Research Article

Integrating plant growth regulators (PGRs) and nano-nutrients to alleviate fruit drop and enhance reproductive efficiency in ber cv. apple ber

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Abstract

Ber (*Ziziphus mauritiana* L.) is a significant fruit crop grown in dry and semi arid areas. However, low fruit retention and significant fruit drop frequently limit production, thereby lowering output in field settings. Therefore, increasing ber output requires the development of efficient agronomic techniques to enhance reproductive performance.The current study set out to assess how melatonin and nano-calcium nitrate together affected apple ber yield, flowering behavior, fruit retention, and fruit drop. The experiment was designed using a Factorial randomized block design (FRBD) with three repetitions, each consisting of 25 combinations of treatments with plant growth regulators (PGRs) and nano-nutrients applied as foliar sprays. The data were recorded as days to flowering, fruit set, fruit drop, fruit retention, number of fruits per plant, and yield. Their interaction [melatonin (A5) 15 ppm + nano calcium nitrate (B5) 0.05%] resulted in the highest fruit retention (29.0%), highest fruit set (87.99%), average number of fruits (1561.0), and average fruit yield (54.23 kg) compared to the control. These interactions (A5B5) also have the earliest days to start flowering (18 days) and the lowest fruit drop (71.0 %) compared to the control. These results highlight the potential of melatonin and nano-calcium nitrate as an effective agronomic strategy to enhance reproductive performance and yield in ber cultivation, contributing to sustainable horticultural practices and future research on nano-enabled PGRs.

Keywords: Brassinosteroids, Melatonin, Nano boric acid, Nano calcium nitrate, Productivity

INTRODUCTION

Ber (*Ziziphus mauritiana* L.) is a tough fruit tree that is also a member of the Rhamnaceae family, with 550 species and 45 genera. It is tetraploid (2n = 48 chromosomes). It is also referred to as poor man food, and Chinese date. The inflorescence fascicle and pericarp of the fruit is edible (Usman *et al*. 2023). Ber is believed to have been of Indian origin. Due to the ability of the tree to thrive in drought and saline water and the capability to grow in poor and damaged land. It can offer food security by being able to acquire the fruit throughout the year. It is useful in many therapeutic fields due to its many medicinal attributes and nutritional value. The ripe fruit of this plant is very nutritious and

an excellent source of calcium, vitamin C, vitamin B, and vitamin A. Ripe Ber fruits are normally eaten fresh, dried, candied, pickled, juiced, or turned into Ber butter (Ruan *et al*. 2024). Various physiological processes, such as vegetative propagation, seed lessness induction, fruit set, pre-harvest drop of fruit, flowering control, fruit dimensions, flower and fruit thinning, fruit quality, and yield in many tree crops are highly affected by several PGRs and nutrients. Fruit drop is a severe physiological disorder that significantly reduces fruit production and marketing quality, posing a major setback to apple production despite its adaptive physiology (Patiyal *et al*. 2025). Fruit drop in most ber crops can be up to 63-91% and particularly at the early and mid-developmental stages. This is largely due to hormonal

imbalances, nutritional deficiencies, and environmental stressors such as moisture stress and temperature fluctuations. The intricate physiological basis of fruit drop is influenced by nutritional relationships between the growing fruit and the pedicel, as well as by endogenous hormonal regulation. Detachment and fruit shedding are stimulated by the formation of an abscission layer induced by ethylene accumulation and the reduced flux of auxin out of the fruit and into the pedicel (Sahoo *et al*. 2022).

Melatonin (MT) and brassinosteroids (BRs) are considered strong natural regulators that play vital roles in fruit development, plant growth, and stress alleviation. MT, or N-acetyl-5-methoxytryptamine, is a versatile signalling molecule that regulates fruit ripening, blooming, defence mechanisms, and photoperiodism. It lowers oxidative stress by increasing photosynthetic efficiency, maintaining hormonal equilibrium, and enhancing antioxidant defence. Moreover, by modulating ethylene sensitivity in growing fruits, MT reduces abscission, delays leaf senescence, and stabilises chlorophyll. Likewise, BRs, a form of plant steroidal hormone, promote fruit set, pollen viability, cell division, and stress tolerance. They enhance retention of fruits and enhancement of the source sink relationship, through mobilization of photosynthate to reproductive organs (Huang & Jin, 2024). Exogenous administration of BRs has been shown to increase fruit retention in mango, citrus, and pomegranate, thereby enhancing fruit production and quality by maintaining hormonal equilibrium and increasing cell wall plasticity (Ashtalakshmi *et al*. 2024).

Nano-nutrients such as nano calcium nitrate and nano boric acid are needed to improve reproductive parameters in fruit crops by enhancing pollen viability, fruit set, and retention. On the one hand, nano boron enhances the translocation of carbohydrates, stigma receptivity, and fertilisation efficiency, whereas on the other hand, nano calcium enhances fruit firmness, lengthening pollen tubes, and the production of cell walls. Tissue-level nutrient uptake was not assessed in this work, and while nanoformulations are proposed to enhance nutrient delivery properties, their effectiveness compared to conventional bulk fertilisers in field settings has not been fully characterised. Future research should incorporate nutrient analysis in leaves and fruits to validate these pathways. The potential of nano-formulations to improve nutrient-use efficiency and reduce environmental losses is now being investigated (El-Salhy *et al*. 2022). Abdelwahed *et al*. (2023) found that foliar application of Nano-Calcium (2%) + Nano-Boron (20 ppm) level in pomegranate drastically enhanced fruit yield as it improved pollen germination, fruit set, and cell wall integrity. Garrido-Auñón *et al*. (2025) observed that 0.1-μM 24-BL treatment, in which the enhanced peel colour led to a 41% increase in the yield of commercial fruits compared to control trees in blood orange fruit. Based on these findings, the PGRs can positively influence the fruit crop reproductive characteristic. The current study was conducted to determine the impact of nanonutrient supplementation and PGRs, individually and in combination, on apple ber blooming behaviour, fruit set, fruit retention, and yield under field conditions.

MATERIALS AND METHODS

Experimental material and design
The present research was conducted in Punjab, India during the 2024-2025 growing season. The region has a semi-arid climate with hot summers, cold winters, and moderate rainfall, mainly during the monsoon season. The experiment used 6-year-old Ber (*Ziziphus mauritiana* L.) trees spaced 6 x 6 m in an established orchard. To conduct the investigation, 150 healthy, consistent trees were selected. Two trees made up each treatment in a replication. For statistical analysis, the mean of the two trees was used as a single experimental unit, with observations from each tree recorded independently. To prevent pseudoreplication, the duplicate mean (n = 3) was used in the ANOVA.

Application of treatments
Melatonin (MT), product code PCT 1840 (CAS No. 73-31-4; chemical formula $C13H16N2O2$), was purchased from CDH (Central Drug House, India). The brassinosteroid treatment involved synthetic brassinolide (technical grade, 90% purity), purchased locally from SRL (Sisco Research Laboratories, India). We bought the formulations of nano-calcium nitrate and nano-boric acid in Vedayukt India Pvt. Ltd. in India. The nano-calcium (CAS No. 7440702) and the nano-boric acid (CAS No. 10043353) supplied by the manufacturer were used. All chemicals have been used at the recommended concentrations as indicated in the treatment plan.

PGRs and nano-nutrient treatment solutions were prepared on the day of application using Ethanol and Hot distilled water. Uniform foliar sprays were applied using a handheld knapsack sprayer to cover all foliage and developing fruit. The experiment entailed two foliar applications where the first foliar application took place at the beginning of the first week of September 2024 before flowering to induce floral initiation and floral synchronization, whereas the second foliar application occurred at the beginning of the first week of November 2024 when the pea stage of the fruit developed in order to induce fruit set, retention, and reduce premature fruit drop. Control treatments (A1 and B1) were sprayed with distilled water only, without ethanol, to exclude solvent effects. All cultural and orchard management activities, such as irrigation, pruning, and pest management, were performed consistently across all treat-

ments to control for external variability.

Treatment details

Factor- A was composed of PGRs like MT and BRs and Factor- B was composed of nanonutrients such as nano-calcium nitrate and nano-boric acid. A_1 – Control, A_2 – BRs (30 ppm), A_3 – BRs (40 ppm), A_4 – MT (10 ppm), A_5 – MT (15 ppm); Factor B (Nano-nutrients) included: B_1 – Control, B_2 – Nano-boric acid (0.08%), B_3 – Nano-boric acid (0.16%), B_4 – Nano-calcium nitrate (0.02%), B_5 – Nano-calcium nitrate (0.05%).

Observations recorded

To determine the effect of PGRs and nanonutrients on flowering, fruit set, fruit drop, fruit retention, average no of fruits, and yield were observed. One of the traits that displayed the effects of treatments on floral induction and days to the start of flowering. It was categorised as the days between the first foliar application and when 10 per cent of the trees would have reached bloom. The proportion of flowers that actually became fruits on the tagged branches, a measure of reproductive success across different combinations of treatments, was referred to as the fruit set percentage. The number of fruits that remain on the trees at harvest to the initial no of fruit set were recorded as fruit retention. The fruit drop is recorded as the number of detached fruits after the initial fruit set in the orchard. The average fruit yield (kg) was then calculated using the total fruit weight per tree which is the cumulative result of better blooming, fruit set, and retention. The average no. of fruits is calculated from the total no. of fruits received after harvest. All these parameters were statistically tested to assess the individual and the interactive effects of PGRs and nanonutrients on the reproductive efficacy and the yield performance of Apple Ber in semi-arid Punjab.

Statistical analysis

The experiment was conducted through a Factorial Randomized Block Design (FRBD) with three replications. The statistical analysis was performed using SPSS Statistics version 20, which was appropriate for the factorial design. The means of the treatments were compared at the 5 percent level of significance using the Fisher Least Significant Difference (LSD) test. In order to determine whether there were significant changes in treatment means, the Critical Difference (CD at 5%) values presented in the tables were calculated accordingly.

RESULTS AND DISCUSSION

Days to start flowering

The nano-nutrients (A x B) interacted statistically with the PGRs ($CD_{0.05}$ = 1.582), as indicated by a critical analysis of the data presented in Table 1. This meant that combinations of treatments, not specific main effects, were key to the interpretation. The earliest flowering (18.00 days) was observed when both the MT 15 ppm and nano calcium nitrate 0.05% (A5B5) were used. This was the statistically superior combination to all others. The absolute control (A1B1) on the other hand recorded the maximum number of days required to activate flower (33.00 days). The large interaction indicates a synergistic effect of the PGRs, with the levels of nano Nutrients required to respond to the initiation of blooming. MT 15 ppm, along with nano calcium nitrate at 0.05%, could be explained by a synergistic effect, which increases metabolic activity and the release of carbohydrates to reproductive buds. Melatonin is also reported to modulate the balance of oxidative stress and to induce genes related to floral transition (Bhalerao and Rai, 2023; Gao *et al*., 2023). These mechanisms are hypothetical in the context of this

Table 1. Effect of PGRs and nano nutrients on the days to start of flowering of ber fruit

	B_1	B_2	B_3	B_4	B_5	Mean (A)
A_1	33.00	29.67	28.33	28.00	27.33	29.27
A_2	31.67	26.67	25.67	25.00	24.67	26.73
A_3	31.33	22.00	21.33	21.00	20.33	23.20
A_4	30.33	24.33	23.33	23.00	22.67	24.73
A_5	30.00	20.00	19.33	18.67	18.00	21.20
Mean (B)	31.27	24.53	23.60	23.13	22.60	
CD at 5%	Factor (A)- 0.708			Factor (B)- 0.708		Factor (A*B)- 1.582
SEM	Factor (A)- 0.248			Factor (B)- 0.248		Factor (A*B)- 0.555

A_1 – Control, A_2 – BRs (30 ppm), A_3 – BRs (40 ppm), A_4 – MT (10 ppm), A_5 – MT (15 ppm); B_1 – Control, B_2 – Nano boric acid (0.08%), B_3 – Nano boric acid (0.16%), B_4 – Nano calcium nitrate (0.02%), B_5 – Nano calcium nitrate (0.05%)

study and were not directly measured. At the same time, nano-calcium nitrate may enhance nutrient and celluar signaling, which coluld contribute to floral development; however actual tissue nutrient content was not measured in this study (Zhu *et al*. 2023). Therefore, the combination of 15 ppm MT and 0.05% nano-calcium nitrate was the most effective in promoting flowering in ber. The results were similar to findings of Oosthuyse & Garziera, (2015) on mango fruit.

Fruit set (%)
The interaction between PGRs and nano-nutrients (A x B) was statistically significant ($CD_{0.05}$ = 0.377), as indicated by a critical analysis of the data shown in Table 2. As a result, treatment combinations rather than specific main effects were the primary basis for interpretation. The combination of MT 15 ppm and nano calcium nitrate 0.05% (A5B5) produced the highest fruit set (87.99%), which was statistically better than other treatment combinations. A3B5 (87.28%) and A2B5 (86.19%) came up close behind, suggesting that increased amounts of nano-calcium nitrate combined with PGRs improved fruit set. On the other hand, the absolute control (A1B1) showed the lowest fruit set (61.50%). The substantial interaction implies that the combined effect of PGRs and nanonutrient levels was necessary for the improvement in fruit set. Improved hormonal regulation and nutritional status may be the cause of the increased fruit set observed under MT at 15 ppm and nano calcium nitrate at 0.05%. Auxin and gibberellin levels have been reported to be modulated by melatonin in other studies, thereby promoting ovarian development and fruit set (Bakić *et al*. 2025). Pollen germination, pollen tube growth, and stigma receptivity may also be enhanced by nano-calcium nitrate, though these parameters were not measured in this study. These explanations are hypothetical. however, calcium availability in leaves or fruits was not quantified in this study (Seydmohammadi *et al*. 2020). Therefore, the observed increase in fruit set is likely associated with

the combined effects of nanonutrients and hormonal regulation rather than with directly confirmed enhanced nutrient uptake. According to Usanmaz *et al*. (2022), foliar melatonin application increases the number and percentage of fruit set in pomegranate when applied twice.

Fruit drop (%)
According to Table 3 results, there was a statistically significant interaction between PGRs and nanonutrients ($CD_{0.05}$ = 0.373), meaning that different treatment combinations had different effects on fruit drop. The combination of MT 15 ppm and nano calcium nitrate 0.05% (A5B5) produced the lowest fruit drop (71.00%) and was noticeably better than the other treatments. On the other hand, the absolute control (A1B1) showed the largest fruit drop (88.07%). When MT treatments were combined with nano-calcium nitrate, especially at higher doses, a consistent decrease in fruit drop was observed. Even though there was no explicit study of the underlying abscission dynamics, this interaction implies that the variation in fruit drop was not solely associated with changes in the treatment combination. According to Hussain *et al*. (2025), melatonin reduces oxidative stress and alters auxin-ethylene interactions, both of which are essential for the formation of the abscission layer. Although endogenous hormone levels and antioxidant activity were not measured in this study, previous literature suggests that melatonin can reduce oxidative stress and modulate auxin–ethylene interactions, which are important for abscission layer formation. These are proposed mechanisms, not directly assessed in this study. Also, the mechanistic role of calcium in the abscission zone was not determined in this study, but it is possible to associate it with the structural stabilisation of tissues (Larocca *et al*. 2025). While the synergistic effect of both the MT and nano-calcium nitrate is likely to have been involved in the dramatic decline in the amount of fruit drop displayed in the A5B5 treatment. According to Abd El *et al*. (2024), the use of melatonin

Table 2. Effect of PGRs and nano nutrients on the fruit set (%) of ber fruit

	B_1	B_2	B_3	B_4	B_5	Mean (A)
A_1	61.50	62.13	64.94	67.62	73.52	65.94
A_2	77.88	79.03	80.12	81.27	86.19	80.90
A_3	78.54	79.59	80.17	82.31	87.28	81.58
A_4	76.59	78.23	79.24	82.70	85.31	80.41
A_5	78.52	78.92	79.65	83.11	87.99	81.64
Mean (B)	74.61	75.58	76.83	79.40	84.06	
CD at 5%	Factor (A)- 0.169		Factor (B)- 0.169		Factor (A*B)- 0.377	
SEM	Factor (A)- 0.059		Factor (B)- 0.059		Factor (A*B)- 0.132	

A_1 – Control, A_2 – BRs (30 ppm), A_3 – BRs (40 ppm), A_4 – MT (10 ppm), A_5 – MT (15 ppm); B_1 – Control, B_2 – Nano boric acid (0.08%), B_3 – Nano boric acid (0.16%), B_4 – Nano calcium nitrate (0.02%), B_5 – Nano calcium nitrate (0.05%)

Table 3. Effect of PGRs and nano nutrients on the fruit drop (%) of ber fruit

	B$_1$	B$_2$	B$_3$	B$_4$	B$_5$	Mean (A)
A$_1$	88.07	84.25	83.92	83.77	83.38	84.68
A$_2$	74.87	74.82	74.50	75.05	73.86	74.62
A$_3$	73.31	72.40	72.12	71.63	71.75	72.24
A$_4$	73.67	73.73	73.42	73.19	73.52	73.51
A$_5$	71.78	71.55	71.24	71.04	71.00	71.32
Mean (B)	76.34	75.35	75.04	74.94	74.70	
CD at 5%	Factor (A)- 0.167		Factor (B)- 0.167		Factor (A*B)- 0.373	
SEM	Factor (A)- 0.059		Factor (B)- 0.059		Factor (A*B)- 0.131	

A$_1$ – Control, A$_2$ – BRs (30 ppm), A$_3$ – BRs (40 ppm), A$_4$ – MT (10 ppm), A$_5$ – MT (15 ppm); B$_1$ – Control, B$_2$ – Nano boric acid (0.08%), B$_3$ – Nano boric acid (0.16%), B$_4$ – Nano calcium nitrate (0.02%), B$_5$ – Nano calcium nitrate (0.05%)

Table 4. Effect of PGRs and nano nutrients on the fruit retention (%) of ber fruit

	B$_1$	B$_2$	B$_3$	B$_4$	B$_5$	Mean A)
A$_1$	11.77	15.75	16.08	16.23	16.63	15.29
A$_2$	25.13	25.18	25.50	24.95	26.14	25.38
A$_3$	26.69	27.60	27.88	28.37	28.25	27.76
A$_4$	26.33	26.27	26.58	26.81	26.48	26.49
A$_5$	28.22	28.45	28.76	28.96	29.00	28.68
Mean (B)	23.63	24.65	24.96	25.06	25.30	
CD at 5%	Factor (A)- 0.163		Factor (B)- 0.163		Factor (A*B)- 0.364	
SEM	Factor (A)- 0.057		Factor (B)- 0.057		Factor (A*B)- 0.128	

A$_1$ – Control, A$_2$ – BRs (30 ppm), A$_3$ – BRs (40 ppm), A$_4$ – MT (10 ppm), A$_5$ – MT (15 ppm); B$_1$ – Control, B$_2$ – Nano boric acid (0.08%), B$_3$ – Nano boric acid (0.16%), B$_4$ – Nano calcium nitrate (0.02%), B$_5$ – Nano calcium nitrate (0.05%)

also decreased the fruit drop percentage in pomegranate.

Fruit retention (%)
The results presented in Table 4 demonstrated a significant interaction between PGRs and nano-nutrients (CD$_{0.05}$ = 0.364), indicating that fruit retention was influenced by specific treatment combinations rather than by individual factors alone. The combination of MT 15 ppm and nano calcium nitrate 0.05% resulted in the highest fruit retention (29.00%), while the absolute control (A1B1) produced the lowest retention (11.77%). When MT treatments were combined with higher concentrations of nano-calcium nitrate, a progressive increase in fruit retention was observed, underscoring the interdependent roles of mineral nutrition and hormone regulation in maintaining fruit attachment. Increased fruit retention under MT 15 ppm with nano-calcium nitrate may be linked to improved antioxidant defence and delayed senescence, as reported previously. These mechanisms are hypothetical and were not measured in this study. According to reports, melatonin supports the ongoing assimilate supply to developing fruits by preserving chlorophyll stability and increasing antioxidant enzyme activity (Ramasamy *et al.* 2023). To prevent premature fruit detachment, calcium simultaneously strengthens the middle lamella and maintains membrane integrity within the abscission zone (Yousefi *et al.* 2025). The enhanced fruit retention observed when MT and nano-calcium nitrate were applied together was likely due to their coordinated physiological and structural effects. This is in accordance with the findings of Arshad *et al.* (2024), who proposed the enhancement of retention of fruits with the use of PGRs in kinnow fruit.

Average number of fruits
Table 5 showed a strong interaction between PGRs and nano-nutrients (CD$_{0.05}$ = 17.964), with a significant effect of the treatment combination on the number of fruits per plant. It has been found that the maximum number of fruits (1561.00 fruits per plant) was observed when combining the use of MT 15 ppm and nano calcium nitrate 0.05% (A5B5) which was much higher than

Table 5. Effect of PGRs and nano nutrients on the average no of fruits of ber fruit

	B₁	B₂	B₃	B₄	B₅	Mean A
A₁	999.33	1076.00	1199.33	1303.67	1150.00	1145.67
A₂	1125.67	1230.00	1350.67	1291.00	1460.67	1291.60
A₃	1199.67	1321.00	1437.33	1379.67	1493.67	1366.27
A₄	1103.00	1210.33	1320.67	1261.33	1429.00	1264.87
A₅	1262.67	1272.00	1377.33	1323.67	1561.00	1359.33
Mean B	1,138.06	1,221.87	1,337.07	1,311.86	1,418.87	
CD at 5%	Factor (A)- 8.034		Factor (B)- 8.034		Factor (A*B)- 17.964	
SEM	Factor (A)- 2.187		Factor (B)- 2.187		Factor (A*B)- 6.298	

A₁ – Control, A₂ – BRs (30 ppm), A₃ – BRs (40 ppm), A₄ – MT (10 ppm), A₅ – MT (15 ppm); B₁ – Control, B₂ – Nano boric acid (0.08%), B₃ – Nano boric acid (0.16%), B₄ – Nano calcium nitrate (0.02%), B₅ – Nano calcium nitrate (0.05%)

Table 6. Effect of PGRs and nano nutrients on the yield of ber fruit

	B1	B2	B3	B4	B5	Mean A
A1	40.00	42.23	43.53	44.23	46.27	43.25
A2	44.03	46.27	47.73	49.20	43.33	46.11
A3	45.50	46.47	48.17	51.20	50.83	48.43
A4	42.37	44.30	45.80	47.00	49.93	45.88
A5	52.30	46.47	48.63	50.13	54.23	50.35
Mean B	44.84	45.15	46.77	48.35	48.92	
CD at 5%	Factor (A)- 0.206		Factor (B)- 0.206		Factor (A*B)- 0.461	
SEM	Factor (A)- 0.072		Factor (B)- 0.072		Factor (A*B)- 0.162	

A₁ – Control, A₂ – BRs (30 ppm), A₃ – BRs (40 ppm), A₄ – MT (10 ppm), A₅ – MT (15 ppm); B₁ – Control, B₂ – Nano boric acid (0.08%), B₃ – Nano boric acid (0.16%), B₄ – Nano calcium nitrate (0.02%), B₅ – Nano calcium nitrate (0.05%)

the combination of other combinations. Conversely, the absolute control (A1B1) had minimum number of fruits (999.33 fruits per plant). An increase in the concentration of nano-calcium nitrate, combined with the MT treatments, had a significant effect on fruit number, indicating the interplay of nutrient provision and hormone regulation in the process of fruit load determination. The increased fruit number under MT at 15 ppm may result from enhanced floral differentiation, fruit set, and auxin–gibberellin signalling, as reported in the literature. These mechanisms are hypothetical in the context of this study (Dzinyela *et al.* 2024). Simultaneously, nano-calcium nitrate likely enhanced enzyme activity, pollen tube development, and nutrient translocation, contributing to fruit set and retention (Lin *et al.* 2025). The joint hormonal and nutritional effect of A5B5 treatment was likely the cause of such a high number of fruits. As similar results were seen in strawberry fruit by Zahedi *et al.* 2020)

Average yield
Based on the findings in Table 6, there was a strong interaction between nanonutrients and PGRs (CD₀.₀₅ =

0.461) and, as such, specific treatment combinations produced a distinct effect on the yield of fruit. The combination of MT 15 ppm and nano calcium nitrate 0.05 per cent (A5B5) gave the highest yield (54.23 kg per plant) in comparison with all other combinations of treatments. In its turn, the absolute control (A1B1) yielded the lowest (40.00 kg per plant) yield. The positive interactions between nutrient delivery and hormone control on fruit production were evident in increased yields at higher concentrations of nano-calcium nitrate combined with MT treatments. Its role in enhancing assimilate translocation, hormonal regulation, increased photosynthetic efficiency, and stimulating fruit formation and retention could explain the increase in production under 15 ppm MT (El-Motaium *et al.* 2025). Nano-calcium nitrate may enhance fruit growth and yield by contributing to cell wall stability and possibly improving nutrient supply; however, tissue nutrient levels were not measured in this study (Zec *et al.* 2025). Increased yield under A5B5 may be attributed to enhanced assimilate translocation, hormonal regulation, and physiological improvements, as reported previously. These are proposed mechanisms, not directly meas-

ured in this study. The result supported the earlier research findings by Badiche-El Hilali *et al*. (2024) on lemon fruit.

It is worth noting that the usual conventional fertiliser treatments were not used as positive controls in the present study. The observed improvements may partly reflect correction of underlying nutritional deficiencies rather than nano-specific properties alone. Direct comparisons of nano- and conventional fertilisers, along with measurements of tissue nutrient content, would be necessary in future studies to confirm the mechanisms underlying enhanced nutrient-use efficiency. To clearly distinguish the impact of nano-formulations from the response to general nutrient supplementation, future studies comparing nano- and conventional formulations under equivalent agronomic conditions are needed.

Since the current study was carried out throughout just one growing season. The observed responses to PGRs and nano-nutrients may differ in other seasons, as ber and other fruit trees may exhibit biennial bearing and year-to-year variability due to environmental conditions. Therefore, it is advised to conduct multi-year studies to verify the consistency and generalizability of these results.

Conclusion

In conclusion, the study demonstrated that the application of PGRs and nano-nutrients significantly improved the overall growth, flowering, and yield performance of ber. Among the treatments, MT at 15 ppm in combination with nano calcium nitrate at 0.05%, proved most effective in enhancing early flowering, maximum fruit set, fruit retention, and yield. The beneficial effects may be attributed to enhanced physiological processes and improved translocation of assimilates to developing fruits, as supported by the measured reproductive and yield parameters. Nonetheless, additional studies are required to determine the exact physiological and biochemical mechanisms that mediate this synergistic response. To establish the role of oxidative stress management in promoting fruit retention, hypothesis-driven future studies should determine levels of lipid peroxidation products (e.g., malondialdehyde) and reactive oxygen species (ROS), as well as the activities of superoxide dismutase, catalase, and peroxidase. In addition, one could more effectively determine the role of hormones in sink strength by tracking changes in endogenous hormones during critical periods of fruit drop development, including auxins, gibberellins, abscisic acid, cytokinins, and ethylene. Molecular-level studies focused on genes related to antioxidant defence, calcium signalling pathways, and sucrose transport may further help explain the mechanistic basis of the described improvements. Therefore, the combined use of suitable PGRs with nano-calcium nitrate can be recommended

as a promising approach to maximize productivity in ber cultivation.

Conflict of interest

The authors declare that they have no conflict of interest.

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