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Research article

Quality-based assessment of natural ripening agents as alternatives to calcium carbide in 'Latundan' banana using mixed statistical methods

Bryl I. Manigo[1*]

[1] College of Agriculture and Related Sciences, University of Southeastern Philippines, Tagum-Mabini Campus, 8100, Philippines
* Correspondence: bryl.manigo@usep.edu.ph

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Abstract: Calcium carbide (CaC_2) is widely utilized for its affordability and efficiency in ripening fruits. However, it poses health risks, which makes natural ethylene-rich alternatives a safer choice. This study evaluated the effectiveness of natural ripening agents such as *Gliricidia* leaves, Calopo leaves, tomato fruit, and banana peel, as alternatives to CaC_2 in enhancing the postharvest quality of 'Latundan' banana (*Musa* × *paradisiaca*, AAB Group). Treated fruits were assessed for multiple quality parameters, including peel color, sensory firmness, chemical properties, organoleptic attributes, weight loss, shriveling, visual quality rating, disease incidence, and shelf life. A one-way analysis of variance (ANOVA) was performed to determine treatment effects, followed by Tukey's HSD test ($p \leq 0.05$) for mean separation. For non-normally distributed variables, the Kruskal-Wallis test was applied. To further evaluate treatment similarities based on overall trait performance, hierarchical cluster analysis (HCA) was conducted using Ward's method and Euclidean distance on standardized trait means. Results showed that CaC_2 significantly enhanced ripening characteristics, followed closely by tomato fruit. Natural agents, particularly the leaves of *Gliricidia* and Calopo, and banana peel, provided moderate improvements across several parameters, while the untreated control consistently ranked lowest. Although CaC_2 induced rapid ripening, it resulted in earlier deterioration and a shorter shelf life. Moreover, HCA revealed three distinct clusters: (1) CaC_2 and tomato fruit, (2) *Gliricidia* and Calopo leaves, and banana peel, and (3) control. These findings support the use of natural agents, especially tomato fruit, as viable alternatives for inducing uniform ripening and maintaining acceptable postharvest quality in bananas.

Keywords: Bio-ethylene; hierarchical cluster analysis; ethylene modulation; ripening enhancement; Philippine bananas

1. Introduction

Bananas are among the most widely produced and consumed tropical fruits worldwide, ranking high in global horticultural trade and agricultural output [1]. As a climacteric fruit, bananas ripen rapidly after harvest, which makes induced ripening essential for commercial distribution to ensure uniform peel color, optimal texture, and desirable flavor [2]. Although bananas naturally produce ethylene, exogenous application is commonly practiced to standardize ripening, particularly due to the uneven maturation of fruits within a single bunch [3]. However, the increasing demand for ripe fruits has led to the widespread yet hazardous use of CaC_2 as a chemical ripening agent, primarily due to its low cost and accessibility [4]. While CaC_2 is effective in accelerating ripening by enhancing respiration and color development [2], commercial-grade formulations often contain toxic contaminants such as arsenic and phosphorus. Prolonged exposure to these substances has been linked to immune suppression, hormonal imbalance, and infertility [5, 6].

In response, numerous plant-based ripening agents rich in ethylene or its precursors have been investigated as safer, locally available alternatives [7]. *Gliricidia sepium* (Kakawate) leaves have shown potential, inducing uniform ripening in 'Saba' bananas within two days [8], although they were less effective in mangoes at higher concentrations [9]. *Ricinus communis* (Venna) leaves produced comparable results to CaC_2 and CaO [7], while Samanea saman and Carica papaya leaves effectively ripened bananas in Nigeria [10]. *Moringa oleifera* leaves have also been noted for enhancing ripening and reducing costs [11]. Other studies have examined *Jatropha curcas, Irvingia gabonensis,* and *Calopogonium mucunoides* (Calopo), with the latter showing lower ethylene production compared to *Gliricidia* and *Samanea* [12]. Additionally, *Ficus septica* (Lagnob) has drawn interest for its bioactive properties [13]. Moreover, several climacteric fruits, such as apples, pears, tomatoes, and ripe bananas, also emit ethylene and have been used effectively as natural ripening agents [14, 15]. In particular, tomatoes demonstrate elevated ethylene emission between the breaker and fully ripe stages, making them a viable ripening alternative [16].

Despite bans in many countries, CaC_2 remains in use due to the lack of affordable and effective substitutes [9]. This has intensified the search for safer, natural ripening technologies. To comprehensively evaluate these alternatives, the present study employed both parametric (ANOVA or analysis of variance, Tukey's HSD) and non-parametric (Kruskal-Wallis) statistical analyses, methods widely applied in postharvest studies to assess treatment effects on banana quality traits [17]. Hierarchical cluster analysis (HCA) was also used to classify treatments based on the overall postharvest performance of some fruits. Previous studies demonstrate that HCA has effectively identified consumer preference segments in apples [18] and key quality indicators in pears when combined with ANOVA, correlation analysis (CA), and principal component analysis (PCA) [19]. This integrated statistical approach enhances the robustness of postharvest evaluation and supports informed decision-making in treatment selection. In this study, the effects of selected natural ripening agents on the ripening behavior and postharvest quality of 'Latundan' banana (*Musa* × *paradisiaca*, AAB Group), a commonly cultivated variety in the Philippines, were evaluated. Specifically, it sought to assess the ripening duration and overall fruit quality influenced by these agents to support the development of safer, sustainable alternatives to chemical ripening.

2. Materials and Methods

2.1 Plant Material

The banana variety used was 'Latundan' (*Musa* × *paradisiaca,* AAB Group). Mature unripe fruits were obtained from farms in Panabo City, Davao del Norte, Philippines. Sample fruits were harvested on the same day. One week before harvesting, tagging was performed to ensure sample uniformity. Fruits with similar characteristics in size, age, and number of leaves were selected for tagging. Fruits from the second, third, and fourth hands of the bunch were used as experimental samples [20].

2.2 Experimental Duration and Location

The experiment, including storage and laboratory analyses, was conducted from February to July 2022 at the Food Technology Laboratory (FTL) of the University of Southeastern Philippines (USeP), Tagum-Mabini Campus, Tagum City, Davao del Norte, Philippines.

2.3 Treatment Screening and Selection

A range of locally available natural ripening agents, including leaves of *Gliricidia sepium* (Kakawate), *Calopogonium mucunoides* (Calopo), *Ricinus communis* (Venna), *Samanea saman* (Rain tree), *Moringa oleifera*, *Carica papaya*, *Jatropha curcas*, and *Ficus septica* (Hauili fig tree or Lagnob), along with ripe tomato fruits and 'Lakatan' banana peels, were initially screened for their ripening efficacy. A preliminary trial was conducted using ten 'Latundan' banana fingers per treatment, with three replications. Banana samples and ripening agents (100 g per kilogram banana) were enclosed in 10 × 7-inch styrofoam containers, with two banana fingers placed in each container, and sealed with transparent plastic wrap. CaC_2 (10 g per kilogram banana) was used as the positive control, while untreated fruits served as the negative control. To prevent oxygen depletion and ensure adequate gas exchange during incubation, the styrofoam containers were modified with small ventilation holes. Specifically, one hole (5 mm in diameter) was made on each side of the container to promote gentle airflow without excessive ethylene loss.

All ripening agents were sourced locally, while commercial-grade CaC_2 was purchased from a chemical supplier in Tagum City, Davao del Norte, Philippines. Before treatment, both fruits and ripening agents were sanitized with 0.01% sodium hypochlorite (NaOCl) for 3 minutes and air-dried at room temperature. Peel yellowing served as the primary selection criterion after 5 days of storage post-incubation. Treatments that induced visible color change comparable to CaC_2 were advanced to the main experiment. Based on the results, the final treatments were the following: T1= control (no treatment), T2= CaC_2 (10 $g\ kg^{-1}$), T3= *Gliricidia* leaves (100 $g\ kg^{-1}$), T4= Calopo leaves (100 $g\ kg^{-1}$), T5= tomato fruit (100 $g\ kg^{-1}$), and T6= banana peel (100 $g\ kg^{-1}$). The main trial followed a completely randomized design (CRD) with three replications, each comprising 10 banana hands and 15 banana fingers (both for destructive and non-destructive sampling), and was evaluated for physical, chemical, and sensory quality parameters as outlined in subsequent sections.

Figure 1. Natural ripening agents were used in this study.

The main trial followed a completely randomized design (CRD) with three replications. Each replicate comprises 10 banana hands allocated for non-destructive monitoring of peel color, weight loss, visual quality rating (VQR), shriveling, disease incidence, and shelf life. When a hand from each treatment reached peel color index 6 (PCI-6; see 2.5), subsamples were taken for chemical analyses (TSS, TTA, pH) and sensory evaluation (pulp color, taste, aroma, overall acceptability). In addition, 15 banana fingers per treatment were used for destructive measurements of firmness, assessed daily. The amount of each ripening agent differed according to its chemical nature and expected ethylene-releasing capacity [2]. Calcium carbide, being highly reactive, was applied at 10 g kg^{-1} fruit, while natural materials were used at 100 g kg^{-1} to compensate for their slower and lower ethylene [3]. Comparison of ripening efficiency was therefore based on the extent and uniformity of peel yellowing rather than on equal mass of material [21].

2.4 Treatment Application

The natural ripening agents, along with the sample fruits to be ripened, were placed inside a 5-ply corrugated cardboard box (53.5 × 40.0 × 24.5 cm) with paper linings. A 10% (w/w) concentration of each natural ripening agent was used relative to the total weight of the bananas in each box. The box openings and holes were covered with newspaper. The fruits were incubated for 48 hours before being removed and placed in ambient room storage (28±3°C), where ripening progress was monitored.

2.5 Data Gathering

Peel color was visually assessed daily using a standardized seven-stage banana color chart [20], with a peel color index (PCI) scale ranging from green (1) to yellow flecked with brown (7). Sensory firmness was measured using a GY-3 portable fruit hardness tester with a 5-mm flat-tipped probe, puncturing each banana finger at three midpoints. Firmness was recorded in Newtons (N). Chemical analyses included total soluble solids (TSS), total titratable acidity (TTA), and pH. TSS was measured using an Atago Pocket digital refractometer (Model PAL-1, Atago Co., Ltd., Tokyo, Japan) by placing 1–2 drops of filtered juice on the prism. TTA was determined via titration with 0.1N sodium hydroxide using phenolphthalein as an indicator, while pH was recorded using a digital pH meter. Organoleptic attributes (OA) such as pulp color, taste, aroma, and overall acceptability were evaluated at PCI 6 using a 9-point hedonic scale [22] by a panel of 25 evaluators. Weight loss (%) was calculated using the formula: weight loss = [(weight difference to initial weight)/(initial weight of the sample or weight at day 0)] x 100. Visual quality rating (VQR) followed Gunathilake *et al.* [23] with slight modification, with fruit categories as excellent (9–8), good (7–6), fair (5–4), poor (3–2), or non-edible (1). Shrivelling was assessed using a 1–4 index ranging from no shrivelling (1) to severe shrivelling (4). Disease incidence was recorded as the percentage of fruits affected by crown rot/mold using the formula: % disease incidence = (number of diseased fruits affected by crown rot/mold)/(total number of hands) x 100 [20]. Shelf life was determined by tracking the number of days to full ripeness (PCI 6), senescence, and the limit of marketability (VQR 5).

2.6 Statistical Analyses

All analyses of data were performed in R (v4.5.0). For each storage day, treatment effects were analyzed separately, and results are reported as mean ± SE. Normality (Shapiro–Wilk) and homoscedasticity (Levene's test) were assessed for every outcome/day. Continuous variables (firmness, TSS, TTA, pH) and time variables (days to marketability, days to ripen, days to senescence) were analyzed by one-way ANOVA with Tukey's HSD ($\alpha = 0.05$). Percentage variables (weight loss and disease incidence) were analyzed after arcsine–square-root transformation. Ordinal outcomes (peel color index, degree of shriveling, visual quality rating, and hedonic sensory attributes [aroma, taste, peel/pulp color, overall acceptability]) were analyzed using Kruskal–Wallis with Dunn's post-hoc comparisons and Holm adjustment ($\alpha = 0.05$). To complement the univariate analysis, a Hierarchical Cluster Analysis (HCA) was conducted using the *hclust()* function in R, which employs Ward's method and Euclidean distance to assess treatment similarities based on overall postharvest performance. Before clustering, trait values were standardized (z-scores), and the means of three replicates per treatment were used to generate a distance matrix. Clustering results were visualized using a dendrogram and a clustered heatmap, allowing the identification of natural groupings among treatments and associated trait patterns. This multivariate approach provided integrative insight to reinforce and validate the findings from ANOVA and nonparametric tests.

3. Results and Discussion

3.1 Preliminary Screening of Natural Ripening Agents

Peel color is one of the most visible and market-relevant indicators of ripeness, which is often used by both consumers and traders to assess banana maturity. To identify effective natural alternatives to CaC_2, a preliminary experiment was conducted to screen various locally available ripening agents based on their ability to induce degreening in 'Latundan' bananas over a five-day incubation period. This initial screening provided critical insights into the ripening efficacy of each treatment and guided the selection of agents for further evaluation. Figure 2A presents the quantitative peel color index for each treatment. Bananas treated with CaC_2 showed the highest peel color index, which is significantly different from the untreated control. Among the natural agents, bananas exposed to *Gliricidia* leaves, Calopo leaves, tomato fruit, and banana peel displayed peel color indices statistically comparable to those treated with CaC_2 ($p \leq 0.05$; Tukey's HSD). In contrast, other treatments such as castor bean leaves, papaya leaves, and Hauili fig tree leaves resulted in lower color indices, which indicates limited ripening influence. These findings are visually supported by Figure 2B, which shows noticeable yellowing in fruits treated with the selected natural agents, comparable to those treated with CaC_2. The untreated control and several other treatments showed minimal or uneven color change, which supports the effectiveness of the selected agents. Similar outcomes were reported by Roy *et al.* [15] in tomato, Acedo [8] in *Gliricidia* leaves, who suggested that these could stimulate color change in bananas at rates similar to chemical ripening agents. The development of color is a key indicator of fruit maturity and is closely tied to ripening. This color change occurs as chlorophyll degrades, and the unmasking of pre-existing pigments takes place, often accelerated by ethylene exposure [2]. A uniform yellow color on the peel not only signifies ripeness but also makes bananas more attractive to buyers, which typically leads to higher market prices [24]. Therefore, these four natural ripening agents were subjected to further testing for physical and chemical measurements to validate their effects on the ripening process.

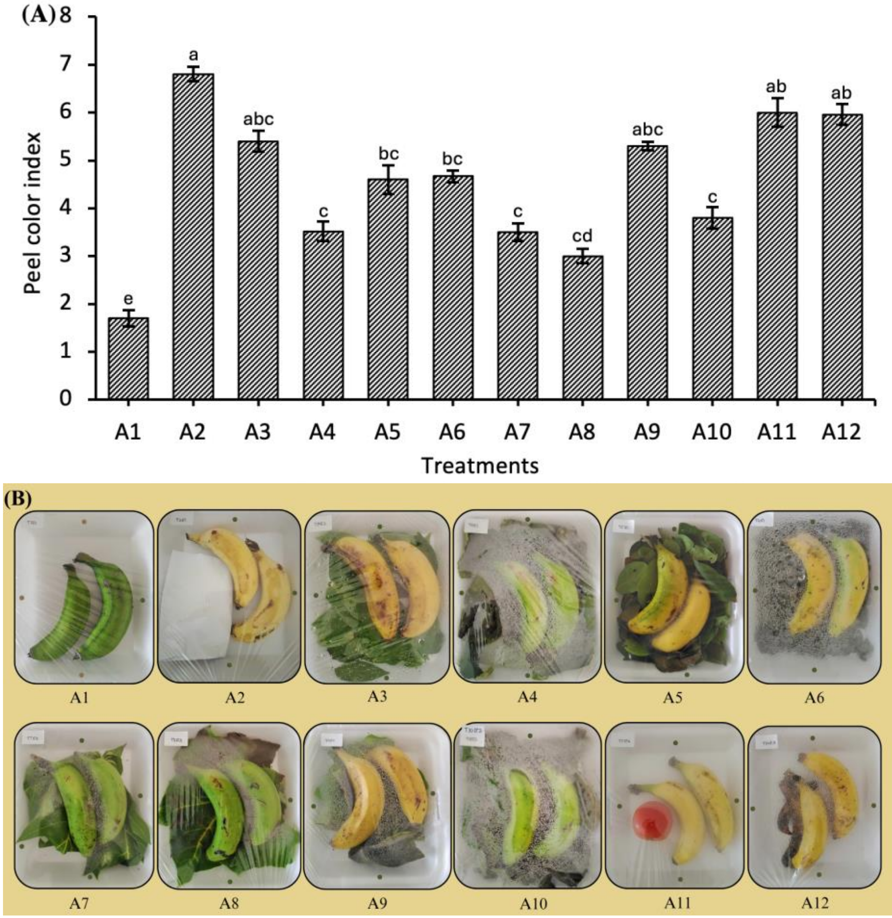

Figure 2. Peel color changes (A) of 'Latundan' bananas showing yellowing (B) as influenced by different natural ripening agents at 5 days of incubation. Legend: A1= control; A2= CaC_2; A3= *Gliricidia* leaves; A4= castor bean plant leaves; A5= rain tree leaves; A6= *Moringa* leaves; A7= papaya leaves; A8= *Jatropha* leaves; A9= calopo leaves; A10= Hauili fig tree leaves; A11= tomato fruit; A12= banana peel; Means sharing the same superscripts are not significantly different from each other ($p \leq 0.05$, n=10) using Tukey's HSD.

3.2 Ripening Evaluation of Selected Ripening Agents for 'Latundan'

Natural agents showing comparable efficacy to CaC_2 in the preliminary screening were selected for further evaluation. This section explores the effects of the six selected treatments on the ripening progression of 'Latundan' bananas, with emphasis on key postharvest quality parameters. The observed changes in ripening-related attributes are presented in Figures 3–5 and Table 1, which collectively illustrate the dynamic transformations in fruit quality during the ripening period.

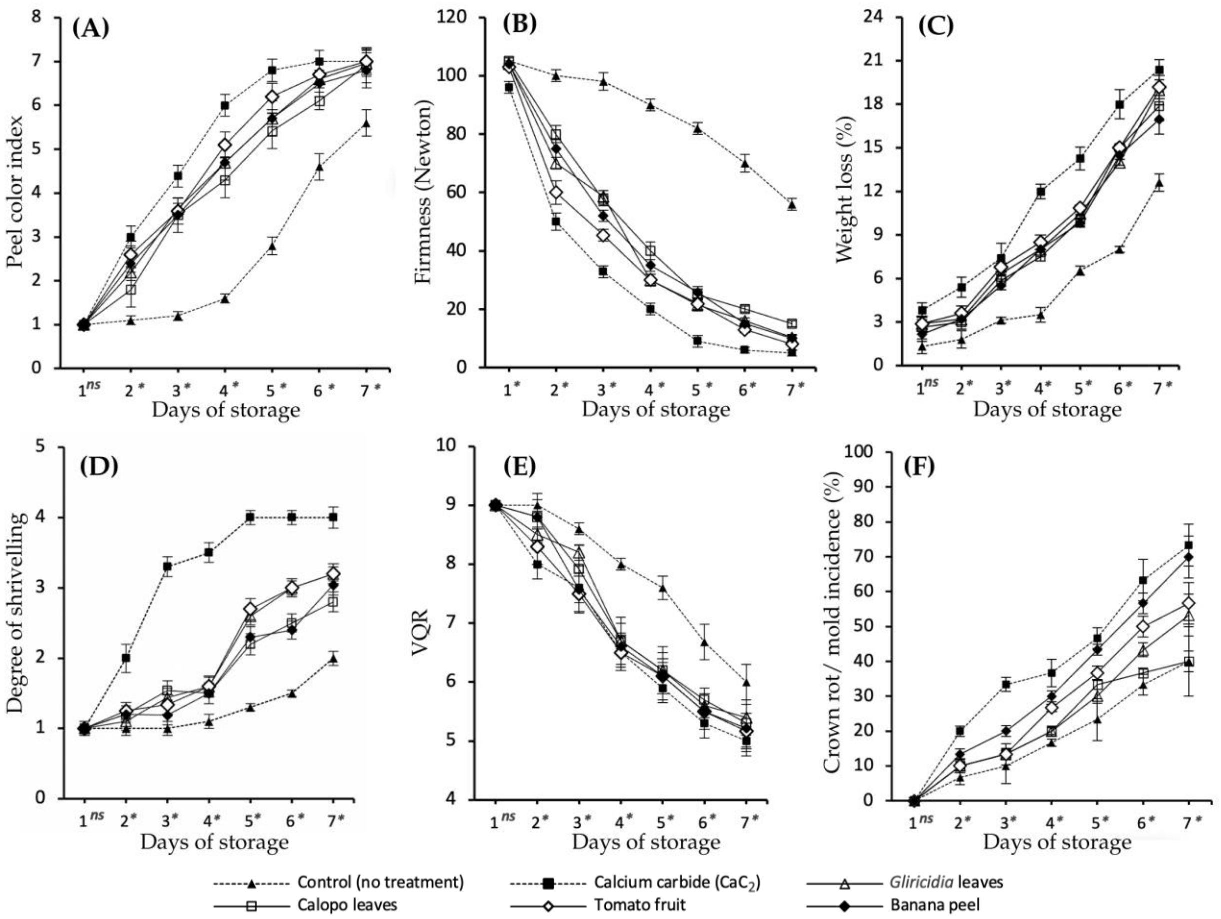

Figure 3. Effects of various ripening agents on the (A) peel color change, (B) firmness, (C) weight loss, (D) degree of shriveling, (E) VQR, and (F) disease incidence of 'Latundan' bananas after 48 hours of incubation. Asterisk (*) denotes significance at 5% level of significance ($p \leq 0.05$; n=10) using Tukey's HSD.

3.2.1 Changes in Peel Color

After 48 hours of incubation, the peel color of 'Latundan' bananas showed significant changes influenced by various natural ripening agents over a 7-day storage period (Figure 3A). As expected, bananas treated with CaC_2 ripened markedly faster than those in other treatments, while untreated fruits remained green (Figure 4). Natural ripening agents, including leaves of *Gliricidia* and Calopo, tomato fruits, and banana peels, induced peel color changes earlier than the control. By day 5 and onwards, these natural agents produced results comparable to CaC_2, with tomato fruit treatments emerging as the most effective among them. The change in peel color of 'Latundan' bananas ripened with natural agents closely resembles that of bananas treated with CaC_2 but occurs at a slightly slower pace. This suggests that natural agents effectively induce ethylene production, thereby accelerating chlorophyll degradation and carotenoid biosynthesis, which are deemed key processes in peel color change [2]. The tomato fruits, for instance, stood out among natural agents, in accordance with Roy *et al.* [15], who reported that tomatoes release bioethylene in quantities sufficient to promote ripening in climacteric fruits. Moreover, banana peel-ripened fruits also showed comparable results among natural agents. It was also known that bananas produced ethylene naturally [2], hence, ethylene release from banana peels probably enhanced the peel color change of the fruit samples. Similarly, *Gliricidia* and Calopo leaves demonstrated efficacy comparable to CaC_2, consistent with findings by Acedo [8], who highlighted the ethylene-generating potential of *Gliricidia sepium.* Untreated fruits that remain green emphasize the importance of external ethylene sources for ripening, particularly in climacteric fruits. These results reinforce the viability of natural agents as safer alternatives to CaC_2, aligning with global calls to phase out harmful ripening chemicals [4].

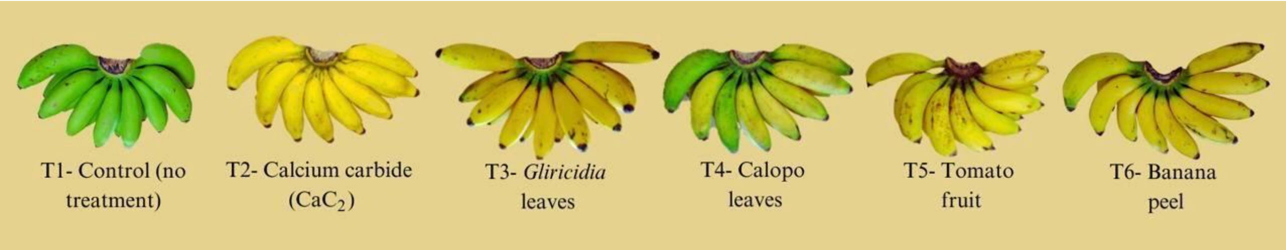

Figure 4. 'Latundan' (*Musa × paradisiaca* AAB Group) at day 4 of storage after 48 hours of incubation

3.2.3 Chemical Properties and Organoleptic Attributes

Ripened 'Latundan' bananas were chemically analyzed to determine the TSS, TTA, and pH, as well as the organoleptic attributes (Table 1). Bananas that reached PCI 6, regardless of when they achieved this stage, were used as samples in the analyses. Among the treatments, natural ripening agents, particularly tomato fruits, produced ripened 'Latundan' bananas with higher TSS levels, comparable to those ripened with *Gliricidia* leaves, while fruits ripened with CaC_2 exhibited lower Brix values. The TTA and pH levels were comparable across all treatments. In terms of organoleptic traits, taste showed a significant statistical difference ($p \leq 0.05$), with bananas ripened using *Gliricidia* leaves and tomato fruits obtained higher taste ratings, similar to those ripened with Calopo leaves. However, other organoleptic attributes, such as aroma, perceived pulp color, and overall acceptability, showed no statistically significant differences ($p \leq 0.05$) among the treatments.

Table 1. Chemical properties and organoleptic attributes of 'Latundan' bananas at PCI 6. Means sharing the same superscripts are not significantly different from each other ($p \leq 0.05$) using Tukey's HSD. CV represents the coefficient of variance, ns means not significant, and an asterisk (*) denotes significant.

Treatments	Chemical Properties			Organoleptic Attributes			
	TSS (°Brix) *	**TTA** (meq/100g) *ns*	**pH** *ns*	**Aroma** *ns*	**Taste** *	**Pulp Color** *ns*	**Overall Acceptability** *ns*
Control	22.67 bc	3.23	4.77	8.20	8.92 c	8.20	8.11
(CaC_2)	22.17 c	3.41	4.90	8.91	9.12 b	9.21	8.78
Gliricidia leaves	23.80 ab	3.24	4.77	8.79	9.53 a	9.33	8.50
Calopo leaves	22.83 bc	3.32	4.83	8.48	9.38 ab	9.37	8.45
Tomato fruit	24.27 a	3.31	4.77	9.03	9.63 a	9.55	8.98
Banana peel	22.53 bc	3.24	4.87	8.36	9.23 ab	9.26	8.83
CV (%)	5.52	2.04	2.16	2.76	5.12	2.52	2.63

The higher TSS values in bananas ripened using tomatoes and *Gliricidia* leaves highlight the ability of these natural agents to enhance sugar accumulation during ripening. However, CaC_2-ripened fruits showed lower Brix values, potentially due to incomplete metabolic shifts associated with rapid ripening [5]. Comparable TTA and pH levels across treatments indicate that natural ripening agents maintain acidity balance, a key quality parameter, consistent with findings by Basak and Akter [7]. Organoleptic attributes such as taste and aroma were positively influenced by *Gliricidia* leaves and tomatoes, which highlights the sensory benefits of natural agents. These results are congruent with the findings of Ademe and Tanga [11], who noted superior sensory profiles in naturally ripened bananas, such as *Moringa* leaves. Moreover, the increase in TSS (°Brix) in bananas ripened with natural agents, such as tomato fruits and *Gliricidia* leaves, reflects their potential to enhance sugar accumulation during ripening. TSS is a critical parameter linked to sweetness and consumer acceptability [2]. The comparable TTA and pH levels across treatments suggest that these natural agents do not significantly alter the fruit's acid content, an essential factor in maintaining flavor balance. Bananas ripened with *Gliricidia* leaves and tomato fruits received higher taste ratings, similar to findings from Ademe and Tanga [11], who noted improved sensory quality with natural ripening agents such as *Moringa* leaves. The lack of significant differences in aroma, pulp color, and overall acceptability suggests that natural agents like tomato fruits can rival CaC_2 in preserving or enhancing sensory quality without toxic risks [7].

3.2.4 Weight Loss and Degree of Shriveling

As ripening progresses and softening occurs, the weight of the fruit decreases due to moisture loss and other physiological changes. This is accompanied by the peel beginning to shrivel, driven by water loss and alterations in cellular structure. In this study, 'Latundan' bananas treated with CaC_2 exhibited significantly higher weight loss throughout the storage period, starting immediately after the 48-hour incubation. In contrast, untreated fruits experienced a slower and more gradual weight loss. All natural ripening agents evaluated resulted in weight loss values that were statistically comparable to one another but significantly lower than those of CaC_2-treated fruits (Figure 3D). Similarly, fruits ripened with CaC_2 exhibited the most pronounced peel wrinkling, which is an indication of accelerated moisture loss and tissue degradation (Figure 3D). In contrast, the untreated control maintained a smooth and firm appearance with minimal signs of shriveling. The fruits treated with natural ripening agents showed moderate and comparable levels of shriveling, which suggests a more gradual and controlled ripening process that better preserved the structural integrity of the fruit compared to the rapid changes induced by chemical treatment. Weight loss during ripening is a natural phenomenon due to moisture evaporation and metabolic processes [21]. The higher weight loss in CaC_2-ripened bananas compared to natural agents can be attributed to the rapid acceleration of respiration and transpiration rates induced by carbide [4]. In contrast, natural agents, such as *Gliricidia* and Calopo leaves, may probably act more gently, enabling a slower moisture loss and maintaining fruit integrity longer. Shrivelling, directly correlated with weight loss, was more pronounced in CaC_2-ripened bananas, and was less pronounced in tomato and banana peel-ripened fruits, likely due to the rapid breakdown of cellular structure induced by the ripening process [15].

3.2.5 VQR

The visual quality apparently changed as ripening progressed, as manifested in this study. Untreated 'Latundan' bananas consistently showed higher VQR compared to those subjected to treatments. In particular, fruits ripened with CaC_2 exhibited significantly lower VQR on days 2, 5, 6, and 7, which reflects a faster deterioration in appearance compared to other treatments (Figure 3E). The superior VQR observed in untreated bananas and those ripened with natural agents highlights their slower ripening process, which helps maintain visual appeal over time. The rapid deterioration in VQR for CaC_2-ripened fruits suggests its aggressive ripening mechanism, which accelerates senescence [26]. These results corroborate with Basak and Akter [7], who emphasized the importance of gradual ripening in preserving aesthetic qualities. Using natural agents like tomato fruits, banana peel, and leaves of *Gliricidia* and Calopo can, thus, offer a safer and more sustainable alternative to maintain the fruit's marketability for extended periods.

3.2.6 Postharvest Disease Incidence

Postharvest diseases, which commonly develop after harvest, can greatly affect the appearance, texture, taste, and shelf life of fruits which resulting in significant economic losses. In this study, 'Latundan' bananas were found to be particularly vulnerable to pathological infections, even though these fruits were disinfected with NaOCl. Fruits treated with CaC_2 exhibited a higher incidence of crown rot and anthracnose (Figure 3F), likely due to accelerated ripening and increased susceptibility. In contrast, untreated fruits showed a slower progression of these diseases, which demonstrates the potential interaction between ripening treatments and disease resistance. The postharvest disease incidence observed in 'Latundan' bananas showcases the complex interplay between ripening treatments and fruit susceptibility to pathogens. CaC_2-ripened bananas exhibited a higher incidence of crown rot and anthracnose, as illustrated in Figure 3F. This finding is consistent with Maduwanthi and Marapana [2], who noted that the accelerated ripening induced by CaC_2 compromises the structural integrity of fruit tissues, which makes them more susceptible to pathogen invasion. The rapid softening and increased moisture content provide an ideal environment for fungal growth. On the other hand, untreated fruits demonstrated a slower progression of postharvest diseases, likely due to their extended ripening duration, which preserves tissue firmness and delays pathogen colonization. Studies by Chandar *et al.* [26] and Ajayi and Mbah [10] support the notion that natural ripening agents, such as plant leaves and other bioethylene sources, can mitigate postharvest disease risks by promoting uniform ripening without inducing excessive moisture release or tissue degradation.

3.2.7 Shelf Life

The shelf life of 'Latundan' bananas is determined by the number of days to full ripeness (PCI 6), the onset of senescence, and the limit of marketability (at VQR 5). As shown in Figure 5, CaC_2-ripened fruits reached PCI 6 in approximately 4 days, the fastest among all treatments. Fruits ripened using natural agents, such as tomato fruits, *Gliricidia* and Calopo leaves, and banana peels, followed closely, which took 5-6 days to reach full ripeness, with tomato-treated fruits lagging just one day behind the CaC_2-treated group. In contrast, untreated 'Latundan' bananas took 8 days to achieve PCI 6, which reflects a slower ripening process. A similar trend was observed for days to senescence, with CaC_2-ripened fruits deteriorating more rapidly than those treated with natural ripening agents or left untreated. These fruits also reached VQR 5 sooner than the others, marking the threshold for marketability. At VQR 5, the fruits are still acceptable for sale, but they are on the verge of declining quality. The accelerated ripening and senescence observed in CaC_2-ripened fruits can be attributed to the treatment's ability to trigger ethylene release, which speeds up ripening but also shortens shelf life. In contrast, natural ripening agents promote a more gradual progression, preserving the fruit's quality for a longer period.

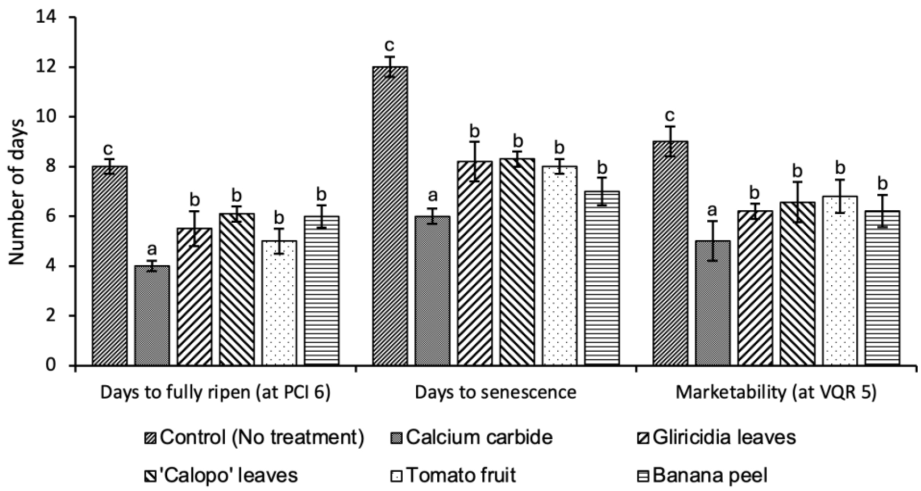

Figure 5. The shelf life of 'Latundan' bananas was determined as days after incubation with different ripening agents. Means sharing the same superscripts are not significantly different from each other ($p \leq 0.05$; n=10) using Tukey's HSD

The findings on shelf life (Figure 5) emphasize the balance between the speed of ripening and the duration of marketability, which reveals the impact of different ripening methods on the fruit's commercial viability. CaC_2-ripened bananas achieved full ripeness (PCI 6) within four days, demonstrating the efficiency of CaC_2 as a ripening agent. However, this rapid ripening led to an accelerated onset of senescence and a shorter marketable shelf life. Similarly, Okeke *et al.* [4] reported that the high ethylene release triggered by CaC_2 accelerates physiological processes, including ripening and senescence. Natural ripening agents such as tomato fruits, *Gliricidia* leaves, and banana peels provided a more balanced approach, achieving full ripeness in 5–6 days. Among these, tomatoes performed comparably to synthetic agents due to their bioethylene content [15]. The slower progression of ripening and senescence in fruits treated with natural agents helps maintain fruit quality and extend marketability. Untreated fruits, while taking the longest to reach full ripeness (8 days), exhibited the most extended shelf life. This agrees with Thompson *et al.* [21], who noted that delaying ripening by avoiding external ethylene exposure helps preserve fruit firmness and quality. The balance between rapid ripening and extended shelf life offered by natural agents suggests their suitability for small-scale and commercial applications where quality preservation is crucial.

3.3 Cluster Analysis of different ripening agents for Latundan

To complement the results of ANOVA and post hoc tests, hierarchical cluster analysis was employed to assess the overall similarity among the six banana ripening treatments based on multiple postharvest quality parameters. Unlike univariate methods that analyze each trait separately, hierarchical clustering provides a multivariate perspective by simultaneously considering all measured traits, such as peel color, firmness, visual quality rating (VQR), disease incidence, total soluble solids (TSS), titratable acidity (TTA), pH, and organoleptic attributes. This approach identifies the most effective treatment for inducing ripening while preserving postharvest quality. Figure 6 presents the hierarchical clustering dendrogram constructed using Ward's method on standardized, averaged values of the measured parameters. The dendrogram revealed three distinct clusters. The first cluster grouped calcium carbide (CaC_2)and tomato fruit, which suggests that these treatments induced similar ripening behaviors, particularly in enhancing peel color, reducing firmness, and improving organoleptic or sensory scores. This finding supports the results of Roy *et al.* [15], who demonstrated that tomato fruit itself can act as a natural ripening agent by emitting ethylene that promotes ripening in bananas.

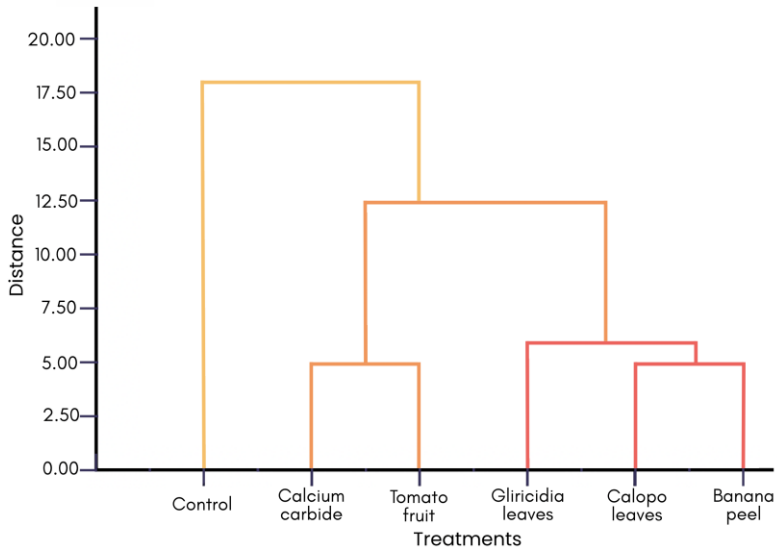

Figure 6. Hierarchical clustering dendrogram of six ripening treatments based on averaged postharvest traits in banana fruit.

The second cluster included *Gliricidia* leaves, Calopo leaves, and banana peel, which indicates moderate similarity in their ripening profiles, particularly in maintaining favorable organoleptic attributes, acceptable color development, and reduced disease incidence. The control treatment formed the third and most distant cluster, which highlights its distinct and generally inferior performance across all traits. To further visualize treatment-level variation, a clustered heatmap was generated using the same standardized dataset (Figure 7). Each row represents a treatment, while columns represent specific postharvest traits. The heatmap displays color intensities ranging from blue (lower performance) to red (higher performance). Treatments like calcium carbide (CaC_2) and tomato fruit exhibited strong red intensities across most parameters, confirming their superior performance. Natural treatments showed intermediate to high performance in traits such as overall acceptability, aroma, and pulp color. In contrast, the control treatment displayed predominantly blue intensities, indicating poor outcomes across several quality indicators.

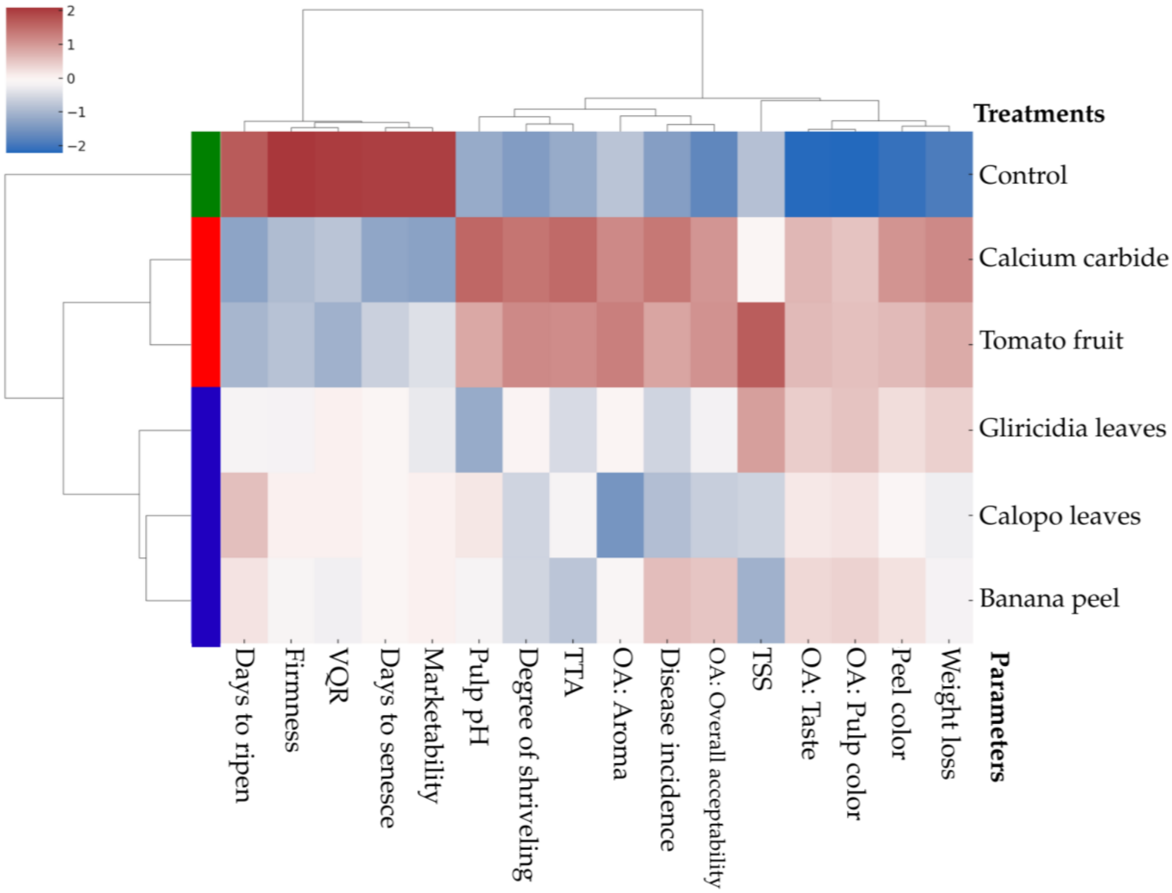

Figure 7. Clustered heatmap of standardized postharvest trait values across six banana ripening treatments, with color-coded clusters.

Color-coded cluster bars adjacent to the rows visually denote the groupings identified in the dendrogram: Cluster 1 (red) includes calcium carbide and tomato fruit; Cluster 2 (blue) includes *Gliricidia* leaves, Calopo leaves, and banana peel; and Cluster 3 (green) includes the control. These clusters underscore the relative efficacy of synthetic and natural treatments in promoting desirable ripening traits. Together, these findings validate the superiority of calcium carbide as a ripening agent while also demonstrating that natural treatments, particularly *Gliricidia,* Calopo, and banana peel, can effectively induce ripening with comparable postharvest quality in certain traits. The clustering results reinforce earlier statistical analyses and highlight the potential of natural alternatives in regions where synthetic ripening agents are restricted or discouraged. This multivariate approach strengthens the study's conclusions by confirming the distinct groupings and performance profiles of the treatments under investigation.

4. Conclusions

This study demonstrated that selected natural ripening agents (*Gliricidia* leaves, Calopo leaves, tomato fruit, and banana peels) can serve as effective alternatives to CaC_2 in inducing ripening in 'Latundan' bananas. While CaC_2-treated fruits reached full ripeness more rapidly, this accelerated ripening also led to earlier senescence and reduced marketable shelf life. In contrast, the natural agents produced comparable ripening-related quality attributes while mitigating the health and safety concerns associated with chemical agents. Among the treatments, tomato fruit showed consistent performance across physical, chemical, and sensory parameters, underscoring its practical potential in both small-scale and commercial applications. The more gradual ripening induced by these natural agents offers a favorable balance between timely ripening and extended shelf life, which is critical for marketability. Furthermore, the use of HCA provided a robust multivariate framework for classifying treatments based on overall fruit quality, which enables a more holistic assessment of ripening outcomes. This integrative approach reinforces the potential of natural ripening agents to promote safer, cost-effective, and more sustainable postharvest management. Future research should explore the biochemical pathways involved, consumer perception, and economic feasibility to further support the adoption of these alternatives in banana supply chains.

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