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Effect of pre-harvest chemical treatments on post-harvest disease control and quality enhancement in banana fruits

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Abstract: Bananas, as climacteric fruits, are highly prone to rapid deterioration caused by fungal pathogens, resulting in considerable post-harvest losses. These pathogens typically infect the fruit during field growth, resulting in latent infections that develop into disease after harvest. Generally, several rounds of fungicides such as Carbendazim, Mancozeb + Carbendazim, Trifloxystrobin + Tebuconazole, and Propiconazole are applied to manage fungal diseases like Fusarium wilt and leaf spot in the field. This study assessed the effectiveness of these chemicals on post-harvest diseases, fruit quality and residual toxicity. All four fungicides recorded 80–100% control against major pathogens responsible for anthracnose (*Colletotrichum musae*) and crown rot (*Lasiodiplodia theobromae* and *C. musae*), at concentrations of 0.05–0.2%. Field application of the chemicals completely controlled anthracnose and significantly reduced crown rot severity. The treatments also improved fruit size (32.10–35.62 mm), yield (18.83–20.06 kg/plant), firmness (13.66–15.67 N), and shelf life (up to 8.25 days at room temperature and 21–23 days at 13.5 ± 0.2 °C) than 28.24 mm,13.5 kg/plant, 11.37 N and (4.5 days and 14 days) in control, respectively. No pesticide residues were detected in the fruit or core stem, ensuring consumer safety.

Keywords: bananas; anthracnose; crown rot; fungicides; insecticides; residue; shelf life

India produces 35.36 million metric tonnes (MMT) of bananas annually, accounting for 26.45% of global production, yet contributes only 0.36 MMT (1%) to exports (APEDA 2024). One of the possible reasons could be due to the challenges in managing post-harvest diseases during long-distance transportation to reach export markets. Banana fruit is highly perishable and susceptible to spoilage, with post-harvest diseases accounting for an estimated loss of more than 80% if not properly treated with suitable chemicals (Alvindia 2012). The primary cause of such losses is fungal diseases, with 42 genera of fungal pathogens reported to be involved in the fruit spoilage (Johnston, Jones 1997; Sahoo, Pawar 2025). However, two major fungal diseases, anthracnose (*Colletotrichum musae*) and crown rot (*Lasiodiplodia theobromae*, *C. musae*, *Fusarium* spp., *Verticillium* sp., etc.), are responsible for significant post-harvest losses. In India, *L. theo-*

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bromae and *C. musae* are considered the major causal agents of crown rot (Thangavelu et al. 2007). Typically, post-harvest pathogens enter the plant system in the field and cause diseases during later stages (latent infection), including fruit ripening, transportation and storage. Several approaches, such as biocontrol, modified atmosphere storage, edible coatings, and the use of essential oils, have been explored for managing post-harvest diseases (Moradinezhad, Ranjbar 2023; Droby et al. 2025). Still, fungicides, both systemic and contact in nature, remain a commonly used method for post-harvest disease management (De Lapeyre de Bellaire et al. 2000; Nath et al. 2014; Snehalatharani et al. 2021; Mevada et al. 2025; Uppala, Sulley 2025). Banana plants are succumbing to two important field diseases: Fusarium wilt (*Fusarium oxysporum* f.sp. *cubense*) and leaf spot (*Pseudocercospora eumusae* synonym *Mycosphaerella eumusae*). To manage these diseases, systemic and contact fungicides are applied multiple times, depending on the disease severity. For example, Carbendazim is applied approximately 15.5 kg/ha through sucker dipping, soil drenching, and pseudostem injection for controlling Fusarium wilt (Thangavelu, Uma 2018). Similarly, sequential sprays with four fungicides for seven times at different intervals are employed for leaf spot disease control (Thangavelu et al. 2020a). However, the impact of these chemicals on post-harvest products (fruits and central core stem) remains unexplored. Previous studies in other crops have shown that chemical applications during pre-harvest stages can play a role in controlling post-harvest diseases (Singh, Sharma, 2018). Therefore, this study aims to evaluate the effectiveness of scheduled chemicals meant for managing leaf spot and Fusarium wilt on post-harvest diseases. Residues in harvested products pose significant challenges in all food and fruit crops, including bananas, which are commercially important, export-oriented, and widely consumed fruits. Therefore, residue analysis in post-harvest products has been included in this study. Additionally, the analysis also encompasses other validated chemicals meant for controlling insects and nematodes to assess their residues in the harvested products. Previously, to our knowledge, no study has been conducted to demonstrate residue status in bananas following the comprehensive application of chemicals intended for pest and disease control.

MATERIAL AND METHODS

Effect of test fungicides on post-harvest pathogens by *in vitro* food poisoning technique

Fungicides such as Mancozeb 63% + Carbendazim 12% WP, Carbendazim 50% WP, Trifloxystrobin 25% + Tebuconazole 50% WG, and Propiconazole 25% EC were prepared in different concentrations (0.05–0.2%) in potato dextrose agar (PDA) by the poisoned food technique (Zentmeyer 1955; Vanani et al. 2024). A 5 mm mycelial disc of *C. musae* or *L. theobromae* was placed at the centre of each agar plate using a sterile cork borer. A control was maintained without adding any fungicide to the medium. Each treatment was performed in triplicate. The plates were incubated at 25 ± 1 °C for 3 days in the case of *L. theobromae*, while 7 days for *C. musae,* and radial colony growth of the pathogen was measured. Per cent inhibition was calculated (Vincent 1947; Vanani et al. 2024) and data were arcsine transformed for statistical analysis.

$$\text{Per cent inhibition} = (C - T/C) \times 100$$

where: C – radial growth in control (mm); T – radial growth in treatment (mm)

Effect of application of pre-harvest chemicals on post-harvest diseases of banana

ICAR-National Research Centre for Banana (ICAR-NRCB), Tiruchirappalli, Tamil Nadu, India recommended chemicals meant for Fusarium wilt, leaf spot and pest management were applied on banana (cultivar 'Grand Nain') during 2021–2022 at ICAR-NRCB (Table 1). Meteorological observations on rainfall, temperature (maximum and minimum) and relative humidity were also recorded (Table S1 in the electronic supplementary material (ESM)). The experiment comprised four treatments (T1–T4), each replicated five times. In general, chemicals used for controlling Fusarium wilt, leaf spot, rhizome rot, nematodes and insects (pseudostem borer and thrips) were included in T1 (Table 1) and with the exclusion of insecticides in T2. Fungicides meant for controlling leaf spot disease alone were included in T3, while T4 was an untreated control. Observations on growing degree days (GDD), yield (bunch weight, fruit girth, etc.), fruit quality at ripening stage, post-harvest diseases (crown rot and anthracnose) and shelf life were recorded at different intervals. Har-

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vested bunches were de-handed, washed, shade-dried, and stored at ambient (25 ± 0.2 °C) and cold storage (13.5 ± 0.2 °C). Post-harvest diseases such as anthracnose and crown rot were scored on a 0–4 scale (Thangavelu 2004) and a 0–5 scale (Finlay, Brown 1993), respectively.

Physicochemical analyses of banana fruit

Total soluble solids (TSS). The TSS content of the mashed fruit pulp was determined using a digital refractometer (Rudolph J57, Rudolph Research Analytical, Germany) after two-point calibration with distilled water and a standard sucrose solution at 20 ± 1 °C. Approximately 2–3 drops of homogenised pulp sample were placed on the prism surface, and the readings were expressed in °Brix. Measurements were carried out in triplicate for each treatment, and the mean values were used for statistical analysis.

Determination of moisture content. Moisture content of the samples (peeled fresh fruit) on a dry weight basis (DW%) was determined according to AOAC (2000).

$$\text{Moisture content (\%)} = (W_1 - W_2)/W_0 \times 100$$

where: W_0 – weight of sample (g); W_1 – weight of Petri dish + sample before drying (g); W_2 – weight of Petri dish + sample after drying (g).

Each treatment consisted of three replications, and the mean values were used for data analysis.

Titratable acidity. Titratable acidity was determined by titration against 0.1N NaOH (AOAC

Table 1. Chemicals applied on banana (cultivar 'Grand Nain') for controlling pests and diseases under field conditions

S. No.	Target pest	Days after transplanting	Chemicals
1.	Fusarium wilt	during planting	drenching of 0.1% Carbendazim 50% WP @ 50 mL/plant 1 h before planting
		90, 150 and 210	pseudostem injection with 3 mL of 0.1% Carbendazim 50% WP solution
		additional application	drenching of 0.1% Carbendazim 50% WP @ 3 L per plant for 3 times at 15 days interval from 5 months after planting
2.	Eumusae leaf spot	150	spray of Carbendazim 50% WP @ 1 g/L + petroleum mineral oil (10 mL/L)
		175	spray of Propiconazole 25% EC @ 1 mL/L + petroleum mineral oil (10 mL/L)
		200	spray of Mancozeb 63% + Carbendazim 12% WP @ 1 g/L + petroleum mineral oil (10 mL/L)
		225	spray of Trifloxystrobin 25% + Tebuconazole 50% WP @ 1 g/L + petroleum mineral oil (10 mL/L)
		250	spray of Carbendazim 50% WP @ 1 g/L + petroleum mineral oil (10 mL/L)
		275	spray of Propiconazole 25% EC @ 1 mL/L + petroleum mineral oil 10 mL/L
		300	spray of Mancozeb 63% + Carbendazim 12% WP @ 1 g/L + petroleum mineral oil (10 mL/L)
3.	other pests and diseases		application of bleaching powder @ 6 g/pit and Cartap hydrochloride 4% GR @ 10 g/plant during planting for controlling rhizome rot disease and nematodes respectively pseudostem injection with Monocrotophos 36% SL @ 5 mL/plant prepared by mixing 150 mL of the chemical in 350 mL water for control of weevil bud injection with Imidacloprid 17.8 SL for control of thrips @ 1 mL (0.6 mL of the chemical in 1 L water)

T1 – applied with the chemicals listed in S. No. 1–3; T2 – applied with the chemicals listed in S. No. 1 and 2; T3 – applied with chemicals listed in S. No. 2 alone; T4 – control (untreated)

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1990). Five g of pulp was ground with 30 mL of single distilled water in a pestle and mortar, and filtered through cotton. From which, 5 mL aliquot was titrated against 0.1 N NaOH with 1% (W/V) phenolphthalein as the indicator. The end point was the appearance of stable pale pink. The volume of 0.1 N NaOH used during titration was recorded. Total acidity is defined as the percentage of titratable acidity.

Titratable acidity (% citric acid) = (titre value × normality of alkali × equivalent weight × volume made up) ÷ (volume of sample taken × weight of sample × 1000) × 100

Firmness of fruit. The firmness of banana fruits, along with the peel, was measured using a digital fruit penetrometer (GY-4, ELIXIR, China). The test was conducted at room temperature (26 ± 2 °C) by applying an 8 mm diameter plunger to a penetration depth of 10 mm. Measurements were taken at three equidistant points along the equatorial region of each fruit (Figure S1 in ESM) after removing a small portion of peel to ensure uniform contact. The force required for penetration was recorded and expressed in Newtons (N). Each treatment consisted of three replicate fruits, and the mean values were used for data analysis.

Determination of total sugar (%) and total starch (%). Total sugar and starch contents of fresh pulp were estimated by the anthrone method (Sadasivam, Manickam 2008). 0.5 g of banana pulp was mixed with 10 mL of 85% (v/v) ethanol and centrifuged at 10 000 rpm for 20 min. The supernatant was used for the estimation of sugar after mixing with anthrone reagent. The soluble sugar removed pellet was treated with 5 mL chilled distilled water and 6.5 mL of 52% perchloric acid (v/v). The content was centrifuged, and the supernatant was used for the estimation of starch after mixing with anthrone reagent. The colour development in both the assays was measured in a UV-Spectrometer (UH5300, Hitachi, Japan) at 630 nm.

Analysis of residues in the harvested products

Analysis of residues was carried out in samples of T1, where all the chemicals were applied as per Table 1, and T4, where no treatment was imposed. Samples consisted of banana fruits from the first, middle and bottom hands, and the central core stem of the top, middle and bottom portions.

Preparation of standard solutions

Individual pesticide stock solutions were made by dissolving 10 (± 0.01) mg of certified reference materials in 10 mL of methanol. Using appropriate dilutions, intermediate standard mixtures of 10 mg per kg and working standard mixtures of 1 mg/kg were prepared by diluting in the solvent. The calibration standards for liquid chromatography mass spectrometry (LC-MS/MS) were prepared by serial dilution in a methanol : water (50 : 50 at concentrations ranging from 0.001–0.050 mg/kg. Similarly, for the carbon disulfide (CS_2) standard solution, the stock solution was prepared by adding 10 mL of isooctane to a 20 mL capacity air-tight screw cap bottle. The weight of the solution was recorded (A). Then 20 µL of pure CS_2 was added to the bottle, and the weight of the standard was again recorded (B). The concentration was calculated by using the weight/volume method. The matrix-matched calibration standards were prepared by using the control matrix extracts.

Sample preparation for analysis of all test chemicals except mancozeb

The entire laboratory sample was thoroughly crushed in a mixer and grinder, and approximately 200 g of sample was homogenised using a high-speed homogeniser (DIAX-900, Heidolph, Schwabach, Germany) to a smooth paste. In a 50 mL polypropylene centrifuge tube, a sample (10 g) was drawn, and 10 mL ethyl acetate and 10 g anhydrous sodium sulphate were added. The mixture was homogenised for 2 min before being centrifuged at 5 000 rpm for 5 min. By vigorously shaking for 30 s, an aliquot of the supernatant ethyl acetate layer (5 mL) was cleaned by dispersive solid phase extraction (dSPE) with PSA (25 mg). The 2 mL extract was then evaporated and reconstituted in a 1 : 1 methanol and water solution containing 0.1% acetic acid, and the extract was filtered using a 0.2 nylon membrane filter paper before being injected into an LC-MS/MS.

LC-MS/MS for multiresidue analysis

The target analytes were separated chromatographically using a Restek column (3 µm, 100 mm length, 2.1 mm ID; Restek Corporation, Bellefonte, USA). Aliquid chromatography system coupled to a QTRAP 5500 mass spectrometer constituted

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the LC-MS/MS system (Sciex, Toronto, Canada). Analyst software (version 1.7.1) was used to execute the test. The mobile phase consisted of 10 mM ammonium formate + 0.1 per cent formic acid in (A) water and (B) methanol. The total run time was 20 min with a 0.5 mL/min flow rate, and the injection volume was 10 µL. The temperature in the column oven was kept at 40 (1 °C). The gradient profile was 0–2.5 min, 95% A; 2.5–5 min, 40% A; decreasing to 5% A; 5–12.5 min, 5% A; 12.5–16.5 min, 2% A increasing to 95% A; and 16.5–20 min, 95% A.

The residue concentration measurements were done with electrospray ionisation (ESI) in positive polarity with optimised multiple reaction monitoring (MRM) transitions. The source parameters, namely, ion source voltage (5 500 V), nebuliser gas (30 psi), heater gas (60 psi), ion source temperature (550 °C), and curtain gas (40 psi), were maintained throughout the analysis.

The pesticide residues estimation was performed by a retention time dependent scheduled MRM with two mass transitions for each test pesticide; one for quantification and the other for qualitative confirmation, all within a 30 per cent ion ratio variation tolerance limit. With a target scan time of 2 s, the MRM detection window was set at 90 s.

Sample preparation for analysis of Mancozeb as CS_2

The homogenised sample, 25 g (± 0.10), was taken in a 250 mL capacity screw-capped bottle and to it 75 mL of the reaction mixture [weigh 30 g of Tin (II) chloride and dissolve it in 1 000 mL of HCl] and 25 mL of isooctane were added. The bottle was closed immediately with a screw cap and placed in a water bath at 80 (± 5) °C. The content of the bottle was mixed thoroughly by inversion every 20 minutes. After the total reaction time of 60 min, the bottle was removed from the water bath and mixed again. The bottle was cooled by placing it in an ice-cooled water bath to about 10–20 °C. An aliquot of the isooctane layer (1.8 mL) was transferred to a 2 mL micro-centrifuge tube. It was centrifuged at 5 000 rpm for 5 min at 10 °C. The supernatant (1 mL) was transferred to an autosampler vial and injected into the GC-MS/MS.

GC-MS for Mancozeb (as CS_2) analysis

The analysis was performed using Agilent GC (7890A) equipped with a CTC Combipal (CTC Analytics, Switzerland) autosampler, connected to a triple quadrupole mass spectrometer (7000B, Agilent Technologies, Santa Clara, USA) with Mass Hunter software (version B.05.00.412). The GC capillary column used for analysis was Agilent 19091M-431 DB-5MS (30 m × 250 µm × 0.25 µm 5% diphenyl/95% dimethylpolysiloxane). Ultrapure helium was used as a carrier gas. Injection in split mode was optimised for the best response of CS_2 in GC-MS, operating in electron ionisation (EI) and selected ion monitoring (SIM) modes, with the target ions of m/z 76 (quantifier) and 78 (qualifier) with an intensity ratio of approximately 100 : 10 for confirmation of CS_2. The residues were quantified using the procedure mentioned in the publication of Mujawar et al. (2014).

Statistical analysis

In all *in vitro* experiments, a completely randomised design was employed, whereas a randomised block design was used for field experiments. Data were reported as mean values ± standard deviation or analysed using analysis of variance (ANOVA). Multiple mean comparisons were conducted using Duncan's multiple range test (DMRT). Statistical analyses were performed using Web-Based Agricultural Statistics Software Package (WASP; version 2.0), developed by ICAR-Central Coastal Agricultural Research Institute, Goa, India.

Principal component analysis (PCA) was performed for all variables using the prcomp() function in R software (version 3.6.1, R Core Team 2019). The factoextra package (Kassambara et al. 2017) in R was utilised to create PCA biplots.

RESULTS AND DISCUSSION

***In vitro* effect of test fungicides on post-harvest pathogens.** Banana cultivation faces numerous disease threats, with Fusarium wilt and leaf spot being particularly concerning (Arzanlou et al. 2008; Thangavelu et al. 2013, 2020a), fungicides, including systemic individual (Carbendazim, Propiconazole), systemic combinations (Tebuconazole + Trifloxystrobin), and systemic-contact blends (Carbendazim + Mancozeb), are commonly used to manage these diseases. While the efficacy of these chemicals against targeted diseases is well-documented (Thangavelu, Uma 2018; Thangavelu et al. 2020a, b), their impact on other fungal diseases, particularly post-harvest

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ones, remains unstudied. Further, the systemic fungicides often have long residue effects and generally many post-harvest pathogens enter plants during pre-harvest stages, thus the focus is to examining the effects of pre-harvest fungicide applications meant for Fusarium wilt and leaf spot diseases on post-harvest diseases.

Fungicides, such as Propiconazole, Carbendazim, Mancozeb + Carbendazim and Tebuconazole + Trifloxystrobin, exhibited greater inhibition of *C. musae* and *L. theobromae* growth. Specifically, even at low concentration (0.05%), the Propiconazole, Carbendazim, and Tebuconazole + Trifloxystrobin exhibited 100% inhibition of *C. musae* and *L. theobromae*, while the same concentration of Mancozeb + Carbendazim recorded more than 80% control of the pathogens (Table 2). These findings suggest that these fungicides could be useful not only in managing leaf spot and Fusarium wilt but also in controlling post-harvest pathogens such as crown rot (*L. theobromae* and *C. musae*) and anthracnose (*C. musae*).

The effectiveness of fungicides could be attributed to their mode of action on fungi. Propiconazole, a triazole fungicide, inhibits the 14-alpha demethylase enzyme in fungi and disrupts ergosterol synthesis and cell membrane formation (Oliver, Beckerman, 2022). Carbendazim, a systemic fungicide, disrupts DNA synthesis during fungal cell division by binding to beta-tubulin subunits, impairing mitotic spindle formation (Oliver, Beckerman 2022). Mancozeb, a polymeric zinc and dithiocarbamate complex, acts as a multisite action fungicide by interfering with fungal cell processes (Gullino et al. 2010). It disrupts the enzymes involved in vital biochemical functions, inhibiting the growth and reproduction of various pathogens. Tebuconazole, a triazole fungicide, inhibits ergosterol synthesis while Trifloxystrobin, a quinone outside inhibitor, disrupts fungal respiration (Saha et al. 2014). Combining these fungicides with different modes of action provides not only effective control of leaf spot and Fusarium wilt diseases in banana but also its post-harvest pathogens.

Effect of the pre-harvest chemical treatments on yield and its associated parameters. Banana cultivation often relies on chemical protection against Fusarium wilt and leaf spot diseases (Gianessi, Williams 2011), which can significantly impact yield. In our study, we observed a substantial difference between treatments with and without chemical application (Table 3). Chemical-treated plants (T1–T3) yielded significantly higher bunch weights (18.83–20.06 kg/bunch) compared to the control (13.5 kg/bunch), besides the chemical ap-

Table 2. *In vitro* effect of different fungicides on mycelial growth inhibition of *Colletotrichum musae* and *Lasiodiplodia theobromae*

S. No	Fungicides	Concentration (%)	Growth inhibition (%)	
			C. musae	*L. theobromae*
1	Propiconazole 250 EC	0.05	100 ± 0.0^{a}	100 ± 0.0^{a}
		0.1	100 ± 0.0^{a}	100 ± 0.0^{a}
		0.2	100 ± 0.0^{a}	100 ± 0.0^{a}
2	Tebuconazole 50% + Trifloxystrobin 25% WP	0.05	100 ± 0.0^{a}	100 ± 0.0^{a}
		0.1	100 ± 0.0^{a}	100 ± 0.0^{a}
		0.2	100 ± 0.0^{a}	100 ± 0.0^{a}
3	Mancozeb 63% + Carbendazim 12% WP	0.05	81.0 ± 1.7^{c}	81.0 ± 1.7^{d}
		0.1	94.1 ± 1.1^{b}	94.1 ± 1.1^{c}
		0.2	96.0 ± 1.8^{b}	97.6 ± 0.1^{b}
4	Carbendazim 50% WP	0.05	100 ± 0.0^{a}	100 ± 0.0^{a}
		0.1	100 ± 0.0^{a}	100 ± 0.0^{a}
		0.2	100 ± 0.0^{a}	100 ± 0.0^{a}
5	Control	–	0 ± 0.0	0 ± 0.0

Values are the means of three replications with SD; means in the columns followed by the different letters are significantly different at $P \leq 0.05$

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Table 3. Effect of different chemical treatments on fruiting and yield-associated characters in banana (cultivar 'Grand Nain')

Treatment	Fruit size calliper (mm)	Fruit firmness (N)	Growing degree days	Bunch weight (kg/plant)
T1	34.04[ab]	15.67[a]	2 284.51[a]	20.06[a]
T2	35.62[a]	13.82[b]	2 464.77[a]	18.83[a]
T3	32.10[b]	13.66[b]	2 374.05[a]	19.77[a]
T4	28.24[c]	11.37[c]	2 077.32[b]	13.50[b]
CV	6.84	4.35	6.89	11.43
CD (5%)	2.68	0.91	190.19	3.16

CV – coefficient of variation; CD – critical difference; N – Newton; means in the columns followed by the different letters are significantly different at $P \leq 0.05$

plication resulting in nearly a 40% increase in yield (Figure S2 in ESM).

Furthermore, the untreated control group exhibited non-marketable bunches with prematurely ripened fruits (Figure S3 in ESM) and fruit shattering (Figure S4 in ESM), likely due to severe leaf spot disease pressure (data recorded and not shown here) and as reported by Marin et al. (2003). This rapid ripening in the control group, where 2–3 fruits ripened on the first day and nearly 90% of fruits ripened by the third day, suggests the pathogens alter the physiology and induce the fast ripening in fruits (Stover 1974; Marin et al. 2003). Additionally, there was a noticeable difference in fruit size between chemical-treated and untreated groups, with fruits in the former treatments ranging from 32.10 to 35.62 mm in calliper size (T1–T3) compared to 28.24 mm in the latter (Table 3). The reduced fruit size in the control group could be attributed to leaf spot fungal pathogen attacks (Gianessi, Williams 2011). Moreover, the control group exhibited significantly lower degree days compared to the chemical-treated group, indicating premature ripening induced by leaf spot disease. These findings emphasise the importance of chemical protection in banana cultivation for disease management and yield enhancement. Further, as Fusarium wilt did not occur in the experimental plot, it was not included in the discussion related to yield and quality.

Efficacy of the pre-harvest treatments on post-harvest diseases and shelf life. Effective field sanitation and protection strategies are indispensable for mitigating these post-harvest diseases. Our research reveals that pre-harvest application of chemicals exerts a substantial effect on the control of post-harvest anthracnose and crown rot diseases, as evidenced by significant differences observed in chemicals applied and non-applied treatments (Table 4; Figure S5 in ESM). Interestingly, anthracnose was completely arrested in chemical treatments (T1–T3) up to 8 days under room temperature, indicating that such applications in pre-harvest stages have a strong role in controlling anthracnose.

This study suggests that fungicides deployed to combat leaf spot and Fusarium wilt during the critical pre-harvest stages also confer protection against anthracnose and crown rot diseases. These findings were in corroboration with our *in vitro* investigations, depicted in Table 2, where fungicides originally intended for Fusarium wilt and leaf spot management demonstrated notable efficacy against post-harvest pathogens. Further, interestingly, fungicides sprayed for leaf spot disease alone (T3) could also significantly control both the post-harvest diseases and the effect was on par with T2 and T1.

Table 4. Effect of different pre-harvest treatments on post-harvest diseases of banana (cultivar 'Grand Nain')

Treatment	Disease severity (%)	
	crown rot	anthracnose
T1	53.32 (46.92)[a]	0.00 (0.68)[a]
T2	60.00 (50.77)[a]	0.00 (0.68)[a]
T3	60.00 (50.77)[a]	0.00 (0.68)[a]
T4	80.00 (63.44)[b]	66.66 (55.00)[b]
CV	6.08	14.39
CD (5%)	5.59	6.29

CV – coefficient of variation; CD – critical difference; recorded on 8th day of storage at room temperature; values in parentheses are arcsine transformed; means in the columns followed by the different letters are significantly different at $P \leq 0.05$

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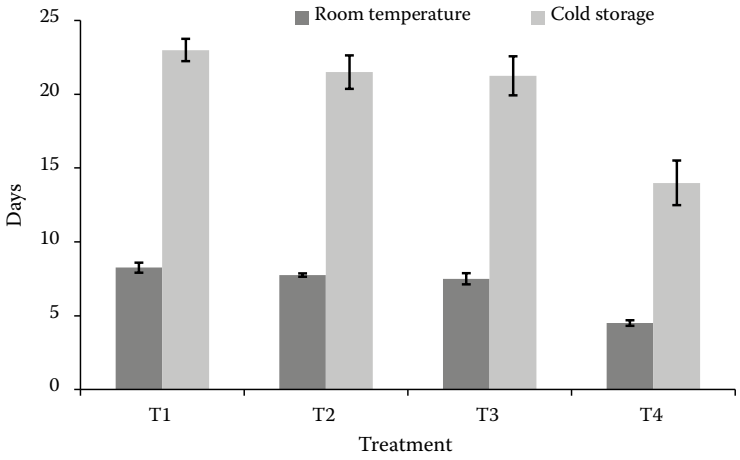

Figure 1. Effect of different pre-harvest treatments on shelf life at room temperature and cold storage
For treatments explanation see Table 1; error bars represent the standard error of the mean

Moreover, our study unveiled an additional benefit of pre-harvest chemical treatments: an extension of banana shelf life by up to 7–8 days, in contrast to the mere 4–5 days observed in untreated control at room temperature (Figure 1), while at 13.5 °C, it was 21–23 days in the chemical-treated and 14 days in the control. This noteworthy enhancement in shelf life further highlights the multifaceted impact of pre-harvest fungicide applications on banana quality and marketability.

Effect of the pre-harvest treatments on fruit quality and residues in the harvested produce. A multivariate analysis using principal component analysis (PCA) was conducted to examine the relationships among growing degree days (GDD), post-harvest biometrics, and anthracnose and crown rot diseases (Table S2 in ESM; Figure 2). Post-harvest parameters such as bunch weight, fruit size, and shelf life under both room and cold storage conditions were positively influenced by pre-harvest treatments (T1, T2, and T3). However, fruit size displayed the strongest expression among harvest biometrics and was closely aligned with GDD, suggesting that temperature accumulation influences fruit development. This observation is further supported by the significantly higher GDD recorded in the chemical treatments compared to the control (Table 3). Further chemical treatments deviated from both anthracnose and crown rot indicate that the chemicals have a great influence on the diseases.

The PCA biplot of post-harvest biometric data (Figure 3) revealed a relationship between fruit quality attributes (pulp–peel ratio, firmness, moisture content, total soluble sugars, acidity, total sugars, and total starch) and both crown

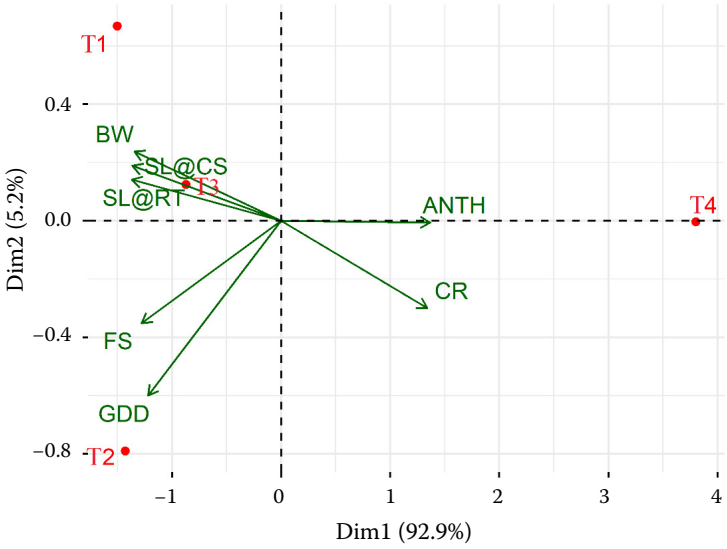

Figure 2. Multivariate analysis (principal component analysis-biplot) for different post-harvest biometric parameters, and anthracnose and crown rot diseases
FS – fruit size (mm); GDD – growing degree days; BW – bunch weight (kg/plant); CR – crown rot (%); ANTH – anthracnose (%); SL@RT – shelf life at room temperature; SL@CS – shelf life at cold storage (13.5 °C)

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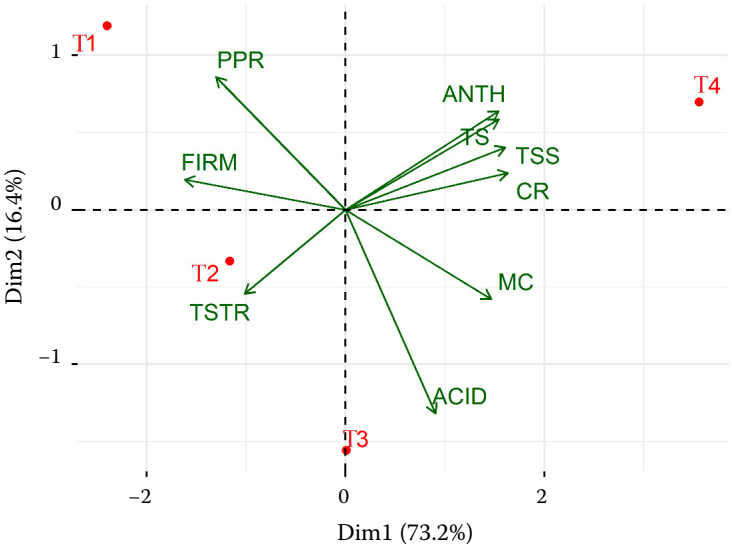

Figure 3. Multivariate analysis (principal component analysis-biplot) for different post-harvest quality parameters, and anthracnose and crown rot diseases
PPR – pulp peel ratio; FIRM – firmness (N); MC – moisture content (%); TSS – total soluble solids (°Brix); ACID – acidity (%); TSTR – total starch; TS – total sugars (%); CR – crown rot (%); ANTH – anthracnose (%)

rot and anthracnose incidence. Total sugars and total soluble salts showed the closest association with the diseases, indicating an increase in sugar content following infection. Pulp–peel ratio and firmness, total starch, and acidity and moisture were closely associated with Treatments 1, 2, and 3, respectively, while they were all distantly associated with T4.

Pre-harvest chemical treatments end with chemical residues in horticultural products can pose health risks to consumers if consumed in excessive amounts. The absence of these residues ensures that consumers are not taking the chemicals when consuming the produce. This is particularly important for fruits, which are often consumed raw and may not undergo extensive processing that could remove chemical residues. Analysis of residues in the harvested produces (fruit and centre core) also reveals that the absence of chemical residues (Bleaching powder, Cartap hydrochloride 4% GR, Imidacloprid 17.8 SL, Monocrotophos 36% SL, Carbendazim 50% WP, Petroleum mineral oil, Mancozeb 63% + Carbendazim 12% WP, Trifloxystrobin 25.0% + Tebuconazole 50.0% WG, and Propiconazole 25% EC) in the products collected from T1 (Table S3 in ESM). As no residue was detected in the combined application of all plant protection measures (T1), further analysis of residue in the rest of the treatments was not necessary. In banana cultivation, various chemicals are commonly used to control pests and diseases at different stages of the growth. However, to date, the impact of all these chemicals on residue levels has not been fully understood, leading to consumer concerns about the safety of consuming such bananas. The absence of detectable residues in this study, however, indicates that the bananas were grown using sustainable practices that minimise pest issues. This not only supports consumer health but also boosts export opportunities by meeting safety standards.

CONCLUSION

Our study demonstrates that pre-harvest fungicide applications (Carbendazim 0.1%, Mancozeb + Carbendazim 0.1%, Trifloxystrobin + Tebuconazole 0.1%, and Propiconazole 0.1%) targeting leaf spot and Fusarium wilt diseases in banana have a strong influence on post-harvest disease control, as these treatments achieved complete control of anthracnose and a significant reduction of crown rot (25–33%). This finding suggests that additional post-harvest chemical interventions for anthracnose management may be unnecessary when regular pre-harvest disease control measures are implemented. Further, pre-harvest chemical applications enhanced the fruit quality and extended shelf life by 3–4 days at room temperature and 7–9 days under cold storage conditions. Notably, the harvested edible portions were free from detectable chemical residues, which ensures consumer safety.

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