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Nutritional changes in plantain (*Musa paradisiaca* var. corne) according to the type of post-harvest ripening in Côte d'Ivoire

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ABSTRACT

Background: *The nutritional quality of fruit and vegetables plays an important role in promoting good health. However, concerns have emerged in Côte d'Ivoire about the artificial ripening of plantains - an increasingly common practice that may pose food safety risks. Despite its growing prevalence, this issue remains underexplored in local research.*

Aim of the study: *This study aimed to assess the comparative effects of artificial ripening - using calcium carbide (CaC_2) and ethephon - versus natural ripening of plantain (Musa paradisiaca var. Horn). Specifically, changes in colorimetric, physicochemical and biochemical properties were investigated to better understand how these ripening methods affect fruit quality and potential health implications.*

Material and methods:*Plantains (Musa paradisiaca var. Horn) were harvested at 80 and 90 days after flowering and stored for eight days under controlled conditions (22 ± 1.6 °C and 75 ± 5% relative humidity). Standard analytical methods were applied to five ripening stages, designated T_0 to T_4 .*

Results: *Calcium carbide (CaC_2) induced ripening started very early, from stage T_1 , followed by ethephon at stage T_2 . In contrast, natural ripening was not evident until the final stage, T_4 . This artificial acceleration resulted in significant changes in fruit colour (L* = 72.4; a* = +8.6; b* = 42.8 at T_2), indicating rapid chlorophyll breakdown and carotenoid accumulation. pH peaked at 7.39 in control fruits, while titratable acidity decreased significantly in CaC_2 treated fruits. Soluble sugars reached 10.93 °Brix in the CaC_2 treatment, compared to only 2.5 °Brix in naturally ripened fruit. In addition, fruit firmness decreased significantly with CaC_2 treatment (from 12.2 to 6.02 N) and weight loss reached 30.64%.At the biochemical level, CaC_2 -treated fruits showed a reduction in total carbohydrates (63.07% DM), proteins (2.12% DM), lipids (0.22% DM) and energy (78.96 kcal/100 g DM). The mineral content also decreased significantly, especially iron (from 5.12 to 2.36 mg/100 g) and calcium.*

Conclusion*: Natural ripening remains the safest and most nutritionally beneficial method compared to more aggressive chemical ripening alternatives such as calcium carbide and ethephon.*

Keywords: *Plantain, calcium carbide, ethephon, artificial ripening, nutritional quality, food safety.*

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I. Introduction

Plantain (Musa paradisiaca) is a staple food in West Africa, particularly in Côte d'Ivoire, where annual production exceeds 1.5 million tonnes, largely driven by smallholder farmers (FAOSTAT, 2022). Rich in carbohydrates, fibre and micronutrients, plantains play an important nutritional and economic role, especially for rural households (Akintunde et al., 2023).

However, plantains are highly perishable after harvest, resulting in significant postharvest losses - estimated at over 30% globally and up to 40% in Côte d'Ivoire (Lacap et al., 2021); (Pérrin et al., 2015). To mitigate these losses, farmers often harvest early and artificially induce ripening - often using empirical methods, especially in informal supply chains. Among these, calcium carbide (CaC_2) and ethephon have become commonly used ripening agents in Côte d'Ivoire (Deli et al., 2024).

These chemical agents enable rapid and uniform ripening, helping to reduce post-harvest losses (Sojinu et al., 2021; Akintunde et al., 2023). However, their use remains largely unregulated. Several studies have

reported the presence of toxic residues and potential deterioration in the organoleptic and nutritional quality of treated fruits (Tallapally et al., 2020; Adekalu et al., 2020; UgbeniandAlagbaoso, 2023).

Internationally, these substances have been shown to significantly alter fruit physiology, affecting texture, nutritional value and metabolic processes (Brummell, 2006; Islam et al., 2018; Triasmoko et al., 2021). Calcium carbide releases acetylene gas, an ethylene analogue that induces rapid but physiologically disorganised ripening. In contrast, ethephon decomposes to release ethylene gas, activating complex signalling pathways associated with cell wall degradation, starch conversion and pigment synthesis (Sisler and Serek, 2003; Barry and Giovannoni, 2007; Hossain et al., 2014; Akter et al., 2019; MaduwanthiandMarapana, 2019; Al-Dairi et al.,2021).

Despite their widespread use in Ivorian markets, few local studies have rigorously investigated the effects of these ripening agents on the physiology and biochemical composition of plantain. Nutritional, mineral and colorimetric effects remain poorly documented, hindering the development of scientifically sound post-harvest best practices.

This study aims to fill this gap by comparing the effects of calcium carbide, ethephon and natural ripening on the development of colorimetric, physicochemical, biochemical and mineral characteristics of plantain (Musa paradisiaca var. Corne) grown in Côte d'Ivoire. The aim is to provide reliable data to inform technical and public health decisions related to post-harvest ripening practices.

II. Material And Methods

Vegetable material.

The plant material used in this study consisted of plantain fruits (Musa paradisiaca var. Corne) harvested at physiological maturity (between 80 and 90 days after flowering) from a village plantation in Mahapleu, Man region, approximately 597 km from Abidjan (7°13′10″N; 7°55′46″W). This place has an average annual temperature of 25°C and receives about 1,182.8 mm of rainfall.

Methods

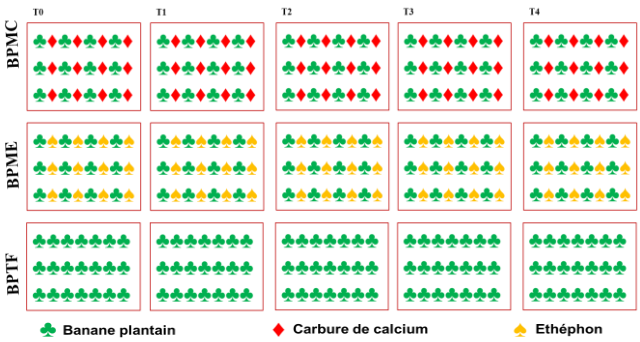
Harvesting and sampling

Harvesting was carried out according to the recommendations of the technical manual of the National Centre for Agronomic Research (CNRA, 2005). The pseudostems of the plantain trees were cut at three quarters of their height, allowing the plants to bend without touching the ground. The bunches were then manually detached and carefully transported to avoid mechanical damage or latex spillage.

Individual fingers were separated and defect-free fruits were selected from the second and third positions of bunches harvested 90 days after flowering. The selected fruits were disinfected with 1% sodium hypochlorite solution, rinsed with clean water and air dried for 30 minutes. Finally, the fruits were packed in plastic boxes, labelled and transported to the Food and Nutrition Safety Laboratory (LNSA) of Nangui ABROGOUA University for experimental treatments.

Experimental design.

The study was conducted using a completely Randomized factorial design (3 × 5) with two factors: postharvest treatment (untreated control - BPFT, ethephon treatment - BPME, and calcium carbide treatment - BPMC) and ripening time in days (T_0 , T_1 , T_2 , T_3 , T_4).For the experiment, uniform plantain fruits with no visible defects were randomly selected. These fruits were divided into three groups corresponding to the three treatment types. Each group was further randomly and equally divided into five batches for successive observations.The post-harvest color development of the fruit was monitored over a period of eight days. Samples were taken at five specific ripening stages: T_0 (day 0), T_1 (day 2), T_2 (day 4), T_3 (day 6) and T_4 (day 8), in order to assess the changes over time associated with each ripening treatment.



Ripening Stages and Treatments : *T_0 :(Day 0) ; T_1 :(Day 2) ; T_2 :(Day 4) ; T_3 :(Day 6) ; T_4 :(Day 8)*

PostharvestTreatments : *BPFT :(Control repning, no treatment)* ***;*** *BPME :(Ethephontreatment)* ***;*** *BPMC* ***:****Calcium carbidetreatment)*

Ripening conditions

After treatment, the fruits were placed in airtight metal containers sealed with cement paper and incubated for 48 hours under controlled conditions (22 ± 1.6 °C and 75 ± 5% relative humidity). These conditions replicate the most commonly observed commercial ripening practices in Abidjan markets (Deli et al., 2024**).** The BPMC group was treated with calcium carbide at a rate of 30 g/kg, placed in perforated bags in contact with the fruit. The BPME group received a 10% ethephon spray (3.125 ml/kg) followed by 30 minutes of air drying. The BPFT group served as a control and was subjected to a natural ripening process without being exposed to any chemical agent. This protocol made it possible to evaluate the specific effects of each ripening agent, as well as the interactions between treatment and time, on the colorimetric, physico-chemical, biochemical and mineral parameters of the plantains.

Analysis of colorimetric and biochemical parameters

Analyses were carried out at regular intervals (T_0 , T_1 , T_2 , T_3 and T_4) to monitor the ripening process.

Colorimetric analysis

The colour of the fruit skin (epicarp) was assessed using a portable colorimeter (KONICA MINOLTA CM-700d). Three measurements were taken per fruit on a uniform surface area. The values of L* (lightness), a* (green-red axis) and b* (blue-yellow axis) were recorded and used to calculate chroma (C*), an indicator of colour intensity (Pathare et al., 2013). The total colour difference (ΔE) was also determined using the formula described by (Rhim et al., 1999) to estimate the total colour shift relative to the control group. These measurements allowed the visual changes induced by different ripening agents to be quantified and compared throughout the ripening process.

Biochemical Analyses

Proximate composition

The proximate composition of plantain pulp was analysed at different ripening stages using homogenised samples. pH was measured using a potentiometric method, while titratable acidity was determined by titration with 0.1 N NaOH according to AOAC guidelines (AOAC, 1990). Soluble solids content (°Brix) was assessed using a digital refractometer, and fruit firmness was assessed by direct penetration with a durometer. Weight loss was calculated as the percentage difference between initial and final weight. Dry matter content was determined by drying at 105 °C and ash content by combustion at 550 °C. Protein content was determined by the Kjeldahl method (conversion factor: 6.25), lipids were extracted with hexane using a Soxhlet apparatus, and crude fibre content was determined by acid hydrolysis under reflux. Total sugars were quantified using the phenol-sulphuric acid colourimetric method (Dubois et al., 1956). Energy was estimated using Atwater factors according to FAO/WHO recommendations (FAO/WHO, 2003).

Mineral composition

Pulp samples from treated plantains (calcium carbide, ethephon and control) were ground and dehydrated at 40 °C for 48 hours. The dried samples were then incinerated at 450 °C for 24 hours. The resulting ash was pressed into 12 mm pellets (230 mg) under a pressure of 5-14 T/cm². Two sample preparation methods were used: deposition of 25 µL of a standard reference material (SRM 1577b) on Kapton film and dry nebulisation (5-25 min). Elemental analysis was performed by X-ray fluorescence spectrometry (XRF) using a Philips PW 1300 system (20-60 kV; 5-80 mA) under a primary vacuum of 10^{-2} Pa. A molybdenum anode was used for light elements ($Z < 41$) and a tungsten anode for heavy elements (up to 50 keV), with detection using a germanium semiconductor spectrometer.

XRF was chosen because of its ability to perform rapid and accurate multi-element analyses of complex plant matrices, offering a simpler sample preparation process compared to methods such as AAS (Atomic Absorption Spectrometry) or ICP-MS (Inductively Coupled Plasma Mass Spectrometry) (Potts and Webb, 1992; Zarcinas et al., 1987; Ene et al., 2010; Nwachokor and Uzu, 2011).

Data Analysis.

Data were analysed using JMP Pro 17 software. One-way analysis of variance (ANOVA) was performed for each parameter. When results were statistically significant ($p < 0.05$), Tukey's honest significant difference (HSD) test was used to identify differences between treatments.

III. Result

Colour evolution of plantain fruit

The visual evolution of plantain peel colour is shown in Figure 1. The results showed significant differences ($p = 0.05$) depending on the post-harvest treatment applied. On T_0 (day 0), all fruits showed a uniform green colour with no visible differences between the treatment groups. On the second day (T_1), a rapid colour change was observed in fruits treated with calcium carbide (BPMC). At the same time, only 35% of the ethephon-treated fruits (BPME) showed visible signs of ripening, while the control fruits (BPFT) remained completely green. By day four (T_2), the BPME fruits showed a uniform yellow colour, while the BPFT group remained predominantly green. At T_3 (day 6), BPMC fruits showed visible signs of senescence while BPME fruits retained a bright yellow colour. At this stage, the control fruits began their transition to yellow colouring. Finally, at T_4 (day 8), fruits in the BPMC group were fully senescent, those in the BPME group showed early signs of advanced breakdown, and control fruits reached their optimal ripening stage, characterized by a uniform yellow color.

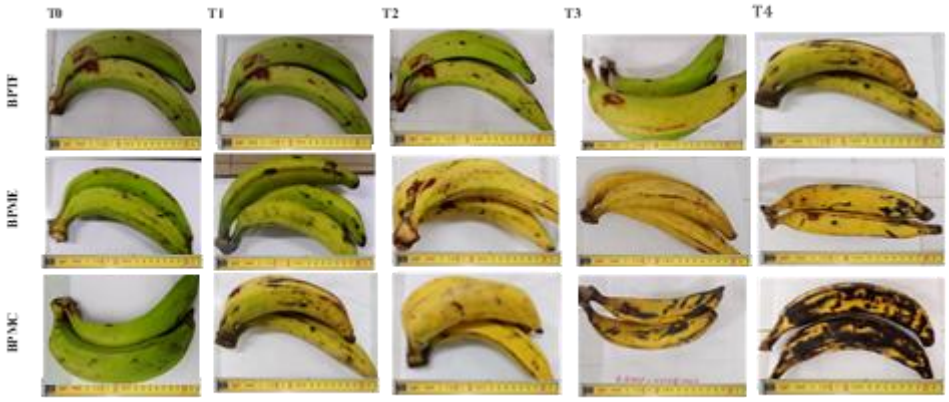
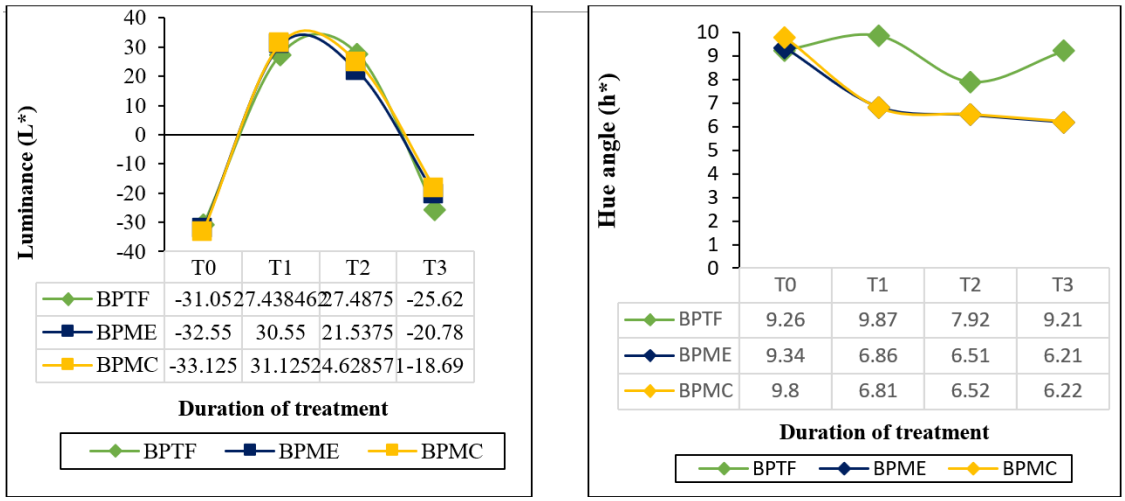


Figure 1: Color changes in plantain fruits as a function of ripening time under different postharvest treatments.

Ripening Stages and Treatments : *T_0 : (Day 0) ; T_1 : (Day 2) ; T_2 : (Day 4) ; T_3 : (Day 6) ; T_4 : (Day 8).* ***PostharvestTreatments :*** *BPFT : (Control repning, no treatment) ; BPME : (Ethephontreatment) ; BPMC : Calcium carbidetreatment)*

Effect on colorimetric indices

Figure 2 shows the evolution of the colorimetric indices (L*, a*, b*, C* and h*) as a function of post-harvest treatment and ripening time. These indices changed significantly ($p < 0.05$) according to the treatment applied and the ripening time. The lightness index (L*) peaked at 72.4 on day 4 (T_2) for calcium carbide treated fruits (BPMC) compared to 68.7 for ethephon treated fruits (BPME) and 62.5 for the control group (BPFT). The a* index (green to red) increased from -4.9 to +8.6 in BPMC fruits, +6.3 in BPME and +2.1 in BPFT. Similarly, the b* index (blue to yellow) reached maximum values of 42.8 (BPMC), 40.2 (BPME) and 36.1 (BPFT). Chroma (C*), which indicates colour saturation, followed a similar trend, with the highest intensity recorded in BPMC fruits (43.7). The hue angle (h*) decreased most in calcium carbide-treated fruits, from 115.4 to 78.2, compared to 84.1 for ethephon and 91.3 for the control group.



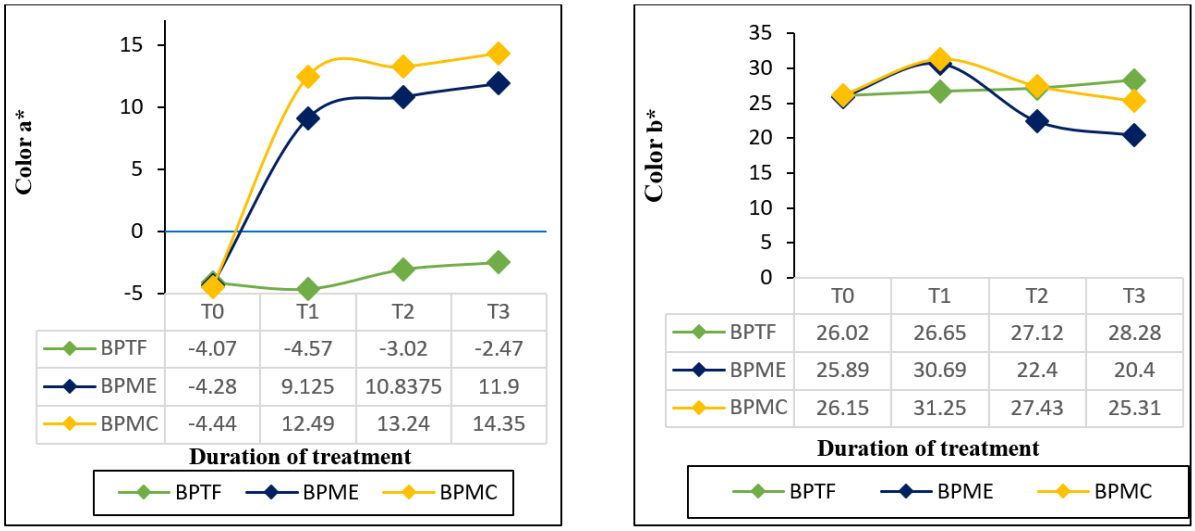


Figure 2. Evolution of colorimetric parameters **(L*, a*, b*)** in plantain fruits during ripening under different postharvest treatments.

Ripening Stages and Treatments : *T_0 : (Day 0) ; T_1 : (Day 2) ; T_2 : (Day 4) ; T_3 : (Day 6) ; T_4 : (Day 8).*
PostharvestTreatments : *BPFT : (Control repning, no treatment)* ***;*** *BPME : (Ethephontreatment)* ***;*** *BPMC :* *Calcium carbidetreatment)*

Biochemical modifications

Effect on physical characteristics

Table 1 shows significant changes ($p < 0.05$) in the physical characteristics of plantain fruits as a function of post-harvest treatment and ripening time. Weight loss increased in all groups, with the most pronounced loss observed in the calcium carbide-treated fruits (30.64% at T_4), followed by the ethephon treated fruits (23.8%) and the control group (20.8%).Pulp firmness decreased progressively, with the greatest decrease in the BPMC group (from 12.2 to 6.02 N), a moderate decrease in the BPME group (12.4 to 8 N) and a slower decrease in the control group (12.1 to 10.1 N).Dry matter content also decreased over time, from 12.6% to 8.01% in calcium carbide treated fruits, from 12.32% to 6.8% in ethephon treated fruits and from 12.2% to 6% in control fruits.Similarly, ash content decreased progressively, with more marked reductions in treated fruit: from 9.4% to 6.55% under ethephon and to 4.28% under calcium carbide, compared with a reduction from 9.48% to 7.80% in the control group.

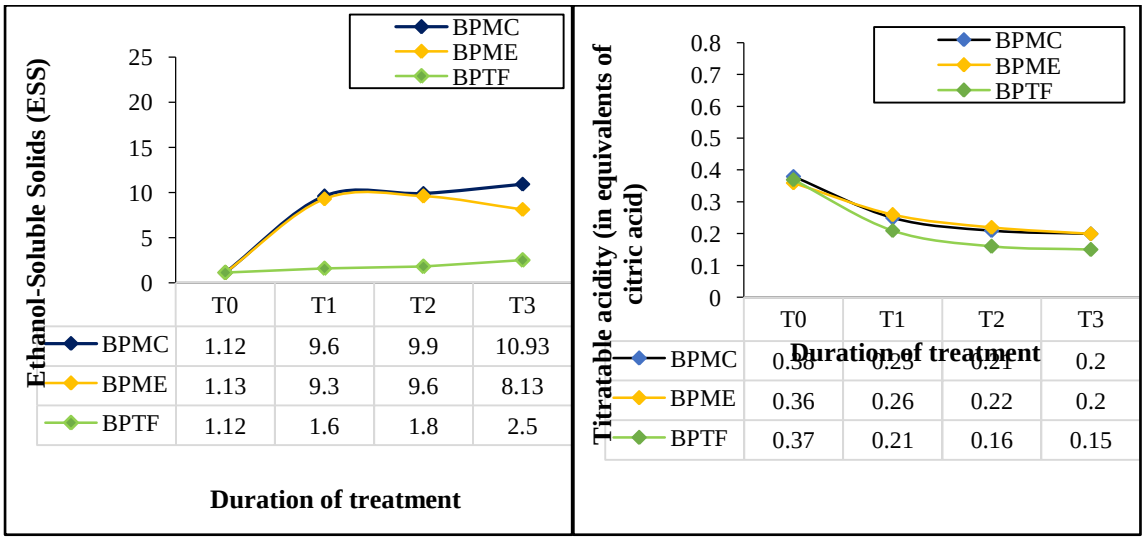
Table1: Evolution of physical parameters of plantain fruits during ripening under different postharvest treatments.

Echantillons	T0	T1	T2	T3	T4	P-Value
Weightloss (%) of plantain						
BPFT	0^{Da}	$10\pm0,01^{Ca}$	$9,2\pm0,5^{Cc}$	$15,2\pm0,02^{Bc}$	$20,8\pm0,13^{Ac}$	0,01
BPME	0^{Da}	$10,58\pm0,7^{Ca}$	$11,38\pm0,03^{Cb}$	$19,26\pm0,09^{Bb}$	$23,8\pm0,3^{Ab}$	0,03
BPMC	0^{Da}	$10,48\pm0,1^{Ca}$	$22,58\pm0,12^{Ca}$	$26,26\pm0,02^{Ba}$	$30,64\pm0,02^{Aa}$	0,01
Plantain fermeté						
BPFT	$12,1\pm0,9^{Aa}$	$11,9\pm0,3^{Ba}$	$11,1\pm0,4^{Ba}$	$11\pm0,01^{Ba}$	$10,1\pm0,9^{Ca}$	0,06
BPME	$12,4\pm0,6^{Aa}$	$11,2\pm0,4^{Bb}$	$10,4\pm0,2^{Cb}$	$9\pm0,1^{Cb}$	$8\pm0,06^{Cb}$	0,35
BPMC	$12,2\pm0,2^{Aa}$	$10,1\pm0,7^{Bc}$	$09,02\pm0,1^{Bc}$	$7,1\pm0,1^{Cc}$	$06,02\pm0,1^{Dc}$	0,22
Dry Matter (% Fresh Mass)						
BPFT	$12,2\pm6^{Aa}$	$10,1\pm7^{Bc}$	$09,02\pm2^{Cc}$	$07,1\pm0,02^{Db}$	$06,02\pm0,1^{Dc}$	0,12
BPME	$12,32\pm5^{Aa}$	$10,6\pm2^{Bb}$	$09,8\pm2^{Bb}$	$07,5\pm0,01^{Cb}$	$06,8\pm0,7^{Db}$	0,1
BPMC	$12,60\pm0,7^{Aa}$	$11,1\pm3^{Ba}$	$10,02\pm4^{Ca}$	$08,3\pm021^{Da}$	$08,01\pm0,3^{Da}$	0,14
Ash Content (% Dry Matter)						
BPTF	$9,47 \pm 0,02^{Aa}$	$9,22\pm 0,02^{Aa}$	$9,05\pm 0,02^{Aa}$	$8,78\pm 0,02^{Ba}$	$7, 8\pm 0,02^{Ca}$	0,2
BPME	$9,49 \pm 0,01^{Aa}$	$8,8 \pm 0,06^{Bb}$	$7,63\pm 0,08^{Bb}$	$7,45\pm 0,04^{Bb}$	$6,55\pm 0,04^{Cb}$	0,92
BPMC	$9,48 \pm 0,03^{Aa}$	$8,20 \pm 0,04^{Bc}$	$6,30 \pm 0,03^{Cc}$	$5,48\pm 0,02^{Dc}$	$4, 28\pm 0,02^{Dc}$	0,03

Mean ± standard deviation. Values in the same row with a different uppercase letter are significantly different at the 5% level according to the Tukey test. Values in the same column with a different lowercase letter are significantly different at the 5% level according to the Tukey test. The values of a block in the same column with a different lower-case letter are significantly different at the 5% level according to the Tukey test. (BPTF) : Banana Plantain Closed Control, (BPME): Banana Plantain Muri à l'Ethéphon, (BPMC) : Banana Plantain Mûri au Carbure de calcium, T0 : Time day 0, T1 : Time 2 days, T2 : Time 4 days, T3 : Time 6 days.

Physico-chemical effects

The evolution of physicochemical parameters during ripening is shown in Figure 3. pH increased significantly ($p < 0.05$) in all treatments. This increase was most pronounced in the control group, rising from 5.23 at T_0 to 7.39 at T_3 , compared with an increase from 5.21 to 6.81 in ethephon-treated fruits and from 5.18 to 6.47 in calcium carbide-treated fruits. In parallel, titratable acidity decreased in all groups. The control group showed the greatest reduction, from 0.37 to 0.15 citric acid equivalents (CAE), compared with a reduction from 0.36 to 0.21 in BPME and from 0.35 to 0.26 in BPMC. Ethanol soluble sugars (ESS) increased significantly over time. At T_3 , the highest values were observed in the calcium carbide treated fruits (10.93 °Brix), followed by the ethephon treated fruits (8.67 °Brix), while the control group showed much lower values (2.5 °Brix at T_3 vs. 1.2 °Brix at T_0).



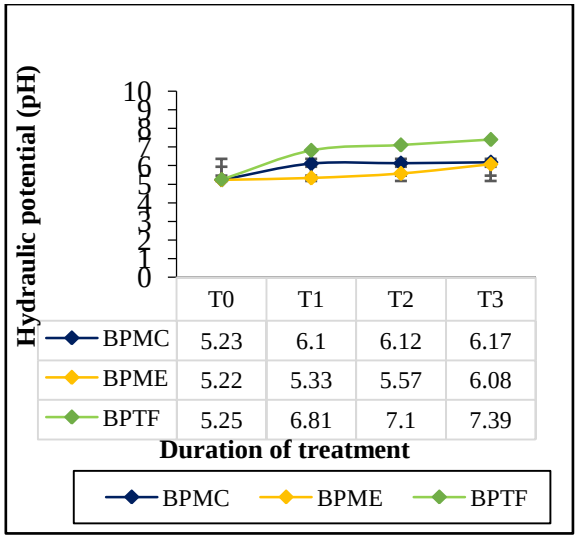


Figure 3. Evolution of physico-chemical parameters of plantain fruits during ripening under different postharvest treatments.

Ripening Stages and Treatments : *T_0 : (Day 0) ; T_1 : (Day 2) ; T_2 : (Day 4) ; T_3 : (Day 6) ; T_4 : (Day 8).* ***PostharvestTreatments :*** *BPFT : (Control repning, no treatment) ; BPME : (Ethephontreatment) ; BPMC : Calcium carbidetreatment)*

Changes in proximate composition

Proximate composition changes

Table 2 shows the variation in the main biochemical constituents during ripening under the different postharvest treatments. The total carbohydrate content decreased in all groups. This decrease was moderate in control fruits (from 80.07% to 74.83% dry matter), more pronounced in ethephon-treated fruits (down to 68.69% at T_4) and most pronounced in calcium carbide-treated fruits (63.07% at T_4). Lipid content followed a similar trend, with the greatest decrease observed in the BPMC group (down to 0.22% dry matter), compared to 0.33% under ethephon and 0.39% in the control group. The protein content also decreased, reaching 2.12% dry matter at T_4 in the calcium carbide treated fruits, 3.78% under ethephon and 5.42% in the control fruits.The energy value showed a progressive increase in the control group, peaking at 154.78 kcal/100 g dry matter at T_3 . In contrast, a

significant decrease was observed in the treated groups, with energy values falling to 78.96 kcal/100 g in BPMC fruits and 96.24 kcal/100 g in BPME fruits at T_4 .

Table 2: Effect of artificial ripening on plantain macromolecules

Samples	Fruit harvested 80- 90 days after blossoming					
	T 0	**T1**	**T 2**	**T3**	**T4**	**P-Value**
			Carbohydrates (% .MS)			
BPTF	80,07± 0,03^{Aa}	78,69± 0,08^{Ba}	78,4± 0,7^{Ba}	76,83± 0,002^{Ca}	74,83± 0,002^{Da}	0,65
BPME	79,89± 0,02^{Aa}	77,91± 0,06^{Bb}	76,16± 0,05^{Bb}	74,69± 0,3^{Cb}	68,69± 0,3^{Db}	0,01
BPMC	80,06± 0,04^{Aa}	76,71± 0,01^{Bc}	74,26± 0,1^{Ca}	73,07± 0,4^{Cc}	63,07± 0,4^{Dc}	0,04
			Fat (%MS)			
BPTF	0,78 ± 0,002^{Aa}	0,84 ± 0,002^{Ba}	0,88 ± 0,002^{Ca}	9,05 ± 0,001^{Da}	8,01 ± 0,4^{Ba}	0,02
BPME	0,76 ± 0,002^{Aa}	0,70 ± 0,002^{Bb}	0,56 ± 0,004^{Cb}	0,50 ± 0,002^{Cb}	0,40 ± 0,05^{Db}	0,01
BPMC	0,77 ± 0,003^{Aa}	0,68 ± 0,003^{Bc}	0,480 ± 0,001^{Cc}	0,36 ± 0,003^{Dc}	0,22 ± 0,53^{Dc}	0,03
			Protein (%MS)			
BPTF	6,22 ± 0,04^{Aa}	6,10 ± 0,01^{Aa}	5,80 ± 0,02^{Aa}	5,44 ± 0,01^{Aa}	5,42 ± 0,01^{Aa}	0,02
BPME	6,30 ± 0,01^{Aa}	4,77 ± 0,09^{Bb}	4,50 ± 0,01^{Bb}	3,28 ± 0,03^{Bb}	2,17± 0,03^{Bb}	0,01
BPMC	6,15 ± 0,5^{Aa}	4,24 ± 0,06^{Cc}	3,71 ± 0,01^{Cc}	2,81 ± 0,07^{Cc}	2,12 ± 0,07^{Cc}	0,05
			VE (Kcal/100 g)			
BPTF	109,23± 0,5^{Aa}	115,61± 0,7^{Aa}	125,70± 0,6^{Aa}	154,78± 0,7^{Aa}	136,78± 0,4^{Aa}	0,03
BPME	108,23± 0,1^{Aa}	101,39± 0,2^{Cc}	115,60± 0,4^{Bc}	100,61± 0,9^{Cc}	115,61± 0,13^{Cb}	0,15
BPMC	108,43± 0,8^{Aa}	110,75± 0,3^{Bb}	126,50± 0,2^{Ab}	107,87± 0,8^{Bb}	78,96± 0,8^{Bc}	0,02

Mean ± standard deviation. Values in the same row with a different uppercase letter are significantly different at the 5% level according to the Tukey test. Values in the same column with a different lowercase letter are significantly different at the 5% level according to the Tukey test. The values of a block in the same column with a different lower-case letter are significantly different at the 5% level according to the Tukey test. (BPTF) : Banana Plantain Closed Control, (BPME): Banana Plantain Muri à l'Ethéphon, (BPMC) : Banana Plantain Mûri au Carbure de calcium, T0 : Time day 0, T1 : Time 2 days, T2 : Time 4 days, T3 : Time 6 days.

variation in mineral content

Table 3 shows the variability in mineral content of plantain pulp according to post-harvest treatment and ripening stage. The minerals content varied significantly ($p < 0.05$) according to the ripening mode. Potassium (K) remained the dominant macro-element in all the batches, with concentrations ranging from 113.5 mg/100 g DM to 147.4 mg/100 g DM. The highest values were recorded in the batch treated with calcium carbide, followed by those treated with ethephon, while the controls showed the lowest concentrations. Calcium (Ca) showed relative stability in the controls, but a significant decrease under treatment, particularly in the BPMC batch. Phosphorus (P) decreased from 18.46 to 14.09 mg/100 g DM at T_3 in the carbide-treated batches, compared with 17.80 to 16.10 in the ethephon-treated batches and 18.12 to 17.04 in the controls. Magnesium (Mg) also decreased significantly in the treated fruit, halving under carbide (from 3.79 to 1.90 mg/100 g DM). With regard to trace elements, sodium (Na) and iodine (I) levels remained relatively stable in all batches, particularly in the controls. On the other hand, significant decreases were observed for iron (Fe) and zinc (Zn) in the fruits treated, particularly with calcium carbide, with decreases from 5.12 to 2.36 mg/100 g DM for Fe and from 1.44 to 0.78 mg/100 g DM for Zn between T_0 and T_4 .

Table 3: Effect of artificial ripening on mineral content

Mineral content	Samples	Fruit harvested 80- 90 daysafterblossoming					
		T 0	**T1**	**T 2**	**T3**	**T4**	**P-Value**
Sodium (mg/100 g)	BPTF	3,14± 0,015A^{a}	3,14± 0,01^{Ab}	3,14± 0,015^{Ab}	3,14± 0,015^{Aa}	3,12± 0,014^{Aa}	0,07
	BPME	3,47± 0,0005^{Ba}	3,5± 0,02^{Ab}	3,5± 0,005^{Ab}	3,37± 0,05^{Ca}	3,37± 0,03^{Ca}	0,02
	BPMC	3,4± 0,05^{Ba}	5,56± 0,05^{Aa}	5,56± 0,005^{Aa}	4,52± 0,05^{Ba}	4,51± 0,02^{Bca}	0,01
Mangnesium (mg/100 g)	BPTF	7,214± 0,005^{Aa}	7,214± 0,15^{Ab}	7,214± 0,015^{Ab}	7,214± 0,05^{Ab}	7,214± 0,5^{Ab}	0,2
	BPME	6,103± 0,005^{Aa}	6,103± 0,05^{Ab}	6,103± 0,02^{Ab}	6,103± 0,05^{Ab}	6,102± 0,06^{Ab}	0,01
	BPMC	7,63± 0,025^{Aa}	8,63± 0,05^{Aa}	8,63± 0,05^{Aa}	8,63± 0,05^{Aa}	8,60± 0,02^{Aa}	0,01
Phosphorus (mg/100 g)	BPTF	19,55± 0,05^{Aa}	18,35± 0,005^{Ba}	16± 0,05^{Ba}	14,35± 0,003^{Ca}	14,33± 0,04^{Ca}	0,02
	BPME	19,55± 0,005^{Aa}	18,24± 0,01^{Ba}	15,09± 0,005^{Bb}	12,09± 0,001^{Bb}	11,08± 0,03^{Bb}	0,03
	BPMC	20,21± 0,005^{Aa}	16,96± 0,005^{Bb}	14,23± 0,001^{Cc}	11,02± 0,1^{Cc}	10,01± 0,01^{Cc}	0,01
Potassium (mg/100 g)	BPTF	107,1± 0,005^{Aa}	108,3± 0,045^{Ab}	120,78± 0,015^{Da}	141,4± 0,005^{Bc}	141± 0,01^{Bc}	0,7
	BPME	101,2± 0,005^{Ba}	103,5± 0,035^{Ac}	108,5± 0,05^{Cc}	123,5± 0,005^{Ac}	123,1± 0,002^{Ac}	0,04
	BPMC	101,010,005^{Ca}	102,47± 0,005^{Cb}	106,67± 0,05A^{b}	101,92± 0,05^{Bb}	101,90± 0,03^{Bb}	0,02
Calcium (mg/100 g)	BPTF	0,719± 0,05^{Aa}	0,708± 0,0005^{Aa}	0,687± 0,0001^{Aa}	4,123± 0,002^{Ba}	4,120± 0,001^{Ba}	0,8
	BPME	0,655± 0,05^{Aa}	0,5± 0,0005^{Bb}	0,425± 0,0005^{Bb}	2,0915± 0,005^{Cb}	1,915± 0,004^{Db}	0,02
	BPMC	0,666± 0,05^{Aa}	0,39± 0,001^{Bc}	3,03± 0,004^{Bc}	1,004± 0,0005^{Cc}	1,002± 0,0006^{Cc}	0,01

Iron (mg/100 g)	BPTF	0,422± 0,01 ^{Aa}	0,422± 0,035 ^{Ab}	0,442± 0,005^{Ac}	0,406± 0,05 ^{Ba}	0,360± 0,03 ^{Ba}	0,12
	BPME	0,422± 0,005^{Ca}	0,402± 0,005 ^{Ba}	0,306± 0,004 B^{a}	0,253± 0,005 ^{Dd}	0,250± 0,004 ^{Dd}	0,02
	BPMC	0,431± 0,01 ^{Aa}	0,338± 0,001^{Ca}	0,247± 0,01 ^{Cb}	0,236± 0,004 ^{Ad}	0,130± 0,002 ^{Ad}	0,03
Zinc (mg/100 g)	BPTF	0,057± 0,005 ^{Aa}	0,054± 0,002^{Aa}	0,052± 0,001$^{A a}$	0,0368± 0,01 ^{Ba}	0,0362± 0,01 ^{Ba}	0,42
	BPME	0,056± 0,0015 ^{Aa}	0,053± 0,0015^{Aa}	0,046± 0,003^{Bb}	0,025± 0,0025 ^{Cb}	0,022± 0,002 ^{Cb}	0,01
	BPMC	0,05± 0,005 ^{Aa}	0,049± 0,001^{Bb}	0,032± 0,004 ^{Cc}	0,02± 0,0005 ^{Cc}	0,019± 0,0003^{Dc}	0,03
Iodine (µg/ 100 g)	BPTF	0,212± 0,005^{Aa}	0,212± 0,005^{Ac}	0,212± 0,0005^{Ac}	0,212± 0,0004 ^{Aa}	0,212± 0,0003 ^{Aa}	0,56
	BPME	0,212± 0,004 ^{Ba}	0,225± 0,0025^{Ab}	0,225± 0,05 ^{Ab}	0,210± 0,003^{Cb}	0,210± 0,004^{Cb}	0,02
	BPMC	0,218± 0,01^{Bb}	0,257± 0,001^{Aa}	0,257± 0,001 ^{Aa}	0,200± 0,001^{Cb}	0,200± 0,001^{Cb}	0,01

Mean ± standard deviation. Values in the same row with a different uppercase letter are significantly different at the 5% level according to the Tukey test. Values in the same column with a different lowercase letter are significantly different at the 5% level according to the Tukey test. The values of a block in the same column with a different lower-case letter are significantly different at the 5% level according to the Tukey test. (BPTF) : Banana Plantain Closed Control, (BPME): Banana Plantain Muri à l'Ethéphon, (BPMC) : Banana Plantain Mûri au Carbure de calcium, T0 : Time day 0, T1 : Time 2 days, T2 : Time 4 days, T3 : Time 6 days.

IV. Discussion

Calcium carbide (CaC_2) treatment induced significantly earlier ripening of plantains, with signs of ripening already visible at T_1 compared to T_2 for ethephon and T_4 for controls. This earliness can be explained by the release of acetylene ($C_2 H_2$) following the hydrolysis of CaC_2 in the presence of moisture. This gas acts as an ethylene analogue capable of activating the ripening signalling cascade, although less specifically (Sisler and Serek, 2003). This early onset of ripening was also reported by Sojinu et al (2021), who observed an early induction of ripening genes in CaC_2 -treated fruit.

In terms of colour, the L*, a* and b* indices changed rapidly in the treated fruit, particularly in the BPMC batch, reaching 72.4, +8.6 and 42.8 respectively at T_2 . These values reflect a loss of the initial green hue and an intensification of the yellow colouration associated with the accelerated degradation of chlorophyll and the accumulation of carotenoids such as lutein and β-carotene (Gross, 1987; Al-Dairi et al., 2021). In addition, the marked decrease in hue angle (h*) in carbide-treated batches confirms faster pigment conversion than in naturally ripened fruit.

At the same time, the physico-chemical parameters showed a marked change. The pH increased progressively in all batches, reaching 7.39 in the controls at T_3 , with a slightly faster increase under treatment. This trend is a consequence of the consumption of organic acids (citric and malic), which are used as substrates in the Krebs cycle to support respiration intensification (Saltveit, 1999; Islam et al., 2018). Consistent with these dynamics, titratable acidity decreased significantly and more rapidly in CaC_2 -treated fruits, reflecting advanced metabolic degradation. These results are consistent with those of Akter et al. (2019), who observed a more rapid decrease in acidity in bananas subjected to chemical ripening.

With regard to ethano-soluble sugars (ESS), their content increased with ripening in all treatments, with maximum values observed in BPMC (10.93 °Brix at T_3). This increase is due to the enzymatic conversion of starch into simple sugars (glucose, fructose, sucrose) by amylases and invertases whose activity is stimulated by ethylene and its analogues (Brummell, 2006; Cissé et al., 2020). These results corroborate those of Akter et al. (2019), who reported an increase of more than 30% in sugars in CaC_2 -treated bananas.

Texturally, a significant decrease in firmness was observed in all batches, especially in BPMCs, where it decreased from 12.2 to 6.02 N. This loss in firmness is explained by the degradation of cell walls under the action of pectolytic enzymes, such as polygalacturonase and pectate lyase, which are activated during ripening (Giovannoni, 2001; Gunasekara et al., 2015). In parallel, weight loss was greater in treated fruit (up to 30.64% at T_4 under CaC_2), the result of more intense evapotranspiration and respiration, enhanced by artificial hormonal stimulation (Wills *et al.*, 2007; Bhuiyan *et al.*, 2020). Similarly, dry matter decreased in all treatments, with a more pronounced decrease in BPMC batches (down to 8.01%), reflecting an accelerated mobilisation of metabolic reserves, especially starch and lipids, as shown by Zhou et al. (2019) and Sampiano et al. (2022).

Biochemically, protein and lipid contents decreased significantly, especially in fruits treated with calcium carbide (2.12% DM for protein, 0.22% DM for lipids). This reduction is due to the activation of proteases and the oxidation of lipids induced by the oxidative stress generated by acetylene (Khairi et al., 2023). As a consequence, the energy value of the fruits also decreased, reaching 78.96 kcal/100 g DM at T_4 under CaC_2 treatment, in agreement with the results of Sogo-Temi et al. (2014).

Finally, the mineral composition was affected during ripening. A general decrease in mineral concentrations was observed, which was more pronounced in the treated lots. Potassium (K) remained dominant but showed fluctuations related to dehydration and metabolic stress. Calcium (Ca), essential for cell wall stability, showed instability under CaC_2 treatment, suggesting structural disorganisation (Brummell, 2006).Phosphorus (P) and magnesium (Mg), both involved in energy metabolism, also decreased, confirming the intensification of catabolic reactions. Trace elements such as iron (Fe) and zinc (Zn) decreased significantly in treated fruits, probably related to the instability of enzyme complexes under oxidative stress (Giovannoni,

2001; Ahsan et al., 2024). As for sodium (Na) and iodine (I), their levels remained relatively stable in the control fruit, but were disturbed in the treated batches.

In addition to the physiological and nutritional effects, the use of calcium carbide raises major toxicological concerns. Several studies have highlighted the presence of contaminants such as phosphorus or arsenic in commercial formulations of CaC_2 , toxic substances that can cause liver, kidney or reproductive damage in animals (Akintunde et al., 2023; Ugbeni and Alagbaoso, 2023).

V. Conclusion

Using artificial ripening agents such as calcium carbide and ethephon significantly alters the nutritional quality of plantain. A more pronounced deterioration is observed in fruit treated with carbide. While these agents are effective in accelerating ripening, their impact on biochemical parameters and nutritional value raises serious public health concerns. Safer alternatives or stricter control procedures should therefore be considered. Future research should assess the long-term effects of these agents on consumer health and explore biological or technological ripening methods that preserve product quality.

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