Original Article
Food Science and Technology

ISSN 0101-2061 (Print)
ISSN 1678-457X (Online)

DOI: https://doi.org/10.5327/fst.507

Activated carbons from Baru (*Dipteryx alata* Vog.) waste impregnated with copper oxide: application in the postharvest preservation of bananas

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Abstract

Banana is an agricultural commodity cultivated extensively in tropical and subtropical regions with consumption demand worldwide. During the ripening process, several biochemical reactions occur that are linked to the production of ethylene, which determines the shelf life and quality of the fruit. Ethylene can promote excessive ripening and decay of fruits and vegetables, even at very low concentrations. Therefore, an ethylene control strategy needs to be developed to address this challenge. This study aimed to evaluate the effects of using activated carbon from baru (*Dipteryx alata* Vog.) waste, impregnated with copper oxide, as potentially efficient materials for eliminating ethylene and maintaining postharvest quality of bananas. The developed adsorbent materials showed high ethylene adsorption capacity, validating their potential application in real storage conditions for climacteric fruits. The evaluation of quality attributes, like color, firmness, weight loss, total titratable acidity, total soluble solids, and total soluble solids/total titratable acidity ratio, confirmed the effectiveness of activated carbon and activated carbon impregnated with copper oxide in delaying the ripening and senescence process compared to bananas in the control group. The results of this study contribute to the development of ethylene adsorbent materials that combine sustainability and efficiency, with promising applications in the food industry to reduce postharvest losses.

Keywords: adsorbents; agro-industrial waste; ethylene; postharvest quality.

Practical Application: Activated carbons from baru waste delay banana ripening and preserve fruit quality.

1 INTRODUCTION

Bananas (*Musa* spp.) are the most widely consumed and cultivated fruit in the world, and one of the most important crops for food security and economic development in many countries, especially in tropical and subtropical regions (Barros et al., 2024; Wang, Song et al., 2024). Brazil plays a significant role in global banana production, ranking among the world's leading producers and influencing both national and international markets (Coltro & Karaski, 2019). However, despite being a commodity of global importance, a challenge associated with the production of this fruit is its high perishability after harvest (Charoensuk et al., 2024).

Bananas are climacteric fruits, meaning they undergo postharvest ripening driven by increased respiration rates and ethylene production (Gierson & Kader, 1986; Zhu et al., 2018). Ethylene, a gaseous plant hormone, plays a key role in accelerating this process (Alonso-Salinas et al., 2024; Saltveit, 1999). The release of ethylene gas in bananas triggers a series of physiological and biochemical changes, including softening (loss of texture due to enzymes that break down cell wall components); enzymatic degradation of starch, resulting in the accumulation of soluble sugars and an increase in total soluble solids content; chlorophyll degradation; an increase in respiration rate; excessive ripening; and a reduction in visual and nutritional quality (Alexander & Grierson, 2002; Hu et al., 2017; Tucker et al., 2017; Wei et al., 2023). These rapid ripening processes not only cause economic losses but also exacerbate food waste, which directly contradicts the goals of the United Nations (UN) Sustainable Development Goals (SDGs). SDG 12, "Responsible Consumption and Production", aims to halve food waste and postharvest losses by 2030 (Motta et al., 2022; Patil et al., 2024).

To reduce postharvest losses of bananas, traditional methods associated with ethylene control and elimination have been used, including cold storage, modified atmosphere, chemical treatment with 1-metilciclopropeno (1-MCP), active packaging, and edible coatings that delay ripening by controlling the production of ethylene (Fonseca et al., 2021). Although these methods have proven to be somewhat effective in postharvest preservation of bananas, each has limitations that need to be considered. For example, cold storage involves high costs and the risk of cold damage, while the use of 1-MCP requires controlled application and may not be accessible to small growers (Murmu & Mishra, 2018; Wang, Song et al., 2024).

For this reason, in recent years there has been growing interest in exploring more innovative and sustainable approaches to the postharvest preservation of bananas, with emphasis on

Received: May 12, 2025.
Accepted: Jun. 11, 2025.
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Conflict of interest: nothing to declare.
Funding: This research was funded by the Federal University of Goiás, the Coordination for the Improvement of Higher Education Personnel (CAPES; Project PDPG-Solidariedade; Academic Solidarity Program), process 88881.923053/2023-01, and the Goiás State Research Support Foundation (FAPEG), to whom the authors are indebted.

ethylene adsorption using adsorbent materials such as activated carbon (AC) and other carbon-based materials (Nooun et al., 2023; Tepamatr, 2023; Xiao et al., 2024). AC is a carbonaceous material characterized by a well-developed porous structure and a high specific surface area (Marsh & Rodríguez-Reinoso, 2006), giving it a high capacity for adsorbing volatile organic compounds, including ethylene (Shenoy et al., 2022). In terms of production, AC can be derived from low-cost biomass sources, such as agro-industrial waste, contributing to an economically viable and environmentally sustainable application (González-García, 2018; Gupta et al., 2022). In addition, it is possible to impregnate the surface of the AC with metal oxides, which provide additional functional groups that can make adsorption more selective and efficient (Zhang et al., 2017).

Although several studies have demonstrated the effectiveness of adsorbent materials in ethylene removal, the practical application of these materials in the storage of climate-controlled fruits is still limited. There is a gap in understanding the performance of these materials in real scenarios where factors such as humidity, temperature, and ethylene production dynamics are constantly varying. In this context, this study aimed to evaluate the effects of the application of AC from baru (*Dipteryx alata* Vog.) residues, impregnated with copper oxide as potentially efficient materials in ethylene elimination and postharvest quality preservation of bananas.

1.1 Relevance of the work

This work presents an innovative, sustainable approach to controlling ethylene in climacteric fruits. This approach uses activated carbons obtained from Baru residues, with and without copper oxide impregnation. The results demonstrate that these materials significantly delay ripening and maintain bananas' postharvest quality. This research is significant because it combines technological efficiency with valorizing agro-industrial residues, providing viable solutions to reduce postharvest losses.

2 MATERIAL AND METHODS

2.1 Synthesis of activated carbon and activated carbon impregnated with copper oxide

AC was prepared by impregnating the precursor material with phosphoric acid (H_3PO_4) (85%, ratio 1:2), followed by heating at 80°C under stirring for 30 min, filtering, and drying at 110°C for 15 h. Then, the material was carbonized in a tubular furnace at 800°C (20°C min^{-1}, nitrogen gas [N_2] or air flow at 160 cm^3 min^{-1}) for 40 min, washed with 37% hydrochloric acid (HCl) and distilled water until neutral pH, and dried at 50°C. For surface modification, 5 g of citric acid (CA) were impregnated in a 0.1 M copper nitrate ($Cu(NO_3)_2$) solution under stirring at 25°C for 12 h, filtered, dried at 110°C for 12 h, and calcined at 280°C (10°C/min, N_2 at 200 cm^3 min^{-1}) for 2 h, obtaining the activated carbon impregnated with copper oxide (CuO/AC) material.

2.2 Characterization of activated carbons

Surface functional groups were evaluated on the samples before and after the storage experiments. The analysis was performed directly by infrared spectroscopy (PerkinElmer Spectrum 400 FTIR spectrometer, Waltham, MA, USA) using the attenuated total reflectance technique in the infrared region of 4,000–500 cm^{-1}, with a resolution of 4 cm^{-1}. The physical and chemical surface properties of AC and CuO/AC and their maximum ethylene adsorption capacities obtained by dynamic adsorption tests (Table 1) were determined in our previous study (Oliveira et al., 2024).

2.3 Application of activated carbon and activated carbon impregnated with copper oxide in banana preservation

The bananas were purchased from a local producer in Goiânia (Goiás, Brazil) and immediately transported to the Food Quality and Control Laboratory (LabFood) of the Federal University of Goiás. Fruit selection was based on uniformity in terms of size, weight, peel color, and physical integrity (absence of mechanical damage). The selected bananas were washed in running water, followed by sanitization by immersion in a sodium hypochlorite solution (100 ppm, 25°C, 15 min), then rinsed in running water and dried naturally at room temperature (25 standard deviation ± 2°C).

Storage was tested in the following three configurations: (i) control (no adsorbent material); (ii) AC (no surface modification); and (iii) CuO/AC, with both adsorbents applied at a rate of 1 g per 100 g of bananas per container. The bananas were stored in 2.6 L airtight plastic containers, kept in a Biochemical Oxygen Demand (BOD) chamber for 16 days at 25°C, in the dark, with relative humidity of 85% controlled by a saturated solution of potassium chloride (KCl) (Figure 1). The quality parameters—weight loss, visual appearance, color, firmness, total titratable acidity, and total soluble solids—were evaluated at time zero (beginning of the experiment) and after 4, 8, 12, and 16 days of storage. For each of the three treatments tested, two experimental units (replicates) were prepared in each sampling period.

2.4 Determination of physicochemical quality

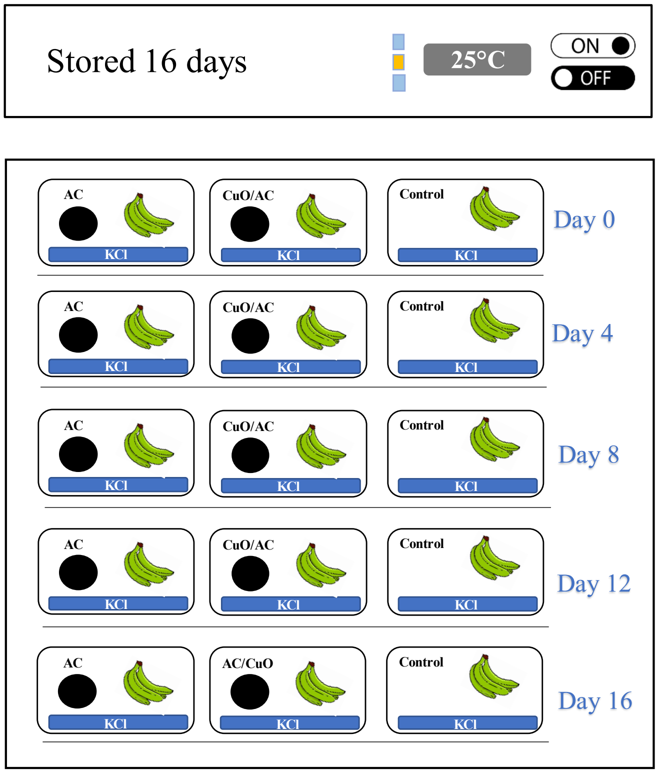
2.4.1 Color

The color parameters expressed in luminosity (L*) from 0 to 100%, green/red (a*), and blue/yellow (b*) chromatic coordinates

Table 1. Physical and chemical characteristics of adsorbent materials.

Samples	S_{BET} [m^2 g^{-1}]	V_T [cm^3 g^{-1}]	V_{meso} [cm^3 g^{-1}]	V_{micro} [cm^3 g^{-1}]	L_0 [nm]	$q_{máx}$ [μg g^{-1}]
AC	886	0.46	0.09	0.37	1.72	1,111
CuO/AC	628	0.34	0.04	0.30	1.37	1,667

S_{BET}: Brunauer-Emmett-Teller surface área; V_T: total pore volume; V_{meso}: mesopore volume; V_{micro}; micropore volume; L_0: average micropore width; q_{max}: maximum adsorption capacity; AC: activated carbon; CuO/AC: activated carbon impregnated with copper oxide.



AC: activated carbon; CuO/AC: activated carbon impregnated with copper oxide; KCl: potassium chloride.

Figure 1. Experimental system for storing bananas.

were determined directly on the banana peel with eight readings at equidistant points of the fruit, using a colorimeter (ColorQuest XE) equipped with EasyMatch QC software, version 4.81.

2.4.2 Weight loss

The weight of bananas in each treatment was measured every four days on a precision scale (± 0.1 mg). Fruit weight loss was determined by the difference between the initial fruit weight and that obtained at each sampling interval, with the result expressed in %, as demonstrated in Equation 1:

$$Weight\ loss\ (\%) = \left[\frac{W_i - W_f}{W_i}\right] x\ 100 \quad (1)$$

Where:

W_i: initial weight (g); and

W_f: weight of the fruit in the period following W_i (g).

2.4.3 Firmness

Firmness was determined using a texturometer (Texture Analyser, TA-XT Plus, Surrey, England) equipped with a penetration probe and operated in compression test mode. The pre-test, test, and post-test speeds were set to 10 mm s^{-1}, 1 mm s^{-1}, and 40 mm s^{-1}, respectively. Two regions of the banana were selected for probe penetration: peel and pulp. Five equidistant points were taken from the surface of the fruit to measure the firmness of the peel. The banana was then cut lengthways into five parts to determine the firmness of the flesh. Two fruit samples were used for each repetition, and the maximum penetration force was recorded in Newtons (N).

2.4.4 Total soluble solids, total titratable acidity, and maturity index

The pulp and peel were separated, and the pulp was ground in a blender to determine the total titratable acidity (TTA) and total soluble solids (TSS) content of the bananas. TTA was determined in triplicate using 5 g of sample mixed in 100 mL of distilled water and 3 drops of 1% phenolphthalein indicator. Titration was carried out in a previously standardized 0.1N sodium hydroxide (NaOH) solution. The results were expressed as % malic acid in 100 g of pulp, according to Equation 2:

$$TTA\ (\%) = \frac{V.f.M.MW}{10.W.n} \quad (2)$$

Where:

TTA: total titratable acidity of malic acid (%);

V: volume spent on NaOH titration (mL);

F: correction factor of the NaOH solution;

M: molarity of the NaOH solution;

MW: molecular weight of malic acid (g);

n: number of ionizable hydrogens; and

W: weight of the sample (g).

Total soluble solids content, expressed in Brix degrees, was measured using a digital refractometer (MFL 0–32%). To do this, a small portion of the whole pulp was dripped onto the refractometer lens for each measurement, and distilled water was used as a liquid standard. The measurements were made in triplicate.

The maturity index (TSS/TTA ratio) was calculated by dividing the total soluble solids by the total titratable acidity of the sample.

2.5 Statistical analysis

The experimental data were statistically analyzed using ANOVA analysis of variance to verify the significance of differences between experimental groups and between fruit storage periods. Tukey's test ($p \leq .05$) was then employed for multiple comparisons using SAS® 2024 OnDemand for Academics. The results were expressed as mean ± standard deviation and measured in triplicate.

3 RESULTS AND DISCUSSION

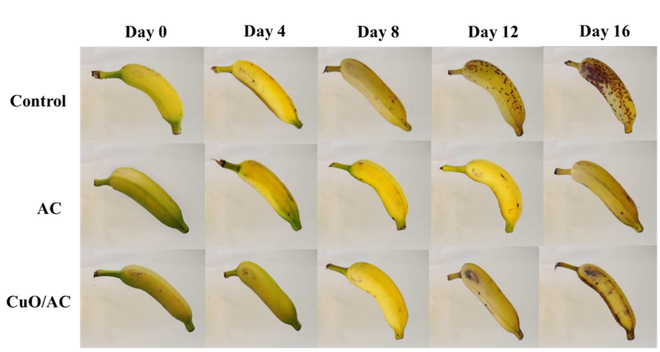
3.1 Effect of activated carbon on postharvest quality of bananas

As shown in our previous study (Oliveira et al., 2024), ethylene removal using baru-based AC occurs through a combination of adsorption mechanisms that include interactions of ethylene with hydroxyl (OH) groups and with copper incorporated into the AC surface. In practical applications, there are several challenges associated with the collection and accurate quantification of ethylene. For this reason, the effectiveness of ethylene removal and the effects of AC and CuO/AC materials on postharvest banana preservation were evaluated using a comprehensive set of well-established physicochemical parameters. Specifically, the study monitored the bananas subjected to different treatments, in terms of weight loss (reflecting transpiration and metabolic degradation rates), peel color development (indicating chlorophyll degradation and carotenoid synthesis), total soluble solids (representing carbohydrate metabolism), pulp and peel firmness (related to enzymatic cell wall breakdown), TTA (an indicator of changes in acid metabolites during ripening), and TSS/TTA ratio (an indicator used to determine the ripeness stage of fruits, determining the balance of sweet and acidic flavor). This approach provides an indirect but robust assessment of ethylene activity, as its production plays a vital role in the ripening process, especially of climacteric fruits, as previously demonstrated (Barry & Giovannoni, 2007; Dai et al., 2025; Saltveit, 1999).

3.1.1 Visual appearance and color

The fruits were photographed throughout the experiment for a visual analysis of sensory quality. As illustrated in Figure 2, all treatment groups exhibited bananas at the same initial ripening stage, characterized by a yellow-green coloration (stage 3) (Ringer et al., 2018). Between days 4 and 8, the AC and CuO/AC treatments demonstrated more uniform ripening patterns than the control group, which developed a predominantly yellow coloration with no green areas.

On day 12, several black spots appeared on the surfaces of the control group samples. In contrast, the two AC treatments exhibit only small, sparse spots, with the AC group showing an even lower incidence. These black spots result from natural senescence processes involving the activity of the enzyme polyphenol oxidase (PPO), which oxidizes phenolic compounds into quinones that subsequently polymerize into melanin (Kamdee et al., 2009; Queiroz et al., 2008). Although ethylene accumulation in storage environments typically increases PPO activity (Ma et al., 2024), both AC-based treatments appear to mitigate this effect.



AC: activated carbon; CuO/AC: activated carbon impregnated with copper oxide.
Figure 2. Effect of adsorption materials on the sensory quality of bananas.

The experimental group treated with AC showed superior preservation capacity compared to the other groups, with the shell reaching a uniform yellow color from day 12 and with no significant change in firmness compared to the initial state on day 16. However, qualitative evaluation revealed that CuO/AC-treated bananas exhibited visibly reduced firmness compared to samples from the AC group. This difference in texture may be attributed to small variations in relative humidity during storage, differentially affecting texture preservation between treatments.

At the end of the experiment, all samples showed signs of advanced ripening. However, the fruits in the control group showed a higher incidence of dark spots, indicating an increased rate of senescence and deterioration. Visual appearance is a fundamental parameter in the marketing and commercialization criteria of fruits in general, directly influencing their attractiveness to the consumer and their market value (Shinga et al., 2025).

In addition to visual assessment, the color change of the banana peel was monitored by colorimetry, using the parameters L* (luminosity), a* (variation between green and red), and b* (variation between blue and yellow) (Table 2). These indexes are widely used in the objective characterization of color in vegetable products, allowing a more precise analysis of the chromatic changes associated with ripening.

The treatments presented homogeneous initial values of L* ($p > .05$), indicative of the initial maturation stage, with a characteristic light green color. On day 8 of storage, there was a significant increase in L* values in all treatments compared to day 0, corresponding to the transition to the climacteric stage. This increase in luminosity is correlated with the enzymatic degradation of chlorophylls and accumulation of carotenoids (Borges et al., 2019). Between day 8 and day 12, there was a decrease in L* values associated with the onset of tissue senescence and the formation of melanoidins (Mowlah et al., 1983). On day 16 of storage, the control treatment showed a significant reduction in luminosity ($p < .05$) compared to the AC and CuO/AC treatments, demonstrating the protective effect of carbon materials against the darkening of bananas during the ripening process.

For the a* parameter, there was an increasing trend in all treatments as respiration progressed, indicating the progress in ripening. Samples from the AC group showed the lowest a* value of 2.65 on day 16, indicating that treatment with AC can effectively inhibit the yellowing of bananas. The b* parameter, which quantifies the intensity of coloration in the yellow-blue spectral region, showed an increase over time for all treatments, indicating the development of the yellow color characteristic of ripening. Although the CuO/AC treatment showed a more pronounced increase in b* compared to the control and AC groups, no significant differences ($p > .05$) were observed between treatments on day 16 of storage.

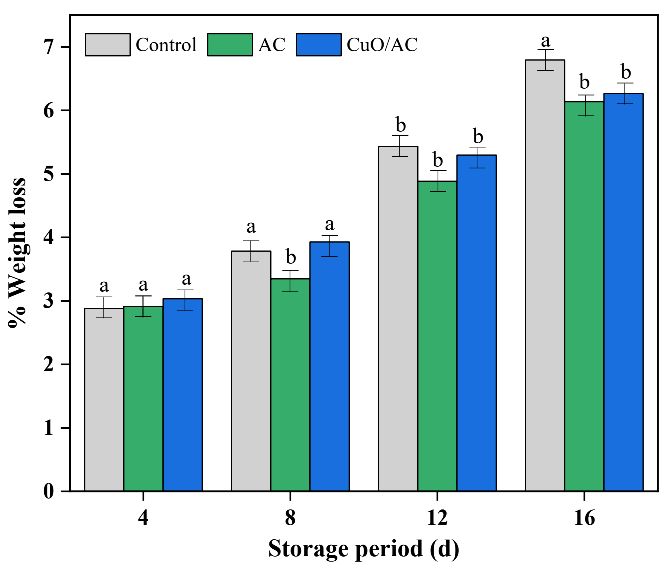
3.1.2 Weight loss

The weight loss primarily stems from transpiration (water loss) and fruit respiration processes (Xie et al., 2022). As presented in Figure 3, the weight loss analysis revealed an increasing

Table 2. Effects of different treatments on the color parameters of bananas stored at 25°C for 16 days.

Parameters	Treatment	Storage period (days)				
		0	4	8	12	16
L*	Control	63.91 ± 3.18^{bA}	73.26 ± 2.93^{aA}	71.33 ± 2.98^{aA}	69.52 ± 2.73^{aA}	54.91 ± 4.50^{cB}
	AC	63.63 ± 2.84^{cA}	72.20 ± 3.41^{abA}	72.99 ± 2.05^{aA}	67.65 ± 3.51^{bcAB}	69.16 ± 1.53^{abA}
	CuO/AC	63.74 ± 1.44^{bA}	70.65 ± 4.54^{aA}	73.96 ± 1.25^{aA}	63.08 ± 4.12^{bB}	64.74 ± 3.28^{bA}
a*	Control	−8.97 ± 0.92^{cA}	2.98 ± 0.68^{bA}	2.22 ± 0.94^{bA}	8.14 ± 1.82^{aA}	7.37 ± 1.01^{aA}
	AC	−8.77 ± 1.11^{bA}	−0.23 ± 3.45^{aA}	−0.26 ± 2.94^{aA}	0.66 ± 2.29^{aB}	2.65 ± 0.98^{aB}
	CuO/AC	−8.46 ± 0.54^{cA}	0.13 ± 2.86^{bA}	1.81 ±2 .36^{bA}	3.28 ± 3.48^{abB}	6.21 ± 0.97^{aA}
b*	Control	36.65 ± 2.28^{bB}	39.54 ± 3.18^{abA}	41.9 ± 2.71^{abA}	41.97 ± 3.52^{abB}	45.62 ± 3.53^{aA}
	AC	38.10 ± 1.67^{aA}	40.62 ± 3.42^{aA}	41.06 ± 2.09^{aA}	37.95 ± 2.73^{aB}	42.33 ± 4.28^{aA}
	CuO/AC	40.78 ± 1.95^{cA}	42.78 ± 2.70^{bcA}	41.01 ± 3.71^{cA}	47.79 ± 2.81^{aA}	47.38 ± 3.15^{abA}

*Different uppercase letters in the same column (concerning each parameter) indicate significant differences between treatments, while different lowercase letters in the same row indicate significant differences between days ($p < .05$).
L: luminosity from 0 to 100%; a*: variation between green and red; b*: variation between blue and yellow; AC: activated carbon; CuO/AC: activated carbon impregnated with copper oxide.



AC: activated carbon; CuO/AC: activated carbon impregnated with copper oxide.
Different letters indicate significant differences between treatments ($p < .05$) and error bars represent standard deviations.

Figure 3. Effect of treatments on weight loss of bananas in day 4, 8, 12, and 16 of storage.

trend during storage for all treatments, with the control group showing a loss of 6.8% after 16 days of storage. Compared to the control group, bananas stored with AC and CuO/AC exhibited significantly lower weight loss ($p < .05$) of 6.14 and 6.26%, respectively. No significant difference was observed between the AC treatments, indicating that unmodified AC alone can effectively reduce weight loss in bananas stored under ambient conditions. Furthermore, from an economic point of view, the absence of additional synthesis steps is a relevant advantage since it simplifies the process, reduces production costs, and minimizes the environmental impact associated with the synthesis of modified materials.

3.1.3 Firmness

Firmness is an essential parameter for assessing postharvest quality, as it directly reflects the stage of fruit ripeness. High values of this attribute indicate greater resistance to handling, transportation, and storage, while its reduction is associated with the processes of ripening and senescence (Fathizadeh et al., 2021; Toivonen & Brummell, 2008). According to the data in Table 3, after 16 days of storage, there were no significant differences ($p > .05$) in peel firmness between the treatments evaluated. However, analyses of pulp firmness showed statistically significant variations ($p < .05$), with the AC treatment standing out, which showed significantly higher values compared to both the control and the CuO/AC treatment.

The softening of the pulp occurs mainly due to enzymatic activity on the components of the cell wall, mainly through the action of cellulase, pectin methylesterase, polygalacturonase, and β-glucosidase. The production of ethylene during ripening increases the activity of these enzymes, promoting the degradation of pectic substances and altering cell structure (Al-Dairi et al., 2023; Barros et al., 2024; Yun et al., 2019). In addition, environmental factors such as temperature and humidity significantly influence the dynamics of ripening and textural changes in the fruit (Wang, Zhou et al., 2024).

The inferior performance of CuO/AC concerning pulp firmness is probably due to competition between water and ethylene molecules for the same active adsorption sites in the CuO/AC. This competition can block interactions with ethylene, reducing its adsorption in the final storage phase of the banana and, consequently, affecting the texture of the fruit. Bruijn et al. (2020) suggest that, in this case, ethylene removal can be improved by increasing the amount of copper to promote efficient ethylene degradation and release the active adsorption sites on the surface of the adsorbent material.

3.1.4 Total soluble solids, total titratable acidity and maturity index

Both TTA and TSS are important postharvest quality parameters for fruit in general. During banana ripening, soluble sugars accumulate, either via sucrose transported from the plant to the fruit or through the hydrolysis of reserve carbohydrates such as starch. The degradation of starch into soluble sugars can occur through the action of several enzymes, such as amylases, phosphorylases, and branching enzymes (Osorio & Fernie, 2013). This biochemical process increases TSS levels, which are directly correlated with the fruit's sweetness and overall sensory quality (Prasanna et al., 2007). According to the data presented in Table 4 and Figure 4A, the control treatment showed a significant increase in TSS during storage, reaching a peak of approximately 25% on day 16.

Fruits stored with AC and CuO/AC showed significantly lower TSS levels compared to the control group. Furthermore, when compared with each other, they also showed statistical differences, with the AC group exhibiting consistently lower TSS values over time, suggesting greater effectiveness in reducing the ripening rate. This difference can be attributed to the physicochemical characteristics of AC, especially its high surface area (886 $m^2 g^{-1}$) and micropore volume (0.37 $cm^3 g^{-1}$), which increase the physisorption of ethylene and thus reduce the synthesis of soluble sugars and, consequently, the TSS in the fruit.

As bananas ripen, a decline in TTA is commonly observed, suggesting that treatments that increase acidity may delay senescence. Many organic acids are present in bananas, with malic acid being the main one (Al-Dairi et al., 2023). As shown in Figure 4B, TTA revealed a decreasing trend throughout storage. The TTA of the control group decreased from 0.30 (day 0) to 0.14% (day 16), indicating that the organic acids present were utilized as substrates for respiration. The treatments with AC and CuO/AC presented higher TTA than the control group on the day 16 of storage ($p < .05$), recording values of 0.18 and 0.17%, respectively. These results indicate that the use of baru AC can decrease the consumption of organic acids and delay the ripening process of bananas.

The maturity index, expressed by the TSS/TTA ratio, showed a significant increase over the days of storage for all treatments (Table 4 and Figure 4C). The increase in this sugar/acid ratio is mainly due to the increase in the TSS of the fruit over time. Bananas stored with AC and CuO/AC presented a significantly lower ripeness index compared to the control group samples, probably due to the ethylene adsorption capacities of these carbon materials.

Table 3. Effect of treatments on changes in the firmness of bananas after 16 days of storage.

Treatments	Firmness (N) - Peel		Firmness (N) - Pulp	
	Day 0	Day 16	Day 0	Day 16
Control	38.37 ± 2.49^{aA}	3.10 ± 0.64^{bA}	13.03 ± 1.54^{aA}	0.99 ± 0.15^{aB}
AC	38.34 ± 2.17^{aA}	3.27 ± 0.46^{bA}	12.88 ± 1.87^{aA}	1.34 ± 0.10^{aA}
CuO/AC	39.57 ± 3.78^{aA}	2.95 ± 0.45^{bA}	12.71 ± 1.27^{aA}	0.76 ± 0.09^{aC}

AC: activated carbon; CuO/AC: activated carbon impregnated with copper oxide.
*Different uppercase letters in the same column indicate significant differences between treatments, while different lowercase letters in the same row indicate significant differences between days ($p < .05$).

3.2 *Fourier transform infrared of activated carbons before and after storage*

To evaluate the influence of the functional groups of ACs on ethylene control (analyzed indirectly through the physical-chemical parameters of bananas), Fourier Transform Infrared (FTIR) spectroscopy of the materials were obtained before and after the storage period (Figure 5).

The band recorded at approximately 3,442 cm^{-1}, typical of phenolic hydroxyl groups (O-H stretching) in lignocellulosic compounds (Singh & Dhepe, 2016), presented a reduction in intensity after 16 days, indicating its consumption during the experiment. These data show that OH groups are decisive in the adsorption of ethylene, altering the surface electrostatic potential of the carbon, facilitating important chemical interactions with the ethylene molecule (Zhang et al., 2023). Furthermore, the mesoporous and microporous structure of all samples allows easy diffusion of small molecules such as ethylene with a kinetic diameter of ~3.9 Å and its consequent interaction with the OH groups on the AC surface (Wang et al., 2020). The peaks observed at 617 cm^{-1} and 477 cm^{-1} in the CuO/AC spectrum before the experiment are attributed to vibrations of the Cu-O bond, confirming the presence of copper oxide impregnated in the AC. After storage, the attenuation of these bands suggests that the CuO underwent chemical changes during storage, possibly due to interaction with ethylene or other compounds released by the bananas.

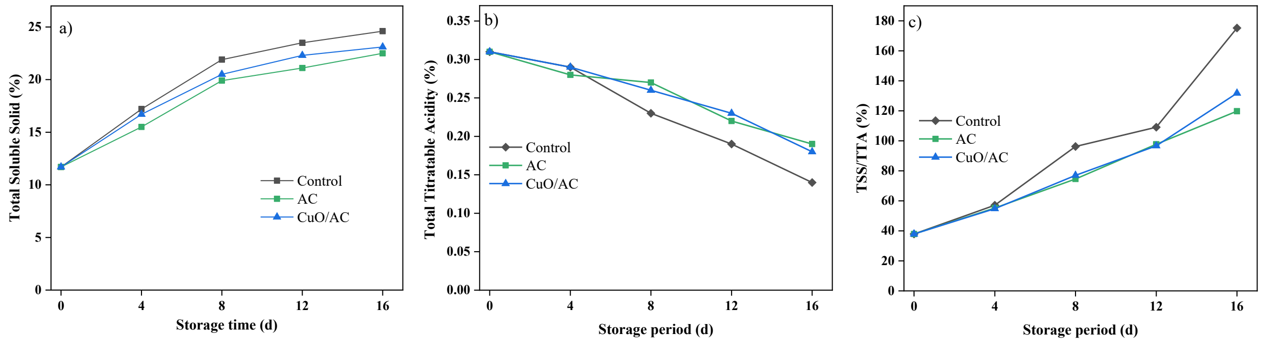
4 CONCLUSIONS

Postharvest preservation experiments showed that both unmodified AC and CuO/AC revealed potential for application as ethylene adsorbents. Both materials were effective in delaying fruit browning and ripening, compared to the control group, as observed by the physicochemical parameters color, weight loss, TTA and TSS/TTA ratio. However, bananas stored with AC

Table 4. Total soluble solids and total titratable acidity of bananas stored at 25°C for 16 days.

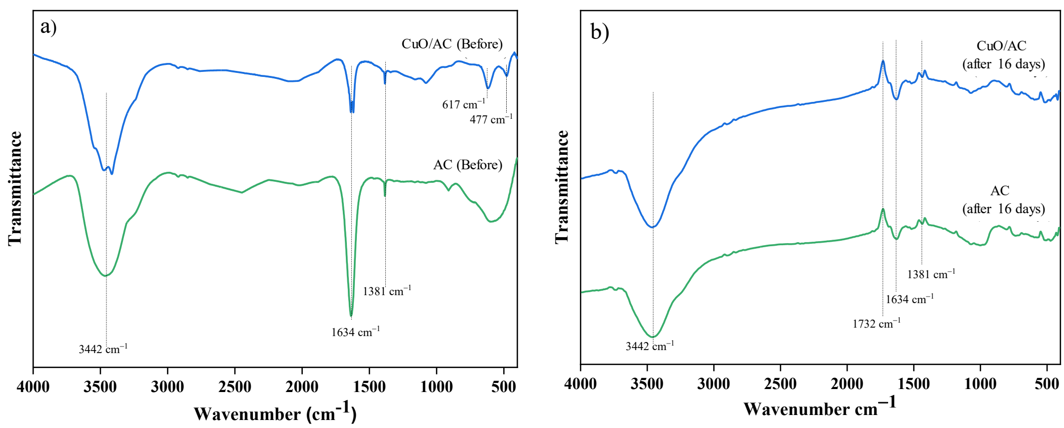
Parameters	Treatment	Storage period (days)				
		0	4	8	12	16
TSS	Control	11.5 ± 0.20^{eA}	17.0 ± 0.15^{dA}	21.7 ± 0.12^{cA}	23.5 ± 0.06^{bA}	24.4 ± 0.15^{aA}
	AC	11.5 ± 0.20^{eA}	15.4 ± 0.15^{dC}	19.8 ± 0.15^{cC}	21.1 ± 0.20^{bC}	22.2 ± 0.21^{aC}
	CuO/AC	11.5 ± 0.20^{eA}	16.3 ± 0.27^{dB}	20.3 ± 0.12^{cB}	22.1 ± 0.12^{bB}	23.0 ± 0.10^{aB}
TTA	Control	0.30 ± 0.01^{aA}	0.28 ± 0.02^{aB}	0.23 ± 0.01^{bB}	0.20 ± 0.02^{bA}	0.14 ± 0.01^{cB}
	AC	0.30 ± 0.01^{aA}	0.28 ± 0.01^{bB}	0.26 ± 0.01^{cA}	0.21 ± 0.01^{dA}	0.18 ± 0.01^{eA}
	CuO/AC	0.30 ± 0.01^{aA}	0.30 ± 0.02^{aA}	0.27 ± 0.01^{bA}	0.23 ± 0.01^{cA}	0.17 ± 0.01^{dA}
Ratio TSS/TTA	Control	37.9 ± 1.32^{eA}	57.08 ± 3.16^{dA}	96.24 ± 3.67^{cA}	109.10 ± 3.91^{bA}	175.2 ± 1.01^{aA}
	AC	37.9 ± 1.32^{eA}	55.23 ± 1.09^{dA}	74.57 ± 2.79^{cB}	97.73 ± 3.87^{bA}	119.8 ± 4.96^{aB}
	CuO/AC	37.9 ± 1.32^{eA}	54.80 ± 4.21^{dA}	77.01 ± 2.58^{cB}	96.68 ± 5.33^{bA}	131.8 ± 5.23^{aB}

TSS: total soluble solids; TTA: total titratable acidity; AC: activated carbon; CuO/AC: activated carbon impregnated with copper oxide.
*Different uppercase letters in the same column (concerning each parameter) indicate significant differences between treatments, while different lowercase letters in the same row indicate significant differences between days ($p < .05$).



AC: activated carbon; CuO/AC: activated carbon impregnated with copper oxide.

Figure 4. (a) Variations in total soluble solids, (b) total titratable acidity, and (c) total titratable acidity/total soluble solids ratio of bananas stored at 25°C for 16 days.



AC: activated carbon; CuO/AC: activated carbon impregnated with copper oxide.

Figure 5. Fourier Transform Infrared Spectroscopy of activated carbon and activated carbon impregnated with copper oxide before and after 16 days of storage.

showed superior outcomes, resulting in greater pulp firmness and lower TSS on day 16 of storage. This performance is mainly due to its high specific surface area and significant volume of micropores, which favors the adsorption of ethylene during fruit respiration, thus delaying the ripening process. These findings contribute to advancing the development of sustainable and efficient ethylene-adsorbing materials, highlighting a promising postharvest strategy to extend fruit shelf life and mitigate losses along the supply chain.

ACKNOWLEDGMENTS

The authors would like to thank the Coordination for the Improvement of Higher Education Personnel (CAPES; process 88881.918286/2023-01), the National Council for Scientific and Technological Development (CNPq; process 441839/2023-1), and the Goiás State Research Support Foundation (FAPEG) for their financial support.

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