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Effects of Artificial Ripening on the Nutritional and Biochemical Characteristics of *Musa paradisiaca* (Plantain): Food Safety and Public Health Implications

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ABSTRACT

Background: *Musa paradisiaca (plantain)* is cultivated and consumed widely across Africa, Asia, Latin America, and the Caribbean, particularly in warm climatic areas where it supports food security, nutrition, and rural livelihoods. Increasing reliance on artificial ripening agents such as calcium carbide and wood ash has raised concerns regarding potential effects on nutritional quality and food safety. This study compared the effects of calcium carbide, wood ash, and natural ripening on the nutritional, biochemical, and physicochemical properties of plantain.

Methods: Plantain fruits were subjected to calcium carbide-induced, wood ash-induced, and natural ripening. Proximate composition, vitamin and mineral profiles, starch characteristics, amylase activity, and functional properties (solubility, swelling capacity, and water and oil absorption capacities) were assessed.

Results: Calcium carbide accelerated ripening (3 days) but reduced shelf life (6 days) and decreased nutritional quality, with lower protein content (1.99%), starch (64.43%), and reduced vitamins A and C, alongside diminished functional properties. Wood ash–ripened samples showed improved nutritional and functional characteristics, including higher starch content (71.81%), vitamin C (6.8 mg/100 g), and increased amylase activity (122.22 U/mL), as well as enhanced absorption capacities. Naturally ripened plantains exhibited the longest shelf life (13 days) and the highest carbohydrate content (24.77%).

Conclusion: Artificial ripening using calcium carbide adversely affects the nutritional and functional quality of plantains, whereas wood ash and natural ripening preserve or enhance key quality attributes. The findings highlight the need for safer ripening practices and improved regulation of chemical ripening agents to ensure food quality.

Keywords: Plantain, artificial ripening, calcium carbide and wood ash ripening, nutritional quality, food safety, biochemical markers.

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INTRODUCTION

Musa paradisiaca (plantain) is an important food crop of global significance, providing a major source of dietary energy and essential micronutrients for millions of people. Its cultivation and consumption are widespread across diverse agroecological settings in Africa, Asia, Latin America, and the Caribbean, where it contributes significantly to food security, nutrition, and rural livelihoods.[1–3] Fruit ripening is a tightly regulated physiological process characterised by extensive biochemical and physicochemical changes, including starch degradation, chlorophyll loss and tissue softening, which collectively determine fruit quality and consumer acceptability.[2,4]

To accelerate market readiness and reduce post-harvest losses, artificial ripening practices are widely employed in many developing countries. Common ripening agents include calcium carbide, ethylene and other chemical treatments that promote rapid fruit maturation.[5] Although these approaches improve marketability, concerns remain regarding their effects on nutritional quality, biochemical composition and food safety. Previous studies have reported alterations in vitamin content, physicochemical characteristics and sensory attributes in artificially ripened fruits [9], while calcium carbide use has been associated with potential toxicological risks arising from contaminant residues.[2,5,7-8,10]

Despite growing evidence of potential risks associated with artificial ripening, most studies have focused primarily on compositional or physicochemical changes, with limited integration of findings into broader public health contexts. In particular, there is a lack of comprehensive assessment of how ripening-induced alterations in plantain translate into potential dietary exposure risks for consumers in regions where these practices are widespread. Furthermore, comparative data on the safety and quality implications of alternative practices such as wood ash-induced ripening remains scarce, despite its informal use in some developing economies.

Consequently, the present study evaluated the effects of calcium carbide, wood ash, and natural ripening on the nutritional composition, biochemical profile, and physicochemical properties of *Musa paradisiaca*, with emphasis on their potential public health implications arising from changes in food quality and safety.

MATERIALS AND METHODS

***Materials*:** All experiments were performed using reagents meeting analytical-grade specifications. Absolute ethanol was obtained from Fisher Scientific (USA); sodium hydroxide, anhydrous potassium sulphate, elemental selenium and laboratory-grade calcium carbide from Sigma-Aldrich (USA); and concentrated sulphuric acid (98%), concentrated hydrochloric acid (35.5%), boric acid and cupric sulphate crystals from Merck (Germany). Other chemicals used included ammonia solution, diethyl ether, petroleum ether, phenolphthalein indicator, perchloric acid, nitric acid, n-butanol, 2,6-dichlorophenolindophenol (DCIP), chloroform, potassium chloride, pyridoxine hydrochloride, potassium permanganate, sodium dichromate, α-amylase, pepsin and vitamin B_{12} nutrient master mix. Reagents not specifically identified by supplier were obtained from departmental laboratory stocks and were of analytical grade.

Sourcing and identification of plantain: Mature unripe plantain fruits were purchased from Kasuwan Gwari Market, Minna, Niger State, Nigeria. The samples were authenticated by Dr. Dangana Mohammed Chata, Department of Plant Biology, Federal University of Technology, Minna, Nigeria.

Processing of the sample: Mature unripe plantain fruits were divided into three treatment groups: natural ripening (control), calcium carbide-induced ripening, and wood ash-induced ripening, with five fruits assigned to each treatment (n = 5). For artificial ripening, aqueous suspensions were prepared by dispersing 5.0 g of calcium carbide or wood ash in 20.0 mL deionised water. The respective suspensions were applied to the fruit batches, which were subsequently enclosed in airtight containers to facilitate ripening, following the method of Islam *et al.*[11] Control fruits were allowed to ripen naturally at ambient temperature without the addition of ripening agents, as described by Maduwanthi and Marapana.[12]

Ripening progression was monitored daily by visual assessment of peel colour. The stage of ripening was determined using a nine-point colour scale described by Aye *et al.*[13] Upon reaching full ripeness, the fruits were peeled and the edible portions were sliced before being dried in a hot-air oven at 50 °C until a constant mass was achieved (Thermo Fisher Scientific, USA). The dried material was then ground into a uniform powder using an electric blender (Panasonic, Japan) and preserved in

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airtight amber glass containers under dry conditions pending physicochemical and biochemical analyses.

Experimental Design: The study was conducted using a completely randomised design. Mature unripe plantain fruits were assigned to three ripening treatments: natural ripening (control), calcium carbide-induced ripening, and wood ash-induced ripening. Each treatment was replicated three times. Fruits were allowed to ripen under their respective conditions until full ripeness was attained, after which samples were collected for biochemical, nutritional and physicochemical analyses.

Quantitative Analysis of Percentage Content of Amylose and Amylopectin

Amylose content was quantified in starch extracted from plantains subjected to the three ripening treatments using an iodine-based colourimetric assay as previously described[14]. Standard amylose solutions spanning concentrations of 0 – 70 mg/L were used to generate the calibration curve. For analysis, 100 mg of the isolated starch was dispersed in an alkaline ethanol–sodium hydroxide medium and heated in a water bath for 15 min to ensure complete solubilisation. After cooling to ambient temperature, the solution was made up to volume with deionised water. Appropriate aliquots were subsequently diluted, acidified with 6 M hydrochloric acid, and allowed to react with iodine reagent to develop the characteristic colour complex. The absorbance of the resulting solution was recorded at 640 nm with a UV–visible spectrophotometer (Shimadzu UV-1800, Shimadzu Corporation, Japan). Amylose concentration was obtained from the standard calibration relationship, whereas amylopectin content was estimated as the difference between total starch and the measured amylose fraction.

Amylase activity: Amylase activity was evaluated according to the spectrophotometric procedure of Fischer and Stein[15]. For each determination, duplicate reaction mixtures were assembled containing equal volumes (1.0 mL each) of starch substrate solution and plantain extract prepared at a ratio of 1g sample to 10 mL extractant. The reaction systems were maintained at 35 °C in a thermostatically controlled water bath for 15 min to allow enzymatic hydrolysis. Enzyme action was inactivated by introducing 2.0 mL of dinitrosalicylic acid (DNS) reagent. Thereafter, the mixtures were heated in boiling water for 15 min to facilitate colour development and subsequently allowed to cool to ambient temperature. Absorbance readings were obtained at 540 nm using a UV–visible spectrophotometer. Enzyme activity was expressed as units corresponding to the quantity of enzyme capable of releasing reducing sugars equivalent to 1 μmol D-glucose min^{-1} under the specified assay conditions.

Proximate analysis

Moisture content: Sample moisture was determined using an oven-drying gravimetric procedure adapted from Abano and Amoah[16]. Approximately 1.0 g of sample was weighed into a previously dried and weighed crucible before drying at 105 °C for 4 h. Following oven treatment, the crucible was placed in a desiccator and allowed to cool before final weighing. Moisture content was expressed as the percentage reduction in mass relative to the original sample weight.

Fat content: Lipid content was assessed using the Rose–Gottlieb extraction method[17]. A 5.0 g test portion was first homogenised with 5 mL of deionised water and transferred into a separatory funnel. Subsequently, 2 mL ammonia solution and 10 mL ethanol were incorporated into the mixture.

Extraction was achieved using 25 mL of a diethyl ether–petroleum ether solvent blend (1:1, v/v). After vigorous agitation and phase separation, the organic layer containing the extracted lipids was collected into a pre-weighed flask. Solvent removal was accomplished by evaporation in a water bath, after which the residue was dried at 60 °C until a constant mass was obtained. The amount of fat present was determined gravimetrically from the increase in flask weight.

Ash content: Mineral residue was quantified by dry ashing. Approximately 1.0 g of sample was transferred into a pre-weighed crucible and subjected to thermal treatment in a muffle furnace (Carbolite Gero, United Kingdom). The temperature programme involved an initial holding stage at 300 °C for 30 min, followed by gradual elevation to 500 °C over a period of 4 h until complete combustion of organic matter had occurred. The crucible containing the residual ash was cooled in a desiccator prior to weighing. Ash content was calculated from the mass of inorganic residue remaining after incineration.

Crude fiber: Crude fibre determination followed the method described by AOAC[18]. A 2.0 g portion of sample was digested in 100 mL of 0.255 N sulphuric acid

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under reflux conditions for 1 h. The resulting mixture was filtered through a 0.5 mm mesh sieve, and the retained residue was subjected to a second digestion in 100 mL of 0.313 N sodium hydroxide for an additional hour. Following filtration, the residue was washed sequentially with acetone and hot water to remove residual soluble materials. The cleaned residue was transferred to a pre-weighed crucible and dried overnight at 105 °C. After recording the dried weight, the material was ashed at 550 °C for 4 h in a muffle furnace. The crucible was cooled in a desiccator and weighed again. Crude fibre content was estimated from the reduction in mass resulting from the ashing step[18].

Protein Content: Total protein was determined by the Kjeldahl technique[18]. Dried plantain powder (2.0 g) was digested with 25.0 mL concentrated sulphuric acid in the presence of selenium tablets (1.0 g) and 0.1 g copper sulphate, which served as digestion catalysts. Heating continued until a clear green digest was obtained. After cooling for 30 min, the digest was quantitatively transferred into a 100 mL volumetric flask and diluted to the calibration mark with distilled water. An aliquot of the prepared digest was subsequently introduced into the distillation apparatus, followed by the addition of 20.0 mL sodium hydroxide solution. Ammonia released during distillation was captured in a receiving solution containing 10.0 mL boric acid mixed with indicator. The collected distillate was titrated with 0.1 M hydrochloric acid, and titres obtained from replicate analyses were recorded. Protein concentration was calculated from the measured nitrogen content using the appropriate Kjeldahl conversion factor.

$$\% \text{ Protein } = (\% \text{ Total Nitrogen}) \times 6.25 \quad \ldots\ldots\ldots\ldots\ldots\ldots (1)$$

Carbohydrate Levels: The carbohydrate content was calculated indirectly using the following formula:

$$\% \text{ Total Carbohydrate } = [100 - \% (\text{Protein } + \text{ Fat } + \text{ Moisture } + \text{ Ash } + \text{ Fiber})] \ldots. (2)$$

Vitamin Profile: The vitamin content of the respective samples was determined using a combination of titrimetric and spectrophotometric methods. Quantification was performed using the following equation:

$$\text{VConc.} \left({}^{\text{mg}}/_{100\text{g}}\right) = \left({}^{\text{Asample}}/_{\text{Astadard}}\right) \text{x C standard x} \left({}^{\text{Valiquot}}/_{\text{Vtotal} - \text{filt}}\right) \text{xMref} \quad \ldots\ldots\ldots\ldots (3)$$

Where:

$V_{Conc.}$ = Final concentration of the specific vitamin in milligrams per 100.0 grams of sample.

M_{ref} = Mass of reference material subjected to analysis.

A_{sample} = Absorbance reading obtained from the analytical sample.

$A_{standard}$ = Absorbance reading of the full-strength reference standard.

$V_{total\text{-}filt}$ = Total volume of the generated filtrate.

$V_{aliquot}$ = Volume of the filtrate aliquot analyzed.

$C_{stanard}$ = Concentration on the standard solution employed.

D_f = Factor accounting for any dilution applied.

Quantification β-Carotene: The β-carotene content of the samples was evaluated according to the procedure described by Prieto *et al.*[19]. A standard β-carotene stock solution (Sigma) was prepared in water-saturated n-butanol (WSB), which consisted of n-butanol and purified water mixed in an 8:2 proportion. Working standards covering the required concentration range were obtained by serial dilution of the stock solution in 10.0 mL volumetric flasks and used to establish the calibration relationship. For extraction, 10.0 g of flour was combined with 100.0 mL WSB in a 250 mL beaker and mixed thoroughly for 5 min. The suspension was subsequently maintained at room temperature for 16 – 18 h before a second agitation step lasting 10 min. Following filtration through Whatman No. 1 filter paper, the extract was collected in a 100 mL volumetric flask. Spectrophotometric measurements were obtained at 440 nm using WSB as the reference blank. Sample concentrations were interpolated from the calibration curve and reported as μg/g (ppm).

Quantification of vitamin B1: Thiamine content was determined by spectrophotometric analysis. Each sample (5.0 g) was homogenised in 50.0 mL ethanolic sodium hydroxide solution and subsequently filtered into a 100 mL volumetric flask. A 10.0 mL portion of the clear extract was transferred into a reaction vessel and treated with an equal volume of potassium dichromate solution. The intensity of the colour formed was quantified spectrophotometrically. Calibration standards were prepared from a 100 mg/L thiamine stock solution by successive two-fold dilutions (1:2, 1:4, 1:8 and 1:16). Aliquots of 10.0 mL from each standard solution were processed under identical conditions to generate the calibration curve[20].

Determination of vitamin B2

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Riboflavin was extracted from 5.0 g of sample using 100.0 mL of 50.0% ethanol for 1 h. The extract was filtered, and a 10.0 mL aliquot was reacted with 10.0 mL of 5.0% potassium permanganate and 10.0 mL of 30.0% hydrogen peroxide. The reaction mixture was maintained in a steam bath for 30 min before the addition of 2.0 mL sodium sulphate solution. After adjusting the final volume to 5.0 mL with deionised water, absorbance was recorded at 510 nm. Standardisation was achieved using a 100 µg/mL riboflavin stock solution serially diluted in two-fold steps (1:2, 1:4, 1:8 and 1:16). Each standard was subjected to the same analytical sequence as the samples.

Determination of vitamin B3: Niacin analysis involved extraction of 5.0 g of sample with 50.0 mL of 1.0 N sulphuric acid under continuous shaking for 30 min. Immediately afterwards, three drops of ammonia solution were introduced, and the mixture was further agitated before filtration into a 50 mL volumetric flask. Colour development was achieved through the addition of 5.0 mL potassium ferrocyanide solution followed by 5.0 mL of 0.02 N sulphuric acid. The absorbance of the resulting solution was measured at 470 nm. Quantification was based on a calibration curve prepared from a 100 mg/L niacin standard solution diluted successively in a 1:2 series (1:2, 1:4, 1:8 and 1:16). Standard solutions were analysed in the same manner as the samples.

Determination of Vitamin C: Ascorbic acid concentration was assessed by a redox titrimetric procedure employing standardised 2,6-dichlorophenolindophenol (DCIP). Approximately 5.0 g of powdered sample was dispersed in 50.0 mL deionised water and filtered. A 5.0 mL portion of the filtrate was transferred into a conical flask, followed by the addition of 1.0 mL chilled acidic reagent and 1.0 mL chloroform. Titration was carried out with DCIP solution until complete disappearance of colour signified the endpoint. The concentration of vitamin C was expressed as mg/L.

Elemental composition

Mineral analysis was performed according to AOAC procedures[17] using an atomic absorption spectrophotometer (Buck Scientific, USA). Briefly, 2.0 g of sample was reduced to ash by heating at 550 °C in a muffle furnace for 6 h. The ash residue was digested with 10.0 mL aqua regia (3:1 v/v HCl:HNO_3) and gently heated for 20 min to ensure dissolution of mineral constituents. After cooling, the digest was diluted with 100.0 mL distilled water and filtered. The resulting filtrate was collected in labelled containers and analysed for sodium, potassium, calcium, magnesium, phosphorus, iron, zinc and manganese. Mineral concentrations were reported in parts per million (ppm).

Total titratable acidity (TTA): The titratable acidity of the samples was evaluated following the method of Adi *et al* [25]. A 50.0 mL aliquot of the prepared filtrate was titrated against standardised 0.1 N sodium hydroxide solution using phenolphthalein as the endpoint indicator. Titrations were conducted in triplicate, and completion of the reaction was indicated by the persistence of a pale pink colour. The titre values obtained were used to calculate acidity and expressed as percentage citric acid equivalent according to the equation below:

$$\%\text{Titratable Acidity} = \frac{\text{VNaOH X NNaOH X EWacid x 100}}{\text{Msample x 10000}} \quad \ldots\ldots\ldots\ldots (4)$$

Where:

% TTA = Total Titratable Acidity, expressed as a percentage.

V_{NaOH} = Volume of sodium hydroxide solution consumed during titration (in mL).

N_{NaOH} = Normality of the NaOH solution (0.1 N).

EW_{acid} = Equivalent weight of citric acid (typically 0.064).

M_{sample} = Mass or volume of the plantain sample aliquot (in mL or g) utilised for the titration

Physicochemical parameters

Extraction of starch: Starch was isolated from artificially ripened plantain following the protocol of Bello-Pérez *et al.*[22] with minor modifications. The plantain tissue was first reduced into small fragments prior to immersion in a sodium sulphite solution (1.22 g/L) to inhibit enzymatic browning. The pre-treated material was then subjected to mechanical disintegration by low-speed blending for 2 min under a 1:1 (w/v) sample-to-solvent ratio. The resulting slurry was passed sequentially through U.S. standard sieves (60 and 100 mesh) until the filtrate appeared clear, ensuring removal of fibrous residues. The clarified suspension was subsequently centrifuged at 3000 × g for 30 min to sediment the starch fraction. The recovered starch pellet was dried in an oven at 60 °C for 2 h, after which it was pulverised using a mortar and pestle to obtain a fine powder. The final product was stored in sealed containers under ambient laboratory conditions until further analysis.

Swelling capacity and solubility: Swelling capacity and solubility were evaluated following the procedure of

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Konik-Rose *et al.*[23] with minor adjustments. Each sample (1.0 g) was dispersed in 50.0 mL of distilled water and transferred into centrifuge tubes for thermal treatment. The suspensions were maintained in a water bath at 60 – 95 °C for 30 min under continuous agitation to facilitate hydration. After heating, the 54 tubes were allowed to cool to ambient temperature before centrifugation at 3000 rpm for 15 min using a Hettich EBA 8S centrifuge (Germany). For solubility assessment, the supernatant was collected and subjected to drying at 105 °C for approximately 5 h to obtain the dissolved solids. Swelling capacity was determined gravimetrically from the mass of the hydrated sediment retained in the centrifuge tubes following separation.

$$Solubility\ \left(\frac{g}{100g}\right) = \frac{Msupernantant}{Minitial}\ x100$$ …….. (5)

Where:

$M_{initial}$ = Initial mass of the dry sample (in grams).

$M_{supernatant}$ = Mass of dry solids recovered from the supernatant (in grams)

The swelling capacity was determined using the subsequent equation:

$$Swelling\ capacity\ (g/g) = \frac{Mass\ of\ \ wet\ residue\ in\ grams}{Mass\ of\ dry\ residue\ in\ grams}\ x100$$ ……. (6)

Water Absorption Capacity (WAC)

Water absorption capacity (WAC) was evaluated following the procedure of Fontes *et al.*[24] with minor modifications. Each sample (1.0 g) was transferred into a 50.0 mL centrifuge tube and reconstituted with 40.0 mL of purified water. The suspension was maintained under continuous agitation for 1 h to allow complete hydration of the matrix. Separation was then achieved by centrifugation at 2200 rpm for 15 min. The supernatant was carefully discarded, and excess surface moisture associated with the sediment was removed using absorbent material. WAC was subsequently calculated gravimetrically and expressed as grams of water retained per 100 g of sample.

Oil Absorption Capacity (OAC): Oil absorption capacity was assessed following the method of Reddy *et al.*[25]. Each sample (1.0 g) was combined with 30.0 mL of fortified soybean oil and allowed to equilibrate at room temperature for 30 min to ensure adequate interaction between the matrix and lipid phase. The suspension was subsequently subjected to centrifugation at 2000 × g for 10 min to separate unbound oil. Oil absorption capacity was then calculated gravimetrically and expressed as grams of oil retained per gram of sample.

Statistical Analysis: All analytical determinations were carried out under identical experimental conditions across all plantain samples, irrespective of ripening treatment, to ensure comparability. Data was analysed using analysis of variance (ANOVA) in IBM SPSS Statistics (Version 22.0). Duncan's New Multiple Range Test (DMRT) was used to determine significant differences at $p < 0.05$. Results are presented as mean ± standard deviation of three independent determinations.

RESULTS

Proximate Analysis of Artificially Ripened Plantain

The proximate composition of plantains subjected to different ripening treatments is presented in Table 1. Moisture content was highest in calcium carbide-treated samples (68.85 – 69.02%), followed by wood ash-treated samples (67.01 – 67.83%), and lowest in naturally ripened plantains (64.99 – 65.42%). Ash content was greatest in wood ash-treated samples (3.59 – 3.65%), intermediate in naturally ripened samples (3.33 – 3.36%), and lowest in calcium carbide-treated samples (3.14 – 3.19%). Crude fibre content was slightly higher in wood ash-treated plantains than in calcium carbide-treated and naturally ripened samples. Fat content was lowest in wood ash-treated samples and marginally higher in calcium carbide-treated samples. Protein content was highest in naturally ripened plantains, intermediate in wood ash-treated samples, and lowest in calcium carbide-treated samples. Carbohydrate content followed a similar trend, with naturally ripened samples exhibiting the highest values, followed by wood ash-treated plantains, lowest in calcium carbide-treated sample

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Table 1: Proximate Composition of Artificial and Natural Ripened Plantain

Sample	Moisture (%)	Ash (%)	Crude fibre (%)	Fat (%)	Crude protein (%)	Carbohydrate (%)
Wood ash	67.42±0.41	3.62±0.03^{c}	1.83±0.03^{b}	2.50±0.07^{a}	2.80±0.05^{c}	21.85±0.45^{b}
Calcium carbide	68.94±0.09^{c}	3.17±0.02^{a}	2.22±0.04^{c}	3.21±0.11^{b}	1.99±0.04^{a}	20.49±0.13^{a}
Natural	65.21±0.22^{a}	3.35±0.20^{b}	1.72±0.03^{a}	2.37±0.40a	2.60±0.04^{b}	24.77±0.11^{c}

Results are reported as mean ± standard deviation of three replicates. Means within each column that do not share a common superscript letter (a–c) differ significantly at $p < 0.05$.

Biochemical Properties of Artificially Ripened Plantain

The biochemical properties of plantains subjected to different ripening treatments are presented in Table 2. Significant differences ($p < 0.05$) were observed in amylose content, amylopectin content and amylase activity among the treatments. Wood ash-treated plantains exhibited the highest amylose content (29.63%) and amylase activity (122.22 U/mL), with a corresponding amylopectin content of 70.37%. In contrast, calcium carbide-treated samples recorded the lowest amylose content (21.79%) and amylase activity (105.18 U/mL), but the highest amylopectin content (78.21%). Naturally ripened plantains showed intermediate values, with amylose and amylopectin contents of 27.13% and 72.88%, respectively, and an amylase activity of 115.00 U/mL.

Table 2: Biochemical Properties of Artificially Ripened Plantain

Samples	Amylose (%)	Amylopectin (%)	Amylase activity (U/mL)
Wood ash	29.63±0.96^{c}	70.37±0.96^{a}	122.22±1.27^{c}
Calcium carbide	21.79±0.59^{a}	78.21±0.59^{c}	105.18±0.66^{a}
Natural	27.13±0.54^{b}	72.88±0.54^{b}	115.00±0.50^{b}

Data is presented as mean ± standard deviation of three replicates. Within each column, means not sharing a common superscript letter (a–c) are significantly different at the 5% probability level ($p < 0.05$).

Ripening duration and shelf life of plantain under various treatments

Table 3 illustrates the effects of different ripening treatments on the ripening duration of plantain fruits. The results showed that plantains treated with calcium carbide ripened within three days, followed by those treated with wood ash, which ripened within four days. In contrast, the control samples required six days to reach the ripe stage. The findings further revealed that treatments which accelerated the ripening process were associated with a reduction in practical shelf life, suggesting that rapid ripening may hasten senescence and subsequent deterioration of fruit quality.

Table 3: Ripening duration of different plantain sample treatments

Ripening Treatments	Ripening Treatments (Days)	Shelf life (Days)
Wood ash	4	9
Calcium carbide	3	6
Natural (Control)	6	13

Vitamins and total titratable acidity concentrations of ripened plantain samples

Table 4 summarises the nutrient composition and total titratable acidity (TTA) of plantains subjected to different ripening treatments. Naturally ripened plantains exhibited the highest vitamin A, vitamin B_2 and vitamin E contents, with values of 1.00 ± 0.01, 0.40 ± 0.01 and 4.20 ± 0.20 mg/100 g, respectively. Plantains treated with wood ash recorded the highest

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vitamin B_1 content (0.40 ± 0.11 mg/100 g), comparable to that of naturally ripened samples (0.40 ± 0.02 mg/100 g), and exhibited the highest L-ascorbic acid content (6.90 ± 0.82 mg/100 g). Calcium carbide-treated samples generally showed lower vitamin concentrations, including the lowest vitamin A (0.80 ± 0.02 mg/100 g), vitamin B_1 (0.20 ± 0.10 mg/100 g), and vitamin E (2.20 ± 1.02 mg/100 g) contents. Vitamin B_3 content was similar in wood ash-treated and naturally ripened samples (1.60 ± 0.22 and 1.60 ± 0.33 mg/100 g, respectively) but slightly lower in calcium carbide-treated samples (1.50 ± 0.12 mg/100 g). Total titratable acidity ranged from 0.30 ± 0.011 to 0.80 ± 0.09 mg/100 g across the treatments, with the lowest value observed in naturally ripened plantains and the highest value recorded in wood ash-treated samples.

Table 4: Vitamin and titratable acidity composition of plantain samples (mg/100g)

Vitamin	Method of ripening		
	Wood ash	**Calcium carbide**	**Natural**
A	0.90 ± 0.02	0.80 ± 0.02	1.00 ± 0.01
B1	0.40± 0.11	0.20± 0.10	0.40± 0.02
B2	0.30± 0.02	0.30± 0.01	0.40± 0.01
B3	1.60± 0.22	1.50± 0.12	1.60± 0.33
E	4.00± 0.02	2.20± 1.02	4.20± 0.20
L-ascorbic acid	6.90± 0.82	6.40± 0.99	6.70± 1.09
Titrable acidity	0.80± 0.09	0.60± 0.10	0.30± 0.011

Elemental composition of ripened plantain samples

Table 5 presents the mineral composition of plantain samples subjected to different ripening treatments. Calcium carbide-treated samples recorded the highest concentrations of sodium (206.55 ± 1.03 mg/100 g) and phosphorus (174.57 ± 0.01 mg/100 g). In contrast, naturally ripened samples exhibited the highest concentrations of potassium, magnesium, iron and zinc, with values of 195.40 ± 0.20, 184.60 ± 0.30, 13.84 ± 0.12 and 9.10 ± 0.18 mg/100 g, respectively. Wood ash-treated samples recorded the highest calcium (88.64 ± 0.48 mg/100 g) and manganese (10.00 ± 0.15 mg/100 g) contents, while also exhibiting the lowest sodium concentration (109.27 ± 0.29 mg/100 g). Calcium carbide-treated samples showed the lowest concentrations of magnesium (102.23 ± 0.11 mg/100 g), iron (4.54 ± 0.001 mg/100 g), zinc (5.95 ± 0.41 mg/100 g) and manganese (3.42 ± 0.22 mg/100 g), whereas naturally ripened samples recorded the lowest calcium content (84.18 ± 1.00 mg/100 g).

Table 5: Elemental composition of plantain samples (mg/100g)

Element	Method of ripening		
	Wood ash	**Calcium carbide**	**Natural**
Na	109.27 ± 0.29	206.55 ± 1.03	121.00 ± 0.30
K	153.50 ± 0.20	132.61 ± 0.32	195.40 ± 0.2
Ca	88.64 ± 0.48	86.20 ± 0.35	84.18 ± 1.00
Mg	165.40 ± 0.22	102.23 ± 0.11	184.60 ± 0.30
P	148.30 ± 0.45	174.57 ± 0.01	156.20 ± 0.50
Fe	9.10 ± 0.08	4.54 ± 0.001	13.84 ± 0.12
Zn	8.30 ± 0.20	5.95 ± 0.41	9.10 ± 0.18
Mn	10 ± 0.15	3.42 ± 0.22	3.00 ± 0.11

Physiochemical composition of artificially ripened plantain

Table 6 summarises the physicochemical properties of plantains subjected to different ripening treatments. Starch content was highest in wood ash-ripened samples (71.81 ± 0.31%), followed by naturally ripened (68.62 ± 0.69%) and calcium carbide-ripened samples (64.43 ± 1.42%). Water absorption capacity was greatest in wood ash-ripened plantains (177.75 ± 0.81 mg/mL), with lower values recorded in naturally ripened (171.59 ± 0.73 mg/mL) and calcium carbide-ripened samples (164.73 ± 0.87 mg/mL). Oil absorption capacity was highest in naturally ripened plantains (135.35 ± 0.76), followed by wood ash-ripened samples (129.59 ± 0.63), and lowest in calcium carbide-ripened samples (125.95 ± 0.26).

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Reducing sugar content was highest in naturally ripened plantains (9.99 ± 0.54), followed by wood ash-ripened (9.00 ± 0.24) and calcium carbide-ripened samples (6.28 ± 0.31).

Table 6: Physicochemical composition of artificially ripened plantain

Ripening Agent	Starch content (%)	Water absorption capacity (%)	Oil absorption capacity (%)	Reducing sugar (mg/mL)
Wood ash	71.81±0.31^{c}	177.75±0.81^{c}	129.59±0.63^{b}	9.00±0.24b
Calcium carbide	64.43±1.42^{a}	164.73±0.87^{a}	125.95±0.26^{a}	6.28±0.31^{a}
Natural	68.62±0.69^{b}	171.59±0.73^{b}	135.35±0.76^{c}	9.99±0.54^{c}

Data are expressed as mean ± standard deviation of three independent replicates. Within each column, different superscript letters (a–c) denote statistically significant differences at $p < 0.05$.

Solubility of artificially ripened plantain

Table 7 presents the solubility (%) of plantain samples subjected to different ripening treatments under controlled temperature conditions. At 30°C, calcium carbide-ripened samples exhibited the lowest solubility (0.43 ± 0.02%), compared with wood ash-ripened (0.53 ± 0.03%) and naturally ripened samples (0.51 ± 0.02%). At 50°C, solubility remained lowest in calcium carbide-ripened samples (1.58 ± 0.02%), while higher values were recorded in wood ash-ripened (1.92 ± 0.07%) and naturally ripened samples (1.82 ± 0.04%). Across 60–70°C, calcium carbide-ripened plantains consistently showed lower solubility than the other treatments, with wood ash-ripened samples exhibiting the highest values. At 80°C, wood ash-ripened samples recorded the highest solubility (6.52 ± 0.20%), followed by calcium carbide-ripened samples (5.80 ± 0.19%), while naturally ripened samples showed the lowest values (5.56 ± 0.32%). At 90°C, solubility increased markedly in all samples, with the highest values recorded in wood ash-ripened (13.44 ± 0.04%) and naturally ripened samples (12.40 ± 0.36%), while calcium carbide-ripened samples remained the least soluble (11.43 ± 0.41%).

Table 7: Solubility (%) of artificially ripened plantain

Ripening Agent	Temperature (°C)					
	30	**50**	**60**	**70**	**80**	**90**
Wood ash	0.53±0.03^{b}	1.92±0.07^{c}	3.64±0.15^{b}	4.72±0.24^{b}	6.52±0.20^{b}	13.44±0.04^{c}
Calcium Carbide	0.43±0.02^{a}	1.58±0.02^{a}	3.18±0.15^{a}	3.54±0.10^{a}	5.80±0.19^{a}	11.43±0.41^{a}
Natural	0.51±0.02^{b}	1.82±0.04^{b}	3.58±0.06^{b}	4.48±0.16^{b}	5.56±0.32^{a}	12.40±0.36^{b}

Results are presented as mean ± standard deviation of three replicates. Within each column, means assigned different superscript letters (a–c) differ significantly at $p < 0.05$.

Swelling capacity of artificially ripened plantain

Table 8 presents the swelling capacity of plantains subjected to different ripening treatments across a range of temperatures. At 30°C, wood ash-ripened samples exhibited a swelling capacity of 1.59 ± 0.09, compared with 1.29 ± 0.03 in calcium carbide-ripened samples and 1.48 ± 0.03 in naturally ripened samples. At 50°C, swelling capacity increased in all treatments, with the highest value recorded in wood ash-ripened plantains (3.63 ± 0.25), followed by naturally ripened (3.23 ± 0.04) and calcium carbide-ripened samples (2.91 ± 0.05). Across 60–80°C, wood ash-ripened samples consistently showed the highest swelling capacity, while calcium carbide-ripened samples remained lower and naturally ripened samples recorded intermediate values. At 90°C, swelling capacity reached maximum values in all treatments, with wood ash-ripened samples again highest (15.33 ± 0.32), followed by naturally ripened (14.24 ± 0.28) and calcium carbide-ripened samples (12.83 ± 0.16).

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Table 8: Swelling capacity of artificially ripened plantain at different temperatures

Ripening Agent	Temperature (°C)					
	30	50	60	70	80	90
Wood ash	1.59±0.09[b]	3.63±0.25[c]	6.43±0.12[b]	8.17±0.28[c]	9.51±0.28[b]	15.33±0.32[c]
Calcium Carbide	1.29±0.03[a]	2.91±0.05[a]	5.60±0.28[a]	7.00±0.13[a]	8.33±0.30[a]	12.83±0.16[a]
Natural	1.48±0.03[b]	3.23±0.04[b]	6.27±0.15[b]	7.60±0.28[b]	9.12±0.14[b]	14.24±0.28[b]

Data are expressed as mean ± standard deviation based on three independent replicates. Within each column, values carrying different superscript letters are significantly different at $p < 0.05$.

DISCUSSION

Moisture content is a key determinant of postharvest stability and microbial susceptibility in plantain. Naturally ripened samples exhibited lower moisture content (64.99 – 65.42%), which may be associated with progressive water loss through respiration and transpiration during physiological ripening of climacteric fruits.[1,21] In contrast, calcium carbide-treated samples showed higher moisture content (68.85 – 69.02%), consistent with evidence that artificial ripening can disrupt normal dehydration processes and accelerate postharvest deterioration.[4,12] From a public health perspective, increased moisture content creates a more favourable environment for microbial proliferation, particularly spoilage organisms and potential foodborne pathogens, thereby increasing the risk of gastrointestinal infections in consumers.[5,6]

Differences in ash content, particularly the higher values in wood ash-treated plantains, may reflect altered mineral dynamics or alkaline effects associated with wood ash application.[26] However, such variations may also arise from postharvest chemical interactions rather than true nutritional enhancement.[26] While ash is often interpreted as a proxy for mineral content, artificial increases do not necessarily translate to bioavailable nutrients and may instead reflect contamination or surface deposition, raising concerns regarding potential ingestion of non-nutritive residues. Crude protein and fibre contents remained generally low across all samples, consistent with plantain being primarily an energy-dense carbohydrate food rather than a significant protein source.[27] The marginal variations observed across treatments are unlikely to be nutritionally meaningful; however, from a dietary perspective, this reinforces the limitation of plantain as a sole protein source, particularly in populations with low dietary diversity, potentially contributing to protein-energy malnutrition when not complemented with other foods.

Carbohydrates were the predominant macronutrient, particularly in naturally ripened plantains (24.77 ± 0.11%), reinforcing their role as a major dietary energy source.[3] Fat content remained low across treatments, in line with established profiles of *Musa paradisiaca*.[19] While this low fat content is generally favourable for cardiovascular health, excessive reliance on carbohydrate-dense staples without dietary balance may contribute to postprandial glycaemic burden, especially in individuals at risk of insulin resistance or type 2 diabetes. Variations in starch composition, particularly amylose content, suggest that ripening treatments influence starch degradation pathways during ripening.[14,20] Higher amylose levels in wood ash-treated samples may indicate slower starch hydrolysis compared with chemically ripened fruits.[12,28] From a nutritional standpoint, higher amylose is associated with lower glycaemic response and improved glycaemic control, suggesting that certain ripening methods may indirectly influence metabolic health outcomes.

Increased amylase activity in calcium carbide-treated plantains reflects accelerated starch breakdown, likely associated with acetylene-mediated ethylene-like effects.[12] Although this accelerates ripening and improves short-term market availability, rapid enzymatic degradation may reduce structural carbohydrate integrity, potentially increase the glycaemic index of the fruit and posing concerns for individuals with diabetes or impaired glucose tolerance. Calcium carbide treatment markedly reduced ripening time, confirming its role as a rapid ripening agent through acetylene release, which mimics ethylene action in climacteric fruits.[12] However, while economically advantageous, this accelerated process may compromise biochemical stability, resulting in faster senescence and reduced shelf life, thereby increasing the likelihood of spoilage-related food losses and indirect public health risks through consumption of deteriorated produce.

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A notable finding is the reduction in vitamins A and C in calcium carbide-treated samples. Ascorbic acid is essential for antioxidant defence, immune function, and collagen synthesis; its depletion may therefore reduce dietary antioxidant intake and compromise immune resilience, particularly in vulnerable populations such as children and the elderly.[8],[29] Similarly, reduced vitamin A levels may contribute to increased risk of night blindness, impaired immune response, and higher susceptibility to infectious diseases in populations relying heavily on plantain as a staple food.[8] In contrast, naturally ripened samples retained higher levels of B vitamins and tocopherols, which support metabolic function, neurological health, and oxidative stress protection,[30] thereby offering superior nutritional quality.

Increased titratable acidity in calcium carbide-treated samples may reflect altered metabolic activity during forced ripening. From a health perspective, although moderate acidity is not harmful, chronically consuming highly acidic diets may contribute to dental enamel erosion and gastrointestinal discomfort in sensitive individuals, particularly when combined with other acidic dietary components.[8]

Elemental analysis showed increased sodium and phosphorus in carbide-treated samples, which may be linked to contamination from impurities in commercial carbide. [31] Excess sodium intake is strongly associated with elevated blood pressure and increased risk of hypertension and cardiovascular diseases. [32] This is particularly concerning in populations already consuming high-sodium processed foods. Additionally, an imbalanced sodium-to-potassium ratio may further exacerbate cardiovascular risk by impairing electrolyte and vascular regulation.[32] Although magnesium levels remained relatively stable, fluctuations in potassium, sodium, and phosphorus could disrupt electrolyte homeostasis, with potential implications for blood pressure control and cardiovascular health.

Functional properties, including water absorption, oil absorption, solubility, and swelling capacity, were influenced by ripening method and temperature. Wood ash-treated samples generally showed higher starch-related functional properties, suggesting greater retention of structural polysaccharides.[14],[21] From a nutritional physiology perspective, these properties may influence digestion rate, satiety, and postprandial glucose response, potentially contributing to improved glycaemic control and reduced overeating.[33] In contrast, calcium carbide-treated samples showed reduced functional properties,[12],[20] indicating more extensive starch degradation, which may lead to faster digestion and higher glycaemic load.[33],[34]

Higher oil absorption capacity may increase caloric density during food preparation, [34] which, if consumed frequently, could contribute to excess energy intake and weight gain, particularly when plantain is deep-fried or prepared with added fats. Reduced sugar content in calcium carbide-treated samples may negatively affect sensory quality and consumer acceptability, potentially driving the addition of sugar or fat during preparation, thereby indirectly increasing dietary health risks.[4]

Overall, the findings suggest that calcium carbide-mediated ripening alters multiple biochemical and physicochemical properties of plantain in ways that extend beyond postharvest quality to potential public health implications. These include increased microbial susceptibility due to higher moisture content, reduced micronutrient density (particularly vitamins A and C), possible exposure to sodium-related cardiovascular risks, and altered starch metabolism that may influence glycaemic response. Collectively, these changes may contribute to increased risk of foodborne illness, micronutrient deficiencies, and diet-related non-communicable diseases in populations with high dependence on plantain as a staple food. In contrast, natural ripening and wood ash treatment appear to better preserve nutritional integrity and functional quality, supporting safer consumption and more favourable health outcomes.

CONCLUSION

This study demonstrated that the method of ripening significantly influences the nutritional, biochemical, functional, and safety characteristics of plantain (*Musa paradisiaca*). Artificial ripening with calcium carbide accelerated the ripening process but adversely affected several quality attributes, including vitamin retention, mineral balance, functional properties, and shelf life. In contrast, plantains ripened naturally or with wood ash generally retained better nutritional quality and exhibited more desirable functional characteristics. The findings indicate that although calcium carbide is effective in hastening ripening, its use may compromise the nutritional value and overall quality of plantains, with potential implications for consumer health and food safety. Therefore, natural ripening and the use of wood ash may be considered safer and more suitable

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alternatives for preserving the nutritional integrity of plantains. These results highlight the need to discourage the indiscriminate use of calcium carbide in fruit ripening and to promote safer ripening practices that support public health and food quality.

Declarations

Authors' contribution: Joseph Akor: Conceived the study, designed the research, supervised the project, contributed to data interpretation, and critically reviewed and edited the manuscript.
Nwamaka Maureen Odu: Conceived the study, developed the methodology, performed the formal data analysis, interpreted the findings, prepared the original manuscript draft, coordinated manuscript revisions as the corresponding author, and approved the final manuscript.
Mary Uchenna Ogunsanya: Conducted laboratory analyses, participated in data interpretation, and reviewed the manuscript.
Nasiru Shako Ahmad: Conducted laboratory analyses, validated the findings, and reviewed the manuscript.
Maryam Umar: Assisted with laboratory analyses, data validation, and manuscript review.
Halimatu Sa'adiya Isah: Participated in laboratory analyses, literature review, and manuscript review.
Lebechi Faith Akor: Collected and curated the research data, maintained study records, and assisted with data organisation.
Olatunji Yussuf Adedokun: Contributed to the study methodology, provided scientific supervision, and critically reviewed and edited the manuscript.
Vivian Ifeoma Okonkwo: Coordinated research activities, contributed to data interpretation, and reviewed the manuscript.
Marygloria Oluchukwu Ugwuja: Assisted with literature review, validated the results, and reviewed the manuscript.
All authors read and approved the final version of the manuscript.

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