate abiotic stresses. However, little research has been conducted to support this hypothesis. Therefore, research is needed to explore the impact of organic osmolytes derived from natural sources on plant resilience. Effect of Carrabiitol, a novel oligosaccharide polyol composition, was previously evaluated on fenugreek (*Trigonella foenum-graecum*), sorghum (*Sorghum bicolor*), and tomatoes (*Solanum lycopersicum*) (Patel et al., 2023, 2024).

Carrabiitol is a novel, pH-agnostic, and compositionally stable oligosaccharide polyol, uniquely formulated without bioactive contaminants and designed to function as an osmo-protectant. It represents a new class of biostimulants known as Single Biostimulant Molecules, which offer a significant departure from traditional, multi-component formulations that often comprise ill-defined mixtures of bioactive substances. Derived from biological sources, Carrabiitol has a well-characterized mode of action and confers enhanced tolerance to abiotic stresses by promoting the endogenous release of osmolytes such as proline, sucrose, and glucose, thereby preserving cellular osmotic balance and protecting membranes and macromolecules under adverse conditions (Patel et al., 2024). Its agronomic efficacy has been validated in accordance with CEN/TS 17700, and it has been certified under CE marking (PFC 6B—Non-microbial Plant Biostimulant) as per EU Regulation FPR 2019/1009.

This research had promising results and suggested that Carrabiitol can improve plant tolerance to abiotic stress. Similar research is needed in soybeans. Therefore, the objective of this study was to investigate the impact of foliar applications

of Carrabiitol on soybean growth and yield across the diverse agro-ecological zones in Himachal Pradesh, India.

2 | MATERIALS AND METHODS

2.1 | Experimental design and treatments

Carrabiitol is a patented product that was prepared by the Agri Biochem Research Lab, Panoli, Gujarat (Shah & Patel, 2020). The study was conducted in three ecological zones where the soybean cultivar Harit Soya was planted in 2022. The three ecological zones were:

1. Zone I: Sub-montane low-hill subtropical zone (Akrot, 31°28'05.5" N, 76°16'10.0" E)
2. Zone II: Mid-hill sub-humid zone (Palampur, 32°07'11.3" N, 76°33'19.0" E)
3. Zone III: High-hill temperate wet zone (Awarna, 31°51'06.8" N, 77°09'02.7" E)

A preliminary study was carried out to optimize Carrabiitol doses and based on those results, three doses were selected. 50 g ha⁻¹ (T1), 75 g ha⁻¹ (T2), and 125 g ha⁻¹ (T3) Carrabiitol doses along with control (0 g ha⁻¹, T4) were selected to check the efficacy on growth and yield of soybean. The experiment was conducted in a randomized block design with three replications. Each plot measured 20 m², with a plant density of 10–15 cm and row spacings of 45 cm.

Soybean seeds (approximately 0.5 million seeds ha⁻¹) were sown on June 18, 20, and 24, 2022 at Palampur, Awarna and Akrot zones, respectively with the first rain in well drained sandy loam soil having pH 5–6.8. nitrogen, phosphorus, and potassium fertilizer was given in a ratio of 20:60:40 kg ha⁻¹ in high rain fall area, whereas 20:30:30 was used in low rainfall area. To control weed, Goal (oxyflourfen) Pre-Targa Super + Quirin was sprayed at the rate of 1.0 L ha⁻¹.

Carrabiitol treatments were applied at (1) two to three leaf stage (2) flowering stage and (3) pod formation stage with a spray volume of 500 L ha⁻¹ using Knapsack sprayer fitted with hollow cone nozzle.

2.2 | Data collection

The growth parameter, plant height (cm) was recorded at 30 DAS (days after sowing), 60 DAS, 90 DAS, and at the time of harvest. The yield parameters, namely, number of branches per plant, number of pods per plant, number of seeds per pod, seed weight (g), seed yield (kg ha⁻¹) and straw yield (kg ha⁻¹) were assessed at the time of harvest. The harvest index was calculated following Elobeid (2010) using the following equation:

Core Ideas

- Carrabiitol, a novel active formulation, enhanced soybean growth and yield across diverse agro-ecological zones.
- Soybean exhibited highest response to Carrabiitol application at 75 and 125 g ha⁻¹.
- Carrabiitol increased maximum seed yield by 54.3% in the low-hill subtropical zone, where temperature was higher.
- Carrabiitol increased pod formation by 22% under water-deficient condition.
- Foliar application of Carrabiitol aided soybean plants in alleviating the detrimental effect of climate change.

$$\% \text{ harvest index} = 100 \times (\text{Seed yield per plant} / \text{Above ground biomass})$$

Soil samples collected at a depth of 0–15 cm from the study sites were analyzed for pH, electrical conductivity (EC), organic carbon (g kg⁻¹), available nitrogen (kg ha⁻¹), available phosphorous (kg ha⁻¹) and available potassium (kg ha⁻¹). The details of the methods are provided in Table 1.

2.3 | Data analysis

The experimental data of each parameter at each agro-ecological zone was analyzed by one-way analysis of variance (ANOVA) and the significant effects were evaluated at $p \leq 0.05$. The significant difference between treatment means was compared by Fisher's post hoc LSD (least significant difference) tests. The standard error of mean and LSD at 5% probability was reported for each ANOVA analysis. The results of all four treatments and three locations were used for factorial Anova using Design-Expert software (Design-Expert 7.0.0, State Ease, Inc.). Mean values were used to generate interaction chart between Carrabiitol treatments and zone.

3 | RESULTS

3.1 | Climatic conditions

During the study period, the temperature of the three sites was moderate from June to August and then declined from September to October. The highest temperature was recorded in June, while the lowest temperature occurred in October, in

TABLE 1 Soil attributes and methods employed for their valuation.

Attributes	Details
pH	Glass electrode pH meter, (Jackson, 1967)
EC	Electrical conductivity (dS/m), digital electrical conductivity meter (Jackson, 1973)
OC (%)	Organic carbon (%), rapid titration method (Walkley & Black, 1934)
N	Available nitrogen (kg ha ⁻¹), alkaline permanganate method, (Subbiah & Asija, 1956)
P	Available phosphorus (kg ha ⁻¹), ammonium molybdate blue color method, (Olsen et al., 1954)
K	Available K (kg ha ⁻¹), neutral normal ammonium acetate extraction method, (AOAC, 1970)

TABLE 2 Meteorological data for the period of study at three different zones.

	Temperature (°C)		Relative humidity (%)			Rainfall (mm)	Number of rainy days
Month	Max	Min	M	E	Mean		
Zone I (Akrot)							
June	39.5	24.4	NA			44.8	6
July	32.7	24.8	NA			272.7	11
August	32.9	25.3	NA			79.4	7
September	31.4	22.5	NA			206.4	10
October	29.0	17.0	NA			2.8	1
Zone II (Palampur)							
June	30.9	19.4	57.4	46.7	52.1	130.6	9
July	27.4	19.8	92	83.8	87.9	587.4	25
August	27.1	19.3	89.8	83.1	86.5	853.8	23
September	26.3	17	87.4	80.8	84.1	254.2	16
October	25	12.5	76.7	59.4	68.1	38.6	5
Zone III (Awarua)							
June	32.4	15.2	76	39	57	67.5	12
July	31.2	20.9	85	58	72	172	19
August	30.8	20.5	86	56	71	190.6	17
September	30.1	17.3	83	53	68	67.2	8
October	27.7	9.1	86	44	65	54.5	4

Abbreviations: E, evening; M, morning; NA, not applicable.

TABLE 3 Soil analysis of samples collected from the three agro-ecological zones.

Soil parameters		Zone I (Akrot)	Zone II (Palampur)	Zone III (Awarua)
pH		6.80	5.54	5.43
Electrical conductivity	dS m ⁻¹	1.382	0.284	0.248
Organic carbon	g kg ⁻¹	7.6	10.6	12.6
Available nitrogen	kg ha ⁻¹	245.3	350.4	316.7
Available phosphorus		28.6	18.2	14.6
Available potassium		268.0	246.4	226.2

each zone. Relative humidity exceeded 50% throughout the study period in Zones II and III. October received the least rainfall compared to other months. Detailed climatic data for the studied zones are presented in Table 2.

Soil data for each zone are presented in Table 3. Soil parameter results reveal distinct differences among the zones. Zone I

has a slightly neutral pH, whereas Zones II and III have acidic pH. The EC in soil of Zone I, at 1.382 dS m⁻¹, indicates moderate salinity, which may impede water absorption and cause nutrient imbalances in plants. In contrast, Zones II and III have EC values ranging from 0.24 to 0.28 dS m⁻¹, indicating non-saline soil. Organic carbon was found to be moderate in Zone I

TABLE 4 Effect of different dosage of Carrabiitol on growth parameters of soybean.

Plant height (cm)					
Zone	Treatments	30 DAS	60 DAS	90 DAS	At harvest
Zone I	T1	37.10a	75.40a	93.57a	98.67a
	T2	38.10a	77.80a	96.58a	102.00a
	T3	38.70a	78.50a	97.70a	104.30a
	T4	35.00a	58.75b	76.99b	81.58b
	SEM	0.81	4.67	4.82	5.15
	LSD	NS	8.76	9.89	12.41
Zone II	T1	35.30ab	78.40a	102.30a	106.80a
	T2	37.20ab	81.20a	107.00a	112.00a
	T3	39.10ac	83.00a	109.50a	115.30a
	T4	32.30b	62.30b	81.83b	88.00b
	SEM	1.45	4.74	6.29	6.10
	LSD	4.63	7.92	9.40	9.17
Zone III	T1	27.30ab	57.80ab	76.87a	80.57a
	T2	28.00b	60.60a	82.00ab	85.67ab
	T3	28.80b	63.50a	85.30b	88.53b
	T4	25.67a	51.77b	66.67c	70.50c
	SEM	0.67	2.50	4.07	3.96
	LSD	2.20	6.29	5.74	5.51

Note: Means followed by the same letter within each DAS are not significantly different ($p < 0.05$) according to the LSD test.

Abbreviations: DAS, days after sowing; LSD, Least Significance Difference; NS: non-significant; SEM, standard error of mean.

but adequate in Zones II and III. Available nitrogen was sufficient in all three zones. Available phosphorous was moderate in Zone I but deficient in Zones II and III. Available potassium content was adequate in all three zones.

3.2 | Growth and yield attributes of soybean

The results of soybean growth attributes are presented in Table 4. The plant height significantly increased from 30 to 90 DAS across all treatments (T1–T4) in the three studied zone, with no significant increase thereafter.

Foliar application of Carrabiitol significantly enhanced plant height compared to control plants (T4) ($p < 0.05$). Among Carrabiitol treatments, T1 resulted in the shortest plants, while T2 and T3 showed similar heights with no significant difference. In each zone, T3 treatment produced tallest plant. In Zone I, no significant difference was observed between the control and Carrabiitol-treated plants at 30 DAS. In Zone II, higher dosage of Carrabiitol (T3) effectively enhanced plant height at 30 DAS, while in Zone III, even the lower dosage (T2) significantly enhanced plant height along with T3 at 30 DAS ($p < 0.05$).

At 60 DAS, T3 (125 g ha⁻¹) treatment increased plant height by 33.61%, 33.22%, and 22.66% in Zones I, II, and III, respectively. Similarly, at 90 DAS, T3 treatment increased plant height by 26.90%, 33.81%, and 27.94% in Zones I, II,

and III, respectively. Table 4 shows that Carrabiitol treatments in Zone II resulted in significantly taller plants compared to Zones I and III.

Zone II recorded the highest number of branches and pods per plant, while Zone III has the lowest (Figure 1a,b). Across all experimental zones, T2 and T3 treatments significantly increased the number of branches compared to the control (T4) ($p < 0.05$) with no significant difference among different Carrabiitol applications. In Zone II, all treatments (T1–T3) significantly enhanced branch numbers compared to the control ($p < 0.05$). In contrast, Zone I and III showed no significant differences in branch numbers between T1 and control (T4).

Figure 3e illustrates that Zone II was the most responsive to treatments, with non-uniform effects across different zones. Compared to the control (T4), treatment T3 increased branch number by 23.88%, 24.86%, and 21.50% in Zone I, II, and III, respectively. In Zones II and III, all treatments significantly enhanced pod number compared to the control ($p < 0.05$). In Zone I, only T2 and T3 treatments showed significantly higher pod numbers compared to the control ($p < 0.05$).

Figure 3f illustrates that Zone III has lowest response compared to Zone I and Zone II. Treatment T3 increased pod numbers by 17.88%, 17.92%, and 22.22% in Zone I, II, and III respectively, compared to the control. In Zone II and III, all Carrabiitol treatments significantly increased seed numbers compared to the control ($p < 0.05$). However, in Zone I, no

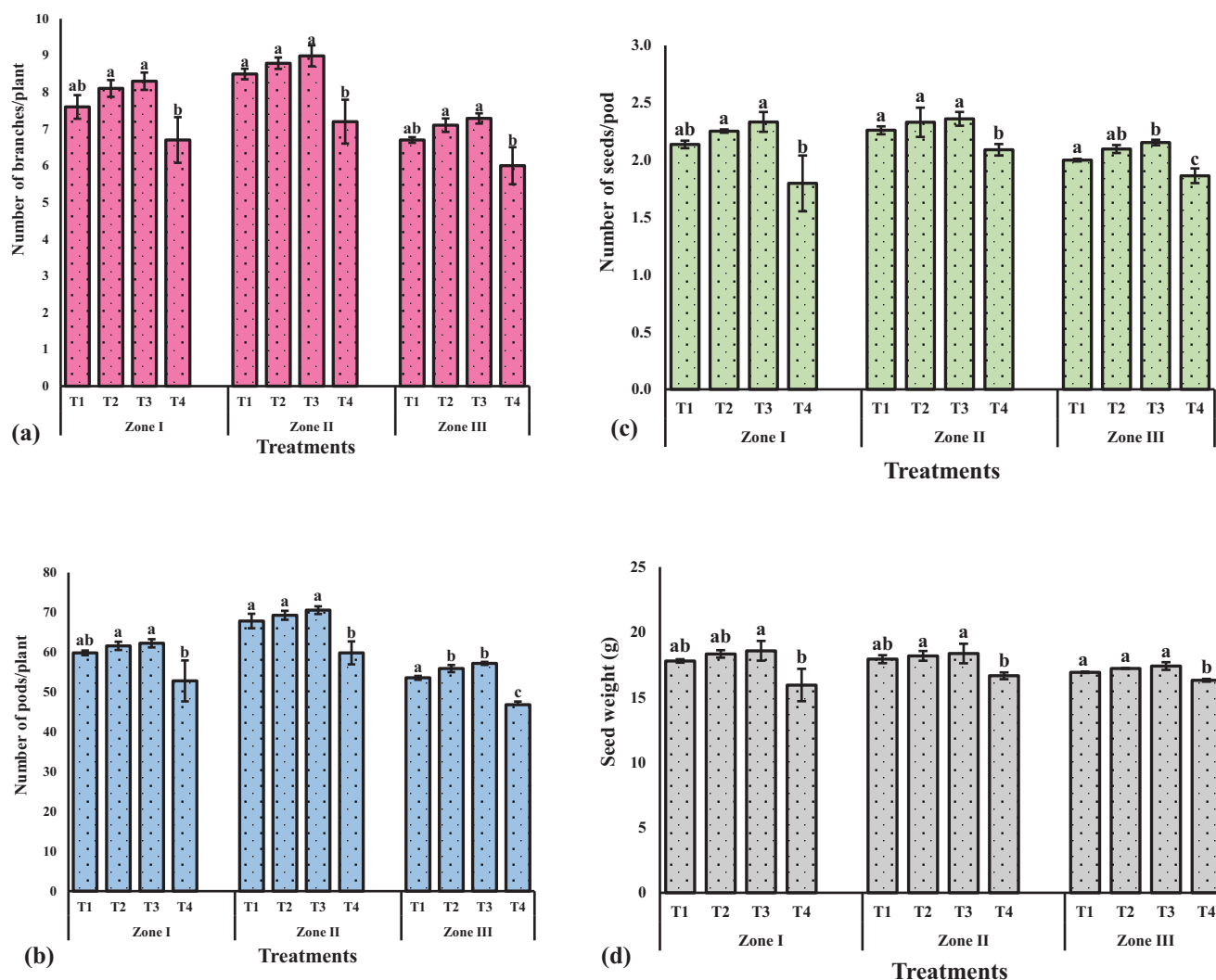


FIGURE 1 Effect of different treatment of Carrabiitol on (a) number of branches; (b) number of pods; (c) number of seeds/pod; and (d) seed weight (g) of soybean evaluated at three agro-ecological zones. The agro-ecological zones included Zone I: Submontane low-hill subtropical zone, Zone II: Mid hill-subhumid zone, and Zone III: High-hill temperate wet zone. Treatments consisted of four Carrabiitol application rates: T1 (50 g ha⁻¹), T2 (75 g ha⁻¹), T3 (125 g ha⁻¹), and T4, the control (0 g ha⁻¹). The means not sharing a common letter are significantly different by post hoc least significant difference (LSD) test at 5% level of significance. Data presented are means $\pm$ standard errors.

significant difference in seed numbers was observed between treatment T1 and the control (T4).

Under Carrabiitol treatment T3 (125 g ha⁻¹), seed numbers increased by 29.44%, 12.92%, and 15.59% in Zones I, II, and III, respectively, compared to the control (Figure 1c). Figure 3g illustrates that Zones II and I responded similarly to Carrabiitol Treatment T3. Across all zones, T3 treatment yielded similar numbers of branches, pods, and seeds as T2 treatments. Seed weights were significantly enhanced in T3 (Zone I), T2 and T3 (Zone II), and T1, T2, and T3 (Zone III) compared to the control (T4) ($p < 0.05$). T3 treatments increased seed weight by 16.48%, 10.27%, and 6.70% in Zones I, II, and III, respectively, compared to the control (T4) (Figure 1d). Figure 3h shows that Zone I was most responsive, followed by Zone II.

Carrabiitol treated plants showed significant enhancements in seed and straw yields compared to control in each zone ($p < 0.05$). Across treatments, Zone II consistently yielded the highest seed and straw yields, followed by Zone I and then Zone III (Figure 2a,b). Compared to the control (T4), T3 treatment increased seed yields by 54.38%, 46.67%, and 53.58% in Zones I, II, and III, respectively. Straw yields were enhanced by 24.70%, 40.00%, and 41.97% in T3 of Zones I, II, and III, respectively. Notably, seed and straw yields under T3 were comparable to those under T2 in each zone.

Figure 3i,j illustrates that Zone II achieved the highest seed and straw yield with increasing Carrabiitol doses, surpassing Zone I and Zone III.

Analysis of mean values revealed no significant differences in seed and straw yields among different

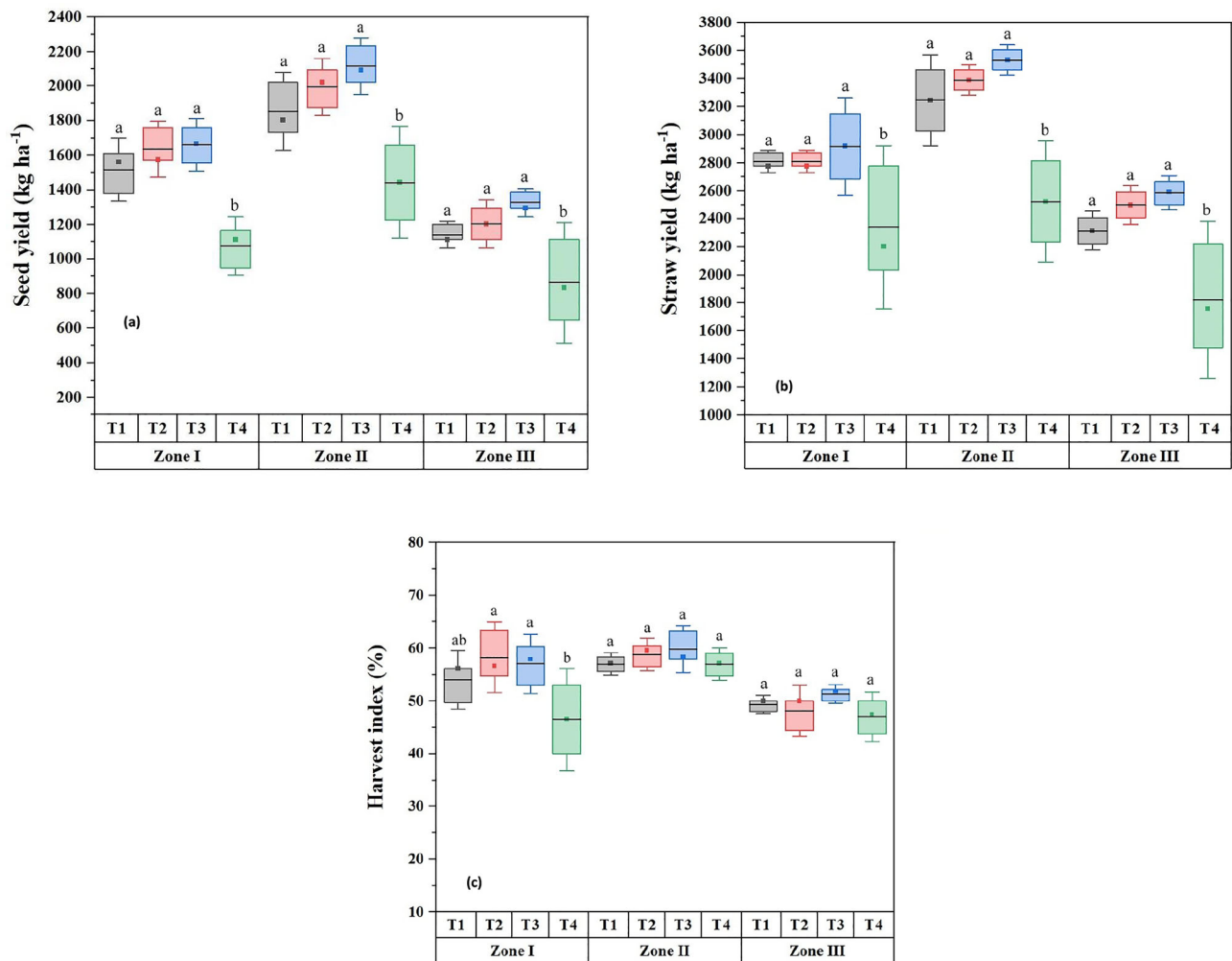


FIGURE 2 Box plot showing the effect of different treatments of Carrabiitol on (a) seed yield (kg ha⁻¹); (b) straw yield (kg ha⁻¹); and (c) harvest index (%) of soybean evaluated at three different agro-ecological zones. The agro-ecological zones included Zone I: Submontane low-hill subtropical zone, Zone II: Mid hill-subhumid zone, and Zone III: High-hill temperate wet zone. Treatments consisted of four Carrabiitol application rates: T1 (50 g ha⁻¹), T2 (75 g ha⁻¹), T3 (125 g ha⁻¹), and T4, the control (0 g ha⁻¹). The means not sharing a common letter are significantly different by post hoc least significant difference (LSD) test at 5% level of significance.

Carrabiitol applications within each zone. The harvest index was similar across zones. In Zones II and III, no significant differences in harvest index were observed among Carrabiitol applications. However, in Zone I, the harvest index was significantly enhanced by 25.30% and 22.66% in T2 and T3, respectively, compared to control T4 ($p < 0.05$) (Figure 2c).

4 | DISCUSSION

Soybean is typically cultivated in warm areas of India's tropics, subtropics, and temperate zones. Ideal temperature for soybean production ranges from 20°C to 30°C, while temperatures above 35°C can limit yield. Adequate moisture, with 400–500 mm of water per season, is essential for productive yields.

Specifically, high moisture levels are critical during germination, blossoming, and pod formation, whereas dry weather is necessary for ripening. Even with minimal in-crop rain (180 mm), soybeans can still grow and produce, albeit with a 40%–60% yield reduction compared to ideal conditions. The optimal rainfall for maximum soybean production ranges from 500 to 1000 mm (ASCI, 2023). In the present study, climatic conditions were found to be different during the studied period in each zone, which was the reason behind selecting different zones of Himachal Pradesh to evaluate the effect of Carrabiitol on the yield of soybean under climate change.

Extreme temperatures, reaching 39.5°C and 24.4°C during seed germination, characterized the submontane low-hill subtropical zone (Zone I). Throughout the soybean life cycle, high temperatures and inadequate rainfall (2.8–272.7 mm) hindered optimal production. Consequently, soybean seed yield

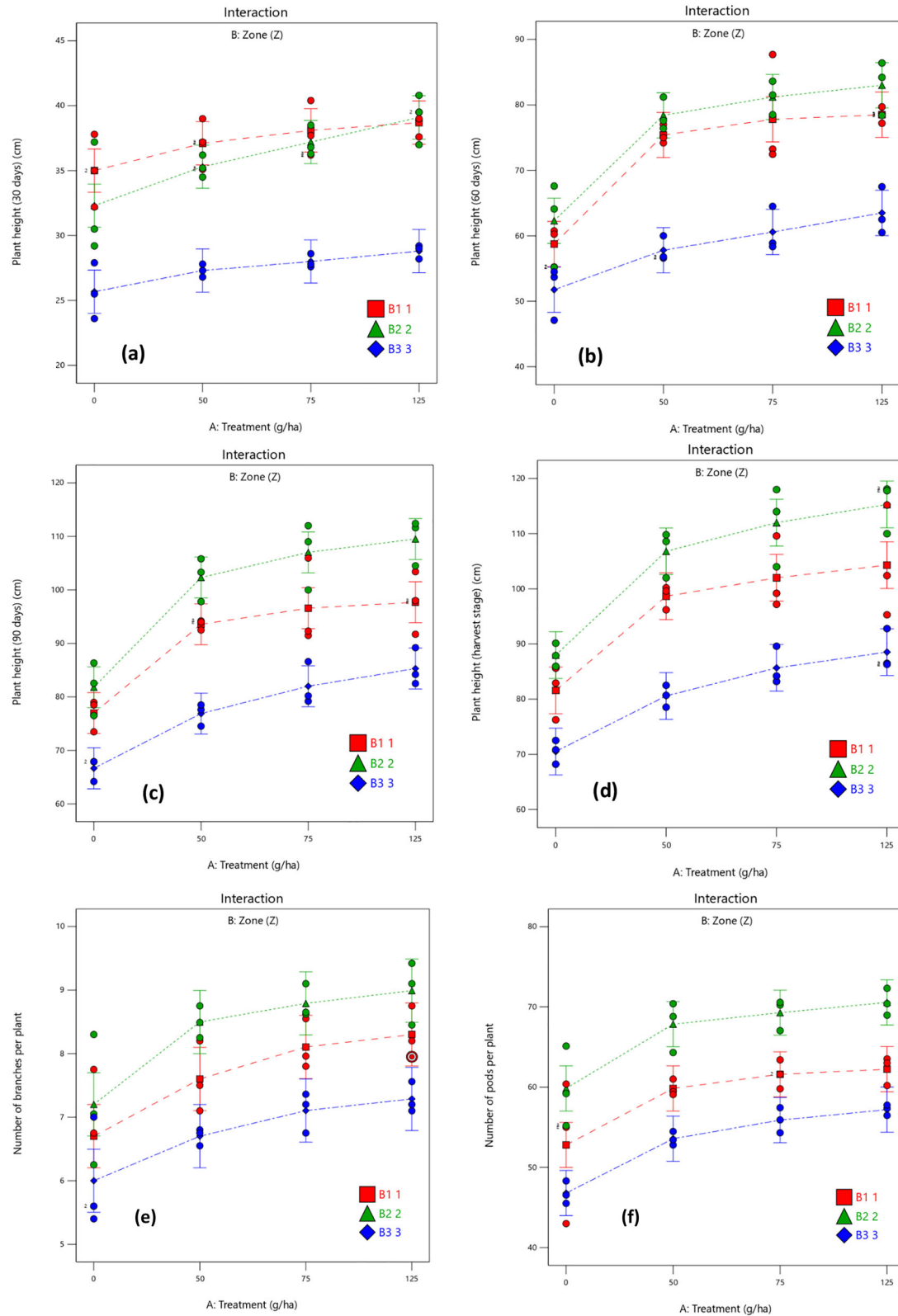


FIGURE 3 Interactive charts between different treatment of Carrabiitol and three agro-ecological Zones, on (a, b, c, and d) plant height at 30 days after sowing, 60 days after sowing (DAS), 90 DAS, and at harvest stage; (e), number of branches; (f), number of pods; (g), number of seeds/pod; (h), seed weight (g); (i) seed yield (kg ha^{-1}); and (j) straw yield (kg ha^{-1}). Evaluation was carried out at three agro-ecological zones. B1 1 (Red) represents Zone I: Submontane low-hill subtropical zone; B2 2 (Green) represents Zone II: Mid hill-subhumid zone; and B3 3 (Blue) represents Zone III: High-hill temperate wet zone. The vertical error bars indicate variability or confidence intervals. Non-parallel lines indicate an interaction between treatment and zone.

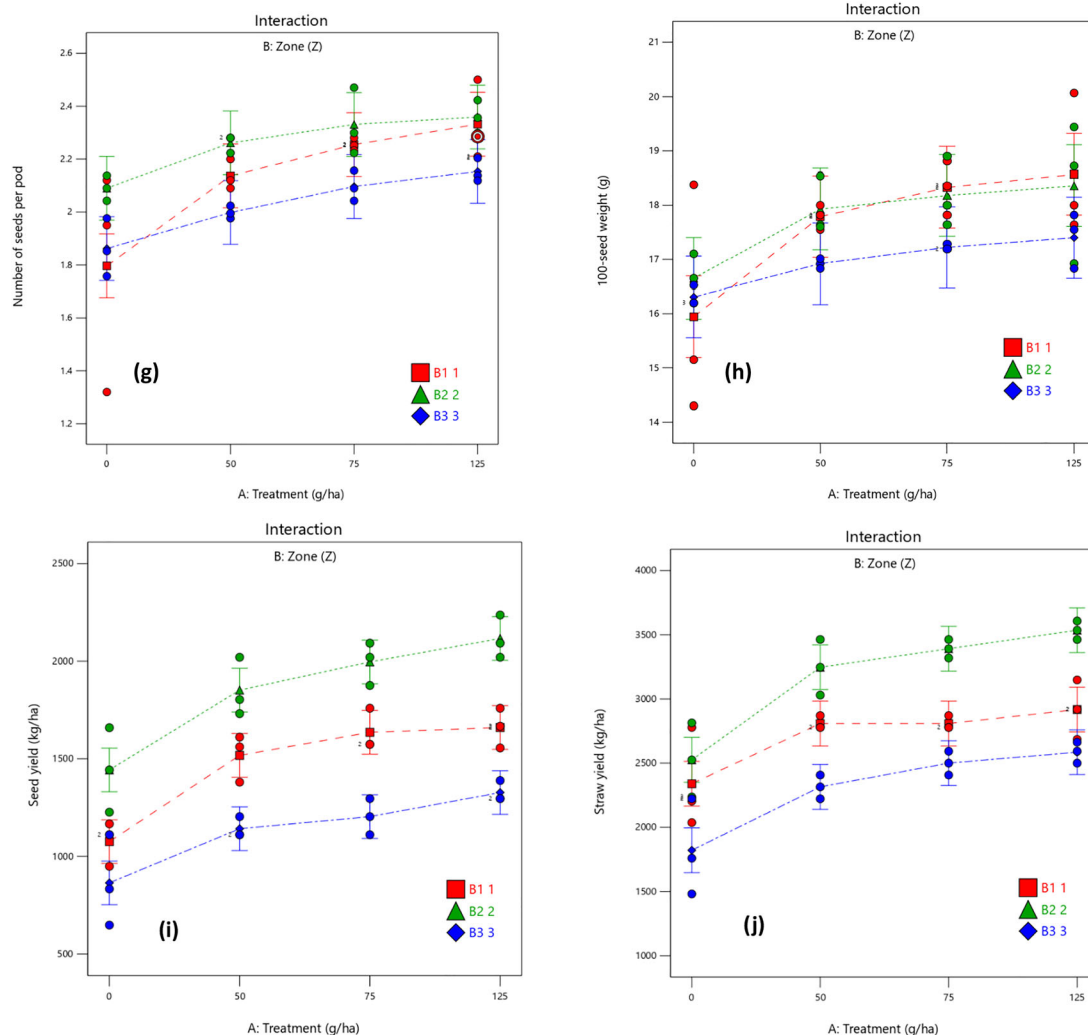


FIGURE 3 Continued

plummeted by 25.46% compared to Zone II, the mid hill sub-humid zone in Palampur. In contrast, Zone II received optimal rainfall (38.6–853.8 mm) with 78 rainy days and experienced favorable temperatures (12.5°C–30.9°C), supporting healthier soybean production. Additionally, the non-saline soil, higher organic carbon content, and available nitrogen and potassium in Zone II, Palampur, created a favorable environment for optimal soybean production (Table 3). In contrast, Zone III, the high-hill temperate wet zone in Awarna, experienced extreme temperature fluctuations, with a high of 32.4°C in June and a low of 9.1°C in October. These uncertain climatic conditions directly limited pod formation and soybean growth. Zone III experienced 60 rainy days with rainfall ranging from 54.5 to 190.6 mm. Compared to Zone II, the number of pods per plant decreased by 21.79% under Zone III's control treatment. These findings are supported by Anda et al. (2020), who noted that water deficits during soybean's reproductive stage shorten the effective period for pod formation and grain filling, resulting in lower pod formation. However, Carrabiitol

treatment T3 increased pod formation by 22.22%, nearly offsetting the reduction. This suggests that Carrabiitol is effective against uncertain climatic changes, likely due to its enhanced tolerance of abiotic stress through osmo-protectant activities, which maintain cell turgidity (Patel et al., 2024).

Seed yield was significantly reduced by 40.11% in Zone III compared to Zone II. This finding is consistent with Prado et al. (2016), who reported a 50% reduction in soybean grain yield due to water stress conditions. Inadequate available phosphorus content in Zone III may have also contributed to the lower seed yield. However, Carrabiitol treatments T2 and T3 mitigated this reduction, increasing seed yield by 39.35% and 53.58%, respectively.

In-depth observation revealed that the foliar application of Carrabiitol significantly enhanced soybean growth and yield compared to the control by mitigating adverse effects of unfavorable climatic conditions in Zone I. Moreover, under optimum conditions in Zone II, Carrabiitol treatment increased key yield parameters, including number of pods,

seeds per pod, seed weight, seed yield, and straw yield, ranging from 10.27% to 46.63%.

The results and interactive charts (Figure 3) demonstrate that foliar Carrabiitol application effectively enhanced soybean growth and yield in a dose-dependent manner across different climatic conditions. Treatment T3 (125 g ha⁻¹) yielded the highest growth and yield in each experimental zone, surpassing the control.

The tallest soybean plants were observed with Carrabiitol application (T3), with increased plant height likely attributed to elevated photosynthetic pigments, which boosted photosynthesis (Patel et al., 2024). This enhancement of photosynthesis contributed to improved vegetative growth in soybean.

Foliar application of Carrabiitol significantly enhanced soybean yield attributes, particularly seed and straw yield by 25%–50%, compared to control plants across different agro-ecological zones. These results align with the findings of Krishnamurthy et al. (2019), who reported that osmo-protectant application enhance the biological yield of soybean by up to 13%. Notably, Carrabiitol treatment increased seed weight by 16.49% under Zone I, despite challenging conditions including inadequate temperature, moderate soil salinity, and less rainfall. A comparative analysis of foliar Carrabiitol application across different agro-ecological zones reveal its osmo-protecting activity in mitigating oxidative stress in soybean plants under diverse conditions (dry, humid, or rain-fed). The application resulted in enhanced growth and yield compared to the control plants. These findings are supported by Hasanuzzaman et al. (2022), who reported the positive effect of osmo-protectants, salicylic acid, and kinetin on soybean growth and yield under waterlogging stress. The present research suggests that the foliar application of Carrabiitol aids soybean plants in alleviate detrimental effects of unfavorable climate conditions.

5 | CONCLUSIONS

Application of Carrabiitol at 75 and 125 g ha⁻¹ significantly improved growth and yield of soybean across three agro-ecological zones in Himachal Pradesh. This study demonstrates the efficacy of Carrabiitol in enhancing plant growth under unfavorable climatic conditions. The findings provide new insights into the application of Carrabiitol in soybean crops, highlighting its potential as a valuable tool in mitigating climate change-related stresses. Further research is recommended to explore its effect on various soybean varieties under different climatic conditions, considering the current climate change scenario. Long-term effects of Carrabiitol application should be investigated through multi-season studies to provide a comprehensive understanding of its benefits.

AUTHOR CONTRIBUTIONS

Femida Y. Patel: Conceptualization; formal analysis; validation; visualization; writing—original draft; writing—review and editing. **Suresh Kumar:** Data curation; investigation; methodology; resources; supervision; validation. **Sandeep Manuja:** Data curation; investigation; methodology; supervision; validation. **Minakshi:** Data curation; investigation; methodology; validation. **Neil J. Shah:** Conceptualization; funding acquisition; project administration; visualization.

CONFLICT OF INTEREST STATEMENT

The authors declare no conflicts of interest.

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