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RESEARCH ARTICLE

# Exogenous application of gibberellic acid and brassinosteroids: Synergistic effects on Nutmeg's growth, yield and color attributes

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**Abstract**

This study evaluates the effects of preharvest spray applications of gibberellic acid ($GA_3$) and brassinosteroids on the growth, fruit drop, fruit set, yield and colour characteristics of nutmeg. Treatments included combinations of $GA_3$ and brassinosteroids with boric acid and calcium nitrate, applied during the flowering stage. The experiment followed a randomized block design with seven treatment combinations; each replicated three times. Among the treatments, the application of $GA_3$ at 75 ppm combined with 0.3 % boric acid yielded the most favourable results. This combination significantly enhanced vegetative growth parameters, including plant height (8.9 m), leaf length (14.5 cm) and leaf width (5.5 cm). It also resulted in the highest fruit set percentage (80.95 %) and the lowest fruit drop rate (43.63 %). Furthermore, this treatment produced the highest yield, with 680 fruits per tree, amounting to 54.46 kg per tree. It also maximized both fresh and dry aril yields (3.19 kg and 2.58 kg per tree, respectively) as well as nut yields (9.08 kg fresh and 6.78 kg dry per tree). In addition, it improved the brightness and vibrancy of the aril colour, achieving the highest values for L* (66.2), a* (53.8) and b* (31.2). Overall, these findings highlight the potential of $GA_3$ and brassinosteroids, especially in combination with boric acid, to enhance mace yield, quality and colour stability offering a promising strategy for improving nutmeg production and postharvest quality.

**Keywords:** aril pigmentation; fruit retention; plant growth regulators; post-harvest quality; yield improvement

## Introduction

Nutmeg (*Myristica fragrans*), a tropical evergreen tree belonging to the Myristicaceae family, comprises 21 genera and approximately 500 species and is indigenous to Eastern Indonesia (1, 2). Nutmeg is greatly valued as a seasoning ingredient in a wide range of cooking dishes such as confections, meats, baked foods, sauces and used a spice mix of gram masala. In traditional medicine, nutmeg exhibits a broad spectrum of pharmacological properties, including anti-inflammatory, antioxidant, hypolipidemic, hallucinogenic, analgesic, diuretic, carminative, antispasmodic, antipyretic, antiulcerogenic, aphrodisiac, hypnotic and stimulant effects (3). *Myristica fragrans* is unique among tree spices, producing both nutmeg seeds and mace, the latter being the lacy red aril surrounding the seed (4, 5). Mace is particularly valued for its vibrant red-to-orange colour, delicate aroma and high essential oil content. The commercial quality of mace is influenced by factors such as fruit maturity, uniform splitting and post-harvest handling. Premature fruit drop can be unpredictable, often triggered by environmental stress, nutrient deficiencies, which directly reduce the harvestable yield. Moreover, nutmeg trees exhibit uneven flowering and fruit set, leading to inconsistent fruit distribution on branches. These irregularities result in seasonal yield fluctuations and substantial losses. To address these challenges, the application of plant growth regulators as preharvest treatments has been explored to improve vegetative growth, enhance fruit set, minimize fruit drop and maximize nutmeg yield and color quality of nutmeg.

Gibberellic acid ($GA_3$) and brassinosteroids (BRs) are two essential plant growth regulators that significantly impact on multiple aspects of fruit development and yield attributes. Gibberellic acid is known to promote fruit set, boost crop yield and improve overall fruit quality in crops like pomegranate (6). In contrast, brassinosteroids enhance stress tolerance, improve fruit quality and increase overall yield.

They also contribute to fruit size and quality while regulating the ripening process through interactions with various physiological factors (7). The synergistic interaction enhances fruit physical attributes such as length, diameter, weight, pulp weight and peel weight. BRs alone tend to increase fruit diameter more effectively, while the combination with $GA_3$ promotes both length and diameter, likely through increased cell division and elongation (8). In mango, the combined foliar application of $GA_3$ and borax (a boron source) significantly increased fruit retention, number of fruits per panicle and yield compared to individual treatments or control. This synergy likely arises from improved physiological functions, such as enhanced pollen viability and metabolite synthesis, supporting better fruit set and development (9). Beyond plant growth regulators, essential micronutrients such as boric acid and calcium nitrate ($CaNO_3$) are crucial for fruit setting, development and quality (10). Boric acid enhances pollen viability, fruit set and pigmentation, all of which directly influence mace quality. Meanwhile, calcium nitrate strengthens cell walls, reduces physiological disorders and improves post-harvest stability, preventing mace deterioration during drying and storage (9, 11).

This study provides important insights into the impact of preharvest applications of plant growth regulators on improving growth and yield, ultimately enhancing the commercial value of nutmeg. The primary objective is to standardize preharvest treatments with plant growth regulators and assess their effects on growth traits, yield and colour quality of nutmeg.

## Materials and Methods

### Experimental field

A research trial was performed at Martin Agro Farms, Coimbatore, during 2024-2025. The farm is in Kalikkanaicken palayam village panchayat, Thondamuthur block, Coimbatore. The experimental site lies in the western region of Tamil Nadu, positioned at 10°99' N latitude and 76°86' E longitude, with an elevation of 442 meters above mean sea level (MSL). The soil in the trial area is alkaline (pH 8.73), has a sandy clay loam texture and is non-calcareous. The experimental site's soil was identified as having a sandy clay loam texture. It exhibited an alkaline pH of 8.13 and was non-calcareous in nature which is suitable for nutmeg cultivation and allows for effective evaluation of treatment responses under locally relevant conditions. The electrical conductivity (EC) was measured at 0.19 dS/m, suggesting non-saline conditions. Organic carbon content was recorded at 10.1 g/kg, indicating a moderate level of soil fertility. Initial nutrient analysis showed the presence of 250.6 kg/ha nitrogen, 39.4 kg/ha phosphorus and 395.74 kg/ha potassium, reflecting a favourable macro-nutrient profile suitable for supporting crop growth.

### Experimental setup

Nutmeg trees in the experimental plot were established in 2006 and are currently 18 years old. The trees, which are of a local variety, were consistently managed using standardized cultural practices throughout the study period. The spray solutions for the seven treatment combinations ($T_1$ to $T_7$) were prepared following the specific formulations outlined in Table 1. The experiment was laid out in a randomized block design (RBD), incorporating three replications for each treatment. The required quantities of plant growth regulators were precisely measured, dissolved in distilled water to prepare a stock solution and subsequently diluted to achieve the desired concentration for foliar application. The initial spray was administered during the flowering stage, with a second application carried out one month afterward. A battery-operated sprayer with a fine nozzle was used to ensure even distribution. Tween-20 was used as a surfactant in a spray solution at a rate of 2 mL/L of water. Application of plant growth regulators during the flowering stage in nutmeg is shown in Fig. 1.

### Measurement of plant growth characters

A total of 21 trees were used for the study. The same 21 treated trees were used for the leaf study. Plant height (m), leaf length (cm) and leaf width (cm) of nutmeg trees were assessed 30 days after spraying. Plant height was measured in centimetres (cm) by using a measuring tape or ruler, starting from the base of the stem at the soil surface up to the tip of the tallest leaf. For each treatment, five mature flush leaves per tree were randomly selected from the mid-canopy. The length of each leaf was measured from the base of the petiole to the apex of the leaf blade. Similarly, the width of each representative leaf was measured at its widest point using a ruler and the mean width was determined from several leaves collected per tree.

### Measurement of fruit set and fruit drop parameters

Initial fruiting percentage was assessed based on the number of

$$\text{Fruit set (\%)} = \frac{\text{Total number of fruit set}}{\text{Number of total perfect flowers}} \times 100$$

flowers that successfully developed into fruits using the formula (12), data were gathered at 15 days intervals until harvest.

$$\text{Fruit dropping (\%)} = \frac{\text{Number of dropped fruits}}{\text{Total number of tested fruits}} \times 100$$

**Table 1**. Composition of treatments used for preharvest application in nutmeg

| Treatments | Composition |
|---|---|
| $T_1$ | Control - water spray |
| $T_2$ | $GA_3$ - 25 ppm+Boric acid - 0.3 % |
| $T_3$ | $GA_3$ - 50 ppm+Boric acid - 0.3 % |
| $T_4$ | $GA_3$ - 75 ppm+Boric acid - 0.3 % |
| $T_5$ | BRs - 0.1 ppm+$CaNO_3$ - 0.5 % |
| $T_6$ | BRs - 0.3 ppm+$CaNO_3$ - 0.5 %, |
| $T_7$ | BRs - 0.5 ppm+$CaNO_3$ - 0.5 % |

$GA_3$ - Gibberellic acid; BRs - Brassinosteroids; $CaNO_3$ - Calcium nitrate

**Fig. 1.** Spraying of plant growth regulators at the flowering stage in nutmeg.

Likewise, the fruit drop percentage, which represents the number of fruits that fell before reaching maturity, was computed using the formula (13), data were gathered at 15 days intervals until harvest.

## Evaluation of crop yield attributes

**Fruit count per tree**

Fruit count per tree was determined by regularly counting the fruits during the peak harvesting period. The total yield from each experimental tree was documented and the average number of fruits per tree was computed and reported accordingly (8).

**Fruit yield (kg/tree)**

Total yield per tree was measured at harvest and recorded for each experimental tree based on the respective treatment. The results were presented in kilograms per tree (8).

**Fruit weight (g)**

Ten fruits were randomly chosen from the non-destructive sample and individually weighed individually on a digital balance. The mean weight was then calculated and reported in grams (g) (9).

**Fresh aril yield per tree**

The aril was promptly weighed after being separated from the nutmeg fruit and seed using a weighing balance, with measurements recorded for each treatment. The total fresh aril yield per tree was determined and documented according to the assigned treatment. The final yield was expressed in kilograms per tree (14).

**Dry aril yield per tree**

The arils were dried in a mechanical dryer at 55 °C for around 4 to 5 hrs until the moisture level reduced to 8-10 % (15). Moisture content (%) was estimated by calculating the percentage reduction in weight before and after drying, using the equation (15):

$$\text{Moisture content (\%)} = \frac{\text{Initial weight - Final weight}}{\text{Initial weight}} \times 100$$

To retain their red colour, freshly harvested mace was pre-treated by blanching in a 0.5 % citric acid solution at 75 °C for 2 min before the drying process. The final yield was expressed in kilograms per tree (16).

**Fresh nut yield per tree**

After separation from the nutmeg fruit and aril, the seed nuts were promptly weighed using a digital balance and the data were recorded for each treatment. The total fresh nut yield per tree was assessed and documented based on the corresponding treatment, with the final yield expressed in kilograms per tree (14).

**Dry nut yield per tree**

Seed nuts were dried in a mechanical dryer at 60 °C for approximately 10-12 hrs until a constant weight was achieved (15). Dried seed nuts were immediately weighed using a digital balance and the measurements were documented for each treatment. The final yield was expressed in kilograms per tree.

**Aril volume**

A measuring cylinder of 5 L capacity was used to assess aril volume, beginning with 500 mL of water. Five fresh arils from each treatment were individually immersed, causing an upward displacement. The change in water level was recorded by subtracting the initial volume (500 $cm^3$) from the new volume. The average aril volume was then calculated and expressed in cubic centimeters ($cm^3$) (9).

**Color values of aril**

The color values of dried samples were evaluated using a Lovibond colorimeter across all power levels and compared with those of fresh arils. The colorimeter provided readings for L, a, -a, b, -b and ΔE, representing deviations in reflection and overall color variation.

- **L** (Lightness)
- **a** (Red-Green Coordinate)
- **b** (Yellow-Blue Coordinate)

Color was adjusted by fixing the calibration slide on the back of the Lovibond colorimeter. After calibration, the fresh aril samples are captured by the colorimeter for color measurement (17).

### Data analysis

A variance analysis for a randomized design was conducted using the statistical software KAU GRAPES to assess the impact of different pre-harvest sprays on nutmeg growth, yield and color values. The LSD test was used to compare the means at a significance level of P = 0.05.

## Results

### Effect of preharvest spray on growth parameters on nutmeg

Application of gibberellic acid ($GA_3$) and brassinosteroids via foliar spray significantly impacted the vegetative growth parameters of nutmeg plants in comparison to the control. Data on nutmeg growth parameters are provided in Table 2. The distinct effect was noticed with the highest concentrations of gibberellic acid. The maximum mean results for plant height (8.9 m), leaf length (14.5 cm) and leaf width (5.5 cm) were recorded 30 days after spraying when treated with $GA_3$ at 75 ppm combined with 0.3 % boric acid. This was followed by $GA_3$ at 50 ppm with 0.3 % boric acid and brassinosteroids at 0.5 ppm combined with 0.5 % $CaNO_3$.

### Effect of pre-harvest spray on fruit set and fruit drop

Preharvest application of plant growth regulators, particularly gibberellic acid ($GA_3$) and brassinosteroids, significantly enhanced fruit set and decreased fruit drop were observed in comparison to the control. Table 2 summarizes the observations on fruit set and fruit drop. The maximum fruit set percentage was achieved with $GA_3$ at 75 ppm combined with 0.3 % boric acid, reaching 80.95 % at 60 days. This was followed by $GA_3$ at 50 ppm with 0.3 % boric acid (75.92 %) and brassinosteroids at 0.5 ppm combined with 0.5 % $CaNO_3$ (74.96 %). Similarly, a significant reduction in fruit drop was noted with these treatments. The lowest fruit drop rate was observed in plants treated with $GA_3$ at 75 ppm + 0.3 % boric acid (43.63 % at 60 days), followed by $GA_3$ at 50 ppm + 0.3 % boric acid (48.44 %) and brassinosteroids at 0.5 ppm + 0.5 % $CaNO_3$ (51.93 %). In contrast, the control treatment had the lowest fruit set (70.45 %) and the highest fruit drop rate (68.62 %).

### Effect of preharvest spray on yield parameters on nutmeg

**Fruit count per tree**

The most effective treatment was $GA_3$ at 75 ppm combined with 0.3 % boric acid, yielding 680 fruits per tree. This was followed by $GA_3$ at 50 ppm with 0.3 % boric acid, which produced 662 fruits per tree and brassinosteroids at 0.5 ppm combined with 0.5 % $CaNO_3$, resulting in 644 fruits per tree. The control treatment recorded the lowest fruit count, with 592 fruits per tree. Table 3 presents the total fruit count per tree in nutmeg.

**Fruits yield per tree and fruit weight**

Gibberellic acid application notably affected nutmeg fruit yield and fruit weight per tree contrast to the control (Fig. 2). The maximum yield was observed with $GA_3$ at 75 ppm combined with 0.3 % boric acid, producing 54.46 kg per tree with an individual fruit weight of 85.98 g. This was followed by $GA_3$ at 50 ppm + 0.3 % boric acid and brassinosteroids at 0.5 ppm + 0.5 % $CaNO_3$, which resulted in yields of 51.32 kg and 49.89 kg per tree, with individual fruit weights of 81.98 g and 80.12 g, respectively. The control treatment yielded the lowest results, producing 40.26 kg per tree with an individual fruit weight of 68.13 g. Table 3 presents the total fruit yield and fruit weight per tree for nutmeg.

**Fresh aril and seed nut yield per tree**

The maximum yield was recorded with the application of $GA_3$ at 75 ppm combined with 0.3 % boric acid, producing 5.19 kg of aril and 10.08 kg of nut per tree. This was followed by $GA_3$ at 50 ppm with 0.3 % boric acid, which yielded 5.03 kg of aril and

**Table 2**. Effect of preharvest spray on growth parameters, fruit set, fruit drop and number of fruits in nutmeg

| Treatment details | Plant height (m) | Leaf length (cm) | Leaf width (cm) | Number of fruits/trees | Fruit set (%) | Fruit drop (%) |
|---|---|---|---|---|---|---|
| **Control - water spray** | 7.01 | 11.5 | 3.4 | 592 | 70.45 | 68.62 |
| **$GA_3$-25 ppm + Boric acid-0.3 %** | 7.8 | 12.5 | 3.1 | 637 | 72.86 | 59.55 |
| **$GA_3$-50 ppm + Boric acid-0.3 %** | 8.5 | 13.9 | 4.7 | 662 | 78.91 | 48.44 |
| **$GA_3$-75 ppm + Boric acid-0.3 %** | 8.9 | 14.5 | 5.5 | 680 | 80.95 | 43.63 |
| **BRs-0.1ppm + $CaNO_3$-0.5 %** | 7.5 | 12.1 | 3.5 | 633 | 72.73 | 62.99 |
| **BRs-0.3ppm + $CaNO_3$-0.5 %** | 8.01 | 12.9 | 4.1 | 640 | 74.96 | 55.39 |
| **BRs-0.5ppm + $CaNO_3$- 0.5 %** | 8.3 | 13.1 | 4.5 | 644 | 75.92 | 51.93 |
| **C.D.** | 0.493 | 0.790 | 0.245 | 39.547 | 4.613 | 3.549 |
| **SE(m)** | 0.158 | 0.254 | 0.079 | 12.694 | 1.481 | 1.139 |
| **SE(d)** | 0.224 | 0.359 | 0.111 | 17.952 | 2.094 | 1.611 |
| **C.V.** | 3.429 | 3.400 | 3.314 | 3.433 | 3.411 | 3.540 |

$GA_3$ - Gibberellic acid; BRs - Brassinosteroids; $CaNO_3$ - Calcium nitrate

**Table 3**. Effect of preharvest spray on yield attributes of nutmeg

| Treatment details | Fruit yield (kg/tree) | Fruit weight (g) | Fresh aril yield (kg/tree) | Aril dry yield (kg/tree) | Fresh nut yield (kg/tree) | Nut dry yield (kg/tree) | Aril volume (cm³) |
|---|---|---|---|---|---|---|---|
| **Control - water spray** | 40.26 | 68.62 | 2.12 | 1.87 | 5.91 | 5.65 | 3.2 |
| **$GA_3$-25 ppm + Boric acid-0.3 %** | 46.13 | 75.27 | 2.57 | 2.17 | 6.31 | 6.06 | 3.9 |
| **$GA_3$-50 ppm + Boric acid-0.3 %** | 51.32 | 81.79 | 3.03 | 2.43 | 6.92 | 6.54 | 4.6 |
| **$GA_3$-75 ppm + Boric acid-0.3 %** | 54.46 | 85.98 | 3.19 | 2.58 | 7.08 | 6.78 | 4.8 |
| **BRs-0.1ppm + $CaNO_3$-0.5 %** | 44.38 | 71.35 | 2.41 | 2.01 | 6.12 | 5.89 | 3.7 |
| **BRs-0.3ppm + $CaNO_3$-0.5 %** | 48.54 | 78.19 | 2.65 | 2.27 | 6.54 | 6.18 | 4.3 |
| **BRs-0.5ppm + $CaNO_3$- 0.5 %** | 49.89 | 80.12 | 2.79 | 2.39 | 6.76 | 6.27 | 4.5 |
| **C.D.** | 2.941 | 4.732 | 0.166 | 0.139 | 0.401 | 0.380 | 0.252 |
| **SE(m)** | 0.944 | 1.519 | 0.053 | 0.045 | 0.129 | 0.122 | 0.081 |
| **SE(d)** | 1.335 | 2.148 | 0.075 | 0.063 | 0.182 | 0.173 | 0.115 |
| **C.V.** | 3.421 | 3.408 | 3.438 | 3.443 | 3.420 | 3.413 | 3.392 |

$GA_3$ - Gibberellic acid; BRs - Brassinosteroids; $CaNO_3$ - Calcium nitrate

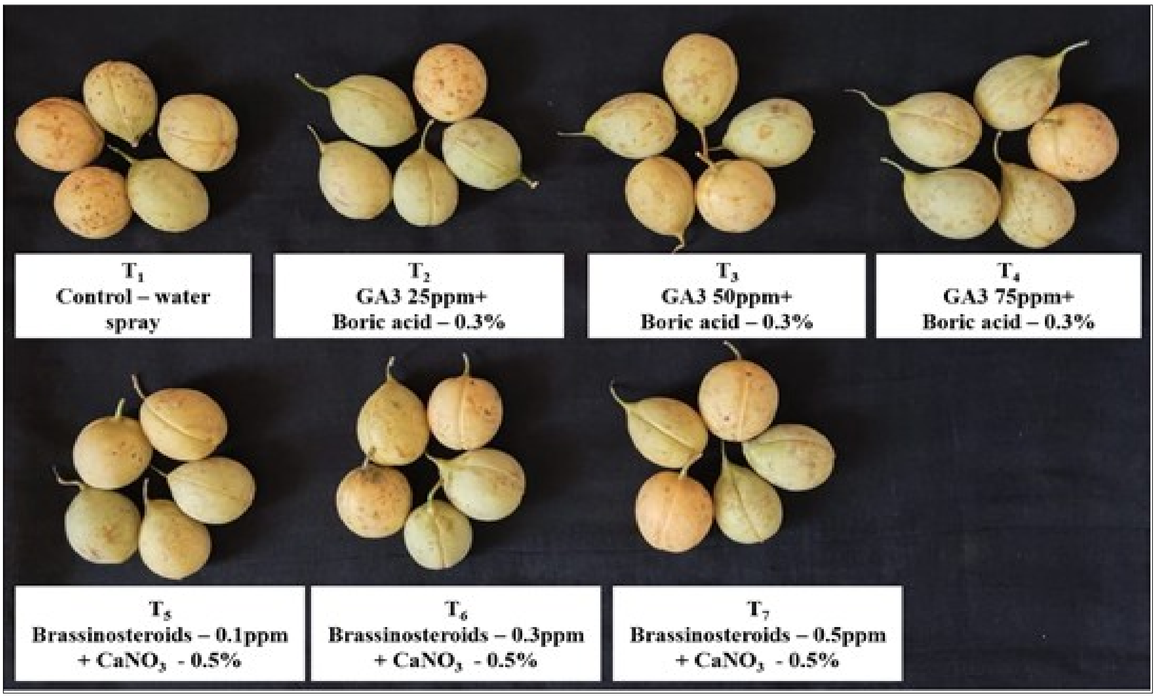


**Fig. 2.** Nutmeg fruits harvested from each treatment after pre-harvest spraying.

9.92 kg of nut per tree. The application of brassinosteroids at 0.5 ppm along with 0.5 % $CaNO_3$ resulted in 4.79 kg of aril and 9.76 kg of nut per tree. In contrast, the control treatment produced the lowest yield, with 4.12 kg of aril and 8.91 kg of seed nut per tree. These findings highlight the significant influence of gibberellic acid on enhancing nutmeg aril and seed nut production. Fresh aril and seed nut yields per tree are summarized in Table 3.

**Dry weight of aril and seed nut**

Dry weight measurements of aril and seed nut per tree are provided in Table 3. The highest dry yield was obtained with $GA_3$ at 75 ppm combined with 0.3 % boric acid, producing 2.58 kg of aril and 6.78 kg of seed nut per tree. This was followed by $GA_3$ at 50 ppm with 0.3 % boric acid, yielding 2.43 kg of aril and 6.54 kg of seed nut per tree. The application of brassinosteroids at 0.5 ppm along with 0.5 % $CaNO_3$ resulted in dry yields of 2.39 kg of aril and 6.27 kg of seed nut per tree. In comparison, the control treatment recorded the lowest dry yields, with 1.89 kg of aril and 5.65 kg of seed nut per tree. Mechanically dried arils after undergoing pre-treatment are presented in Fig. 3. Fig. 4 presents the influence of preharvest spray applications on the yield of aril and nut.

**Fig. 3.** Mechanically dried arils after pre-treatment.

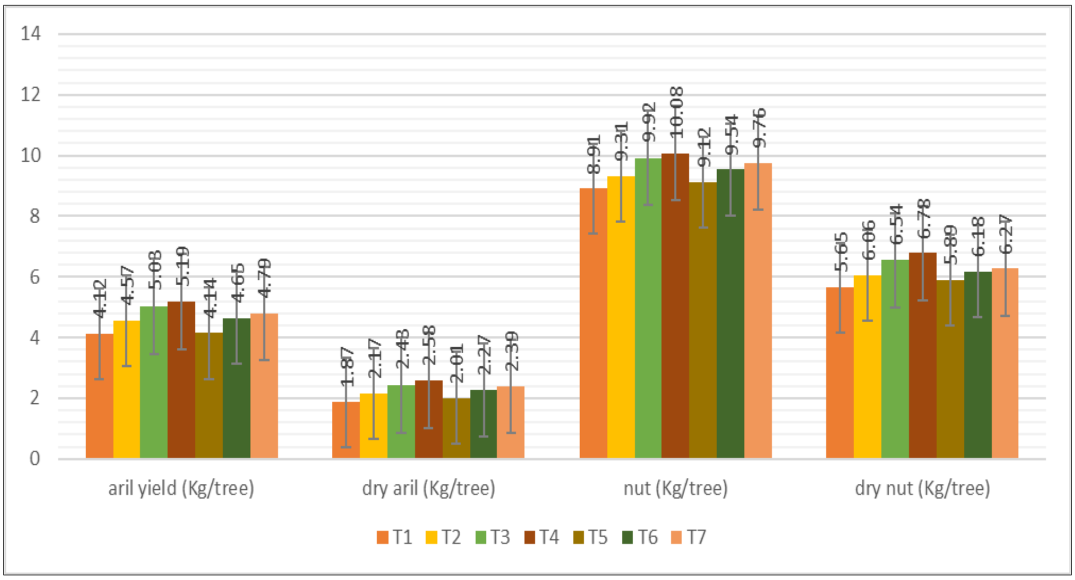


**Fig. 4.** Effect of preharvest spray treatments on aril and nut yield.

### Aril volume

Aril volume measurements are provided in Table 3. Among the treatments, the highest aril volume of 5.8 $cm^3$ was observed with $GA_3$ at 75 ppm combined with 0.3 % boric acid. This was followed by $GA_3$ at 50 ppm with 0.3 % boric acid and brassinosteroids at 0.5 ppm with 0.5 % $CaNO_3$, which recorded aril volumes of 5.6 $cm^3$ and 5.5 $cm^3$, respectively. Conversely, the control treatment showed the lowest aril volume of 3.2 $cm^3$. These results emphasize the notable impact of preharvest application of growth regulators in improving aril volume.

### Color values of aril

Colour analysis of fresh mace revealed that the $GA_3$ (75 ppm) + Boric Acid (0.3 %) treatment resulted in the highest L* value (66.2), indicating maximum brightness and lightness. This treatment also recorded the highest a* value (53.8), representing the most intense red hue, while the b* value (31.2) reflected a stronger yellow component, enhancing overall colour vibrancy. Colour measurements of aril are provided in Table 4. Similarly, the $GA_3$ (50 ppm) + Boric Acid (0.3 %) treatment exhibited L* value of 65.8, a* value of 51.7 and b* value of 28.4. This was followed by the Brassinosteroids (0.5 ppm) + $CaNO_3$ (0.5 %) treatment, which achieved L* value of 64.3, a* value of 52.3 and b* value of 29.9. In contrast, the control treatment recorded the lowest colour values, with an L* value of 60.5, a* value of 48.8 and b* value of 25.9. Fig. 5 illustrates the impact of various pre-harvest spray treatments on the colour values of arils.

## Discussion

Pre-harvest application of plant growth regulators such as gibberellic acid ($GA_3$) and brassinosteroids, in conjunction with micronutrients including boric acid and calcium nitrate, resulted in substantial enhancement of vegetative growth, reproductive performance and quality parameters in nutmeg. The foliar spray of $GA_3$, particularly at 75 ppm in combination with boric acid (0.3 %), led to superior vegetative growth, as evidenced by increased plant height, leaf length and leaf width. This enhancement is attributable to $GA_3$'s role in promoting cell elongation and division by stimulating the biosynthesis of hydrolytic enzymes and expansins that loosen cell walls, allowing for increased turgor-driven expansion (18). Concurrently, boron facilitates cell wall structural integrity and lignin synthesis, thereby reinforcing tissue development. Correlatively, improved vegetative vigour is directly associated with enhanced photosynthetic capacity due to increased leaf surface area, contributing to greater assimilate availability for reproductive processes. The combination of gibberellic acid and boric acid enhanced nutrient uptake and

**Table 4**. Effect of preharvest spray on the color attributes in nutmeg

| Treatment details | Color values | | |
|---|---|---|---|
| | **L*** | **a*** | **b*** |
| **Control - water spray** | 60.5 | 48.8 | 25.9 |
| **$GA_3$-25 ppm + Boric acid-0.3 %** | 61.9 | 49.4 | 26.2 |
| **$GA_3$-50 ppm + Boric acid-0.3 %** | 65.8 | 52.3 | 29.9 |
| **$GA_3$-75 ppm + Boric acid-0.3 %** | 66.2 | 53.8 | 31.2 |
| **BRs-0.1ppm + $CaNO_3$-0.5 %** | 61.4 | 50.1 | 27.7 |
| **BRs-0.3ppm + $CaNO_3$-0.5 %** | 62.7 | 50.5 | 28.1 |
| **BRs-0.5ppm + $CaNO_3$- 0.5 %** | 64.3 | 51.7 | 28.4 |
| **C.D.** | 3.884 | 3.128 | 1.721 |
| **SE(m)** | 1.247 | 1.004 | 0.552 |
| **SE(d)** | 1.763 | 1.420 | 0.781 |
| **C.V.** | 3.417 | 3.417 | 3.396 |

$GA_3$ - Gibberellic acid; BRs – Brassinosteroids; $CaNO_3$ - Calcium nitrate; L*-Lightness; a*- Red-Green Coordinate; b*- Yellow-Blue Coordinate.

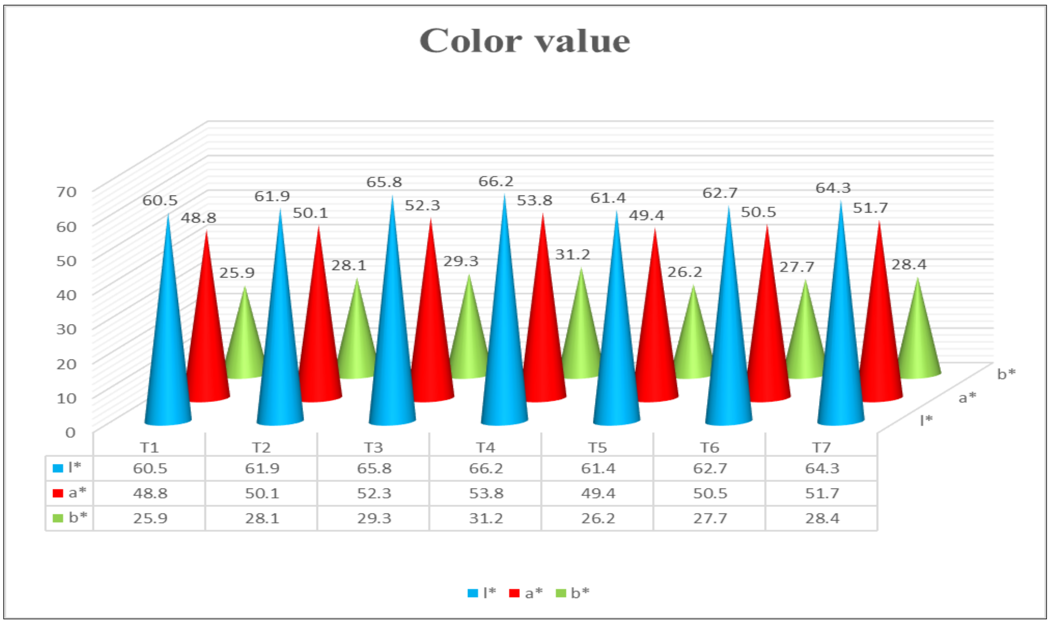


**Fig. 5.** Effect of different preharvest spray treatments on color values of arils.

hormonal balance, leading to superior vegetative growth. Similarly, brassinosteroids, in combination with calcium nitrate, also contributed to improved growth parameters, though to a slightly lesser extent.

Gibberellic acid ($GA_3$) was predominantly produced by the fungus *Fusarium fujikuroi* through submerged or solid-state fermentation. However, several bacterial species such as *Azospirillum brasilense*, *Rhizobium* spp., *Pseudomonas putida*, *Acinetobacter calcoaceticus* and *Bacillus* spp. also naturally produced $GA_3$ and gained attention for their sustainable agricultural applications (19). In present study, gibberellic acid ($GA_3$) was applied in its synthetic form to evaluate its direct and immediate effects on flowering and fruit development in nutmeg trees. Gibberellic acid ($GA_3$) is essential for promoting cell elongation, cell division and nutrient mobilization, thereby enhancing plant growth, yield and color values. Its application leads to increased mace fresh biomass, accelerated flowering, a higher floral count per plant and improved fruit set, ultimately contributing to enhanced mace productivity (20). Similar results were reported by (21) in mango where $GA_3$ treatment enhanced floral induction, fruit retention, fruit set, yield and key quality attributes. Additionally, $GA_3$ treated nutmeg trees exhibited more uniform mace development and enhanced surface expansion. Moreover, the role of boron in enhancing pollen germination and pollen tube development likely contributed to a reduction in fruit drop. Boric acid supports carbohydrate translocation and enzyme activation, contributing to fruit quality and improved fruit retention. These findings are consistent with previous studies in aonla and strawberry (22, 23).

Fruit set and fruit drop are crucial factors in nutmeg production and the application of $GA_3$ and born substantially improved flower development is tightly linked to higher fruit set. $GA_3$'s role in hormonal regulation that promotes floral induction and development, as well as nutrient mobilization to reproductive organs. Boron plays a pivotal role in pollen viability and tube elongation, essential for successful fertilization. Its influence on membrane function and carbohydrate metabolism facilitates effective pollen-pistil interaction, directly contributing to increased fruit set and reduced fruit drop. This indicates that $GA_3$ performs a key role in promoting fruit retention by reducing premature fruit drop, possibly by improving nutrient mobilization and hormonal balance within the plant (24).

Yield-related traits, such as the fruit count per tree, overall fruit yield and individual fruit weight, exhibited significant enhancement with $GA_3$ and boron treatments. Yield is closely associated with efficient photosynthate partitioning, optimal nutrient availability and successful reproductive development. The observed enhancements can be primarily attributed to the action of gibberellic acid ($GA_3$), which modulates carbohydrate metabolism, facilitates the translocation of assimilates and strengthens the sink-source dynamic. Moreover, boron plays a pivotal role in cell wall biosynthesis and sugar alcohol transport, thereby improving nutrient allocation and promoting the expansion of fruit tissues. The contribution of brassinosteroids with $CaNO_3$ further supported fruit development by improving nutrient absorption and cell division in fruit tissues (25).

Fresh and dry aril and nut yields further highlighted the positive impact of plant growth regulators. The highest values were observed in $GA_3$ (75 ppm) + boric acid (0.3 %), with aril and nut dry yields indicating improved biomass accumulation and metabolic efficiency. These results are indicative of improved biomass accumulation and metabolic efficiency in treated plants. Additionally, aril volume and color parameters were significantly enhanced, with $GA_3$ (75 ppm) + boric acid (0.3 %) producing the most visually appealing aril, as evidenced by superior brightness ($L^*$ = 66.2), red intensity ($a^*$ = 53.8) and yellow hue ($b^*$ = 31.2). Aril pigmentation is closely associated with uniform maturity, anthocyanin synthesis and overall market value (17). The application of gibberellic acid ($GA_3$) enhances pigmentation by stimulating the biosynthesis of anthocyanins, key compounds responsible for red and purple coloration. At the same time, boron plays a vital role by supporting enzymatic activity and ensuring an adequate sugar supply both of which are critical for consistent pigment development. Furthermore, $GA_3$

promotes aril surface expansion, which not only enhances the fruit's visual appeal but also contributes to a more favorable perception of quality among consumers (18).

The synergy between $GA_3$ and boric acid in nutmeg reflects the integration of hormonal and micronutrient effects, optimizing reproductive processes and fruit maturation. The combined hormonal and micronutrient treatments optimize physiological and biochemical processes, leading to superior vegetative growth, reproductive success, fruit retention and market-preferred aril characteristics. These results provide a strong basis for recommending integrated plant growth regulators and micronutrient foliar sprays to improve nutmeg production and quality.

## Conclusion

This study highlights the critical role of preharvest plant growth regulators in improving growth characters, yield and color intensity of nutmeg (*Myristica fragrans*) productivity. The application of $GA_3$ at 75 ppm in combination with 0.3 % boric acid emerged as the most effective treatment, resulting in superior vegetative growth, increased fruit set, reduced fruit drop and enhanced overall yield parameters. The number of fruits per tree, fruit weight and total fruit yield were significantly improved with $GA_3$ and boric acid application, demonstrating their role in nutrient mobilization and reproductive efficiency. Furthermore, the treatment positively influenced seed nut and aril yields, both in fresh and dry forms, emphasizing the importance of growth regulators in improving commercial yield. The highest aril volume and superior color values were recorded in $GA_3$ treated plants, indicating an enhancement in nutmeg quality attributes, which is critical for market acceptance and value addition. Brassinosteroids, particularly in combination with $CaNO_3$, also contributed to yield and quality improvements, though to a slightly lesser extent than $GA_3$. These findings provide valuable insights into optimizing nutmeg cultivation through sustainable agronomic practices. The combined application of gibberellic acid, brassinosteroids and nutrient sprays of boric acid and calcium nitrate effectively addresses the challenge of uneven flowering and fruit set in nutmeg trees. These treatments modulate hormonal homeostasis and nutrient availability, which are critical determinants of flower initiation and fruit development. By promoting uniform flowering and fruit development, they mitigate seasonal yield variability and reduce losses arising from inconsistent fruit distribution. Collectively, these interventions facilitate synchronized flowering and improved fruit set. The targeted application of growth regulators presents a promising strategy for increasing overall yield and minimizing postharvest losses, offering significant benefits to farmers. Future investigations should focus on scaling these applications, long-term impact assessment and potential synergies with other agronomic factors to further enhance nutmeg production and economic sustainability.

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## Authors' contributions

SS conceptualization of the research, methodology design, significantly to writing the original draft and editing the manuscript. AM conducted the literature search, organized the data, ensured the integrity of the research and wrote sections of the original draft and overall supervision. IVP contributed to data visualization and formatting of the manuscript. AG played a key role in writing parts of the original draft and in the review and editing process. VK contributed to the formal analysis and validation of the collected data and participated in writing the manuscript.

## Compliance with ethical standards

**Conflict of interest:** Authors do not have any conflict of interests to declare.

**Ethical issues:** None

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