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Scientific Article

Post-harvest banana conservation strategies with salicylic acid and *Trichoderma harzianum*

Estratégias de conservação pós-colheita de banana com ácido salicílico e *Tricoderma harzianum*

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ABSTRACT - Bananas are a food of great global importance, playing an essential role in food security, economy and nutrition. However, they are highly perishable fruits, subject to significant post -harvest losses, making it necessary to use post-harvest technologies to enable the processing, storage, transportation and distribution of the fruits, while preserving their quality and safety, reducing economic losses. In this context, the objective of this study was to evaluate the post-harvest quality of bananas coated with different concentrations of salicylic acid and *Trichoderma harzianum*. The design used was completely randomized, consisting of two experiments, the first with six concentrations of salicylic acid (0; 0.5; 1.5; 3.0; 4.5 and 6.0 mM) and the second with five concentrations of *Trichoderma harzianum* (0; 0.5; 1.0; 1.5 and 2.0 mL L^{-1}), with three replicates and each experimental plot consisting of a cluster containing three fruits. The quality of banana fruits varies according to the concentration of salicylic acid. The use of coatings with *Trichoderma harzianum* at concentrations of 1.0 and 2.0 mL L^{-1} and with salicylic acid at concentrations of 3.0 and 6.0 mM L^{-1} delays fruit ripening, maintaining firmness and a greener color. Bananas cv. Nanicão coated with salicylic acid at a concentration of 1.5 mM have lower acidity, sugar content and a higher quantity of flavonoids, antioxidants, in addition to being firmer. Coating with *Trichoderma harzianum* at a concentration of 2.0 mL L^{-1} promotes higher levels of flavonoids, anthocyanins, pH and firmness of banana fruits.

Keywords: *Musa* spp.. Coating. Physical-chemical characterization. Shelf life.

RESUMO - A banana é um alimento de grande importância global, desempenha papel essencial na segurança alimentar, na economia e na nutrição. Contudo, trata-se de uma fruta altamente perecível, sujeita a significativas perdas pós-colheita, fazendo-se necessário o emprego de tecnologias pós-colheita viabilizando o processamento, armazenamento, transporte e distribuição dos frutos, ao mesmo tempo em que preserva sua qualidade e segurança, reduzindo prejuízos econômicas. Neste contexto, objetivou-se com este estudo avaliar a qualidade pós-colheita de bananas revestidas com diferentes concentrações de ácido salicílico e *Trichoderma harzianum*. O delineamento utilizado foi o inteiramente casualizados, consistindo em dois experimentos, o primeiro com seis concentrações de ácido salicílico (0; 0,5; 1,5; 3,0; 4,5 e 6,0 mM) e o segundo com cinco concentrações de *Trichoderma harzianum* (0; 0,5; 1,0; 1,5 e 2,0 mL L^{-1}), com três repetições e cada parcela experimental constituída por um buquê contendo três frutos. A qualidade dos frutos de banana varia conforme a concentração de ácido salicílico. O uso dos revestimentos com *Trichoderma harzianum* nas concentrações de 1,0 e 2,0 mL L^{-1} e com ácido salicílico nas concentrações de 3,0 e 6,0 mM L^{-1} retardam o amadurecimento dos frutos, mantendo a firmeza e a coloração mais verde. Bananas c. Nanicão revestidas com ácido salicílico na concentração de 1,5 mM possuem menor acidez, teores de açúcares e maior quantidade de flavonóides, antioxidantes, além de serem mais firmes. O revestimento na concentração de 2,0 mL L^{-1} de *Trichoderma harzianum* proporciona maiores teores de flavonóides, antocianinas, pH e firmeza dos frutos de banana.

Palavras-chave: *Musa* spp.. Revestimento. Caracterização Físico-química. Tempo de prateleira.

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INTRODUCTION

Banana plays significant roles in food security, job creation, economic development, and nutrition for many developing countries (ABRAHAM; SALEH; ZELELEW, 2022). Brazil stands out as one of the largest producers and exporters of bananas in the world, occupying the fourth position globally (FAO, 2023). In 2023, national production reached 6,825,724 tons in a cultivated area of 460,521 hectares. The Northeast region stands out as the main producer, accounting for 35% of the national production, with a total of 2,394,403 tons, and the states of Bahia, Pernambuco and Ceará stand out (IBGE, 2024).

The Nanicão banana plant, belonging to the Cavendish group, is widely recognized for its economic, nutritional and social importance, being one of the most consumed and exported banana varieties worldwide due to its high yield and wide acceptance in the market (NASCIMENTO JÚNIOR et al., 2008). In addition to being a significant source of carbohydrates, the fruit is rich in potassium, fiber, B vitamins, and antioxidants, playing an essential role in the human diet by contributing to cardiovascular and digestive health (FAO, 2023).

However, bananas are climacteric fruits, characterized by a high respiratory rate and ethylene production, which accelerates their ripening, a process which involves the conversion of starch into sugar, softening of the pulp, and changes in the aroma, flavor, and color of the peel, which acquires a yellow hue (THANGAVELU et al., 2024). In addition, mechanical damage caused by inadequate handling during the production chain, including storage conditions, can promote rapid ripening of banana fruits, compromising their commercial quality after harvest (ABRAHAM; SALEH; ZELELEW, 2022).

Salicylic acid application has shown a significant impact on the conservation and extension of the shelf life of fruits. Studies indicate that the use of salicylic acid coatings reduces ethylene production and respiration rate, delaying ripening and senescence in blueberries (JIANG et al., 2022), papaya (HANIF et al., 2020) and blackberries (WU et al., 2025), increasing the content of phenols and flavonoids (WU et al., 2025). Therefore, salicylic acid presents itself as an efficient solution to improve the conservation and extend the shelf life of bananas during storage.

In addition, biological agents, such as *Trichoderma* spp., constitute a viable option for post-harvest conservation. Thangavelu et al. (2024), when evaluating the use of *Trichoderma asperellum* in the post-harvest conservation of banana cv. Grand Nain, found that the fungus effectively controls the pathogens responsible for diseases, such as crown rot and anthracnose, besides increasing banana shelf life. However, studies investigating different concentrations of acid and *Trichoderma* spp. in banana fruits produced under different edaphoclimatic conditions and in other banana cultivars are necessary.

In this context, the present study tested the hypothesis that the application of salicylic acid and *Trichoderma harzianum* in the post-harvest of banana cv. Nanicão contributes to increasing shelf life and preserving fruit quality. Thus, the objective was to evaluate the post-harvest quality of banana coated with different concentrations of salicylic acid and *T. harzianum*.

MATERIAL AND METHODS

Banana fruits, cv. Nanicão, came from a commercial orchard located in the Várzeas de Sousa Irrigated Perimeter, sector 6 – lot 7, in the municipality of Sousa, PB, Brazil, at the geographic coordinates of 6°48’37.9’’S latitude and 38° 08’20.6’’W longitude, at an altitude of 223 m. After harvesting, the fruits were taken to the Hydraulics and Irrigation Laboratory of the Center for Science and Agrifood Technology – CCTA of the Federal University of Campina Grande – UFCG, in the municipality of Pombal, PB, with geographic coordinates of 6º 46’ 13” S latitude, 37° 48’ 06” W longitude, at an altitude of 193 m.

The study was conducted in a completely randomized design, consisting of two experiments, the first with six concentrations of salicylic acid – SA (0; 0.5; 1.5; 3.0; 4.5 and 6.0 mM) and the second with five concentrations of *Trichoderma harzianum* – TRI (0; 0.5; 1.0; 1.5 and 2.0 mL L^{-1}), with three replicates and each experimental plot consisting of one cluster with three fruits. Salicylic acid and *Trichoderma harzianum* concentrations were based on the studies of Xing et al. (2021) and Viencz et al. (2023), respectively.

Fruits were harvested at the pre-climacteric stage, peel color 1 (totally green), according to the Von Loesecke scale (PBMH; PIF, 2006), and the bunches were divided to form clusters with three bananas. The clusters were first cleaned in a solution of water and neutral detergent at 2% (2 mL L^{-1}) to remove latex and clean the surface, then sanitized in a solution of sodium hypochlorite at 0.5% (5 mL L^{-1}) for three minutes and then washed in running water.

After cleaning, the fruits were immersed for three minutes in the preservative solutions at the following concentrations: 0 (distilled water), 0.5, 1.5, 3.0, 4.5 and 6.0 mM of salicylic acid and 0 (distilled water), 0.5, 1.0, 1.5 and 2.0 mL L^{-1} of *T. harzianum*. The salicylic acid (SA) solution was prepared by dissolution in 30% ethyl alcohol (95.5% purity), followed by dilution in distilled water, reaching the desired concentrations. For the preservative solution with *T. harzianum*, the commercial product Trichodermil© (*T. harzianum* CEPA ESALQ 1306) was used, with a minimum concentration of 2.0×10^9 viable conidia mL^{-1}, added to the distilled water according the concentrations established.

Then, the fruits were weighed, placed in polystyrene trays, kept in the space and placed on opposite ends under light, temperature and humidity conditions so as to avoid interference between the experiments and ensure standardization of environmental conditions. The fruits were stored for 24 days at a temperature of 20±2 ºC and relative humidity of 70±5%. Plastic film was not used to coat the fruits to avoid its action as catalyzer of the banana ripening process. During this period, the physicochemical characteristics of the fruits were determined by colorimetry (L* - lightness, *C – chromaticity and °H – hue angle), mass loss – ML (g), firmness – FIR (Newton - N), hydrogen potential – pH, total titratable acidity – TTA (% malic acid), ascorbic acid – AA (mg 100 g^{-1} of pulp), total soluble solids – TSS (ºBrix), maturation index – MI (%), total sugars – TS (mg 100 g^{-1} of pulp), reducing sugars – RS (mg 100 g^{-1} of pulp), flavonoids – FLA (mg g^{-1} of pulp), anthocyanins – ANT (mg g^{-1} of pulp) and phenolic compounds – PHC (mg 100 g^{-1} of pulp).

Colorimetric parameters were determined using a colorimeter (Konica Minolta, CR 300): coordinate L, referring to lightness (results close to 0 characterize dark or opaque color and results close to 100 characterize white color), coordinate a* (representing red color when positive and green color when negative), coordinate b* (representing yellow when positive and blue when negative), coordinate C (chromaticity or color intensity), and Hº (Hue angle) according to MINOLTA (2007). Mass loss was quantified gravimetrically, using an analytical scale (SF-400 model).

The banana samples were macerated manually with the aid of mortar and pestle until a homogeneous paste was obtained, using all bananas from each experimental unit in order to ensure the representativeness of the sample in the analyses. Pulp firmness was determined after making an opening in the equatorial region of the fruit, using a digital penetrometer (SoilControl) with a 5-mm diameter tip. The pH was measured by inserting the electrode in the sample and recording the value after the pH meter stabilized (IAL, 2008). Total titratable acidity was determined using 5 g of sample, by titration with 0.1 M NaOH and phenolphthalein as an indicator. The results were expressed as a percentage (%) of malic acid, as described by IAL (2008).

Ascorbic acid was homogenized in 0.5% oxalic acid using 5 grams of sample and then titrated in the 2,6-dichlorophenoldophenol solution until persistent pink color was observed (STROHECKER; HENNING, 1967). Total soluble solids were measured using a digital refractometer (Atago, Pocket model). The maturation index was obtained by dividing the values of soluble solids by the values of titratable acidity.

For the quantification of total sugars, the sample was diluted in a ratio of 1:50, using 20 µL of this solution, which was mixed with 980 µL of distilled water and 2000 µL of anthrone. The reaction occurred in a water bath at 100 °C for 3 minutes. After cooling, reading was performed in a spectrophotometer (SP 2000 UV) at 620 nm (IAL, 2008). For the quantification of reducing sugars, the sample was diluted in a ratio of 1:50, using 500 µL of this solution, which was mixed with 500 µL of 3,5-dinitrosalicylic acid (DNS). The reaction occurred in a water bath at 100 °C for 15 minutes, followed by the addition of 4,000 µL of distilled water. Reading was performed in a spectrophotometer (SP 2000 UV) at 540 nm (IAL, 2008).

Flavonoid and anthocyanin contents were determined using 0.25 g of pulp macerated with mortar and pestle in 5 mL of ethanol-HCl (1.5 N), keeping the samples in the refrigerator at 6 °C for 24 hours. The samples were filtered on filter paper, and the flavonoid and anthocyanin contents were determined by spectrophotometry at 374 and 535 nm, respectively (FRANCIS, 1982). Total phenolic compounds were quantified using the Folin-Ciocalteau spectrophotometric method (WATERHOUSE, 2006).

The collected data were analyzed using principal component analysis (PCA). This technique aims to reduce the amount of relevant information from the original datasets by transforming it into a smaller number of dimensions. The dimensions were generated from linear combinations of the original variables, based on the eigenvalues ($\lambda \geq 1.0$) of the correlation matrix, and can explain more than 10% of the total variance. Only variables with a correlation coefficient equal to or greater than 0.5 were maintained in the PCA, using the FactoMineR package (Factor Analysis and Data Mining with R). The analysis was performed on the R platform, version 4.3.2 (R CORE TEAM, 2022).

RESULTS AND DISCUSSION

Principal component analysis (PCA) revealed that the first principal component explains 42.01% of the original variance of the data, showing significant correlations ($p \leq 0.01$) with lightness (r = -0.89) and chromaticity (r = -0.95) (Table 1). The second component contributes 34.54% of the variance, correlating significantly with the ascorbic acid content (r=0.90) and total sugars (r=0.88). Therefore, the first two components add up to 76.55% of the original variance of the data (Figure 1), meeting the retention criteria established by Kaiser (1960).

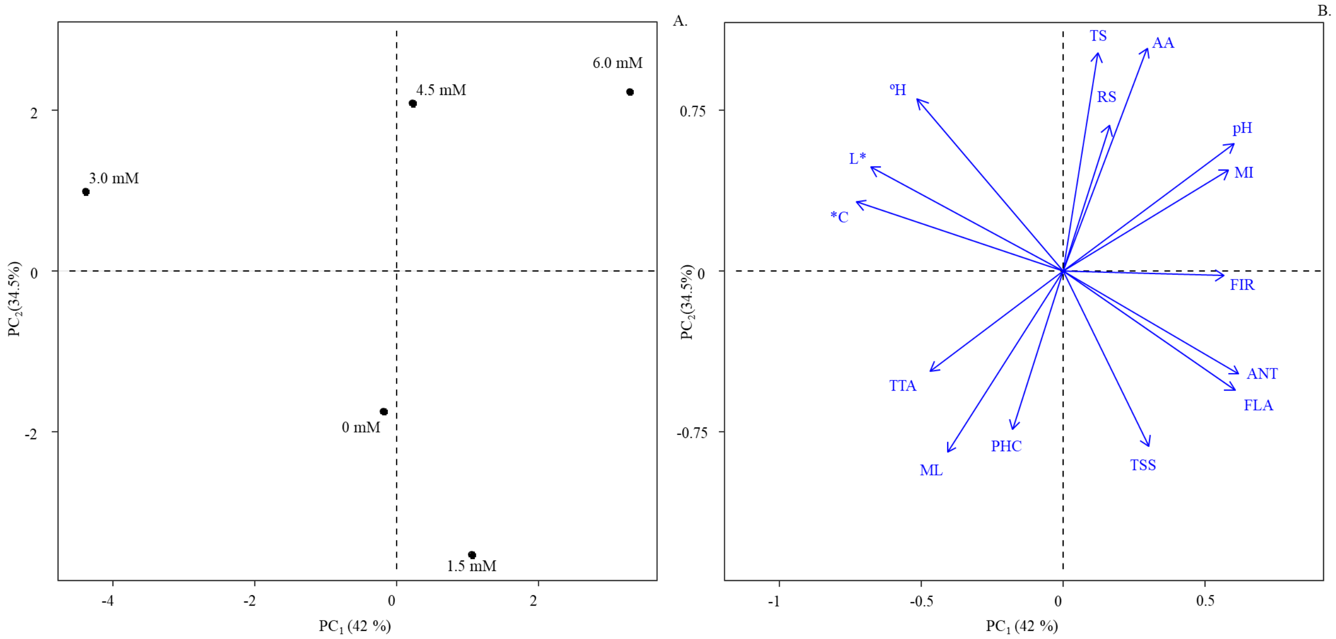
Table 1. Eigenvalues, percentage of total variance explained in the multivariate analysis of variance, and probability of significance by Hotelling's test (p-value) for salicylic acid (SA) concentrations applied to banana fruits of cv. Nanicão at 24 days after treatments.

	Principal components (PC)	
	CP1	CP2
Eigenvalues (λ)	6.30	5.18
Percentage of total variance (S^2 %)	42.01	34.54
Hotelling's test for SA concentrations	<0.01	<0.01

CPs	Correlation coefficients (r)							
	L	C	H	ML	FIR	pH	TTA	AA
CP1	-0.89	-0.95	-0.67	-0.53	0.74	0.79	-0.61	0.38
CP2	0.42	-0.28	0.70	-0.74	-0.21	0.51	-0.41	0.90
Concentrations (mM)								
0.0	53.23 ± 7.41	40.05 ± 2.13	79.30 ± 5.51	146.33 ± 14.57	2.73 ± 0.20	4.56 ± 0.03	7.28 ± 0.48	1.57 ± 0.09
1.5	46.32 ± 2.05	36.92 ± 2.09	75.72 ± 2.08	119.33 ± 6.66	3.67 ± 0.20	4.53 ± 0.02	8.09 ± 0.29	1.57 ± 0.03
3.0	68.64± 1.80	45.23 ± 2.84	87.30 ± 2.77	135.00 ± 13.75	2.86 ± 0.45	4.47 ± 0.04	7.93 ± 0.60	1.72 ± 0.11
4.5	60.40 ± 10.44	41.00 ± 1.23	81.55 ± 5.54	111.17 ± 8.74	2.99 ± 0.54	4.64 ± 0.04	7.92 ± 1.00	1.95 ± 0.10
6.0	46.82 ± 1.85	37.42 ± 2.57	81.36 ± 3.64	135.00 ± 7.47	3.88 ± 0.98	4.65 ± 0.02	6.28 ± 0.20	2.03 ± 0.03

	Correlation coefficients (r)						
CPs	TSS	MI	TS	RS	FLA	ANT	PHC
CP1	0.40	0.76	0.16	0.21	0.79	0.81	-0.23
CP2	-0.71	0.41	0.88	0.60	-0.49	-0.42	-0.64
Concentrations (mM)							
0.0	24.20 ±0.01	3.35 ± 0.21	16.71 ± 0.73	12.73 ± 1.52	2.89 ± 0.38	0.29 ± 0.20	17.21 ± 3.41
1.5	23.52 ± 0.65	2.91 ± 0.04	13.76 ± 1.82	8.97 ± 0.48	3.19 ± 0.52	0.45 ± 0.11	11.78 ± 7.32
3.0	21.98 ± 0.38	2.80 ± 0.23	16.34 ± 0.63	10.28 ± 2.40	2.02 ± 0.04	0.07 ± 0.01	10.53 ± 2.32
4.5	21.71 ± 0.72	3.22 ± 0.49	18.06 ± 1.41	13.93 ± 1.37	2.85 ± 0.56	0.34 ± 0.24	10.18 ± 1.50
6.0	23.03 ± 0.52	3.68 ± 0.18	18.03 ± 1.91	12.04 ± 0.91	2.81 ± 0.18	0.33 ± 0.06	7.74 ± 0.78

CPs – Principal components; CP1 – Principal component 1; CP2 – Principal Component 2; L* – lightness, *C – chromaticity, ºH – hue angle, ML – mass loss (g), FIR – firmness (Newton - N), pH – hydrogen potential, TTA – total titratable acidity (% malic acid), AA – ascorbic acid (mg 100 g^{-1} of pulp), TSS – total soluble solids (ºBrix), MI – maturation index (%), TS - total sugars (mg 100 g^{-1} of pulp), RS – reducing sugars (mg 100 g^{-1} of pulp), FLA – flavonoids (mg g^{-1} of pulp), ANT – anthocyanins (mg g^{-1} of pulp) and PHC – phenolic compounds (mg 100 g^{-1} of pulp).



CP1 – Principal component 1; CP2 – Principal Component 2; L* – lightness, *C – chromaticity, ºH – hue angle, ML – mass loss, FIR – firmness, pH – hydrogen potential, TTA – total titratable acidity, TSS – total soluble solids, MI – maturation index, TS – total sugars, RS – reducing sugars, FLA – flavonoids, ANT – anthocyanins and PHC – phenolic compounds.

Figure 1. Two-dimensional projection of principal component scores for salicylic acid concentrations (A) and the analyzed variables (B) in the two principal components (PC_1 and PC_2).

Regarding fruit peel color, it is known that the lightness (L*) can vary from 0 (black) to 100 (white), that is, a totally dark and a totally light fruit, respectively (DIAS et al., 2024). In the present study, the fruits coated with 1.5 mM of acid showed the lowest lightness (46.32) compared to the other acid concentrations and to uncoated fruits (Table 1). Therefore, the lower the value of the fruit's lightness, the more opaque its color (DIAS et al., 2024).

Color is one of the main attributes that defines the level of acceptance of fruits by consumers (BAJAJ et al., 2023). Similarly, chromaticity (*C) and hue angle (ºH) were lower at this salicylic acid concentration (1.5 mM), showing reductions of 7.8 and 4.5%, respectively, compared to uncoated fruits (Table 1). The chromaticity values found here were close to those observed by Xu et al. (2019) when evaluating the application of salicylic acid in the coating of bananas, which ranged from 40.12 (uncoated bananas) to 38.96 (bananas coated with 1.0 mM of salicylic acid) after 8 days of storage. This delay in the elevation of color values demonstrates a retardation in ethylene production, as color change is a natural indicator of maturity, and the intense change in peel color is caused by a peak in ethylene production (SRIVASTAVA; DWIVEDI, 2000). This is justified by the application of salicylic acid coating to improve the quality of storage by reducing ethylene production and respiration rate, suppressing fruit softening and color change, besides maintaining sugars, organic acids, aroma and antioxidant system (KUMAR et al., 2021).

Mass loss was accentuated in bananas subjected to a solution of 4.5 mM of salicylic acid, showing a reduction of 24.03% compared to uncoated bananas. It was also observed that the lowest mass loss among acid concentrations occurred at concentrations of 3.0 and 6.0 mM, corresponding to 7.74% compared to uncoated bananas (Table 1).

Bananas are climacteric fruits, which means that they continue to ripen after harvest, resulting in decreased firmness and loss of mass due to dehydration of cell walls and water loss (BORGES et al., 2019). It was observed that the application of SA coating intensified mass loss, but contributed to the maintenance of fruit firmness, especially at concentrations of 1.5 and 6.0 mM. This indicates that, although water loss occurred, cell wall degradation (due to the breakdown of pectins) was slowed by SA. According to Kumar et al. (2021), SA reduces fruit softening by inhibiting the activity of enzymes such as polygalacturonase, pectin methylesterase, and cellulase to maintain cell wall integrity. Similarly, Srivastava and Dwivedi (2000) found that treatment with SA (0.5 and 1 mM) resulted in reduced levels of all cell wall degradation enzymes in a concentration-dependent manner during ripening, resulting in inhibition of the softening process of 'Hari chhal' banana preserved for 8 days at room temperature.

The pH was lower in bananas coated with 3.0 mM of salicylic acid, being 1.97% lower than that of uncoated fruits (Table 1). This is because the use of salicylic acid coating delays the ripening process by reducing gas exchange and respiration rate during storage, causing retardation in the increase in pH during the fruit ripening process (AMIRI et al., 2021). Similarly, Alali et al. (2018) studied the post-harvest dipping of 'Grand Nain' bananas in salicylic acid and found a reduction in the pH of fruits subjected to the treatment.

During storage, titratable acidity is generally reduced, and the value of 7.28% of malic acid was found in bananas without coating (Table 1). This is caused by the decrease in the hydrolysis of organic acids due to the pyruvate decarboxylation reaction, which occurs during the ripening process (HAZARIKA et al., 2019). However, it is observed that this process was delayed with the application of salicylic acid, especially with the concentration of 1.5 mM, which led to the highest acidity value, 8.09% of malic acid (Table 1). Possibly, salicylic acid reduces enzymatic activity, which leads to the decarboxylation of pyruvate, thus delaying the breakdown of organic acids during ripening, maintaining titratable acidity for a longer period (MEENU et al., 2024).

The lowest soluble solids content was observed in banana fruits coated with 4.5 mM of salicylic acid, being 10.29% lower compared to the content found in bananas that were not coated with the acid (Table 1). According to Kumar et al. (2021), the delay in the accumulation of soluble solids with the application of salicylic acid coating is due to the retardation of metabolic activity and the hydrolysis of carbohydrates, such as starch and other insoluble carbohydrates, which are converted into soluble sugars. Similarly, Xu et al. (2019) state that the combination of salicylic acid and 1-methylcyclopropene effectively inhibited the increase in soluble solids, contributing to the maintenance of the post-harvest quality of bananas.

There was a gradual increase in the concentration of ascorbic acid in the bananas as the salicylic acid in the coating increased, with the highest concentration (2.03 mg/100 g^{-1} of pulp) found in those coated with a salicylic acid concentration of 6.0 mM. This is justified by the reduced oxidase activity of ascorbic acid and the late ripening, as well as the senescence process, caused by the coating with salicylic acid (WU et al., 2025).

The concentrations of total and reducing sugars were lower in bananas subjected to coating with salicylic acid at a concentration of 1.5 mM, with reductions of 17.65% in total sugars and 29.54% in reducing sugars compared to bananas that were not coated with the acid. This reduction in the amount of sugars occurred because salicylic acid has the ability to suppress the activity of the enzyme sucrose-phosphate synthase, thus preventing ripening and accumulation of total soluble solids during storage (HANIF et al., 2020). Similar results were reported by Srivastava and Dwivedi (2000), who found that treatments with 0.5 and 1 mM salicylic acid resulted in reductions of 25 and 42% in the reducing sugars of banana fruits, respectively.

Regarding the maturation index, bananas treated with SA at a concentration of 6.0 mM had a higher index (3.68). On the other hand, bananas that were uncoated and coated with SA at a concentration of 3.0 mM had lower MI, with values of 3.35 and 2.80, respectively. As the maturation index tends to increase with fruit ripening, due to the increase in soluble solids and the decrease in titratable acidity, resulting from the degradation of polysaccharides and the oxidation of acids during the tricarboxylic acid cycle in respiration (HANIF et al., 2020). It was observed that the maturation index of bananas coated with 3.0 mM of acid increased more slowly. Similarly, Hanif et al. (2020) observed that papaya fruits coated with salicylic acid were able to delay the maturation index compared to uncoated fruits. Thus, it is concluded that treatment with exogenous salicylic acid contributes to the maintenance of fruit quality, possibly by increasing the endogenous salicylic acid content, which reduces respiratory metabolism and delays fruit senescence (JIANG et al., 2022).

The concentrations of flavonoids and anthocyanins were higher in bananas coated in the preservative solution of 1.5 mM salicylic acid compared to uncoated fruits. This is because salicylic acid increases the activity of the AOX (Alternative Oxidase) enzyme, thereby increasing antioxidant activity, which delays the senescence process (HANIF et al., 2020). Similar results were reported by Wu et al. (2025), who studied the post-harvest of blackberry fruits coated with salicylic acid and observed an increase in antioxidants, such as flavonoids and anthocyanins, in fruits coated with salicylic acid.

Bananas without salicylic acid coating showed the highest concentration of phenolic compounds compared to those that received the treatment. A reduction of these compounds was observed as the salicylic acid concentration in the coating increased, with the lowest values at the salicylic acid concentration of 6.0 mM. This effect can be explained by the fact that the synthesis of phenolic compounds occurs through the partial oxidation of sugars and organic acids in glycolysis and in the tricarboxylic acid cycle (AMIRI et al., 2021), so acid-coated bananas had lower sugar contents, which led to lower synthesis of phenolic compounds. Hanif et al. (2020), when studying the post-harvest application of salicylic acid in papaya, also observed that fruits coated with salicylic acid showed a decrease in the synthesis of phenolic compounds compared to the control (uncoated).

According to principal component analysis (PCA), the first two components accumulate 79.83% of the variability of the data, with a significant effect for the concentrations of *T. harzianum* in the two components. The first component explains 58.57% of the original variance of the data, with significant correlations ($p \leq 0.01$) in most of the variables studied, namely titratable acidity (r = 0.97), total sugars (r = 0.96), reducing sugars (r = 0.90), mass loss (r = -0.89), pH (r = -0.97). In turn, the second component explains 21.25% of the variability of the data (Table 2).

In general, it was observed that bananas coated with 1.5 and 2.0 mL L^{-1} of *T. harzianum* had higher values of firmness, flavonoids and anthocyanins and lower values of lightness and chromaticity, i.e., banana fruits coated with *T. harzianum* were more opaque and with a less advanced stage of maturation, hence demonstrating that the coating allows for a longer shelf life for bananas (Figure 2).

The values of lightness, chromaticity and hue angle of the banana fruits ranged from 43.16, 32.64 and 54.38 (1.5 mL L^{-1} of *T. harzianum*) to 52.96, 38.78 and 76.42 (uncoated), respectively (Table 2). Teodosio et al. (2021a) also observed that fruits from the control treatment underwent a faster maturation process during the storage period, whereas fruits coated with a film composed of microorganisms became more opaque, consequently retarding pigment degradation and promoting brightness to fruits.

With the use of *T. harzianum* as a coating on bananas, less mass loss was observed at a concentration of 0.5 mL L^{-1}, and firmness gradually increased with the increase in the application of *T. harzianum*, with a maximum value observed at a concentration of 2.0 mL L^{-1} (Table 2). Softening is an important manifestation of banana ripening, and the greater firmness in coated fruits may be related to peel lignification or delayed ripening (ALALI et al., 2018). Mass loss in fresh fruits corresponds to reduction in water content by metabolic processes and degradation of the product during storage (BORGES et al., 2019). However, the use of coatings mitigates this loss of mass and promotes greater fruit firmness, as observed in the present study.

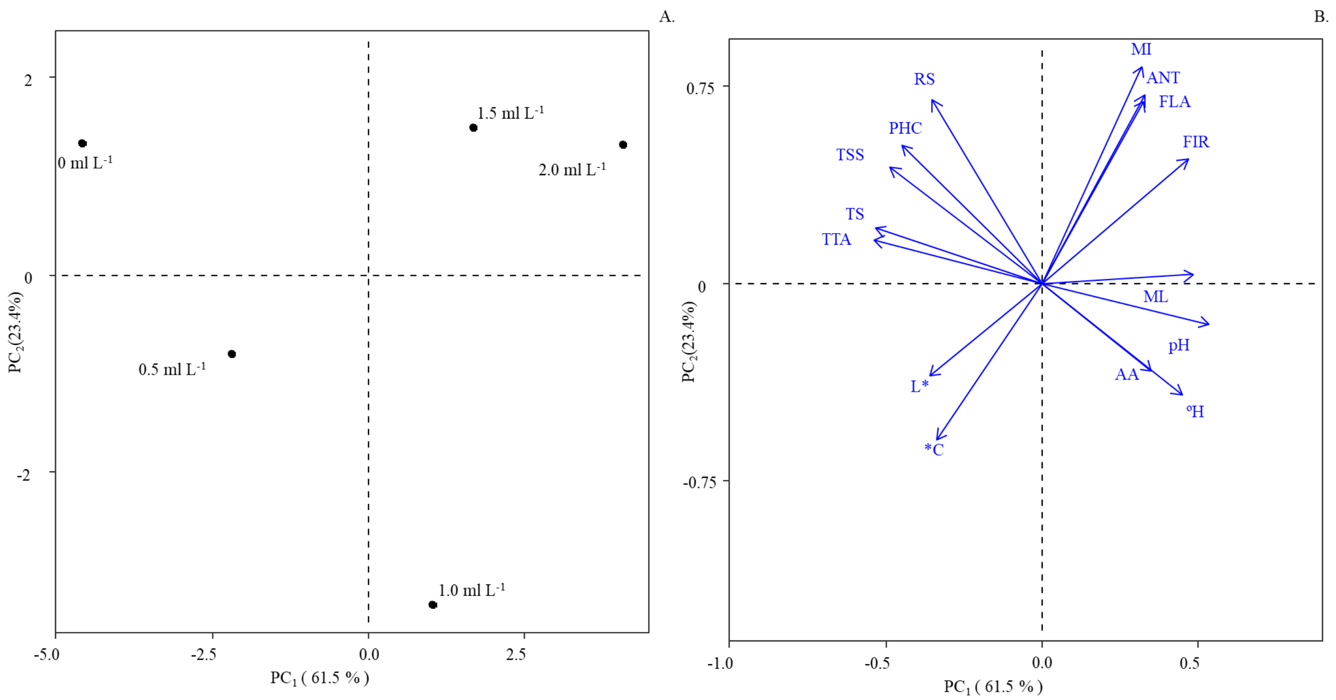
Table 2. Eigenvalues, percentage of total variance explained in the multivariate analysis of variance and probability of significance by the Hotelling's test (p-value) for the concentrations of *Trichoderma harzianum* (TRI) applied to banana fruits of cv. Nanicão at 24 days after treatments.

	Principal components (CP)	
	CP1	CP2
Eigenvalues (λ)	9.23	3.52
Percentage of total variance (S^2 %)	61.53	23.44
Hotelling's test for TRI concentrations	<0.01	<0.01

CPs	Coefficients of correlation (r)								
	*L	*C	ºH	ML	FIR	pH	TTA	AA	TSS
CP1	0.65	0.62	-0.81	0.89	0.85	0.98	0.98	-0.64	-0.89
CP2	-0.34	-0.58	-0.41	0.03	0.46	-0.15	0.17	-0.33	0.43
Concentrations (mL L^{-1})									
0.0	52.96 ± 1.10	38.78 ± 1.07	76.42 ± 0.75	133.33 ± 8.14	3.10 ± 0.08	4.63 ± 0.12	7.95 ± 0.03	1.57 ± 0.37	23.58 ± 1.29
0.5	44.83 ± 0.43	35.72 ±0.48	77.12 ± 1.23	122.33 ± 18.90	3.45 ± 0.30	4.76 ± 0.29	6.56 ± 0.10	1.37 ± 0.06	17.74 ± 1.34
1.0	50.59 ± 0.51	38.95 ± 0.15	81.13 ± 3.26	195.00 ± 72.77	4.64 ± 0.25	5.01 ± 0.13	5.09 ± 0.24	1.96 ± 0.03	13.62 ± 1.87
1.5	43.16 ± 0.90	32.64 ± 1.82	54.38 ± 3.81	210.83 ± 39.25	9.71 ± 0.67	5.00 ± 0.09	5.19 ± 0.16	1.74 ± 0.14	16.18 ± 1.81
2.0	43.26 ± 0.45	33.70 ± 0.65	81.69 ± 0.06	203.83 ± 9.67	16.79 ± 0.14	5.07 ± 0.07	4.42 ± 0.36	1.77 ± 0.06	14.04 ± 0.47

CPs	Coefficients of correlation (r)					
	MI	TS	RS	FLA	ANT	PHC
CP1	0.59	-0.98	-0.64	0.60	0.60	-0.82
CP2	0.80	0.20	0.68	0.67	0.69	0.51
Concentrations (mL L^{-1})						
0.0	2.99 ± 0.17	17.99 ± 0.32	10.54 ± 0.30	2.89 ± 0.17	0.30 ± 0.12	12.12 ± 0.25
0.5	2.83 ± 0.20	14.90 ± 0.50	7.87 ± 0.90	2.20 ± 0.12	0.20 ± 0.06	9.03 ± 0.01
1.0	2.80 ± 0.24	7.56 ± 2.63	4.19 ± 0.39	2.52 ± 0.11	0.20 ± 0.11	6.53 ± 0.67
1.5	3.25 ± 0.33	10.07 ± 0.02	9.39 ± 0.29	3.11 ± 0.02	0.34 ± 0.04	9.45 ± 0.68
2.0	3.30 ± 0.33	8.86 ± 0.27	5.50 ± 0.66	3.59 ± 0.08	0.52 ± 0.01	6.60 ± 0.23

CPs – Principal components; CP1 – Principal component 1; CP2 – Principal Component 2; L* – lightness, *C – chromaticity, ºH – hue angle, ML – mass loss (g), FIR – firmness (Newton - N), pH – hydrogen potential, TTA – total titratable acidity (% malic acid), TSS – total soluble solids (ºBrix), MI – maturation index (%), TS – total sugars (mg 100 g^{-1} of pulp), RS – reducing sugars (mg 100 g^{-1} of pulp), FLA – flavonoids (mg g^{-1} of pulp), ANT – anthocyanins (mg g^{-1} of pulp) and PHC – phenolic compounds (mg 100 g^{-1} of pulp).



CP_1 – Principal component 1; CP_2 – Principal Component 2; L* – lightness, *C – chromaticity, ºH – hue angle, ML – mass loss, FIR – firmness, pH – hydrogen potential, TTA – total titratable acidity, TSS – total soluble solids, MI – maturation index, TS – total sugars, RS – reducing sugars, FLA – flavonoids, ANT – anthocyanins, PHC – phenolic compounds.

Figure 2. Two-dimensional projection of principal component scores for *Trichoderma harzianum* concentrations (A) and the analyzed variables (B) in the two principal components (PC_1 and PC_2).

The pH increased gradually with the increase of *T. harzianum* in the coating from 4.63 in uncoated bananas to 5.07 in bananas coated with 2.0 mL L^{-1} of *T. harzianum*. The pH reduction observed in uncoated bananas occurs due to the formation of organic acids and sugars in connection with fruit respiration (TEODOSIO et al., 2021b). Thus, delayed ripening is observed in coated bananas because, according to Nascimento Júnior et al. (2008), the pH values observed for cv. Nanicão when the fruits are green is 5.14, and throughout ripening the fruits have a pH of 4.76.

Titratable acidity and soluble solids in banana fruits decreased with the use of coating compared to uncoated bananas; a 44.40% reduction in acidity was observed in fruits coated with 2.0 mL L^{-1} compared to those without coating. Similarly, the soluble solids content decreased from 23.58 ºBrix in fruits without *T. harzianum* application to 13.62 ºBrix in fruits coated with 1.0 mL L^{-1} of *T. harzianum* (Table 2). The reduction in acidity and soluble solids in the coated fruits can be attributed to the slowdown in the synthesis and degradation of organic acids. Titratable acidity in fruits is related to the presence of these organic acids, while soluble solids are associated with the sugars formed from the degradation of the acids present in the fruit (BAJAJ et al., 2023). Similarly, Thangavelu et al. (2024) found that the application of *T. harzianum asperellum* resulted in less mass loss up to 60 days of storage, with better biochemical characteristics, such as soluble solids, total sugar, and ascorbic acid content, compared to uncoated bananas.

The maturation index also decreased, by 6.35% when comparing uncoated fruits with fruits coated with *T. harzianum* at the concentration of 1.0 mL L^{-1}. This decline occurred because the maturation process and the consequent increase in the TSS/TTA ratio are due to the degradation of polysaccharides and the increase in oxidation of tricarboxylic acids during the respiratory process of fruits (TEODOSIO et al., 2021a). As respiration was delayed in fruits coated with *T. harzianum*, there was a retardation in ripening. The concentration of ascorbic acid was elevated in banana fruits coated with a 1.0 mL L^{-1} *T. harzianum* solution. Thangavelu et al. (2024), when evaluating the use of biocontrol agents in the post-harvest quality of bananas, including *T. harzianum*, also found mitigation in the reduction in ascorbic acid content, preventing postharvest deterioration and minimizing physiological changes.

The concentrations of total and reducing sugars were lower in fruits coated with *T. harzianum* at a concentration of 1.0 mL L^{-1}, showing reductions of 57.98 and 60.25%, respectively, compared to banana fruits without *T. harzianum* application (Table 2). This is due to the fact that the increase in sugar levels is associated with the degradation of starch and other polysaccharides during the maturation process, which increases soluble solids (TEODOSIO et al., 2021a). As the coated fruits had their maturation delayed, there was less degradation of these polysaccharides, resulting in lower amounts of sugars.

Coating with 2.0 mL L^{-1} of *T. harzianum* promoted high amounts of flavonoids and anthocyanins in the banana fruits, with increments of 24.22 and 73.33% compared with banana fruits that were not coated, respectively (Table 2). The total contents of flavonoids and anthocyanins decrease with fruit ripening, as defense materials, such as hesperidin, naringin, and flavones, are degraded (ALALI et al., 2018). In this context, it can be observed that the use of *T. harzianum* delays the ripening of banana fruits and the degradation of these compounds, which could be seen by the high values of antioxidants.

On the other hand, the amount of phenolic compounds decreased from 12.12 mg 100 g^{-1} of pulp in fruits without coating to 6.53 mg 100 g^{-1} of pulp in fruits coated with 1.0 mL L^{-1} of *T. harzianum*. It was observed, therefore, that uncoated bananas contained higher content of phenolic compounds than those coated with *T. harzianum* at this concentration. Borges et al. (2019) also observed an increase in the content of phenolic compounds in banana genotypes from stage 2 to 7, that is, throughout ripening. Thus, the use of coating with *T. harzianum* delays ripening.

CONCLUSIONS

Coatings with *Trichoderma harzianum* at concentrations of 1.0 and 2.0 mL L^{-1} and with salicylic acid at concentrations of 3.0 and 6.0 mM L^{-1} delay fruit ripening, maintaining firmness and a greener color. Bananas of cv. Nanicão coated with salicylic acid at 1.5 mM had lower titratable acidity and sugar contents and higher amounts of flavonoids and antioxidants. Coating with *Trichoderma harzianum* at a concentration of 2.0 mL L^{-1} promoted higher levels of flavonoids, anthocyanins and pH in banana fruits cv. Nanicão.

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