Retraction Notice

Title of retracted article: **Efficacy of Ethylene and Heat Treatment on the Physico-Chemical Properties and Storability of Two Banana (*Musa spp.*) Cultivars**

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Journal:	Agricultural Sciences (AS)
Year:	2025
Volume:	16
Number:	11
Pages (from - to):	1162 - 1181
DOI (to PDF):	https://doi.org/10.4236/as.2025.1611067
Paper ID at SCIRP:	147189
Article page:	https://www.scirp.org/journal/paperinformation?paperid=147189
Retraction date:	2026-5-20

Retraction initiative (multiple responses allowed; mark with **X**):
☐ All authors
☐ Some of the authors:
☐ Editor with hints from
X Journal owner (publisher)
Institution:
X Reader:
Other:
Date initiative is launched: 2026-5-19

Retraction type (multiple responses allowed):
☐ Unreliable findings
Lab error Inconsistent data Analytical error Biased interpretation
Other:
☐ Irreproducible results
☐ Failure to disclose a major competing interest likely to influence interpretations or recommendations
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X Plagiarism ☐ Self plagiarism **X** Overlap ☐ Redundant publication *
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☐ are still valid.
X were found to be overall invalid.

Author's conduct (only one response allowed):
☐ honest error
X academic misconduct
☐ none (not applicable in this case – e.g. in case of editorial reasons)

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History
Expression of Concern:
X yes, date: 2025-5-19
☐ no

Correction:
☐ yes, date: yyyy-mm-dd
X no

Comment:

This article has been retracted to straighten the academic record. In making this decision the Editorial Board follows COPE's Retraction Guidelines. Aim is to promote the circulation of scientific research by offering an ideal research publication platform with due consideration of internationally accepted standards on publication ethics. The Editorial Board would like to extend its sincere apologies for any inconvenience this retraction may have caused.

Editor guiding this retraction: Prof. Daniele De Wrachien (EiC of AS)

Agricultural Sciences, 2025, 16(11), 1162-1181
https://www.scirp.org/journal/as
ISSN Online: 2156-8561
ISSN Print: 2156-8553

Efficacy of Ethylene and Heat Treatment on the Physico-Chemical Properties and Storability of Two Banana (*Musa* spp.) Cultivars

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How to cite this paper: Gony, O., Hossen, M.I., Rahman, M.M., Rahman, A. and Rahman, A. (2025) Efficacy of Ethylene and Heat Treatment on the Physico-Chemical Properties and Storability of Two Banana (*Musa* spp.) Cultivars. *Agricultural Sciences*, **16**, 1162-1181.
https://doi.org/10.4236/as.2025.1611067

Received: September 25, 2025
Accepted: November 10, 2025
Published: November 13, 2025

Abstract

This study examined the efficacy of post-harvest treatments, specifically the application of ethephon (25 - 150 ppm) and exposure to heat generated by smouldering rice husk (12 - 30 hours), on the physicochemical quality and storability of two prominent banana cultivars, Amritasagar and Sabri. Quality parameters, including pulp-to-peel ratio, total soluble solids (TSS), sugar content, titratable acidity (TA), physiological weight loss (PLW), moisture content, and shelf life, were quantitatively assessed at two-day intervals throughout the storage period. The highest post-ripening values for key consumer attributes were achieved in a dose-dependent manner at the maximum intensity: 150 ppm ethephon resulted in a pulp-to-peel ratio of 5.25, total sugars of 23.50%, and TSS of 27.93 ˚Bx, while 30 hours of heat exposure produced comparable enhancements. Both methods significantly accelerated the ripening process and improved this primary quality metrics compared to the untreated controls. Notably, increased treatment intensity led to a concomitant reduction in post-harvest shelf life, decreasing from an average of 11 days (control) to approximately 7 - 8 days in the most intensely treated fruits. These findings confirm that controlled ethephon and non-chemical heat treatment are effective and practical post-harvest strategies to accelerate ripening and enhance banana quality metrics but require precise optimization to effectively balance the desired quality improvements against the resultant reduction in marketability period.

Keywords

Banana, Post-Harvest, Ripening, Ethylene, Heat Treatment

1. Introduction

Bananas (*Musa* spp.) are among the world's most economically important fruit crops, ranking fourth after rice, wheat, and maize [1] [2]. Global banana production reached approximately 139 million metric tons in 2023, with leading producers including India, China, Ecuador, and Brazil contributing substantially to international trade [3]. In Bangladesh, bananas dominate fruit production, accounting for nearly 20% of total fruit production and covering 36% of the cultivation area, with about 840,000 tons produced in 2023 [4]. This substantial output solidifies its position as the third most produced fruit crop in the nation (Munia *et al.*, 2020).

Due to their climacteric nature, bananas undergo rapid post-harvest ripening, which often leads to quality deterioration such as excessive softening, uneven coloration, and substantial weight loss [5]. These factors contribute to high post-harvest losses, estimated between 20% - 50%, primarily due to poor handling and quality degradation [6]. To mitigate these losses, artificial ripening agents such as calcium carbide, ethylene gas, commonly employed. However, these substances pose serious health and environmental risks, including toxicity and potential organ damage [7].

Alternatively, safer post-harvest approaches show promise but are still limited in adoption. Ethylene, classified as non-carcinogenic by the International Agency for Research on Cancer with a maximum daily intake limit of 0.05 mg/kg body weight, requires careful management due to its flammability at high concentrations [8]. Smoke treatments, though considered relatively safe, may generate harmful carbon monoxide and tend to be crude and inconsistent. Heat treatments using rice husks and wood materials lack standardization, leading to uneven ripening [9].

Among promising non-toxic alternatives, ethephon spray a controlled ethylene-releasing agent and traditional heat treatments, such as smouldering rice husk exposure, have emerged as effective post-harvest interventions [10]. Ethephon promotes biochemical ripening processes, including increased sugar accumulation and pulp softening, while heat treatment offers pathogen control and modulates ripening-associated enzyme activities without chemical residues [11] [12].

Despite these advances, systematic studies evaluating ethephon spray and smouldering rice husk heat treatments on banana quality parameters including storability are particularly limited in Bangladesh. This study aims to fill this gap by comprehensively assessing the effects of these treatments on two prominent commercial cultivars, Amritasagar and Sabri. The research focuses on their impact on physicochemical properties, nutritional quality, and storability to develop optimized protocols that can reduce post-harvest losses and extend banana marketability, thereby supporting sustainable agriculture and food security. Additionally, this study compares the efficacy of these methods against traditional ripening agents, contributing to safer and more sustainable post-harvest management strategies for banana producers.

2. Materials and Methods

2.1. Plant Material and Experimental Site

The research was conducted in the laboratories of the Department of Horticulture and the Department of Molecular Biology at Bangladesh Agricultural University, Mymensingh. All experiments were conducted under ambient laboratory conditions, with a maintained temperature of 27˚C ± 2˚C and a relative humidity (RH) of 72% ± 3%. Freshly harvested, mature-green banana bunches (*Musa* spp.) from two commercial Bangladeshi cultivars, Amritasagar and Sabri, were sourced from a local grower in Mymensingh (**Figure 1(A)**, **Figure 1(B)**). The bunches were carefully transported to the laboratory to avoid any mechanical injury. For the experiments, individual banana fingers were selected based on uniform size, shape, and colour, and the absence of any physical blemishes or signs of disease.

Figure 1. (A) Amritasagar banana variety; (B) Sabri banana variety.

2.2. Experimental Design and Treatments

The study consisted of two separate experiments, each structured as a two-factor experiment laid out in a completely randomised design (CRD). Each treatment combination was replicated five times, with each replicate consisting of ten banana fingers. The two factors were cultivar (V1: "Sabri", V2: "Amritasagar") and post-harvest ripening treatment.

2.3. Ethylene Treatment

Banana fingers were treated with aqueous solutions of ethephon (42% active ingredient) to achieve the following final ethylene concentrations. The solutions were applied as fine sprays. The control (sprayed with distilled water) was designated as T1, and T2, T3, T4, T5, and T6 were treated with ethylene at concentrations of 25, 50, 75, 100, 125, and 150 ppm, respectively (**Table 1**).

Table 1. Preparation of ethylene solutions for treatment.

Treatment	Concentration (ppm)	Amount of Ethylene (ml)	Amount of distilled water (ml)
T0 (Control)	0	0.00	50.00
T1	25	4.13	45.87
T2	50	8.26	41.74

Continued

T3	75	12.40	37.60
T4	100	16.53	33.47
T5	125	20.67	29.33
T6	150	24.80	25.20

2.4. Heat Treatment

The banana fingers were subjected to heat treatment within a sealed chamber, where heat was generated using smouldering rice husks, simulating traditional ripening practices. The treatments varied in duration: T0 (control, no heat exposure), T1 (12 hours), T2 (18 hours), T3 (24 hours), and T4 (30 hours). Following treatment, all samples were placed on laboratory benches and stored under controlled conditions for the remainder of the study.

2.5. Data Collection and Physicochemical Analyses

Fruit quality parameters were evaluated at 2-day intervals (*i.e.*, on days 0, 2, 4, 6, and 8) after the application of the treatments. All chemical analyses were performed in triplicate.

2.6. Physical Parameters

Skin colour change: The progression of ripening was visually assessed by monitoring skin colour according to a 7-point standard colour chart (1 = evenly green; 7 = overripe with diffuse brown spots). Weight Loss (%): Physiological loss in weight (PLW) was calculated by recording the initial weight (IW) and final weight (Wf) of the fruits at each sampling interval. The percentage of weight loss was calculated using the following formula:

$$\text{Weight Loss}(\%) = \frac{\text{IW} - \text{Wf}}{\text{W}i} \times 100$$

Pulp to Peel Ratio: Fruits were manually peeled, and the weights of the Pulp (Wp) and weight of Peel (Wpeel) were recorded separately. The ratio was calculated as follows:

$$\text{Pulp to Peel Ratio} = \frac{\text{Weight of Pulp (Wp)}}{\text{Weight of Peel (Wpeel)}}$$

2.7. Chemical Analyses

Chemical analyses were conducted on homogenised pulp tissue using standard procedures outlined by Ranganna (1979), unless otherwise specified. Moisture and Dry Matter Content (%): A 10-g sample of Pulp was oven-dried at 80˚C until a constant weight was achieved. The moisture content was determined gravimetrically. The dry matter percentage was calculated as follows: Dry Matter (%) = 100 – Moisture content (%).

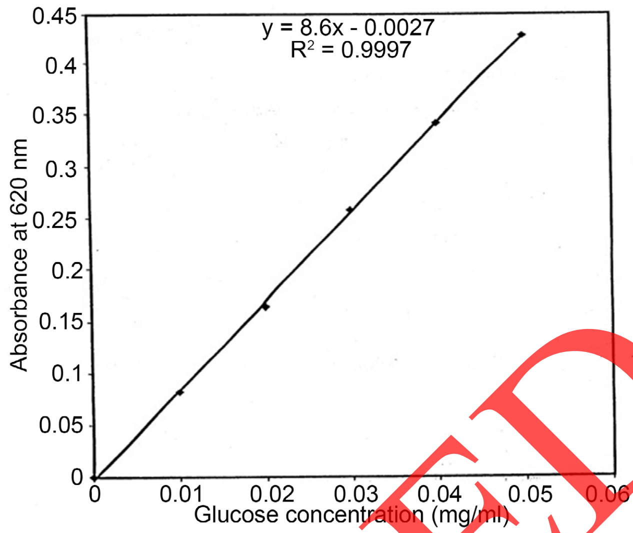

Figure 2. Standard curve of glucose for estimation of total sugar.

Total Soluble Solids (TSS): The TSS content was measured from fruit juice using a hand-held Abbe refractometer. The readings were expressed in degrees Brix (˚Bx), with corrections made for temperature (Figure 2).

Titratable Acidity (TA): Ten mL of fruit extract was titrated against a standardised 0.1 N NaOH solution using phenolphthalein as an indicator. TA was expressed as the percentage of malic acid content. Sugar Content (%): The total sugar content was determined spectrophotometrically at 620 nm using the anthrone method [13]. Reducing sugars were quantified at 575 nm using the dinitrosalicylic acid (DNS) method [14]. The non-reducing sugar content was calculated by subtracting the reducing sugar content from the total sugar content.

2.8. Ripening Time and Shelf Life

The shelf life was specifically defined as the number of days from treatment until the banana fruit became unmarketable or inedible. This determination was based on objective criteria including the visual appearance of peel browning and softening, corresponding to color stage 7 on a standardized 7-point peel color scale, as well as the onset of microbial decay [15]. These criteria provide clear, reproducible markers to assess the end of marketable quality (Figure 3).

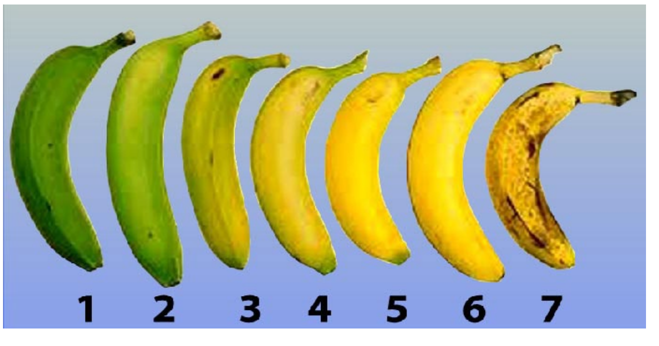

Figure 3. Standard colour chart for banana ripening.

2.9. Statistical Analysis

The collected data were subjected to Analysis of Variance (ANOVA) using the MSTAT-C statistical software package. Mean comparisons among treatments were performed using the Least Significant Difference (LSD) test at a 5% level of significance ($p \leq 0.05$) [16].

3. Results

3.1. Artificial Ripening of Banana by the Application of Ethylene and Heat Treatment

3.1.1. Total Weight Loss

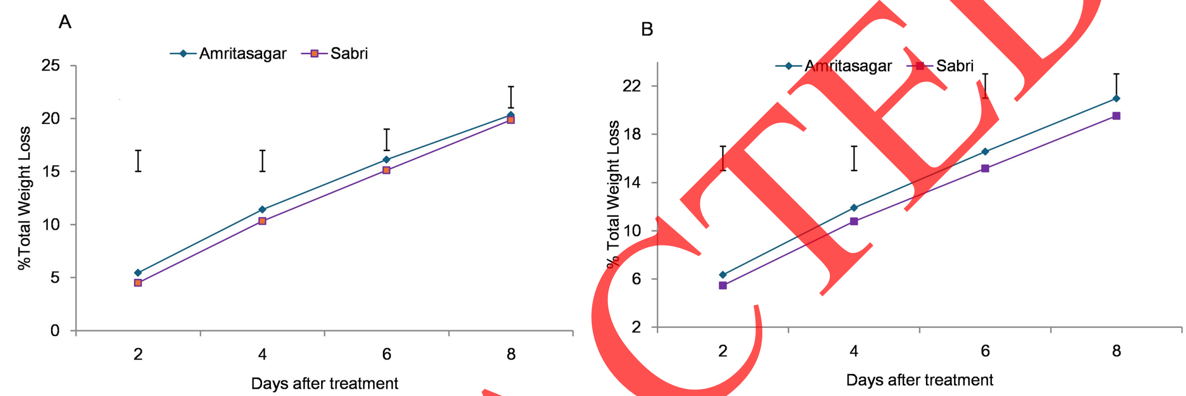

Figure 4. The effect of (A) ethylene and (B) heat on the percentage of weight loss in different banana varieties over time (DAT - Days After Treatment), with a least significant difference (LSD) of 1%.

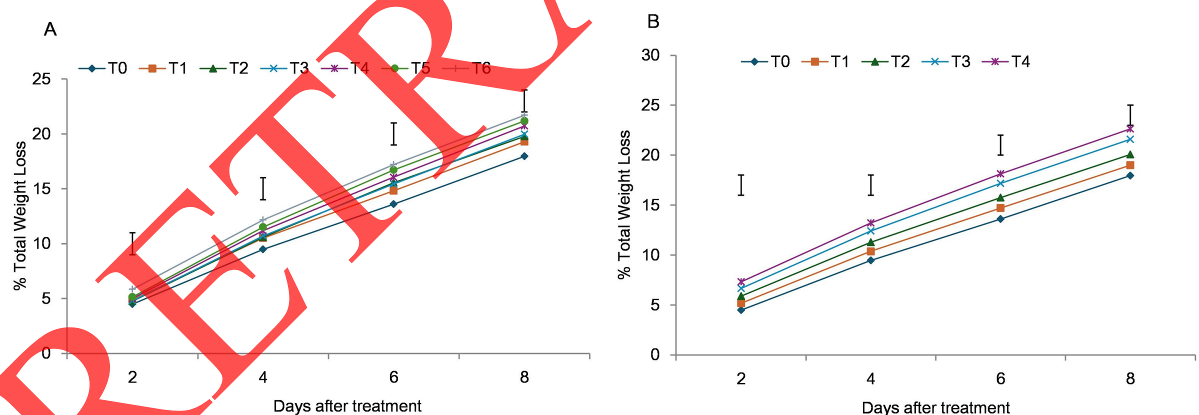

Figure 5. Effect of (A) ethylene and (B) heat treatments on the total weight loss of bananas over eight days. In (A), T0 is the control, and T1 - T6 represent ethylene treatments (25 - 150 ppm). In (B), T0 is the control, and T1 - T4 represents heat treatments (12 - 30 hours). Vertical bars indicate the Least Significant Difference (LSD) at a 1% level of significance.

The study revealed that total weight loss during banana storage was significantly influenced by variety, treatment type, and storage duration. The Amritasagar variety consistently exhibited higher weight losses compared to Sabri, with both varieties showing progressive weight loss, ranging from 4.51% to 5.64% at 2 days to 19.85% to 20.32% at 8 days post-treatment (**Figure 4(A)**). Ethylene treatments intensified weight loss, with maximum losses of 21.69% recorded at an ethylene concentration of 125 ppm after 8 days (**Figure 5(A)**). In contrast, heat treatments produced similar effects, with 30-hour heat exposure resulting in a 22.64% weight loss (**Figure 4(B)**). The highest combined weight loss (23.22% at 8 days) occurred in Amritasagar treated with 30-hour heat exposure, whereas untreated Sabri fruits maintained the lowest weight loss (17.21% at 8 days) (**Figure 5(B)**). Both ethylene concentration and heat exposure duration exhibited dose-dependent relationships with weight loss. In contrast, the untreated control fruits consistently demonstrated minimal weight loss across all time points, confirming that artificial ripening treatments accelerate moisture loss and overall fruit deterioration during storage.

3.1.2. Dry Matter Content

Dry matter content analysis revealed significant varietal differences and treatment effects, with Sabri consistently maintaining higher dry matter levels (38.96% - 32.97% from 2 - 8 days) compared to Amritasagar (34.19% - 28.12% from 2 - 8 days) throughout the storage period (**Figure 6(A)**). All treatments showed progressive decline in dry matter content over time, with control groups maintaining the highest levels (38.97% - 32.96% from 2 - 8 days), followed by low-dose treatments, while maximum ethylene concentration (150 ppm) resulted in the lowest dry matter content (34.07% - 27.82% from 2 - 8 days) (**Figure 7(A)**). The combined effect demonstrated that untreated Sabri achieved the highest dry matter retention (35.42% at 8 days), whereas Amritasagar treated with 150 ppm ethylene recorded the minimum (25.92% at 8 days). Heat treatments exhibited similar patterns, with the control maintaining the highest dry matter content and 30-hour heat exposure producing the lowest values (33.95% - 27.67% from 2 to 8 days) (**Figure 6(B)** and **Figure 7(B)**). These findings confirm that both ethylene concentration and heat exposure duration inversely correlate with dry matter retention, while varietal characteristics significantly influence moisture regulation during artificial ripening processes.

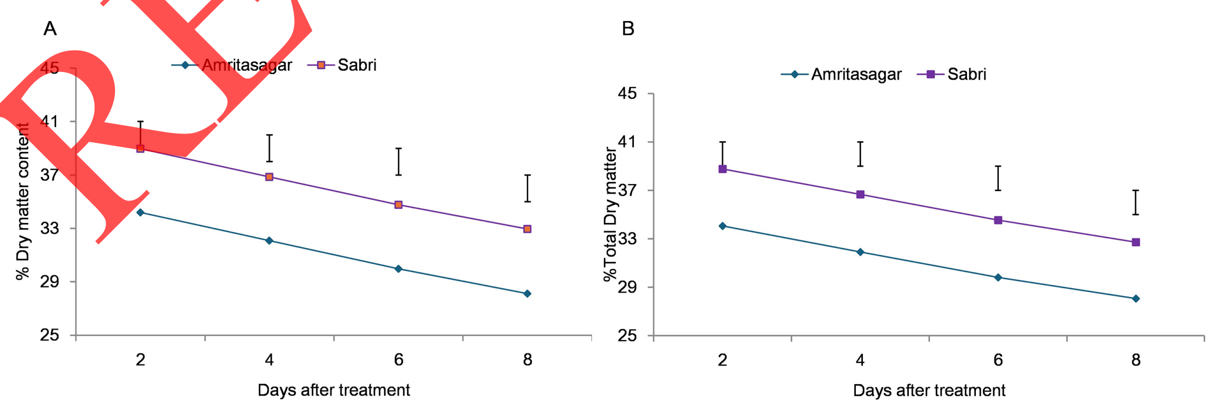

Figure 6. The effect of (A) ethylene and (B) heat on the percentage of dry matter content in different banana varieties over time (DAT - Days After Treatment), with a least significant difference (LSD) of 1%.

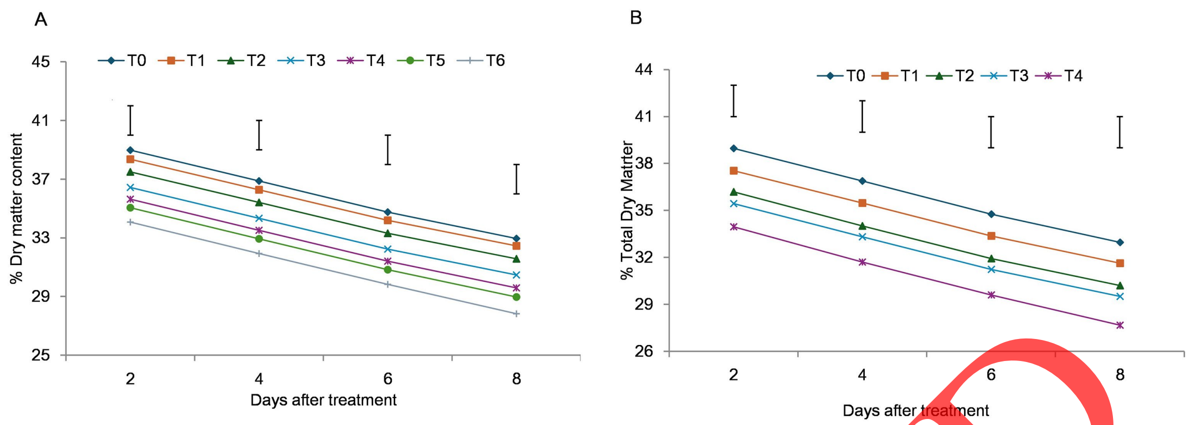

Figure 7. Effect of (A) ethylene and (B) heat treatments on the total dry matter content of bananas over eight days. In (A), T0 is the control, and T1 - T6 represent ethylene treatments (25 - 150 ppm). In (B), T0 is the control, and T1 - T4 represent heat treatments (12 - 30 hours). Vertical bars indicate the Least Significant Difference (LSD) at a 1% level of significance.

3.1.3. Moisture Content

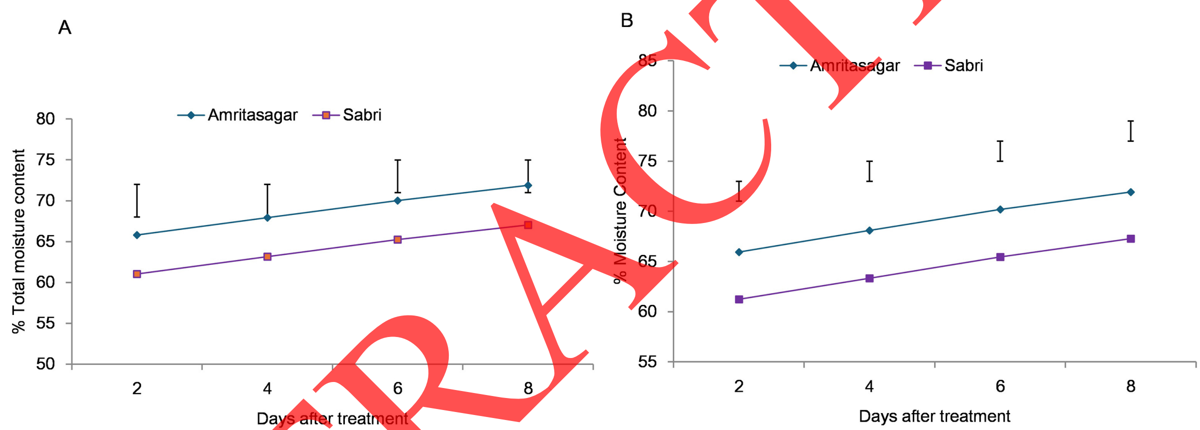

Figure 8. The effects of (A) ethylene and (B) heat on the percentage of moisture content in different banana varieties over time (DAT - Days After Treatment), with a least significant difference (LSD) of 1%.

Moisture content progressively increased in both treated and untreated banana fruits throughout the ripening period, with significant varietal and treatment differences observed. Amritasagar consistently exhibited higher moisture levels than Sabri, reaching 71.87% and 67.03%, respectively, at 8 days post-treatment, compared to 65.81% and 61.04% at 2 days (**Figure 8(A)**). Ethylene treatments dose-dependently increased moisture content, with maximum levels (65.93% - 72.18% from 2 - 8 days) recorded in 150 ppm ethylene treatment, while control fruits maintained minimum moisture content (61.03% - 67.07% from 2 - 8 days) (**Figure 9(A)**). The interaction effects demonstrated that Amritasagar treated with 150 ppm ethylene achieved the highest moisture content (67.86% - 74.08% from 2 to 8 days), whereas untreated Sabri recorded the lowest values (58.64% - 64.58% from 2 to 8 days). Heat treatments followed similar patterns, with a 30-hour exposure producing a maximum moisture content (72.33% at 8 days), and the control maintaining minimum levels (**Figure 8(B)** and **Figure 9(B)**). The combined heat and variety effects showed that Amritasagar, with a 30-hour heat treatment, reached peak moisture levels (68.14% - 74.09% from 2 to 8 days), while untreated Sabri remained at the lowest levels throughout storage.

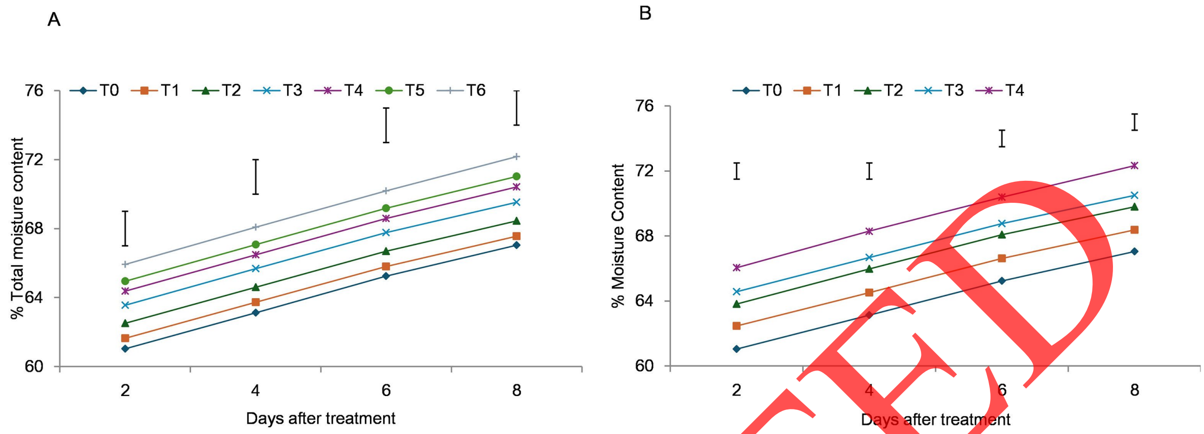

Figure 9. Effect of (A) ethylene and (B) heat treatments on the total moisture content of bananas over eight days. In (A), T0 is the control, and T1 - T6 represent ethylene treatments (25 - 150 ppm). In (B), T0 is the control, and T1 - T4 represent heat treatments (12 - 30 hours). Vertical bars indicate the Least Significant Difference (LSD) at a 1% level of significance.

3.1.4. Pulp to Peel Ratio

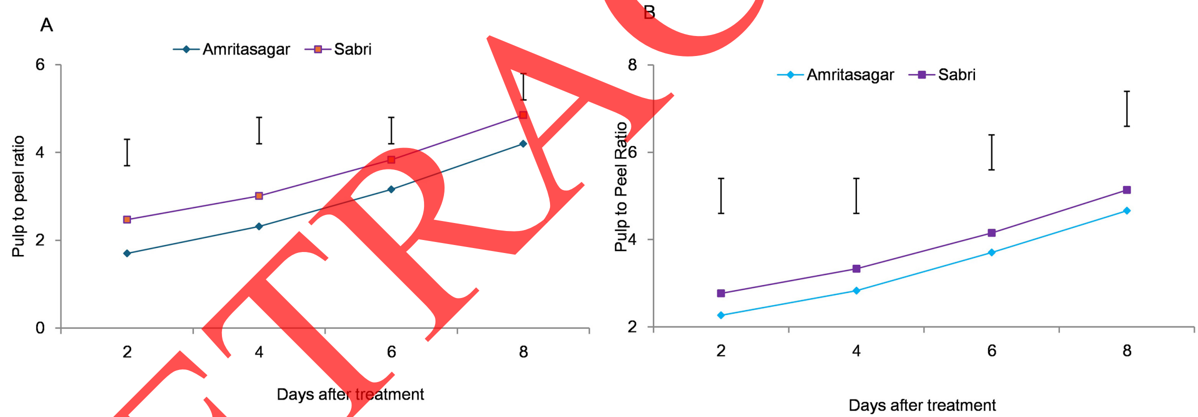

Figure 10. The effect of (A) ethylene and (B) heat on the percentage of Pulp to peel ratio in different banana varieties over time (DAT - Days After Treatment), with a least significant difference (LSD) of 1%.

Pulp to peel ratio progressively increased throughout the storage period in both treated and untreated banana fruits, with significant varietal differences consistently favouring Sabri over Amritasagar. During storage, Sabri showed an increase from 2.47 to 4.86, while Amritasagar increased from 1.70 to 4.20 (**Figure 10(A)**). Ethylene treatments enhanced pulp-to-peak ratios dose-dependently, with maximum ratios (5.25 at 8 days) achieved using a 150-ppm ethylene concentration, compared to control treatments (3.97 at 8 days) (**Figure 11(A)**). The interaction effects demonstrated that Sabri treated with 150 ppm ethylene achieved the highest ratios (3.38 - 5.79 from 2 to 8 days), while untreated Amritasagar recorded the lowest values (1.40 - 3.74 from 2 to 8 days). Heat treatments exhibited similar patterns, with 30-hour exposure producing maximum ratios (3.47 - 5.88 from 2 to 8 days) compared to the control (1.59 - 3.97 from 2 to 8 days) (Figure 10(B) and Figure 11(B)). The combined heat and variety effects showed that Sabri, with a 30-hour heat treatment, achieved peak performance (3.61 - 6.02 from 2 to 8 days). At the same time, untreated Amritasagar maintained the lowest ratios throughout storage, confirming that both artificial ripening treatments and varietal characteristics significantly influence the development of edible pulp relative to peel weight.

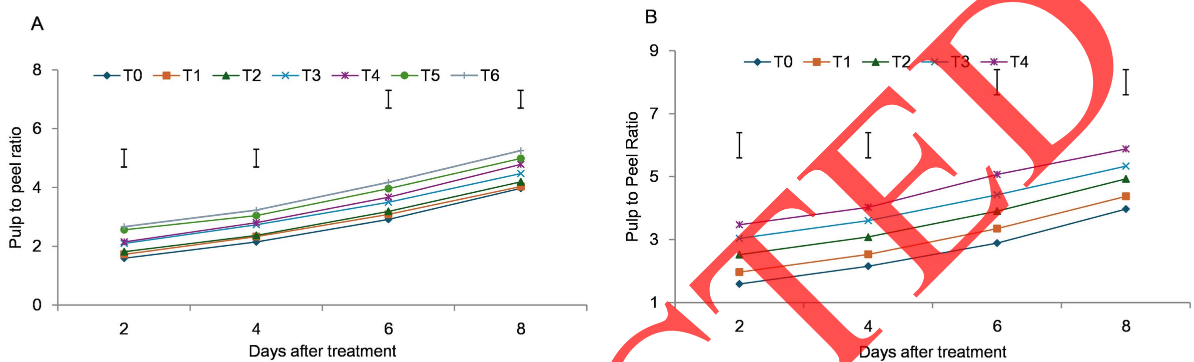

Figure 11. Effect of (A) ethylene and (B) heat treatments on the total pulp-to-peak ratio of bananas over eight days. In (A), T0 is the control, and T1 - T6 represent ethylene treatments (25 - 150 ppm). In (B), T0 is the control, and T1 - T4 represent heat treatments (12 - 30 hours). Vertical bars indicate the Least Significant Difference (LSD) at a 1% level of significance.

3.1.5. Total Sugar Content

Total sugar content analysis revealed significant varietal, treatment, and interaction effects throughout the storage period, with Sabri consistently exhibiting higher sugar levels than Amritasagar. Both varieties exhibited progressive sugar accumulation during ripening, with Amritasagar increasing from 9.12% to 21.02% and Sabri increasing from 9.94% to 22.51% from 2 to 8 days post-treatment (Figure 12(A)). Ethylene treatments dose-dependently enhanced sugar development, with maximum concentrations (150 ppm) producing the highest sugar content (11.04% - 23.50% from 2 to 8 days) compared to control treatments (7.62-19.40% from 2 to 8 days) (Figure 12(A)). The interaction effects demonstrated that Sabri treated with 150 ppm ethylene achieved peak sugar levels (11.06% at 2 days, 23.79% at 8 days), while untreated Amritasagar recorded the lowest values (7.32% - 18.47% from 2 to 8 days). Heat treatments exhibited similar patterns, with 30-hour exposure producing maximum sugar content (11.23% - 23.79% from 2 to 8 days) compared to the control (7.62% - 19.40% from 2 to 8 days) (Figure 13(A), Figure 13(B)). The combined heat and variety effects showed that Sabri, with a 30-hour heat treatment, achieved the highest sugar accumulation (24.41% at 8 days), while untreated Amritasagar maintained the lowest levels (18.47% at 8 days), confirming that artificial ripening treatments significantly accelerate sugar synthesis and accumulation in banana fruits.

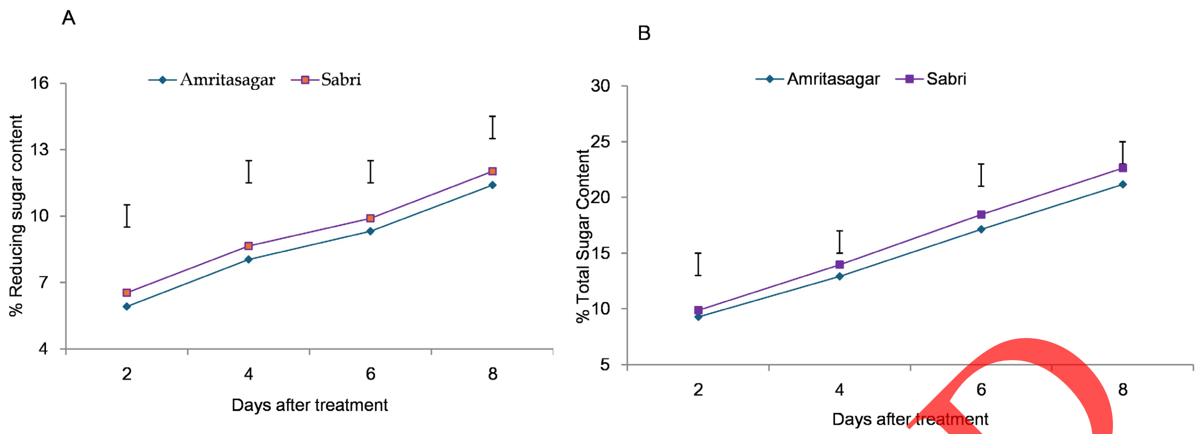

Figure 12. The effect of (A) ethylene and (B) heat on the percentage of Total sugar content in different banana varieties over time (DAT - Days After Treatment), with a least significant difference (LSD) of 1%.

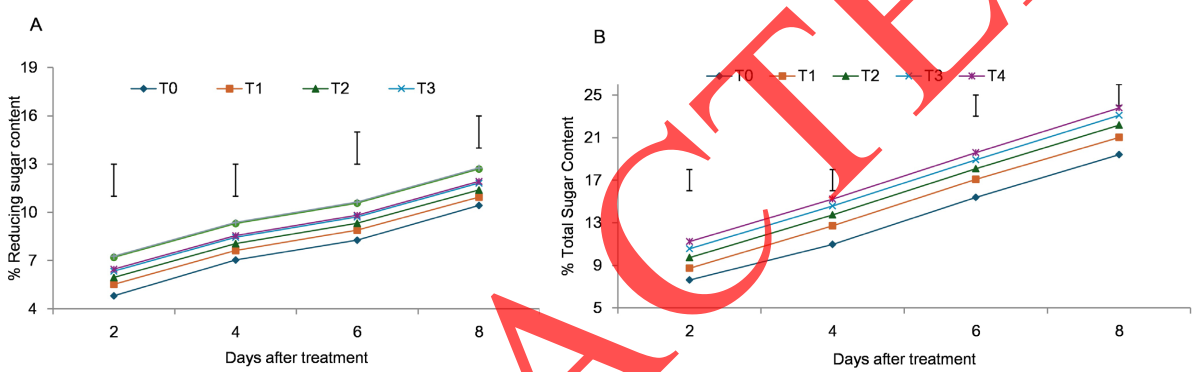

Figure 13. Effect of (A) ethylene and (B) heat treatments on the Total sugar content of bananas over eight days. In (A), T0 is the control, and T1 - T6 represent ethylene treatments (25 - 150 ppm). In (B), T0 is the control, and T1 - T4 represent heat treatments (12 - 30 hours). Vertical bars indicate the Least Significant Difference (LSD) at a 1% level of significance.

3.1.6. Reducing Sugar Content

Reducing sugar content analysis revealed significant varietal and treatment differences, with progressive increases observed throughout the ripening period in both varieties. Sabri consistently maintained higher sugar levels than Amritasagar, showing increases from 6.54% to 12.02% compared to Amritasagar's 5.91% to 11.40% from 2 to 8 days post-treatment (Figure 14(A), Figure 14(B)). Ethylene treatments dose-dependently enhanced reducing sugar accumulation, with maximum levels (12.77% at 8 days) recorded in 150 ppm ethylene treatment compared to control (11.92% at 8 days) (Figure 15(A)). Heat treatments exhibited similar patterns, with a 30-hour exposure producing a peak reducing sugar content (12.62% at 8 days), while the control maintained minimum levels (4.81% - 11.92% from 2 to 8 days) (Figure 15(B)). The interaction effects demonstrated that Sabri, with a 30-hour heat treatment, achieved the highest reducing sugar accumulation (7.17% - 12.81% from 2 to 8 days), whereas untreated Amritasagar recorded the lowest values (4.36% - 9.93% from 2 to 8 days). These findings confirm that reducing sugar content follows similar trends to total sugar content, with both artificial ripening treatments and varietal characteristics significantly influencing sugar metabolism and accumulation during banana maturation and storage.

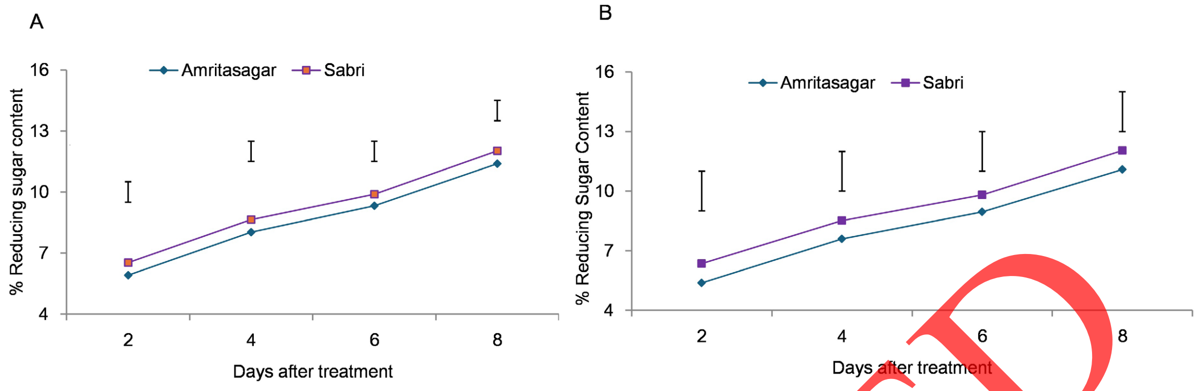

Figure 14. The effect of (A) ethylene and (B) heat on the percentage of reducing sugar content in different banana varieties over time (DAT - Days After Treatment), with a least significant difference (LSD) of 1%.

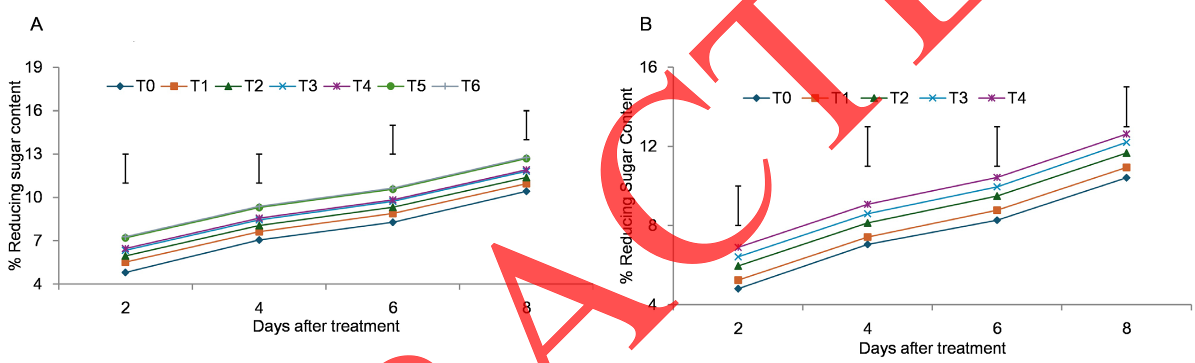

Figure 15. Effect of (A) ethylene and (B) heat treatments on the reducing sugar content of bananas over eight days. In (A), T0 is the control, and T1 - T6 represent ethylene treatments (25 - 150 ppm). In (B), T0 is the control, and T1 - T4 represent heat treatments (12 - 30 hours). Vertical bars indicate the Least Significant Difference (LSD) at a 1% level of significance.

3.1.7. Titratable Acid (TA) Content

Titratable acidity progressively increased with treatment duration and ethylene concentration, reaching peak levels around 6 days post-treatment before plateauing, with significant varietal, treatment, and interaction effects observed throughout the study period. Amritasagar consistently exhibited a higher titratable acid content (0.36% - 0.66%) compared to Sabri (0.34% - 0.64%) during storage (Figure 16(A) and Figure 16(B)). Ethylene treatments dose-dependently enhanced acidity development, with maximum levels (0.40% - 0.68%) recorded in the 150 ppm ethylene treatment, while the control maintained minimum values throughout storage (Figure 17(A)). The interaction effects demonstrated that Amritasagar treated with 150 ppm ethylene achieved peak acidity levels (0.43% - 0.69% from 2 to 6 days), with the highest value at 6 days, while untreated Sabri recorded the lowest acidity (0.30% - 0.58% from 2 to 8 days). Heat treatments exhibited similar patterns, with 30-hour exposure producing maximum acidity at early stages (0.45% - 0.69% at 2 - 6 days) and 18-hour treatment achieving peak levels (0.68%) at 8 days, compared to control (0.31% - 0.60% from 2 - 8 days) (Figure

17(B)). These findings confirm that artificial ripening treatments significantly accelerate organic acid synthesis, with varietal characteristics influencing acid metabolism during banana maturation and storage.

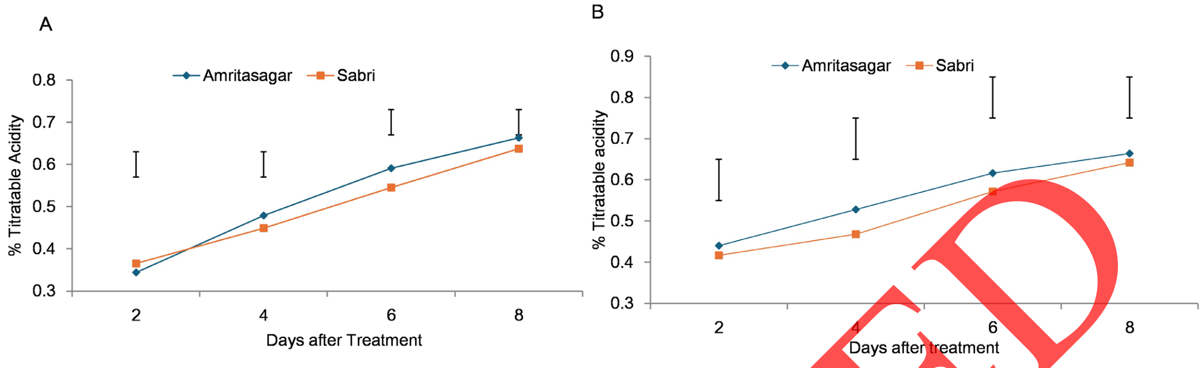

Figure 16. The effect of (A) ethylene and (B) heat on the percentage of Titratable acidity in different banana varieties over time (DAT - Days After Treatment), with a least significant difference (LSD) of 1%.

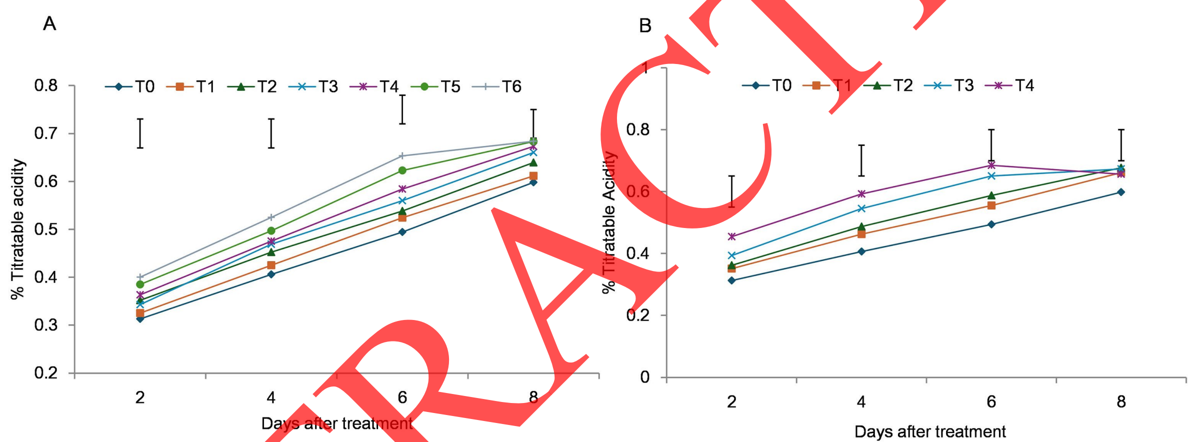

Figure 17. Effect of (A) ethylene and (B) heat treatments on the Titratable acidity of bananas over eight days. In (A), T0 is the control, and T1 - T6 represent ethylene treatments (25 - 150 ppm). In (B), T0 is the control, and T1 - T4 represent heat treatments (12 - 30 hours). Vertical bars indicate the Least Significant Difference (LSD) at a 1% level of significance.

3.1.8. Total Soluble Solids (TSS) Content

The total soluble solids content progressively increased throughout the ripening period, reaching maximum levels at 8 days post-treatment, with significant varietal differences consistently favouring Sabri over Amritasagar (Figure 18(A) and Figure 18(B)). Ethylene treatments dose-dependently enhanced TSS accumulation, with maximum concentrations (150 ppm) producing the highest levels (19.84% - 27.93% from 2 to 8 days) compared to control treatments (12.98% - 21.52% from 2 to 8 days) (Figure 19(A)). The interaction effects demonstrated that Sabri treated with 150 ppm ethylene achieved peak TSS content (19.91% - 27.94% from 2 - 8 days), while untreated Amritasagar recorded the lowest values (12.26% - 20.95% from 2 - 8 days). Heat treatments exhibited similar enhancement patterns, with 30-hour exposure producing maximum TSS levels (19.93% - 28.85% from 2 to 8 days) compared to the control (12.98% - 21.52% from 2 to 8 days) (Figure

19(B)). The combined heat and variety effects showed that Sabri, with 30-hour heat treatment achieved the highest TSS accumulation (20.24% - 29.11% from 2 - 8 days), while untreated Amritasagar maintained the lowest levels throughout storage, confirming that artificial ripening treatments significantly accelerate soluble solids concentration and that varietal characteristics substantially influence sugar and solids metabolism during banana maturation.

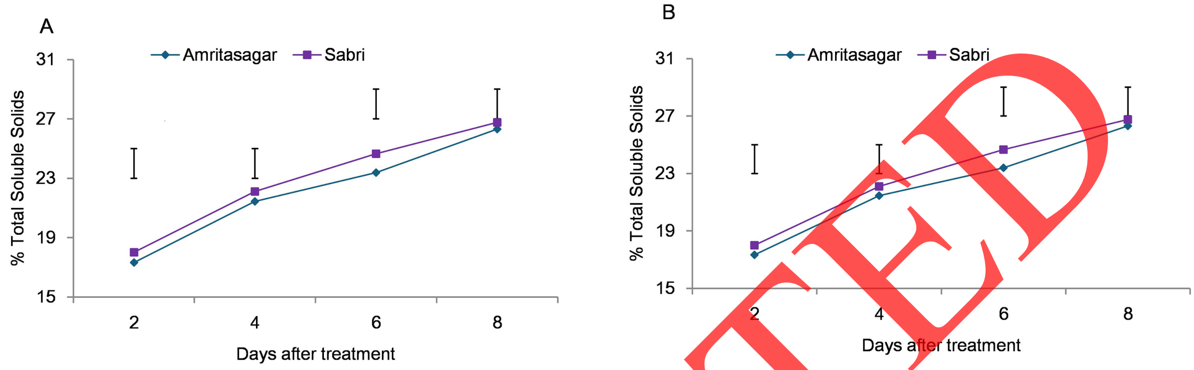

Figure 18. The effect of (A) ethylene and (B) heat on the percentage of Total soluble solids content in different banana varieties over time (DAT - Days After Treatment), with a least significant difference (LSD) of 1%.

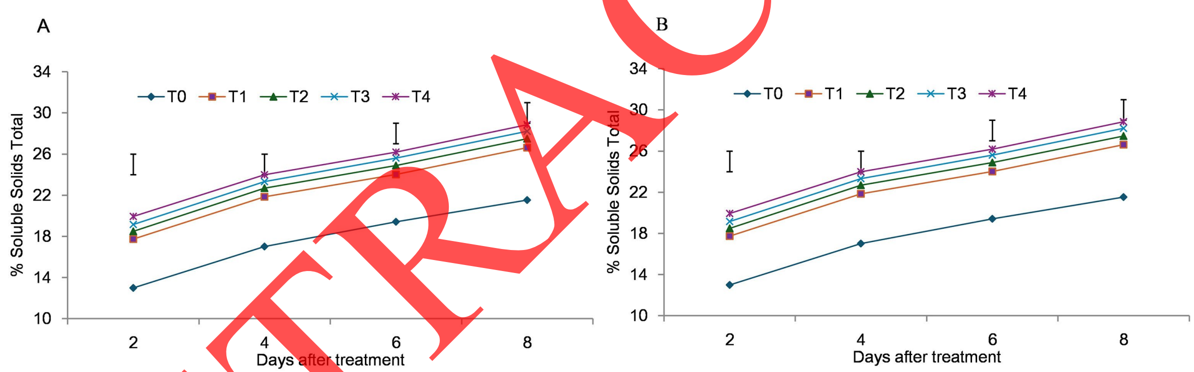

Figure 19. Effect of (A) ethylene and (B) heat treatments on the Total soluble solids content of bananas over eight days. In (A), T0 is the control, and T1 - T6 represent ethylene treatments (25 - 150 ppm). In (B), T0 is the control, and T1 - T4 represent heat treatments (12 - 30 hours). Vertical bars indicate the Least Significant Difference (LSD) at a 1% level of significance.

3.1.9. Time Taken to Ripen a Banana

Ripening time analysis demonstrated significant effects of both variety and ethylene treatment, with control fruits (T0) requiring 10.1 days for Amritasagar and 9.4 days for Sabri under natural conditions (Figure 20). Ethylene exposure reduced ripening time in a dose-dependent manner, with T1 fruits achieving full maturity in 5.8 days (Amritasagar) and 5.3 days (Sabri), and T2 in 4.7 and 4.1 days, respectively (Figure 20). At intermediate dosage (T3), both varieties ripened in approximately 4.0 days, while the highest concentration (T4) shortened ripening to 3.8 days for Amritasagar and 3.4 days for Sabri (Figure 20). Sabri consistently matured faster than Amritasagar across all ethylene levels, with the greatest difference (0.4 days) observed at T4 (**Figure 20**). These findings confirm that increasing ethylene concentration progressively accelerates banana ripening, and varietal characteristics modulate the magnitude of response in both cultivars.

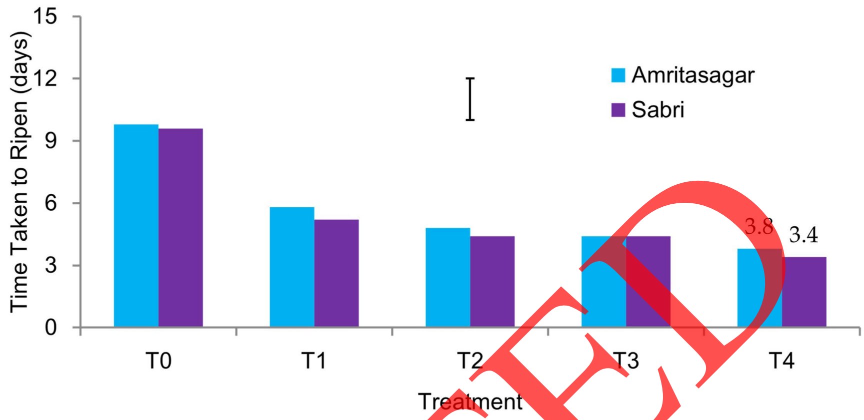

Figure 20. Effect of banana variety and ethylene concentration on ripening time. Vertical bars denote the least significant difference (LSD) at $p < 0.01$. T0: control; T1 - T6: ethylene at 25, 50, 75, 100, 125, and 150 ppm, respectively.

3.1.10. Shelf Life of Banana

The shelf life of any fruit is calculated from the period of harvest up to rotting. Pinal (2014) reported that the shelf life was the period of time that started from the time of harvesting and extended up to the start of rotting of fruit and it is the basic quality of fruit, as well as the most important parameter in the loss of biochemical reaction of fruit [17].

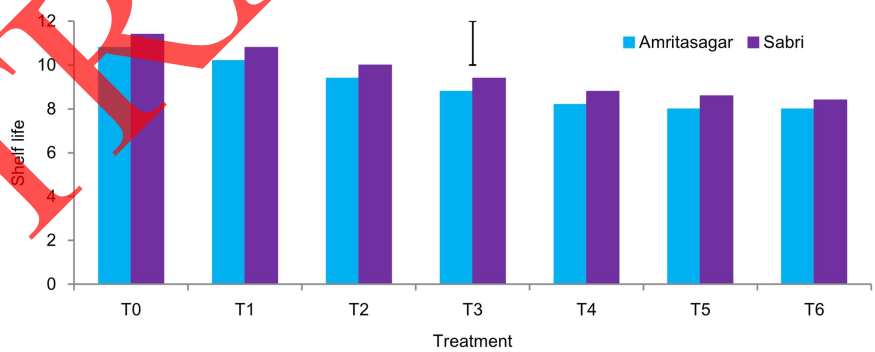

Figure 21. Effect of banana variety and ethylene concentration on shelf life. Vertical bars denote the least significant difference (LSD) at $p < 0.01$. T0: control; T1 - T6: ethylene at 25, 50, 75, 100, 125, and 150 ppm, respectively.

The shelf life of a banana was defined as the period from harvest to the onset of rotting, reflecting a key quality attribute and an important factor in post-harvest biochemical losses. Analysis indicated significant effects of both variety and ethylene treatment intensity, with control fruits (T0) attaining maximum storage durations of 10.7 days for Amritasagar and 11.2 days for Sabri, while 150 ppm ethylene (T6) reduced these to 7.9 days and 8.3 days, respectively (**Figure 21**). Across all treatments, Sabri outperformed Amritasagar in storage longevity, averaging 9.54 days versus 8.86 days. Dose-dependent reductions in shelf-life paralleled increases in ethylene concentration: control fruits showed the longest life (11.1 days) and the highest ethylene dose the shortest (8.0 days). Heat exposure produced similar effects, with untreated fruits maintaining 11.1 days of storage compared to just 7.6 days following 30 hours of heat treatment. Although interaction effects were not significant, untreated Sabri again achieved the peak shelf life of 11.4 days, whereas Amritasagar subjected to 30 hours of heat, recorded the minimum duration. These results demonstrate that while artificial ripening and heat treatments accelerate maturation and enhance certain quality parameters, they concomitantly shorten post-harvest storage life in a treatment-intensity-dependent manner across both varieties.

4. Discussion

This study examined how different ethephon concentrations and heat durations from smoldering rice husk affected the physical and chemical properties of Amritasagar and Sabri bananas, comparing them to untreated controls. Exposure to ethephon and heat changed peel color and external appearance by breaking down chlorophyll and shifting pigments, leading to significant color changes as doses and durations increased [18]-[21]. Fruit weight loss increased with higher ethephon levels, longer heat exposure, and storage time, due to respiration and transpiration [22]-[24]. Moisture content rose during storage and with treatment intensity, likely from water movement and starch breakdown surpassing water loss [25] [26]. The pulp-to-peel ratio grew progressively during ripening, accelerating in heat-then-ethephon-treated fruits, linked to water migration and reduced peel weight [23] [27]. Total sugar content increased with ripening as starch converted to sugar [5]. Reducing sugars rose from starch degradation by enzymes like amylase and maltase [28]. Non-reducing sugars were initially low, then increased to a peak before declining. Titratable acidity peaked during ripening and then fell, influenced by ethephon and heat [25]. Total soluble solids increased due to solute concentration and starch hydrolysis [29]. Ethephon and heat sped up ripening, acting as climacteric triggers, which shortened the time to ripeness and reduced storability, with heat showing a quicker effect [22]. Overall, treatments caused rapid physiological and chemical changes, improving ripening and quality but shortening the marketable period. The objectives were to find suitable ripening methods and safe treatment doses, assess ripening effectiveness, and evaluate physical, chemical changes, and storability under various treatments. Mature green bananas from two cultivars were collected, pre-cooled, and treated with ethephon at six concentrations or heat from smoldering rice husk for four durations, plus controls. Treated fruits were stored on brown paper at ambient lab conditions. Experiments used a completely randomized design with five replications. Measured parameters included physical and chemical traits, ripening time, and shelf life. Data, collected every 2 days, were analyzed using MSTAT-C, with means compared by LSD at 1%

and 5% probability levels. Results showed increases in physiological weight loss, pulp-to-peel ratio, moisture, sugars, total soluble solids, and titratable acidity, and decreases in dry matter, as ripening progressed, with higher ethephon concentrations, and longer heat exposures. Physiological weight loss varied significantly, being higher in Amritasagar than Sabri. Maximum loss at 8 days was 21.69% and 22.64%; minimum in controls. In combinations, Amritasagar with 150 ppm ethephon or 30-hour heat showed the highest loss; Sabri controls showed the lowest. Dry matter was higher in Sabri, decreasing with storage and treatment levels. The lowest dry matter at 8 days was 27.82% and 27.67%. In combinations, the lowest was in Amritasagar; the highest in Sabri controls. Moisture showed the opposite trend. The pulp-to-peel ratio increased with treatments and storage, reaching its highest at 8 days: 5.25, 5.87; the lowest was 3.97. Sabri had a higher ratio than Amritasagar. In combinations, Sabri with 150 ppm or 30-hour heat showed the highest ratio; Amritasagar controls showed the lowest. Sugar contents increased with storage and treatments, being higher in Sabri. In Sabri: total sugar ranged from 9.94% - 22.51% and 9.88% - 22.64%; reducing sugars from 6.53% - 12.02% and 6.36% - 12.04%; non-reducing sugars from 3.40% - 10.50% and 3.52% - 10.60%. The maximum was seen with 150 ppm ethephon or 30-hour heat; the minimum in controls. In combinations, Sabri with 150 ppm showed 23.79% total sugar, 12.66% reducing sugar, and 11.14% non-reducing sugar; Amritasagar controls showed the lowest. Titratable acidity increased to peaks then declined, with a maximum of 0.68% and 0.69% at 8 days; minimum in controls. In combinations, peaks occurred at 6 days in high treatments, declining thereafter. TSS increased with treatments and ripening, being higher in Sabri than Amritasagar. Minimum in controls; maximum 27.93 ˚Bx, 28.85 ˚Bx. In combinations, Sabri with 150 ppm or 30-hour heat showed the highest TSS; Amritasagar controls showed the lowest. Ripening time and shelf life varied significantly. Sabri ripened faster with a longer shelf life than Amritasagar. Ripening took 3.9 days and 3.6 days, with a maximum of 9.7 days. Shelf life was 8.2 days and 7.6 days. In combinations, Sabri: 3.8 days, 3.4 days; maximum shelf life 11.4 days. In conclusion, ethephon and heat from smoldering rice husk effectively speed up ripening and improve physical and chemical properties of Amritasagar and Sabri bananas in a dose-dependent way. This enhances consumer traits like pulp-to-peel ratio, TSS, and sugar content but reduces storability. Optimal doses balance quality gains against reduced shelf life, supporting practical post-harvest strategies; further research could optimize for commercial scaling and minimal quality compromises.

5. Conclusion

Post-harvest treatments with ethephon (25 - 150 ppm) and smouldering rice husk heat exposure (12 - 30 h) significantly enhanced key quality attributes of both "Amritasagar" and "Sabri" bananas. Specifically, treated fruits exhibited increased pulp-to-peel ratio, higher total soluble solids, elevated sugar content, and greater titratable acidity compared to untreated controls. However, these benefits were accompanied by a dose-dependent reduction in shelf life, with the highest ethephon concentration and longest heat exposure shortening marketable life by up to 20%. Thus, while ethylene and heat treatments can improve banana eating quality, their application must be balanced against accelerated post-harvest senescence to optimize overall storability and consumer acceptance.

Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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