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Interactive Effects of Chemical Ripening and Moisture Management on Physicochemical Quality of Raja Banana (*Musa* spp.)

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ABSTRACT

Raja banana (*Musa spp.*) is a climacteric fruit whose postharvest quality is strongly influenced by ripening-induced physicochemical changes, particularly in sugar and acid metabolism. Effective ripening management is therefore essential to balance fruit quality, shelf life, and market readiness. This study evaluated the effects of calcium carbide and silica gel treatments, combined with storage duration, on the physicochemical quality of Raja banana. Mature-green fruits were subjected to calcium carbide (1 g and 2 g) and silica gel (2 g and 4 g) treatments and stored at ambient temperature for up to six days. Total Dissolved Solids (TDS), relative TDS increase, total titratable acidity, and sugar–acid ratio were analyzed to assess ripening progression. The results showed that all treatments exhibited significant physicochemical changes during storage ($p < 0.05$), although the magnitude varied substantially. Calcium carbide significantly accelerated ripening, as indicated by higher TDS accumulation; the 2 g treatment reached 26.33 ± 3.78 °Brix, with the highest relative TDS increase (777.7%) and the highest sugar–acid ratio (26.84 ± 7.77) by day 6. In contrast, silica gel treatments delayed ripening, particularly at 4 g, maintaining the lowest final TDS (18.00 ± 1.00 °Brix) and a lower sugar–acid ratio while preserving relatively stable acidity. These findings demonstrate that calcium carbide promotes rapid ripening by accelerating carbohydrate metabolism, whereas silica gel delays physiological maturation by altering the storage microenvironment. This study provides cultivar-specific evidence for Raja banana and offers practical implications for optimizing postharvest ripening strategies according to supply chain requirements.

KEY WORDS: Raja banana; calcium carbide; silica gel; postharvest ripening; total dissolved solids; sugar-acid ratio

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1. INTRODUCTION

Banana (*Musa* spp.) is one of the most widely cultivated and economically significant fruit commodities in tropical and subtropical regions, playing an essential role in food security, rural livelihoods, and horticultural trade. In Indonesia, bananas represent an important agricultural commodity due to their widespread cultivation, consumer demand, and versatility for both fresh consumption and processed food applications. Among the numerous cultivars, Raja banana is particularly appreciated for its distinctive sensory attributes, including its characteristic aroma, soft yet cohesive pulp texture, and balanced sweetness-to-acidity profile, making it highly desirable for direct consumption as well as traditional culinary uses (Kumar et al., 2023). As a climacteric fruit, the banana undergoes rapid physiological and biochemical transformations during ripening, primarily regulated by increased ethylene production and respiration activity (Xia et al., 2020). These processes include chlorophyll degradation leading to peel color changes, enzymatic breakdown of cell wall polysaccharides causing tissue softening, hydrolysis of starch into soluble sugars that enhance sweetness, depletion of organic acids through respiratory metabolism, and synthesis of volatile compounds responsible for characteristic aroma development(Ghosh et al., 2016). While these transformations improve sensory acceptability and marketability, they simultaneously accelerate senescence and postharvest deterioration, thereby limiting storage life and increasing economic losses.

To manage these challenges, various postharvest interventions have been developed to either accelerate or delay ripening depending on supply chain requirements. One of the most commonly applied methods in commercial practice is the use of CaC_2 as an artificial ripening agent due to its affordability, accessibility, and ease of application (Ogo et al., 2024). In the presence of moisture, CaC_2 generates acetylene gas, which mimics the physiological action of ethylene and stimulates ripening-associated metabolic responses (Gomes et al., 2023a). Although effective in accelerating fruit maturation and synchronizing ripening, concerns persist regarding its potential effects on fruit quality, ripening uniformity, and consumer safety. In contrast, passive storage-based strategies aimed at delaying ripening have gained increasing attention (Neo et al., 2025). Silica gel, a hygroscopic desiccant material, has been investigated for its ability to absorb moisture and modify the storage microenvironment by reducing relative humidity, thereby potentially suppressing respiration activity and slowing ethylene-mediated ripening processes (Ramiro et al., 2024a). Such low-cost and technically simple interventions are particularly relevant for practical postharvest management in developing agricultural systems (Tripathy et al., 2025).

Evaluation of ripening progression and postharvest quality commonly relies on physicochemical indicators that reflect metabolic changes and consumer acceptability. Total Dissolved Solids (TDS) serves as an indirect indicator of soluble sugar accumulation and sweetness development, while total titratable acidity reflects the concentration of organic acids that contribute to flavor complexity and metabolic status (Yang et al., 2021). The sugar-acid ratio integrates these two quality dimensions and is widely considered an important indicator of flavor balance and overall fruit palatability (Milosavljević et al., 2023). Monitoring these parameters provides valuable insights into the effects of postharvest treatments on the evolution of fruit quality during storage.

Although postharvest ripening management in bananas has been extensively investigated, the existing body of literature has primarily emphasized general ripening physiology, ethylene-induced maturation, and broad quality changes across commercially dominant banana cultivars, with comparatively limited attention to cultivar-specific responses in local varieties such as Raja banana (Maduwanthi & Marapana, 2019; Moreno et al., 2021; Ramírez-Sánchez et al., 2018). Previous studies have demonstrated that CaC_2 effectively accelerates ripening through acetylene-mediated ethylene-like activity, leading to changes in respiration rate, starch degradation, sugar accumulation, and acidity modulation (Gomes et al., 2023b; Hussain et al., 2024). Similarly, moisture-control approaches, including desiccant-based storage systems such as silica gel, have been explored for their potential to regulate the storage microenvironment, reduce excess moisture accumulation, and delay quality deterioration during postharvest handling (Bradford et al., 2018; Sunita et al., 2024). However, these investigations have largely examined each intervention independently rather than through direct comparative evaluation within a unified experimental framework. Furthermore, most prior research has focused on general quality attributes such as color development, firmness loss, weight reduction, and overall shelf life, while comparatively fewer studies have specifically examined the dynamic interplay between total dissolved solids, total titratable acidity, and sugar-acid ratio as integrated indicators of ripening quality. An additional limitation is the insufficient consideration of storage duration as an interacting factor, despite its critical role in determining metabolic progression and physicochemical transformations during ripening. Consequently, the differential effectiveness of ripening acceleration (CaC_2) versus moisture-control intervention (silica) in modulating the physicochemical quality trajectory of Raja banana remains inadequately understood. Addressing this gap, the present study comparatively evaluates the effects of CaC_2 treatment and storage duration on key physicochemical quality parameters of Raja banana to generate cultivar-specific evidence for optimizing postharvest ripening management strategies.

2. MATERIALS AND METHODS

2.1. Plant Material and Experimental Design

Mature-green Raja bananas (*Musa* spp.) were harvested from a commercial farm [Semarang, Central Java, Indonesia]. Fruits were selected for uniformity in size, shape, physiological maturity (approximately 85-90% maturity), and the absence of physical defects or fungal contamination. After harvest, fruits were transported under ambient conditions (~26°C, 65-75% RH) to the Food Processing Laboratory, Faculty of Animal and Agricultural Sciences, Universitas Diponegoro.

The study employed a completely randomized design (CRD) with four postharvest treatment groups and four sampling intervals (0, 2, 4, and 6 days). The treatment groups included T1: CaC_2 1 g per treatment; T2: CaC_2 2 g per treatment; T3: Silica gel 2 g per treatment; T4: Silica gel 4 g per treatment. Each treatment was replicated three times, with each replicate consisting of three banana fingers placed in ripening chambers (plastic containers, 30 × 20 × 15 cm). CaC_2 and silica gel were enclosed in perforated paper sachets and placed in the chamber without direct contact with the fruit. All fruits were stored at ambient temperature (26±2°C) and monitored under controlled room conditions without additional light or airflow.

2.2. Measurement of Total Dissolved Solids (TDS)

TDS was measured using a digital handheld refractometer (Atago PAL-1, Japan). Approximately 2-3 mL of juice was extracted from the homogenized pulp and placed on the refractometer prism. The TDS value was recorded in degrees Brix (°Brix) and measured in triplicate.

2.3. Determination of Total Titratable Acidity

Total titratable acidity (TTA) was determined following AOAC (2005) guidelines. A 10 g portion of banana pulp was homogenized with 50 mL distilled water, filtered, and titrated with standardized 0.1 N NaOH using phenolphthalein as an indicator. Results were expressed as a percentage of citric acid equivalents (% citric acid).

2.4. Calculation of Sugar-Acid Ratio

The sugar–acid ratio was calculated as the quotient of TDS (°Brix) and total acidity (% citric acid), providing a dimensionless index that reflects the sweetness-to-acidity balance, which is a critical sensory parameter in banana quality evaluation.

2.5. Statistical Analysis

All data were analyzed using SPSS statistical software (IBM Corp., Armonk, NY, USA) via analysis of variance (ANOVA). When significant differences were found ($p < 0.05$), treatment means were compared using Duncan's Multiple Range Test (DMRT). Data are presented as mean ± standard deviation (SD). Differences among means were considered significant when $p < 0.05$.

3. RESULTS

3.1. Total Dissolved Solids (TDS)

The Total Dissolved Solids (TDS) of Raja banana increased significantly throughout storage across all treatments ($p < 0.05$), indicating progressive ripening and the conversion of starch reserves into soluble sugars. As presented in Table 1, bananas treated with CaC_2 exhibited a more rapid accumulation of TDS compared with silica gel-treated fruits. The highest absolute TDS value was observed in the 2 g CaC_2 treatment, reaching 26.33 ± 3.78 °Brix on day 6, followed by the 1 g CaC_2 treatment at 24.00 ± 1.00 °Brix. In contrast, silica gel treatments resulted in lower TDS accumulation, with the 4 g silica gel treatment showing the lowest final value (18.00 ± 1.00 °Brix). Statistical analysis confirmed significant differences among treatments and storage periods ($p < 0.05$).

Table 1: Total Dissolved Solids (TDS) of Raja Banana During Storage

Treatment	Day			
	0	2	4	6
CaC_2 1 gr	$3.33±1.53^{aD}$	$17.00±4.36^{aC}$	$22.67±0.57^{aB}$	$24.00±1.00^{aA}$
CaC_2 2 gr	$3.00±1.00^{aD}$	$16.67±1.53^{aC}$	$22.00±2.00^{aB}$	$26.33±3.78^{aA}$
Silica 2 gr	$4.00±0.00^{bD}$	$13.67±1.15^{bC}$	$19.67±2.08^{bB}$	$21.33±0.57^{bA}$
Silica 4 gr	$2.33±0.57^{cD}$	$11.67±4.04^{cC}$	$15.00±1.73^{cB}$	$18.00±1.00^{cA}$

*Data are presented as mean ± standard deviation (n = 3). Different superscripts in the same column and row indicate significant differences ($p < 0.05$) between treatments (lowercase) and days (uppercase).

To further illustrate the ripening progression, the relative increase in TDS from the initial storage condition was calculated (Table 2). The CaC_2 treatments showed the greatest proportional increase, with the 2 g treatment exhibiting the highest rise (777.7%) by day 6, followed by the 1 g treatment (620.7%), confirming the strong acceleration of carbohydrate metabolism under CaC_2 exposure. The silica gel treatments showed comparatively lower increases, particularly the 2 g treatment (433.3%), indicating slower ripening progression. Although the 4 g silica gel treatment exhibited a relatively high percentage increase (672.5%), this should be interpreted cautiously, as the initial TDS in this treatment was substantially lower, mathematically amplifying the relative change despite the lower absolute final TDS. Collectively, these findings indicate that CaC_2 accelerated sugar accumulation more effectively, whereas silica gel delayed the ripening process by suppressing the rate of TDS increase.

Table 2: Relative Increase in Total Dissolved Solids (TDS) of Raja Banana during Storage

Treatment	Day 2 (%)	Day 4 (%)	Day 6 (%)
CaC_2 1 g	410.5	580.8	620.7
CaC_2 2 g	455.7	633.3	777.7
Silica 2 g	241.8	391.8	433.3
Silica 4 g	400.8	543.8	672.5

3.2. Total Titratable Acidity

Total titratable acidity showed a general decreasing trend during storage, particularly in CaC_2-treated bananas (Table 3). The 1 g and 2 g CaC_2 treatments decreased from 1.66 ± 0.27% and 1.94 ± 0.06% at day 0 to 0.96 ± 0.28% and 1.02 ± 0.18% at day 6, respectively. Meanwhile, silica gel-treated fruits maintained relatively stable acidity levels throughout storage, ranging between 1.01% and 1.30%. No substantial fluctuations were observed in the silica gel groups compared with those in the CaC_2 treatments. Statistical analysis indicated that storage duration significantly influenced the reduction in acidity in CaC_2-treated bananas ($p < 0.05$).

Table 3: Total Acid of Raja Banana between Treatments

Treatment	Day			
	0	2	4	6
CaC_2 1 gr	$1.66{\pm}0.27^{aA}$	$1.32{\pm}0.16^{aAB}$	$1.10{\pm}0.33^{aB}$	$0.96{\pm}0.28^{aB}$
CaC_2 2 gr	$1.94{\pm}0.06^{aA}$	$1.40{\pm}0.41^{aAB}$	$1.30{\pm}0.12^{aB}$	$1.02{\pm}0.18^{aB}$
Silica 2 gr	$1.10{\pm}0.07^{aA}$	$1.11{\pm}0.10^{aAB}$	$1.01{\pm}0.09^{aB}$	$1.27{\pm}0.55^{aB}$
Silica 4 gr	$1.33{\pm}0.55^{aA}$	$1.30{\pm}0.55^{aAB}$	$1.29{\pm}0.54^{aB}$	$1.27{\pm}0.52^{a}$

*Data are presented as mean ± standard deviation (n = 3). Different superscripts in the same column and row indicate significant differences ($p < 0.05$) between treatments (lowercase) and days (uppercase).

3.3. Sugar-Acid Ratio

The sugar-acid ratio increased progressively throughout storage in all treatments, reflecting the combined effects of sugar accumulation and acid degradation during ripening (Table 4). CaC_2 treatments produced the highest sugar-acid ratios, with final values of 26.51±7.34 and 26.84±7.77 for the 1 g and 2 g treatments, respectively. In contrast, silica gel-treated bananas exhibited lower sugar–acid ratios, particularly the 4 g silica gel treatment, which reached only 16.31 ± 7.88 by day 6. Significant differences among treatments were observed ($p < 0.05$), indicating that postharvest treatment strongly affected flavor development and ripening progression.

Table 4: Sugar Acid Ratio of Raja Banana Between Treatments

Treatment	Day			
	0	2	4	6
CaC_2 1 gr	$3.15{\pm}1.34^{aC}$	$13.05{\pm}4.02^{aB}$	$22.78{\pm}8.74^{aA}$	$26.51{\pm}7.34^{aA}$
CaC_2 2 gr	$1.56{\pm}0.56^{aC}$	$12.77{\pm}4.28^{aB}$	$17.59{\pm}3.36^{aA}$	$26.84{\pm}7.77^{aA}$
Silica 2 gr	$3.79{\pm}0.25^{abC}$	$12.37{\pm}0.70^{abB}$	$19.51{\pm}2.63^{abA}$	$18.75{\pm}6.72^{abA}$
Silica 4 gr	$1.96{\pm}0.82^{bC}$	$9.26{\pm}1.11^{bB}$	$13.12{\pm}5.45^{bA}$	$16.31{\pm}7.88^{bA}$

*Data are presented as mean ± standard deviation (n = 3). Different superscripts in the same column and row indicate significant differences ($p < 0.05$) between treatment (lower case) and day (upper case).

4. DISCUSSION

The present study demonstrates that postharvest treatment substantially influenced the ripening kinetics and physicochemical quality of Raja banana, as evidenced by changes in total dissolved solids (TDS), total titratable acidity, and sugar-acid ratio during storage. The inclusion of both absolute TDS values and relative TDS increase provides a more comprehensive understanding of ripening progression, allowing interpretation not only of the final physicochemical state but also of the metabolic rate at which ripening occurred under different postharvest interventions.

The increase in TDS across all treatments confirms the expected progression of ripening in climacteric fruits, where starch reserves are progressively hydrolyzed into soluble sugars, including glucose, fructose, and sucrose (Nicolaï et al., 2023; Wu et al., 2025). However, the magnitude and rate of this transformation varied substantially depending on treatment conditions. Based on the absolute values (Table 1), CaC_2-treated bananas consistently exhibited the highest TDS accumulation, particularly at the 2 g dosage, which reached 26.33±3.78°Brix by day 6. This indicates a rapid transition toward advanced ripening characterized by enhanced sweetness and increased metabolic activity. The relative increase data (Table 2) further strengthen this observation, with the CaC_2 2 g treatment showing the highest proportional increase in TDS (777.7%), followed by the 1 g treatment (620.7%). These findings indicate that CaC_2 not only increased the final sugar concentration but also accelerated the kinetics of carbohydrate conversion.

This acceleration can be explained by the mechanism of CaC_2 as an artificial ripening inducer (Cissé et al., 2020). Upon exposure to moisture, CaC2 generates acetylene gas, which acts as an ethylene analogue in climacteric fruits. Ethylene signaling plays a central role in coordinating ripening by activating transcriptional and enzymatic pathways involved in carbohydrate metabolism, cell wall softening, pigment transformation, and volatile synthesis (Tipu & Sherif, 2024a). The stronger response at the higher CaC_2 concentration suggests a dose-dependent effect, in which greater acetylene availability intensifies ethylene-mediated ripening metabolism (Gomes et al., 2023c).

In contrast, silica gel treatments delayed TDS accumulation, as shown by lower absolute final values and reduced proportional increases, particularly in the 2 g treatment. This indicates slower ripening progression and reduced metabolic turnover. Silica gel functions differently from CaC_2, not as a direct ripening stimulant but as an environmental modifier that alters storage microclimate through moisture adsorption (Han et al., 2021). By reducing relative humidity, silica gel may suppress endogenous ethylene biosynthesis, impair ethylene diffusion, and reduce tissue hydration required for enzymatic activity, collectively slowing carbohydrate metabolism (Alonso-Salinas et al., 2024). Interestingly, the 4 g silica gel treatment exhibited a relatively high proportional increase in TDS (672.5%) despite producing the lowest final absolute TDS value. This apparent contradiction reflects a mathematical limitation of percentage-based normalization: the very low baseline TDS value (2.33°Brix) amplifies relative changes despite slower physiological progression. Therefore, relative increase metrics should be interpreted alongside absolute values to avoid overestimating biological effects. Nevertheless, the consistently lower final TDS values in silica gel treatments confirm their inhibitory effect on ripening.

Changes in total titratable acidity further reinforce the contrasting physiological responses induced by the treatments. The marked decline in acidity observed in CaC_2-treated bananas reflects accelerated organic acid catabolism, a characteristic feature of climacteric ripening. Organic acids function as substrates in respiratory metabolism and are progressively consumed through the tricarboxylic acid cycle to meet the increasing energy demands associated with fruit maturation (Batista-Silva et al., 2018). Enhanced ethylene-like stimulation likely intensified respiration, leading to faster acid depletion (Tipu & Sherif, 2024b). Conversely, silica gel-treated fruits maintained relatively stable acidity throughout storage, suggesting suppression of respiratory activity and delayed metabolic maturation. The preservation of acidity during silica gel treatment supports the hypothesis that reduced humidity slows physiological aging by limiting metabolic turnover rather than directly altering fruit biochemistry (Prange et al., 2025).

The sugar-acid ratio provides an integrated indicator of flavor development because it reflects the balance between sweetness and acidity, two primary determinants of sensory acceptability in fruit (Qiao et al., 2017). In the present study, CaC_2 treatments produced substantially higher sugar-to-acid ratios than silica gel treatments, indicating a faster progression toward commercially desirable eating quality. This increase was driven by the combined effect of rapid sugar accumulation and accelerated acid degradation. From a sensory perspective, a higher sugar-acid ratio is generally associated with sweeter taste perception, reduced sourness, and greater consumer acceptability (Mao et al., 2024). In contrast, the lower ratios observed in silica gel-treated bananas indicate delayed flavor maturation and the retention of a less-ripe physicochemical profile. This distinction is particularly relevant in postharvest management, where flavor optimization and shelf-life extension often compete (Ghandehari-Alavijeh et al., 2024).

Taken together, the contrasting responses observed between CaC_2 and silica gel treatments represent two fundamentally different postharvest intervention strategies, active ripening induction versus passive ripening suppression. CaC_2 promotes rapid physiological maturation through hormone-like biochemical stimulation, making it effective when immediate market readiness and accelerated turnover are desired (Gomes et al., 2023d). However, its practical use remains contentious due to food safety concerns associated with potential impurities such as arsenic and phosphine residues, which may compromise consumer safety and regulatory compliance (Freitas et al., 2021). In contrast, silica gel offers a non-hormonal, low-technology alternative for delaying ripening by modifying storage conditions, thereby extending shelf life and preserving physicochemical stability (Ramiro et al., 2024b).

Importantly, this study provides cultivar-specific evidence for Raja banana, a locally important cultivar for which comparative postharvest data remain limited. Ripening behavior can vary substantially among banana cultivars due to differences in starch composition, ethylene sensitivity, respiration intensity, and biochemical regulation. Therefore, the present findings contribute valuable insight into the postharvest physiology of Raja banana and provide a scientific basis for selecting ripening management strategies tailored to specific supply chain objectives. From a practical standpoint, CaC_2 may be suitable for short distribution chains requiring rapid ripening, whereas silica gel may offer greater utility for extended storage, transportation, and postharvest loss reduction.

5. CONCLUSION

This study demonstrated that postharvest treatment significantly influenced the physicochemical ripening behavior of Raja banana during storage. Calcium carbide accelerated ripening by promoting rapid sugar accumulation, reducing titratable acidity, and increasing the sugar–acid ratio, with the 2 g treatment showing the strongest ripening effect. In contrast, silica gel delayed ripening progression by suppressing total dissolved solids accumulation, maintaining relatively stable acidity, and producing lower sugar–acid ratios, particularly at the 4 g treatment level. These findings highlight the contrasting roles of active ripening induction and passive moisture management in modulating fruit quality. The study provides cultivar-specific evidence for Raja banana and offers practical guidance for selecting postharvest strategies based on market readiness or shelf-life extension objectives. Further research should evaluate sensory quality, safety aspects, and storage performance under broader commercial conditions.

6. CONFLICTS OF INTEREST

The authors declare no competing financial interests or conflicts of interest relevant to this work.

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