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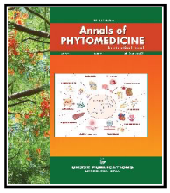

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Exploring the role of biostimulants in enhancing fruit quality and biochemical attributes of *Musa paradisiaca* L. cv. Virupakshi

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Abstract

This study was conducted to assess the effects of various biostimulants on the quality and biochemical attributes of banana cultivar 'Virupakshi'(*Musa paradisiaca* L.), belonging to the genome AAB. In this study, seven biostimulants, *viz*., seaweed extract (2% and 3%), liqorice extract (2% and 3%), neem leaf extract (2% and 3%), moringa leaf extract (2% and 4%), legume derived protein hydrolysate (1% and 2%), aloevera extract (2% and 3%), orthosilicic acid (2% and 4%) at different concentrations were sprayed on Virupakshi banana in a randomized block design with three replications. The experimental results indicated that among the treatments tested, T2 (seaweed extract 3%) was found effective in enhancing physiological and biochemical attributes. This treatment exhibited maximum total sugar (18.95%), reducing sugars (11.15%), non-reducing sugars (7.41%), total carbohydrates (29.57 g), starch (14.30%), carotene (36.65 µg/g), calcium (5.63 mg/100 g) and potassium (363.38 mg/100 g). The secondary metabolite analysis also showed enhanced tannin (9.85 mg/100 g), oxalic acid (3.21 mg/100 g) and lignin content (8.82%), this was followed by the treatment (T8), foliar spraying of moringa leaf extract (2%) which depicted a significant enhancement in the biochemical attributes. In contrast, the control treatment (T15) exhibited minimum values across all measured parameters. These results confirm that the application of biostimulants significantly improves fruit quality and nutrient content of Virupakshi.

1. Introduction

Banana is one of the leading fruit crops grown in tropical and subtropical regions around the globe. It is a highly valued and exportable crop grown in more than 150 countries (Falcomer *et al.,* 2019; Sitthiya *et al.,* 2018). It is regarded as the fourth staple food after rice, maize and wheat, yielding 110 million tonnes of banana fruit annually and world trade of banana has recorded 20 million tonnes in the recent years (FAO, 2024). Banana is the second most significant fruit crop in India next to mango. Their popularity is due to year round availability, delicious taste, low cost and rich nutritional content. Fruits and vegetables are vital for health, strengthening the body defenses against numerous diseases (Chellammal, 2022). Because of their nutritional richness, fruits are a significant part of the diet. They are essential for the body defense system and boost the immune system's ability to fight off various diseases (Sangeeta *et al.,* 2023). India is the world's largest producer of bananas, followed by China, Philippines, Brazil and Ecuador. India produces 30,184 metric tonnes of bananas. About 87% of global banana production is grown by small farmers for domestic use, while the remaining 14% mostly dessert bananas are exported. The highest banana production state is Andhra Pradesh with 5,838.88 metric tonnes, followed by Maharashtra with 4,628.04 metric tonnes. Banana account for 13% of the total fruit cultivation area and 33% of fruit production in the country (APEDA, 2022).

Virupakshi banana is grown at higher altitudes in the Palani Hills of the Western Ghats, primarily as a rain-fed crop during the South-west monsoon season. Cultivation observed a drastic decline for about 70% due to the occurrence of banana bunchy top virus disease, but it has effectively recovered through proper management and plant protection measures. Each tree produces 70-100 fruits per bunch, harvested after 18 months. Virupakshi banana is known for its yellowish-green color, sweetness and firm texture. Ripe bananas are one of the key ingredients in the Palani Panchamirtham, a traditional offering made at the Dhandayuthapani Swamy Temple, Palani (Sivaraj *et al.,* 2016). The demand for Virupakshi banana is always in upper side for the domestic utilization, to meet out these raising demand, development organic packages of practices to increase the production

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and quality is the need of the agricultural sector. Biostimulants, whether natural or synthetic, increase plant growth and stress resistance, improve nutrient uptake and reduce reliance on chemicals. These include substances like seaweed extracts, humic materials and amino acids. Humic substances, complex organic materials (such as urban waste products, sewage sludge extracts, compost and manures), beneficial chemical elements (Al, Na, Se, and Si), inorganic salts such as phosphate, seaweed extracts, leaf extracts, chitin and chitosan derivatives, anti-transparent (kaolin and polyacrylamide), free amino acids and N-containing substances (peptides, polyamines) are the eight categories in biostimulants (Tarafdar, 2022). Bananas are rich in potassium which is essential for numerous physiological functions and calcium, although present in lower amounts, remains important for overall health. Evidence suggests that these substances positively affect plant growth, yield, quality and stress resilience (Gupta *et al.,* 2023).

Biostimulants application to Virupakshi banana may greatly enhance fruit quality and biochemical characters (Patel and Mukherjee, 2021). However, limited research on the impact of stimulant on yield and quality of Virupakshi banana (AAB) is available. Taking all these into consideration, the present study was performed with the objective to find out the effect of biostimulants on quality and biochemical attributes of Virupakshi banana.

2. Materials and Methods

2.1 Authentication of Virupakshi banana

The Virupakshi banana leaf samples were identified and authenticated by Dr. R. Ramasubbu, Plant Taxonomists from the Department of Biology at The Gandhigram Rural Institute in Gandhigram, Tamil Nadu. These samples are cataloged as Collection Number 319 in the GUD (Gandhigram University Dindigul) Herbarium.

2.1.1 Virupakshi banana

The Virupakshi banana cultivar (AAB), belongs to Pome subgroup, is one of the few premium hill bananas cultivated exclusively in the Lower Pulney, Sirumalai and Kolli hills of the Western Ghats in Tamil Nadu, India, at altitudes ranging from 1000 to 1500 m above sea level. It belongs to the section Eumusa with unique nature of ashy green pseudostem with maroon colored male flower and bracts are deciduous. Virupakshi bananas are highly prized for their exceptional flavor, taste, and religious significance, this variety is grown in a limited area using traditional planting materials and cultivation methods, with minimal scientific intervention. It has long shelf-life and low moisture content. These bananas can maintain quality upto 10 days at ambient temperature. They thrive as a rain-fed, perennial crop, benefiting from an annual rainfall of 1250 - 1500 mm (Valsalakumari and Nair, 2001).

2.2 Field experiment details and collection of samples

The study was carried out during 2023-24 in farmer's field at Kilakkuchettipatti, part of Kodaikanal Taluk located in lower Pulney hills of Western Ghats in Tamil Nadu. The field experiment was executed in a Randomized Block Design with fifteen treatments and three replications. The treatments details were T_1 - 2% seaweed extract, T_2 - 3% seaweed extract, T_3 - 2% liqorice extract, T_4 - 3% liqorice extract, T_5 - 2% neem leaf extract , T_6 - 3% neem leaf extract, T_7 - 2% moringa extract, T_8 - 4% moringa leaf extract, T_9 - 1% legume derived protein hydrolysate, T_{10} - 2% legume derived protein hydrolysate, T_{11} - 2% vermiwash, T_{12} - 3% vermiwash, T_{13} - 2% orthosilicic acid, T_{14} - 4% orthosilicic acid and T_{15} - control. Five plants from each treatment were randomly selected for observation. Plants at the last hand opening stage were tagged with the respective treatment details. The treatments were imposed as foliar sprays after the last hand opening and repeated twice at 15 days interval. Samples were collected in all the treatments and analysed for the parameters, *viz.,* total sugars (%), reducing sugars (%), non-reducing sugars (%), total carbohydrates (g), starch (%), carotene content (µg/g), calcium content (mg/100 g), potassium content (mg/100 g), tannin content (mg/100 g), oxalic acid (mg/100 g) and lignin (%).

Figure 1: General field view of experimental plot.

2.3 Quality attributes

2.3.1 Total sugars (%)

The Lane and Eynon titration method is a recognized technique for quantifying reducing sugars. In this procedure, a diluted fruit juice sample was titrated with Fehling's solution, which contains copper sulfate in an alkaline medium. The endpoint was indicated by the fading of the blue color, signifying the reduction of copper (II) ions. This method involved preparing Fehling's solutions A and B and heating the sample to facilitate the reaction (Sewwandi *et al.,* 2020).

2.3.2 Reducing sugars (%)

Reducing sugars were estimated by Nelson-Somogyi method given by Sadasivam and Manickam (1992). One hundredmg of sample was weighed and extracted using hot 80% alcohol twice (5 ml each). The supernatant was evaporated on a water bath, then dissolved the sugars in 10 ml of water. Aliquots of the alcohol-free extract and standard solutions were prepared in separate test tubes and brought to the total volume of 2 ml with distilled water. Then 1 ml of alkaline copper tartrate reagent was added to each tube, heated for 10 min, then cooled and 1 ml of arsenomolybdic acid was added and the content in each tube was diluted to 10 ml and incubated for ten min the absorbance was measured at 620 nm.

2.3.3 Non-reducing sugars (%)

The sample was prepared by following steps 1 to 3 of the Nelson-Somogyi method as mentioned above. Briefly, 1 ml of extract was mixed with 1 ml of 1N H, SO, and hydrolyzed at 49°C for 30 min. After cooling, 1 or 2 drops of methyl red was added and neutralized with 1N NaOH drop wise, ensuring appropriate reagent blanks were included. The total reducing sugars content was estimated using the Nelson-Somogyi method, then non-reducing sugars content was arrived by subtracting reducing sugars from total sugar content.

2.4 Biochemical attributes

2.4.1 Total carbohydrate

The sample 100 mg was weighed and hydrolyzed with 5 ml of 2.5N HCl in a boiling water bath for 3 h. After cooling, it was neutralized with sodium carbonate. The volume was then adjusted to 100 ml and the resultant mixture was centrifuged. Standard and sample solutions were pipetted out to test tubes to which phenol and sulfuric acid were added. Then these test tubes were incubated at 25-30°C for 20 min, after which the color was measured at 490 nm to calculate the total carbohydrate content (Dubois *et al.,* 1956).

2.4.2 Starch (%)

The estimation of starch in banana was conducted using anthrone method as described by Hedge *et al.* (1962). To estimate starch, the sample was first extracted using ethanol and the residue was filtered. The residue was then hydrolyzed with dilute hydrochloric acid and neutralized with sodium hydroxide before adding iodine solution. Finally, the intensity of the blue-black color formed was measured, which was correlated with starch concentration, using a standard curve for quantification.

2.4.3 Carotene content (µg/g)

The carotene content of banana was assessed as per the method recommended by Ranganna (1986). Estimating carotene involve use of organic solvents such as acetone or hexane from the sample. The extract was treated with iodine and sodium sulfate for separation and the carotene content was quantified by measuring the absorbance at 450 nm.

2.4.4 Calcium content (mg/100 g)

The calcium content of bananas was determined by using normal titration method, as it is expressed in mg/100 g given by Jackson(1973). Twenty five ml of the triple acid extract of sample was transferred into a porcelain basin. To this, 10% of sodium hydroxide was carefully added drop by drop until the acidity was neutralized, as indicated by a color change of red litmus paper to blue. An additional 5 ml was then added to reach a pH of 12, this was followed by the addition of a pinch of murexide indicator. Then, the final solution was titrated with 0.02 N EDTA until the color change from pinkish-red to purple or violet.

2.4.5 Potassium content (mg/100 g)

To evaluate the potassium content, 5 ml of a triple acid extract was mixed with 5 ml of 1:4 ammonium hydroxide for neutralization of sample. The mixture was then analyzed using a flame photometer, which had been calibrated to zero with a blank and standardized with a 100 ppm potassium solution, resulted in galvanometer readings. These readings were subsequently compared with a standard curve to determine the total potassium percentage (Sumner, 1944).

2.5 Secondary metabolites

2.5.1 Tannin content (mg/100 g)

To estimate tannin content using a methanolic volatile solvent, the sample (banana pulp) was extracted with methanol and the solution was filtered. A colorimetric assay was conducted by mixing the methanolic extract with Folin-Ciocalteu reagent and sodium carbonate and the absorbance was measured at 725 nm. Finally, the absorbance was compared to a standard curve of tannic acid to determine the tannin concentration, expressed as mg of tannic acid equivalents per 100 g of sample (Kritsi *et al.,* 2023).

2.5.2 Oxalic acid (mg/100 g)

To estimate oxalic acid, 500 mg of the dry sample was weighed and mixed with 1 g of asbestos and 1.5 ml of $4NH^{-}SO^{-}$. Soxhlet extraction was then conducted using 500 ml of diethyl ether for 48 h. After centrifugation and processing, the residue was dissolved in 4NOH, SO_1, heated and the solution was filtered. The solution was titrated with 0.02N potassium permanganate and the concentration of oxalic acid was calculated in mg per 100 g of the sample (De Souza *et al.*, 2024).

2.5.3 Lignin (%)

The sample was extracted and centrifuged at 2000g for 5 min, after which the supernatant was discarded. The sediment was washed with water and centrifuged again, discarding the supernatant and repeating the wash process twice. Subsequently, 2 ml of NaOH was added to the residue and the mixture was extracted at 70 - 80°C for 12-16 h. After cooling, 0.45 ml of 2N HCl was added and the pH was adjusted to 7 or 8 using NaOH. The final volume was brought to 3 ml with water and the solution was centrifuged once more at 2000 g for 5 min to collect the supernatant for analysis, 0.8 ml of 0.1M sodium phosphate buffer (pH 7.0) was added to 0.8 ml aliquot of the extract, while 0.8 ml of 0.1N NaOH (pH 12.3) was added to another 0.8 ml aliquot. The absorbance was measured at 245 nm and 350 nm and the lignin concentration was calculated from the difference between A245 and A350 (AE350) for both the pH 7.0 and 12.3 samples, expressing the lignin content as AE350 per sample (Stafford, 1960).

3. Results

3.1 Quality parameters

The data presented in Table 1 revealed that biostimulant sprays had a significant difference on the total sugar content of Virupakshi banana. The highest total sugar percentage of 18.95% was found in treatment (T_2), spraying of 3% seaweed extract and it was followed by the treatment T_8- application of 4% moringa leaf extract with 18.64% and it is on par with treatment T_4 (3% liqorice extract). Conversely, the control (T_{15}) had the lowest total sugar percentage of 13.35%. The impact of biostimulant sprays on the reducing sugars content resulted in significant difference between the treatments. The results revealed that the treatment T_2 (seaweed extract 3%) recorded high reducing sugars content of 11.15%, followed by T_8 (moringa leaf extract 4%) which exhibited a significant level (11.11%). Whereas, the control (T_{15}) showed a comparatively lower reducing sugars content of 8.21%. The percentage of non-reducing sugars in the biostimulant treated plants showed a significant difference. Notably, the treatment T_2 (seaweed extract 3%) showed a remarkably high percentage of non-reducing sugars of 7.41%, followed by T_3 (2%

liqorice extract) with 7.22% and T_8 (moringa leaf extract 4%) with 7.15%. In contrast, the control treatment (T_{15}) exhibited lower percentage of non-reducing sugars of 4.88% (Table 1). Shelf-life also showed a significant difference among the treatments, T_2, which used a 3% seaweed extract, resulted in the longest shelf-life of 11.50 days. The treatment T_8 (4% moringa leaf extract) recorded shelf-life of 10.90 days. In contrast, the control treatment (T_{15}) had the shortest shelf-life of 8.10 days (Figure 4).

Figure 2: Virupakshi banana bunch.

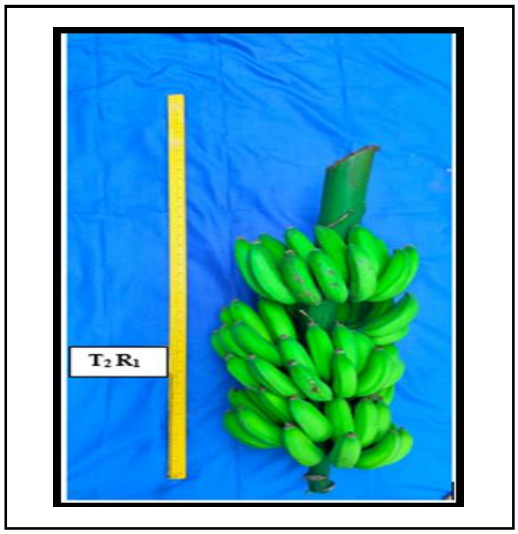

Figure 3: Seaweed extract treated banana bunch (T_2).

Table 1: Effect of biostimulants on quality parameters of Virupakshi banana

Treatments	Total sugars (%)	Reducing sugars (%)	Non-reducing sugars (%)
T_1 - Seaweed extract (2%)	17.63	10.56	6.72
T_2 - Seaweed extract (3%)	18.95	11.15	7.41
T_3 - Liqorice extract (2%)	17.48	9.88	7.22
T_4 - Liqorice extract (3%)	18.17	10.94	6.87
T_5 - Neem leaf extract (2%)	14.98	9.20	5.49
T_6 - Neem leaf extract (3%)	17.51	10.16	6.98
T_7 - Moringa leaf extract (2%)	16.70	9.66	6.69
T_8 - Moringa leaf extract (4%)	18.65	11.11	7.16
T_9 - Legume derived protein hydrolysate (1%)	13.77	8.59	4.92
T_{10} - Legume derived protein hydrolysate (2%)	15.86	8.92	6.59
T_{11} - Aloevera extract (2%)	16.66	9.47	6.83
T_{12} - Aloevera extract (3%)	17.91	10.75	6.80
T_{13} - Orthosilicicacid (2%)	14.25	8.70	5.27
T_{14} - Orthosilicic acid (4%)	15.11	8.78	6.01
T_{15} - Control	13.35	8.21	4.88

3.2 Biochemical parameters

The biostimulant sprays affect the total carbohydrate content in Virupakshi banana, showing significant variation among treatments. Notably, treatment T_2 (seaweed extract 3%) exhibited a high total carbohydrate content with 29.57 g and it was followed by T_8 (moringa leaf extract 4%) with 29.39 g, T_4 (3% liqorice extract) with 27.88 g whereas, control (T_{15}) displayed notablyminimum total carbohydrate content of 19.20 g.

The application of biostimulants had increased the starch content of bananas. The highest starch content of 14.30% was found in the fruits treated with three sprays of 3% seaweed extract (T_2). This was closely followed by the 4% moringa leaf extract treated fruits (T_8), which resulted in a starch content of 14.10%. In comparison, the control, had the lowest starch content at 9.10% (Figure 5) and it also showed significant impact on the carotene content of bananas. The highest level of carotene content (36.65 µg/g) was found with three sprays of 3% seaweed extract (T_2). This was closely followed

by the 4% moringa leaf extract treatment (T_8), which recorded a carotene content of 35.99 µg/g. But, the control (T_{15}) had the lowest carotene content at 15.25 µg/g. The application of biostimulants had a significant effect between the calcium content of bananas. The highest calcium content of 5.63 mg/100 g, was found in the group treated with three sprays of 3% seaweed extract (T_2), followed by 4% moringa leaf extract (T_8), which recorded a calcium content of 5.49 µg/100 g and control attained low level of calcium content (Figure 5) and significant influence on the amount of potassium content of bananas was observed. The highest potassium content of 363.38 µg/100 g was found in 3% seaweed extract applied fruits (T_2), followed by 4% moringa leaf extract treatment (T_8), which recorded a potassium content of 358.22 µg/100 g and the control showed a lowest potassium content (252.17 µg/100 g) represented in Figure 6.

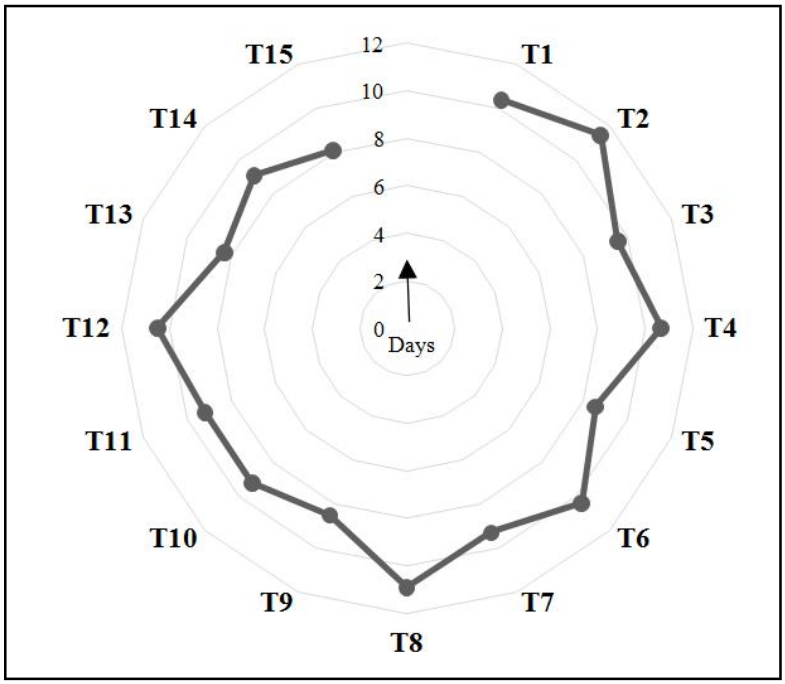

Figure 4: Impact of biostimulants on shelf-life of Virupakshi banana.

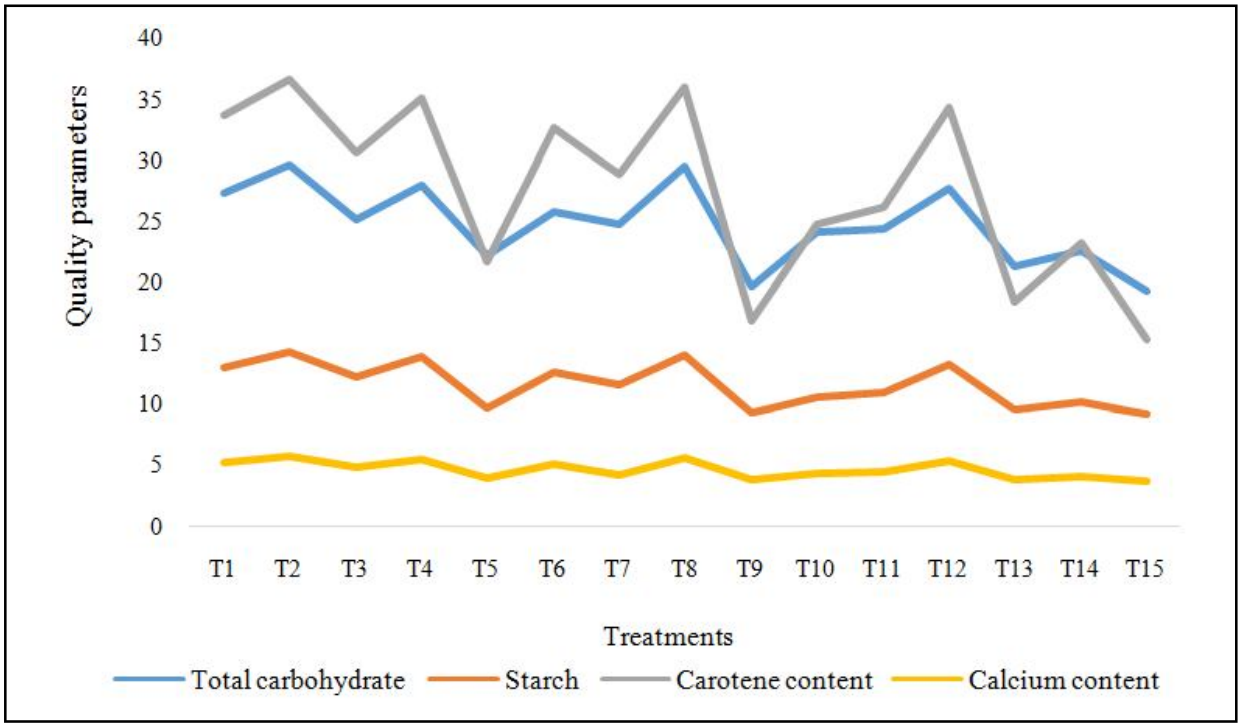

Figure 5: Impact of biostimulants on biochemical parameters of Virupakshi banana.

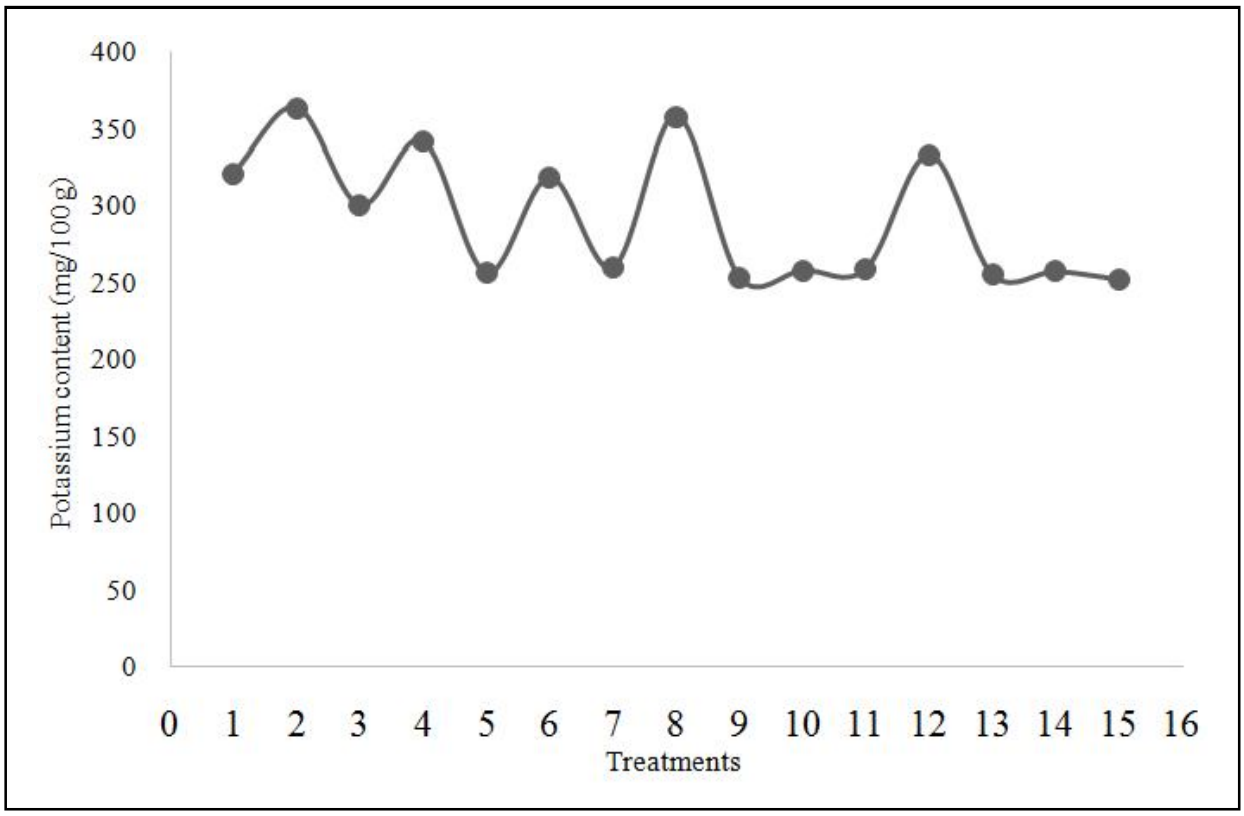

Figure 6: Influence of biostimulants on potassium level of Virupakshi banana.

3.3 Secondary metabolites

The application of biostimulants have a significant difference between the tannin content in Virupakshi bananas. The highest level was observed in 3% seaweed extract sprayed fruits (T_2), which had a tannin content of 9.85 mg/100 g. This was closely followed by the 4% moringa leaf extract treatment (T_8), which measured 9.62 mg/100 g. Conversely, the control had the lowest tannin concentration at 8.30 mg/100 g (Figure 7). The data presented in Figure 6 clearly show the effect of biostimulant sprays on the oxalic acid content and exhibited a significant difference. Specifically, treatment T_2 (3% seaweed extract) recorded a high oxalic acid content of 3.21 mg/100 g, followed by T_8 (4% moringa leaf extract) at 3.18 mg/100 g both indicating significant levels. In contrast, the control treatment (T_{15}) shows lower oxalic acid content of 2.51 mg/100 g. The application of biostimulants hadshown a significant difference and had notable effect on the lignin content in bananas. Treatment T_2 (3% seaweed extract) recorded a high lignin content of 8.82%, followed by T_8 (2% moringa leaf extract) at 8.56%. In comparison, the control (T_{15}) exhibited lower lignin content of 7.20% as shown in Figure 7.

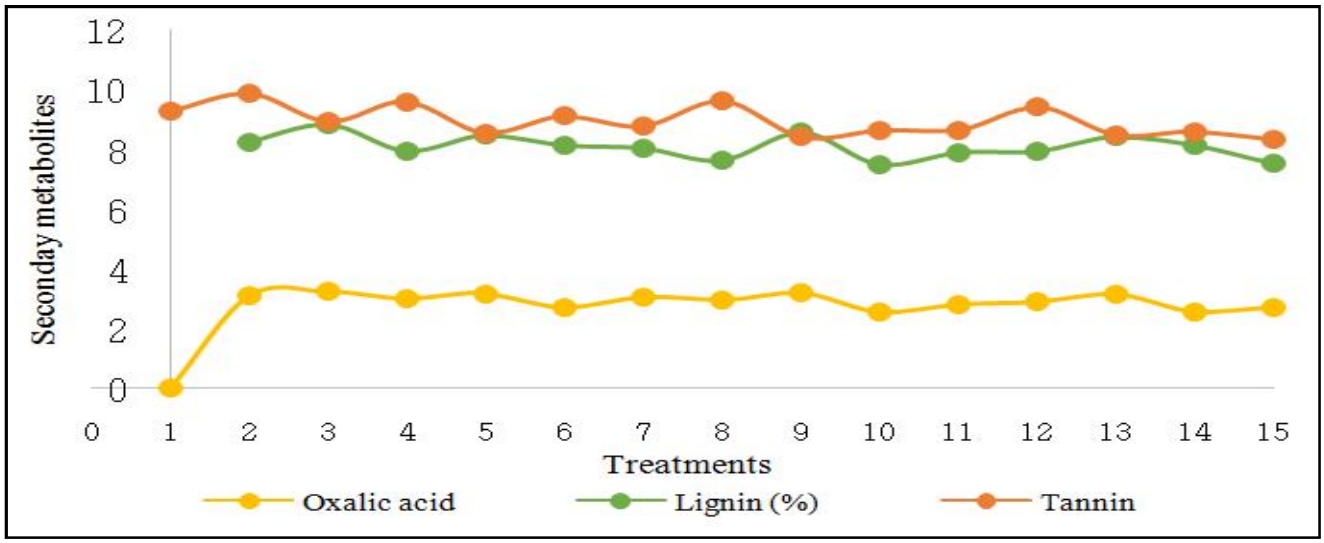

Figure 7: Effect of biostimulants on tannin and oxalic acid content of Virupakshi banana.

4. Discussion

Plant-derived natural products have been used to promote and maintain human health (Manju and Pushpa, 2020). The application of seaweed extract and moringa leaf extract has resulted in notable improvement in the physiological traits and quality attributes of banana plants. The seaweed extract 3% (T_2) induced the Virupakshi banana to exhibit a significantly increased sugar content. Multiple enzymes such as glutamine synthetase, superoxide dismutase, nitogen metabolishing enzyme and catalase are activated by the seaweed extract infusion, affecting physiological functions. These enzymatic activities are essential for enhancing physiological functions in plants, ultimately contributing to better growth and resilience against stress (Hamouda *et al.,* 2022). The amount of sugar in banana increased as a result of these activities, which also promoted metabolic activity during the starch to sugar conversion. Our findings are in accordance with Chen *et al.* (2021) and Sivasankari *et al.* (2006).

Seaweed extract 3% (T_2) significantly increased the levels of both reducing and non-reducing sugars in Virupakshi cultivar fruits (Melo *et al.,* 2018). This effect is attributed to the activation of enzymes such as amylases, which convert complex polysaccharides into simpler sugars. This process is controlled at the molecular level by hormonal signals, particularly gibberellins, which stimulate the transcription of amylase genes and boost enzyme production. In addition, transcription factors are vital for regulating gene expression, while sugar signaling pathways adjust metabolic processes based on the plants sugar levels. These combined mechanisms ensure efficient sugar mobilization in response to environmental changes (Ju*et al.,* 2019).The present study demonstrated that the foliar application of seaweed extract significantly increased the reducing and non-reducing sugar content. These results are in line with those reported by Khan *et al.* (2012), who found that applying a mixture of amino acids and *A. nodosum* (seaweed) extract to grapevines resulted in higherreducing and non-reducing sugars compared with other treatments. Similar observations have been reported in various crops*, viz.,* banana, watermelon, date palm and avocado (Abd el Moniem *et al.,* 2008; Abdel-Mawgoud *et al.,* 2010; Omar *et al.*, 2017; El-Shamma *et al.*, 2017).

The observed increase in sugar content may be attributed to a greater accumulation of photoassimilates such as sugars, amino acids and organic acids in the fruits of plants treated with seaweed extract 3% (T_2). Following seaweed extract (3%),moringa leaf extract (4%) increased the biochemical attributes is mainly due to the presence of zeatin which facilitated the movement of sugars from the leaves to the fruits (Nazmy *et al.*, 2016). Similarly, Rady and Mohamed (2015) and Bakhsh *et al.* (2020) reported that applying moringa leaf extract can increase the levels of total sugar, reducing sugar and non-reducing sugars.

Carbohydrates are essential not only as an energy source for plant cells but also for their roles in signaling pathways, photosynthesis and cell differentiation. High level of carbohydrate accumulation in the seaweed extract (3%) sprayed plants (T_2) and it was due its richness in micronutrients that played a role in the production of proteins, amino acids, carbohydrates and other essential compounds (Mannino *et al.,* 2020). These results arein consistent with those of El-Miniawy *et al.* (2014) who found that certain natural extracts significantly increased carbohydrate levels in banana and the presence of cytokinin and starch improvement in moringa leaf extract which increases the carbohydrate level in the banana. A similar findings were reported by Kamran *et al.* (2016); Tesfay and Magwaza (2017) and Bakry *et al.* (2021).

The application of seaweed extract 3% (T_2) significantly resultedinincreased starch levels. This enhancement was attributed to the bioactive compounds such as phytohormones, phenols, vitamins, minerals and fatty acids in the extract which promote growth and accelerate fruit development (Karthikeyan and Shanmugam, 2016). As the fruit matures faster, starch accumulates earlier, benefited in both quantity and quality (Rana *et al.,* 2023). Seaweed extract 3% (T_2) have shown increased carotene content due to unique physiological adaptations to environmental factors such as light intensity, nutrient availability and growth conditions. Seaweed extract increases carotene content in bananas through various physiological processes, including the enhancement of chlorophyll synthesis, improved photosynthetic efficiency and better nutrient uptake (Ali *et al.,* 2021). Bioactive compounds in seaweed extracts, such as phytohormones and polysaccharides, activate signaling pathways that enhance gene expression for chlorophyll biosynthesis, improving photosynthesis. Additionally, these compounds interact with carotenoid synthesis pathways, increasing the expression of enzymes like phytoene synthase, which is crucial for carotenoid production (Mughunth *et al.,* 2024).

Seaweed extract 3% (T_2) serve as natural biostimulant that improve the nutrient uptake of banana especially for potassium and calcium, as it is rich in bioactive compounds such as polysaccharides and phytohormones, these extracts promote plant growth and development and enhancing overall fruit quality, including nutrient content. Notably, the application of seaweed extracts has led to significant improvements in biochemical characteristics and also significantly increased mineral levels, particularly potassium and calcium (Mughunth *et al.,* 2024). Additionally, the interaction between seaweed extract and soil microbes creates a conducive environment for nutrient availability, resulting in elevated levels of potassium and calcium in the plant tissues (Anli *et al.,* 2020). Studies suggest that these enhancements positively influence fruit quality traits and nutritional value. And these results may vary depending on the crop and environmental conditions such as soil type, moisture levels, temperature (Ali *et al.,* 2021). Research indicates that applying seaweed extract significantly increase potassium levels in golden delicious apple, demonstrating its versatility as a biostimulant across different species (Mousavi *et al.,* 2024) and it also led to increased calcium concentration in grapevines benefitted in improving yield and quality (Islam *et al.,* 2023).

Plants yield various chemicals from different parts, such as bark, leaves, roots, seeds and fruits (Reddy *et al.,* 2012). The impact of seaweed extract 3% (T_2) on the production of secondary metabolites in bananas is mainly due to the bioactive compounds within the extracts, which stimulate various physiological processes. These compounds enhance plant metabolism and activate the biosynthetic

pathways responsible for the synthesis of tannins, oxalic acid and lignin. The increased chlorophyll production and improved photosynthetic efficiency lead to greater energy availability for metabolic processes, resulting in higher accumulation of these metabolites, which are vital for plant defense and nutrient storage. Similar results have been witnessed in various studies in strawberry and Fuji apples by Kapur *et al.* (2024) and Yang *et al.* (2023) highlighting the role of seaweed extract in enhancing secondary metabolite production in different crops.

5. Conclusion

This study outlined the quality, biochemical and secondary metabolite parameters of the Virupakshi banana. The utilization of biostimulants, particularly 3% seaweed and 4% moringa leaf extracts, significantly enhanced the biochemical attributes and quality of Virupakshi banana. These treatments increased total sugar, reducing sugars, starch, carotene, calcium and potassium levels, thereby improved the fruit quality and nutritional value of fruits. Additionally, seaweed extract induced the production of beneficial secondary metabolites such as tannins, oxalic acid and lignin. This study explored the potential of biostimulants in sustainable agriculture. Overall, application of seaweed extract and moringa leaf extract can enhance both crop quality and nutritional benefits of banana.

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Conflict of interest

The authors declare no conflicts of interest relevant to this article.

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