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Comparative evaluation of postharvest treatment efficacy in trimmed coconuts using citric acid, sodium chloride, and peroxyacetic acid

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ABSTRACT

The shelf life of trimmed aromatic coconuts is limited by enzymatic browning and microbial growth after husk removal. Although chemical treatments can delay these deteriorative processes, their application in fresh produce is constrained by regulatory and consumer safety considerations. This study evaluated and compared the effects of citric acid (CA), sodium chloride (NaCl), and peroxyacetic acid (PAA) on the quality and microbial stability of trimmed coconuts during 15 days into the storage room at 5-8°C. Before packaging, coconuts were immersed for 5 minutes in CA solutions (10% and 20%), NaCl solutions (10% and 20%), and PAA solution (80 ppm), while untreated samples served as the control. Throughout the storage period, visual quality and color parameters (L*, a*, b*) were assessed. Additionally, the total soluble solids (TSS), pH, titratable acidity (TA), total plate count, and yeast and mold count of the homogenized coconut water and meat mixture were analyzed to evaluate changes in chemical composition and microbial quality. Treatments with 20% CA and 20% NaCl significantly ($P < 0.05$) reduced microbial growth and effectively maintained visual quality and color throughout storage. In contrast, PAA treatment exhibited only short-term antimicrobial effects (up to six days) and led to rapid discoloration thereafter. These results indicate that citric acid, particularly at 20%, is the most effective among the tested treatments for preserving the visual, physicochemical, and microbiological quality of trimmed coconuts under refrigerated conditions.

Keywords: Trimmed coconut, Shelf-life extension, Citric acid, Sodium chloride, Peroxyacetic acid

INTRODUCTION

Aromatic coconuts (*Cocos nucifera* L.) are a distinct variety of young coconuts cultivated primarily in Thailand and valued for their naturally sweet, fragrant water and tender endosperm. This cultivar belongs to the dwarf coconut group and is commonly referred to as the *Nam Hom* variety [1]. It plays a significant role in Thailand's export economy due to its premium sensory quality and consumer demand in international markets. The characteristic aroma, present in both the coconut water and endosperm, is attributed to volatile compounds such as 2-acetyl-1-pyrroline, which are also found in pandan (*Pandanus amaryllifolius*) leaves [2]. Trimmed aromatic coconuts, produced by removing the outer husk and shaping the shell into a cylindrical or diamond form, are increasingly popular in foreign markets due to their convenience, reduced transportation costs, and attractive appearance [3]. However, removal of the outer exocarp accelerates microbial spoilage and enzymatic browning, thereby shortening shelf life. These deteriorative changes negatively affect sensory quality and nutritional value, underscoring the need for effective postharvest preservation strategies.

Chlorine- and sulfite-based compounds, such as sodium hypochlorite, calcium hypochlorite, sodium metabisulfite, and sulfur dioxide gas, have been traditionally used to extend the shelf life of trimmed coconuts. However, these agents are associated with adverse health effects, including allergic reactions [4-6]. Consequently, the use of sulfites has been prohibited, and chlorine residuals in wash water are now restricted to 4 ppm [7], reinforcing the need to

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identify safe and effective alternatives for maintaining coconut quality.

Several alternative treatments have been investigated for their potential to replace sulfites in fresh produce preservation, including ascorbic acid [8], calcium chloride ($CaCl_2$) [9], sodium chlorite [10], and combinations of sanitizers and inhibitors such as acidic electrolyzed water, peracetic acid (PAA), and chlorine [11]. Among these, citric acid (CA) and sodium chloride (NaCl) are recognized as safe and effective agents for preserving fresh-cut fruits and vegetables [3, 12, 13]. Citric acid acts as a copper-chelating agent that inhibits polyphenol oxidase (PPO) activity by sequestering its metal cofactor [10], while NaCl inhibits PPO by modifying the enzyme's active site through halide binding [10]. Thus, both compounds can effectively reduce discoloration and extend shelf life in fresh-cut produce.

Despite their advantages, the performance of these chemical agents can be influenced by product surface condition, potential off-flavors, and variable antimicrobial efficacy [10]. Peracetic acid (PAA), a mixture of acetic acid (CH_3COOH) and hydrogen peroxide (H_2O_2), exhibits strong antimicrobial activity and has emerged as a promising alternative to chlorine-based disinfectants for fresh produce sanitation [14]. However, limited information is available on the comparative efficacy of CA, NaCl, and PAA in preserving the microbiological quality and color stability of trimmed coconuts.

Therefore, this study aimed to systematically evaluate and compare the effects of CA, NaCl, and PAA on the color stability, physicochemical attributes, and microbial quality of trimmed aromatic coconuts during refrigerated storage. This study presents new comparative data showing that 10–20% CA, 10–20% NaCl, and 80 ppm PAA treatments effectively extend the shelf life of coconuts while maintaining safety and sensory acceptability, offering practical alternatives to conventional chlorine- and sulfite-based methods.

MATERIALS AND METHODS

1. Sample preparation

Aromatic coconuts (*Cocos nucifera* L., "*Nam Hom*" variety) were harvested from a commercial plantation in Ban Phaeo District, Samut Sakhon Province, Thailand, at 6–8 months after inflorescence emergence [15]. A total of 120 fruits (approximately 1,200–1,500 g each) of uniform size and maturity were selected. The basal end of each fruit was trimmed to form a stable base. The coconuts were then inverted, and the outer husk (pericarp) was removed by slicing at an angle to expose the mesocarp and create a conical apex (Figure 1). Figure 1 illustrates a representative trimmed coconut prepared for treatment and storage. Each coconut served as an independent experimental unit. For each treatment and sampling day, three coconuts were randomly selected for analysis, and each measurement was performed in triplicate to ensure reproducibility.

Figure 1 Showed a conical coconut that has been trimmed and placed at the summit of the fruit.

2. Pre-treatment with chemical soaking process

Chemical pretreatments consisted of citric acid (CA) at 10% and 20% (w/v), sodium chloride (NaCl) at 10% and 20% (w/v), and peroxyacetic acid (PAA) at 80 ppm. Immediately after trimming, coconuts were immersed in the respective treatment solution for 5 minutes at room temperature, following Nguyen et al. [16] with minor modifications. After immersion, each fruit was rinsed with ~500 mL of tap water for 10 seconds to remove excess surface solution while minimizing dilution of active residues. The coconuts were then blotted dry with sterile paper towels, wrapped in polyvinyl chloride (PVC) film, and stored at 5°C and 80–90% relative humidity. Untreated coconuts served as controls. Quality assessments were performed every 3 days intervals for 15 days.

3. Monitoring quality changes during storage

Coconuts were analyzed for weight loss, color, pH, total soluble solids (TSS), titratable acidity (TTA), and microbial load. The experiment followed a completely randomized design (CRD) with three replications (one coconut per replicate per sampling time).

3.1 Weight loss

Samples of trimmed coconuts that had been immersed in chemical solutions to extend shelf life were collected and packaged in polyvinyl chloride (PVC) film. These treated samples were compared with control coconuts, which did not receive any chemical treatment. Initial and subsequent weights of each coconut were recorded at each sampling interval. Weight loss (%) was calculated using the recorded weights according to Equation (1). The percentage of weight loss (%) was determined using the following formula:

$$\text{Weight Loss (\%)} = \left[\frac{W_i - W_s}{W_i}\right] \times 100 \qquad (1)$$

Where, W_i is initial weight, W_s is weight after storage of sample.

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By comparing the sample's initial weight to its weight after storage, this formula determines the percentage of weight loss that occurred during storage.

3.2 The measurement of the pH and TSS in coconut flesh meat and water mixture.

The coconuts were opened, and coconut water and flesh were combined in a sterile stainless-steel bowl. The mixture was homogenized with a handheld immersion blender. TSS was measured with a refractometer (Atago N-1E, Japan) and expressed in °Brix. The pH was measured using a pH meter (Mettler Toledo FE20, USA).

3.3 Determination of total acidity (TA)

A 10 g aliquot of the homogenized mixture was titrated with 0.1 N NaOH following AOAC [17]. Results were expressed as grams of malic acid equivalent per 100 g of fresh weight:

$$\text{Titratable Acidity (\%)} = \left[\frac{A \times B \times 0.067}{C}\right] \times 100 \qquad (2)$$

where A = NaOH concentration, B = NaOH volume (mL), and C = sample volume (mL).

3.4 Color measurement

Color of the mesocarp surface was measured using a colorimeter (Konica Minolta CR-400, Japan) at 10 locations per fruit. L*, a*, and b* values were recorded, and the browning index (BI) was calculated as:

$$BI = \left[\frac{X-0.31}{0.172}\right] \times 100 \qquad (3)$$

$$X=[a^*+1.75L^*]/[5.646L^*+a^*-3.012b^*] \qquad (4)$$

3.5 The determination of the count of the total plate count and yeast and mold count of coconut meat and water

Microbial analysis was conducted following the Bacteriological Analytical Manual [18] using the pour plate technique to determine total plate counts as well as yeast and mold counts. A homogeneous mixture was prepared by combining the coconut meat and coconut water in a sterile stainless-steel container. All materials and tools were sterilized prior to use, and the procedure was performed under aseptic conditions within a laminar flow hood to minimize the risk of microbial contamination. The coconut samples were handled with sterile gloves, and the container was covered during mixing. Homogenization was carried out using a stomacher for 2–3 minutes until a uniform and smooth consistency was achieved. This approach ensured that the mixture was prepared consistently while maintaining sterility for subsequent chemical and microbiological analyses. For total microbial counts, 1 mL of the homogenized sample was pipetted into a sterile petri dish, followed by the addition of 15–20 mL of plate count agar pre-cooled at 40–42°C. The mixture was gently swirled to ensure thorough mixing. Plates were incubated at 37 °C for 48 hours before enumeration. Yeast and mold counts were determined using potato dextrose agar (PDA). A 0.1 mL aliquot of a 1:100 pre-diluted sample was spread evenly onto the surface of PDA plates. Tenfold serial dilutions were prepared using phosphate-buffered saline and distilled water to achieve the desired dilution range. Inoculated PDA plates were incubated at 30 °C for 48 hours before counting. All microbiological analyses were performed in triplicate, with two coconuts randomly selected per treatment to ensure reproducibility and accuracy.

4. Statistical analysis

Statistical analysis was performed using SPSS software. Data was analyzed using a factorial analysis of variance (ANOVA) under a completely randomized design (CRD) to assess the effects of chemical treatments and storage time. Mean comparisons were conducted using Duncan's Multiple Range Test (DMRT) at a 95% confidence level ($P < 0.05$). All experiments were carried out in triplicate to ensure data reliability and reproducibility.

RESULTS AND DISCUSSION

1. Effect of immersion solutions on the physical and chemical properties of trimmed coconuts during storage

A total of 120 aromatic coconuts (*Cocos nucifera* L.) were processed; each fruit represented a statistically independent experimental unit, with three fruits per treatment per sampling day analyzed in triplicate. The effects of immersion treatments on visual quality and physicochemical parameters are summarized in Tables 1 and 3.

Throughout 15 days of refrigerated storage (5 ± 1°C), coconuts treated with CA and NaCl exhibited significantly superior visual quality compared with untreated controls, confirming their effectiveness in mitigating surface browning. Conversely, coconuts treated with PAA showed no improvement and often displayed discoloration similar to the control. On day 0, control samples already appeared darker and more reddish-brown than chemically treated coconuts, suggesting that chemical immersion delayed enzymatic oxidation and enhanced color stability.

Enzymatic browning is a major cause of discoloration in trimmed coconuts, triggered by tissue injury during trimming that exposes the parenchymatous mesocarp to oxygen. Polyphenol oxidase (PPO) and peroxidase (POD) catalyze the oxidation of phenolic compounds into quinones, which polymerize to brown pigments [19]. This reaction depends on oxygen availability and is influenced by temperature and humidity. Such browning not only alters color but also diminishes flavor, texture, and consumer acceptance, accounting for more than 50% of postharvest losses in perishable crops [20]. Therefore, immersion in anti-browning agents such as CA and NaCl effectively retards pigment formation and extends marketable shelf life [21, 22].

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Untreated coconuts exhibited rapid surface discoloration and loss of commercial appeal within 3 days, while those immersed in 10%–20% NaCl solutions maintained acceptable appearance for up to 6 days. The most effective treatment was 20% CA, which preserved both color and quality for 15 days at 5–8 °C. These findings corroborate earlier reports demonstrating that CA and NaCl effectively inhibit enzymatic browning in trimmed coconuts [16, 28] and fresh-cut potatoes [10].

Citric acid and sodium chloride exert anti-browning effects via different biochemical mechanisms. Citric acid lowers tissue pH and chelates the copper cofactor at the active site of PPO, thus suppressing enzyme activity. PPO is most active at pH 6.0–7.0 but becomes inactive below pH 3.0 [24–26]. Consequently, acidification reduces quinone formation and pigment polymerization. Similar inhibitory effects of citric acid on PPO have been observed in sugarcane juice [24], litchi fruit [25], and fresh-cut cabbage [27]. In this study, immersion in 20% CA maintained mesocarp lightness (L^*) and minimized browning index (BI) values over storage, consistent with extended shelf life observed in other acid-treated produce.

Table 1 The appearance of trimmed coconuts treated with various anti-browning compounds was monitored during storage at 5 °C for 15 days.

Sample	0 day	3 days	6 days	9 days	15 days
Control					
10% CA					
20% CA					
10% NaCl					
20% NaCl					
80 ppm PAA					

NaCl has been shown to inhibit PPO activity in various commodities. Zhang et al. [28] reported that PPO activity in two potato cultivars was effectively suppressed by NaCl concentrations exceeding 20 mmol/L. Lim et al. [29] further demonstrated that NaCl interacts directly with the enzyme's structure, particularly at halide-binding sites, altering the conformation of the active site and impairing enzymatic function. In coconut products, Nguyen et al. [16] found that a combination of 15% NaCl and 20% citric acid effectively prevented browning, extending the shelf life of trimmed coconuts up to 8 weeks at 2°C while maintaining marketability and key quality parameters, including color, pH, TA, TSS, and microbial counts. Based on the data in Table 1, immersion of trimmed coconuts in 10% CA was more effective in reducing

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mesocarp browning than treatment with 20% NaCl, indicating that CA is particularly efficient at preserving the visual quality of coconut products during refrigerated storage.

A multivariate analysis of variance (MANOVA) was performed to assess the effects of chemical treatment, storage time, and their interaction on the physicochemical properties of trimmed coconuts, including L*, browning index BI, TSS, TA, and pH. The model demonstrated a strong overall significance for all parameters except TA ($P > 0.05$), indicating that the experimental factors substantially influenced most measured attributes.

The main effect of chemical treatment was highly significant ($P < 0.05$) for L*, BI, TSS, and pH. Treatments with CA and NaCl maintained significantly higher L* values and lower BI compared with the control and PAA treatments, reflecting superior color preservation and reduced enzymatic browning. Similarly, treatment type significantly affected TSS and pH, suggesting that chemical composition and acid–base balance were influenced by the applied solutions. However, there was no significant difference among treatments for TA, indicating that acid levels remained relatively stable regardless of solution type. The main effect of storage time was also highly significant ($P < 0.05$) for L*, BI, TSS, and pH, showing that quality parameters changed markedly over the 15-day storage period. Lightness values declined and BI increased with longer storage, particularly in untreated and PAA-treated samples, indicating progressive browning and deterioration. TSS and pH values also fluctuated significantly with time, reflecting biochemical and microbial changes associated with storage.

A significant interaction between chemical treatment and storage time ($P < 0.05$) was observed for L*, BI, TSS, and pH. Both chemical treatment and storage time significantly influenced the lightness (L*) and browning index (BI) of trimmed coconut husk ($P < 0.05$), as confirmed by the MANOVA results. The main effects of treated solution and storage time were highly significant for both parameters, with very large F values for solution and storage time. Moreover, the interaction between treated solution and storage time was also significant, indicating that the influence of storage duration on color stability depended on the type of chemical treatment applied. As shown in Table 2, coconuts treated with CA and sodium NaCl consistently maintained higher L* values and lower browning index (BI) throughout the 15-day storage period compared with the untreated control and PAA-treated samples, demonstrating greater resistance to enzymatic browning. The highest L* values were observed in coconuts treated with 10% and 20% CA, followed by those treated with 10% and 20% NaCl. Among the NaCl treatments, the 10% NaCl treatment maintained higher L* values (76.29–80.21) and lower BI values (38.05–42.13) than the 20% NaCl treatment, particularly after 6–15 days of storage, indicating better color stability at the lower salt concentration. Consistent with the physicochemical results (Table 3), the 10% CA and 10% NaCl treatments also exhibited smaller changes in TSS and pH compared with the 20% NaCl treatment, confirming their greater effectiveness in preserving the quality of trimmed coconuts during refrigerated storage.

Consistent with the color data, the MANOVA results also showed significant effects of treatment, storage time, and their interaction on TSS and pH (Table 2). As presented in Table 3, all samples exhibited gradual decreases in TSS and TA and concomitant increases in pH during storage, reflecting ongoing metabolic and microbial activities. However, CA- and NaCl-treated coconuts showed a slower decline in TSS and more moderate increases in pH compared with the control and PAA-treated samples. In contrast, PAA-treated coconuts displayed the most pronounced changes in TSS (decreasing to 6.52 °Brix at day 15) and pH (increasing to 6.27), in agreement with their rapid discoloration and high BI values. The MANOVA demonstrate that CA and NaCl treatments, particularly CA, effectively modulated the rates of browning and physicochemical changes during refrigerated storage. These treatments maintained higher lightness, suppressed browning development, and stabilized TSS and pH, thereby preserving the postharvest quality of trimmed coconuts more effectively than the control and PAA treatments.

Table 2 presents the effects of different browning inhibitors and storage durations on the lightness (L*) and browning index (BI) of trimmed coconut husk during refrigerated storage. Both factors significantly affected color parameters ($P < 0.05$). Citric acid and sodium chloride treatments effectively delayed discoloration and maintained higher L* values than the control and peroxyacetic acid (PAA) treatments. Among all treatments, 20% CA consistently achieved the highest lightness and lowest BI, indicating superior inhibition of enzymatic browning. In contrast, PAA-treated samples showed pronounced darkening and the highest BI, confirming limited color stability.

The highest L* values were observed in coconuts treated with 10% and 20% CA solutions, followed by those treated with 10% and 20% NaCl solutions, over the 15-day storage period. Untreated control samples exhibited the lowest L* values, indicating greater discoloration. Samples immersed in 80 ppm PAA displayed significantly lower lightness (62.88–68.11) compared with the other treatments ($P < 0.05$), whereas the L* values for the CA and NaCl treatments ranged from 68.66 to 83.72 (Table 2). These results indicate that PAA was less

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effective at maintaining mesocarp lightness, while CA and NaCl treatments better preserved the visual brightness of trimmed coconuts during refrigerated storage.

Table 2 Effects of different browning inhibitors and storage durations on the lightness (L*) and browning index (BI) of trimmed coconut husk.

Treated solution	Storage time (day)	Lightness (L*)	Browning index (BI, %)
Control	0	84.65±1.20 ^{a}	23.47±2.58 ^{e}
	3	72.90±2.91 ^{d}	56.73±9.21 ^{b}
	6	72.74±2.58 ^{d}	54.90±8.40 ^{b}
	9	69.66±4.77 ^{de}	57.65±13.36 ^{b}
	15	69.79±4.46 ^{de}	61.62±7.81 ^{b}
10% CA	3	82.99±1.37 ^{ab}	27.92±3.25 ^{de}
	6	83.47±1.41 ^{a}	23.11±1.82 ^{e}
	9	80.29±1.77 ^{b}	21.27±1.60 ^{e}
	15	81.03±1.32 ^{b}	20.95±1.60 ^{e}
20% CA	3	83.64±0.94 ^{a}	27.14±2.32 ^{de}
	6	83.69±1.24 ^{a}	23.05±1.42 ^{e}
	9	83.72±1.30 ^{a}	22.84±1.60 ^{e}
	15	82.12±1.79 ^{a}	21.34±1.78 ^{e}
10% NaCl	3	80.21±2.29 ^{ab}	38.06±3.84 ^{c}
	6	79.09±2.75 ^{b}	38.05±9.08 ^{c}
	9	77.03±2.41 ^{b}	38.27±5.69 ^{c}
	15	76.29±2.26 ^{c}	42.13±4.72 ^{bc}
20% NaCl	3	80.42±1.68 ^{b}	34.95±4.08 ^{d}
	6	71.96±3.09 ^{d}	38.72±7.77 ^{d}
	9	74.54±3.76 ^{d}	47.45±5.94 ^{bc}
	15	73.20±2.06 ^{d}	47.81±4.63 ^{bc}
80 ppm PAA	3	68.11±3.11 ^{de}	89.71±11.61 ^{a}
	6	63.42±4.19 ^{e}	97.85±10.09 ^{a}
	9	63.59±3.99 ^{e}	98.86±8.16 ^{a}
	15	62.88±3.32 ^{e}	99.11±33.4 3 ^{a}
F-test value			
Solutions		3.82×10^{4} **	2.07×10^{8} **
Storage time		2.59×10^{4} **	2.07×10^{7} **
Solution * Storage time		2.87×10^{3} **	1.38×10^{7} **
% C.V.		0.147	0.014

Note: The values in the table are expressed as the mean ± standard deviation (S.D.). The means within each column, which are preceded by the same lowercase letter, are not significantly different, as indicated by Duncan's multiple range test ($P<0.05$). ** indicate significance of MANOVA effects at $P < 0.05$.

The results of this study indicate that CA and NaCl were more effective than PAA in inhibiting browning reactions, primarily through suppression of PPO activity. In contrast, PAA not only failed to reduce browning but also appeared to exacerbate it, as evidenced by decreased L* values and increased BI. This effect is likely due to tissue damage caused by PAA, which facilitates the oxidation of phenolic compounds and the release of enzymes from cells. These findings are consistent with previous reports by Wang et al. [11] and Ghidelli et al. [30], who observed that PAA was ineffective in preventing browning in minimally processed persimmons and sliced apples.

The BI of trimmed coconuts that were not immersed in any browning inhibitors increased substantially (23.47–56.73) from day 0 to day 3. Compared to other treatments, coconuts that were immersed in an 80 ppm PAA solution exhibited yellow or light brown hues, resulting in a higher BI. The BI remained consistent throughout 15 days of storage period. The most effective interventions in controlling browning were 10% and 20% CA solutions, which outperformed both NaCl and PAA.

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Table 3 summarizes the effects of different browning inhibitors and storage durations on the TSS, TA, and pH of the coconut water–meat mixture during refrigerated storage. Both treatment type and storage duration significantly influenced these chemical parameters ($P < 0.05$). TSS gradually decreased across all treatments, while TA declined and pH increased with prolonged storage, reflecting ongoing metabolic and biochemical changes. Among treatments, 20% CA best maintained stable TSS and TA values and minimized pH fluctuations, indicating its superior ability to preserve chemical quality compared with NaCl and PAA treatments.

Table 3 Effects of different browning inhibitors and storage durations on the total soluble solids (TSS), titratable acidity (TA), and pH of the coconut water–meat mixture.

Treated solution	Storage time (day)	TSS (°Brix)	TA (%)	pH
Control	0	8.50±0.08 ^{a}	0.09±0.01 ^{a}	5.43±0.10 ^{c}
	3	8.45±0.05 ^{a}	0.06±0.01 ^{b}	5.58±0.08 ^{c}
	6	7.42±0.09 ^{ab}	0.04±0.00 ^{bc}	5.81±0.05 ^{c}
	9	7.01±0.05 ^{ab}	0.03±0.00 ^{c}	6.13±0.10 ^{ab}
	15	6.75±0.10 ^{bc}	0.03±0.00 ^{c}	6.15±0.06 ^{ab}
10% CA	3	8.85±0.05 ^{a}	0.07±0.01 ^{b}	5.64±0.10 ^{c}
	6	7.46±0.10 ^{ab}	0.04±0.00 ^{bc}	5.95±0.07 ^{c}
	9	7.24±0.05 ^{ab}	0.03±0.01 ^{c}	6.53±0.05 ^{a}
	15	6.64±0.05 ^{b}	0.03±0.00 ^{c}	6.62±0.05 ^{a}
20% CA	3	8.45±0.05 ^{a}	0.07±0.01 ^{b}	5.54±0.05 ^{c}
	6	7.42±0.09 ^{ab}	0.04±0.00 ^{bc}	5.67±0.05 ^{c}
	9	7.01±0.05 ^{ab}	0.03±0.00 ^{c}	6.27±0.08 ^{b}
	15	6.75±0.10 ^{bc}	0.03±0.00 ^{c}	6.43±0.10 ^{a}
10% NaCl	3	8.62±0.05 ^{a}	0.06±0.01 ^{b}	5.48±0.05 ^{c}
	6	7.58±0.10 ^{ab}	0.04±0.00 ^{bc}	5.64±0.05 ^{c}
	9	7.24±0.06 ^{ab}	0.03±0.00 ^{c}	6.11±0.10 ^{b}
	15	6.92±0.05 ^{bc}	0.03±0.00 ^{c}	6.23±0.05 ^{ab}
20% NaCl	3	8.36±0.08 ^{a}	0.06±0.01 ^{b}	5.59±0.05 ^{c}
	6	7.52±0.10 ^{ab}	0.03±0.00 ^{c}	5.62±0.05 ^{c}
	9	7.13±0.05 ^{ab}	0.03±0.00 ^{c}	6.16±0.10 ^{b}
	15	6.84±0.05 ^{bc}	0.03±0.00 ^{c}	6.27±0.05 ^{b}
80 ppm PAA	3	8.37±0.05 ^{a}	0.06±0.01 ^{b}	5.24±0.05 ^{c}
	6	7.35±0.05 ^{ab}	0.03±0.00 ^{c}	5.42±0.10 ^{c}
	9	6.97±0.05 ^{bc}	0.03±0.00 ^{c}	6.15±0.05 ^{b}
	15	6.52±0.08 ^{c}	0.03±0.00 ^{c}	6.27±0.05 ^{ab}
F-test value				
Solutions		3.03×10^{3} **	-	1.34×10^{2} **
Storage time		3.53×10^{5} **	-	2.46×10^{3} **
Solution * Storage time		9.45×10^{2} **	-	26.20 **
% C.V.		0.076	-	5.84

Note: The values in the table are expressed as the mean ± standard deviation (S.D.). The means within each column, which are preceded by the same lowercase letter, are not significantly different, as indicated by Duncan's multiple range test ($P<0.05$). ** indicate significance of MANOVA effects at $P < 0.05$.

During refrigerated storage, the TA of the coconut water–meat mixture decreased significantly within the first three days for all treatments, followed by relatively stable values from day 6 to day 15, ranging from 0.03% to 0.07% (Table 3). This rapid early decline is likely associated with metabolism activity and enzyme activity. Quasi-steady state was reached under low-temperature conditions [31]. In parallel, pH values increased gradually throughout storage, indicating progressive degradation of organic acids.

The MANOVA results confirmed that both chemical treatment and storage time significantly affected pH ($P < 0.05$), with a significant interaction between these factors (Table 3). In the control samples,

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pH increased from 5.43 to 6.15 after 15 days, reflecting the loss of acidity and accumulation of basic metabolites during storage [25]. In contrast, CA-treated coconuts maintained lower and more stable pH values, particularly at 20% CA (5.54–6.43), demonstrating the buffering and acidifying effects of citric acid. Citric acid reduces enzymatic browning by lowering tissue pH and chelating metal ions at the active sites of polyphenol oxidase and peroxidase [32, 33]. Sodium chloride treatments exhibited moderate increases in pH, whereas PAA-treated samples showed the largest pH shifts, rising from 5.24 to 6.27 over the storage period. Although PAA is inherently acidic, its antimicrobial action is mainly attributed to strong oxidative activity rather than sustained pH control [12, 34].

The total soluble solids (TSS), titratable acidity (TA), and pH of the coconut water–meat mixture exhibited similar trends across all treatments during refrigerated storage, with no significant differences among chemical treatments ($P > 0.05$) (Table 3). Overall, TSS gradually decreased, TA declined, and pH increased with storage time, indicating progressive metabolic activity and depletion of organic acids. These changes are commonly associated with respiration, enzymatic reactions, and microbial metabolism in fresh-cut fruits [5, 35, 37].

In the control samples, TSS declined from 8.50 to 6.75 °Brix after 15 days, while CA- and NaCl-treated samples showed comparable reductions, with final values ranging between 6.64 and 6.92 °Brix. Similarly, TA decreased rapidly within the first three days and then remained relatively stable at approximately 0.03–0.04%, and pH increased from approximately 5.4–5.6 to 6.1–6.6 across all treatments. These results indicate that the applied chemical treatments did not induce significant differences in the physicochemical quality of the coconut water–meat mixture ($P > 0.05$). This behavior is consistent with previous studies reporting that coconut water quality changes during storage are mainly driven by internal metabolic processes rather than by surface-applied treatments, as the mechanisms governing chemical changes differ between the internal liquid endosperm and the external trimmed tissues [2, 16, 38].

Despite the lack of significant differences in TSS, TA, and pH, the total plate count (TPC) of the coconut water–meat mixture (Table 4) differed significantly among treatments. This discrepancy suggests that while chemical treatments had limited influence on bulk physicochemical parameters within the coconut matrix, they were more effective at controlling microbial proliferation on the product surface and in the surrounding aqueous phase. Citric acid and sodium chloride are known to inhibit microbial growth through pH reduction, osmotic stress, and membrane disruption, whereas peracetic acid exerts transient antimicrobial effects due to its strong oxidative activity [12,34,36]. Consequently, microbial populations responded more sensitively to the applied treatments than did TSS, TA, and pH, explaining why significant differences were observed for TPC but not for the physicochemical properties of the coconut water–meat mixture.

2. The microbiological determinations of trimmed coconuts during storage are influenced by the type and concentration of immersion solutions.

The microbiological quality of trimmed coconuts, measured as total plate count (TPC) and yeast and mold (YM) in the flesh and coconut water, varied according to treatment and storage duration at 5–8°C (Table 4). In untreated control samples, TPC increased from 3.98×10^3 CFU/g at day 0 to 3.16×10^4 CFU/g by day 6. Further microbiological analysis was not conducted at days 9 and 15 due to external deterioration of the coconuts, while YM remained below detection limits (<25 CFU/g) throughout storage.

Coconuts treated with CA exhibited substantially lower microbial counts. For 10% CA, TPC ranged from 29.8 CFU/g on day 3 to 3.16×10^3 CFU/g on day 15, with YM consistently below detection. Similarly, 20% CA maintained low TPC values (25 CFU/g on day 3 to 1.58×10^3 CFU/g on day 15) and YM consistently below detection ($P > 0.05$). NaCl treatments provided moderate microbial control. For 10% NaCl, TPC increased from 31 CFU/g on day 3 to 1.26×10^4 CFU/g on day 9, while YM remained below detection. The 20% NaCl treatment showed TPC values of 39.8 CFU/g on day 3, rising to 7.94×10^4 CFU/g on day 15, with YM remaining <25 CFU/g. Coconuts treated with 80 ppm PAA initially showed low TPC (31.6 CFU/g on day 3) but increased to 6.31×10^4 CFU/g at day 9. YM was not detected in any PAA-treated samples during storage. For several treatments, microbiological assessment was not conducted at later time points (NA) due to severe external deterioration that rendered the coconuts unmarketable.

Citric acid treatments, particularly at 10% and 20%, were the most effective in maintaining low microbial counts and inhibiting yeast and mold proliferation throughout 15 days of storage period. These treatments consistently preserved both the microbiological and sensory quality of trimmed coconuts. Sodium chloride treatments provided moderate microbial control, with 10% and 20% solutions effectively limiting microbial growth, though to a lesser extent than CA. In contrast, peracetic acid initially suppressed microbial proliferation during the first six days of storage; however, its effectiveness declined after day 9, resulting in increased microbial growth. Coconuts treated with PAA ultimately exhibited compromised sensory quality, characterized by dark brown discoloration of the husk, rendering them unacceptable for consumption. These findings highlight the superior efficacy of CA as a postharvest

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treatment for extending the shelf life and preserving the quality of trimmed coconuts.

TPC in trimmed coconuts treated with 20% CA increased only slightly during 15 days of storage at 5–8°C, while coconuts treated with the other solutions showed much greater microbial growth. This trend agrees with earlier reports demonstrating the strong antimicrobial activity of high CA concentrations, particularly in refrigerated fresh produce such as leafy vegetables [39-40]. In leafy vegetables, CA comes into direct contact with leaf and stem tissues and can be absorbed into plant cells, producing immediate antimicrobial and physicochemical effects [39]. In coconuts, however, CA is largely retained in the mesocarp and is unlikely to reach the endosperm because the shell and endocarp form effective diffusion barriers [41]. This limited penetration likely accounts for the absence of significant changes in pH, TA, and TSS of the coconut water–meat mixture following CA treatment. Nevertheless, CA-treated coconuts exhibited reduced microbial growth in the endosperm. This reduction is presumed to be an indirect effect arising from the substantial decrease in surface microbial populations on the mesocarp and shell, which in turn limits microbial ingress into the endosperm via natural openings or microcracks during storage [41-42]. As a result, the initial microbial load in the edible tissues is lower, leading to reduced TPC throughout storage despite the absence of detectable changes in pH, TA, or TSS. The antimicrobial activity of CA is associated with damage to microbial cell membranes, disruption of cellular metabolism, accumulation of undissociated acid within the cell, and subsequent intracellular acidification [43]. Thus, although CA does not readily penetrate coconut tissues, its surface decontamination effect is sufficient to improve the microbiological quality of trimmed coconuts during refrigerated storage.

Table 4 The amount of total plate count (TPC) and yeast and mold (YM) in the flesh meat and coconut water of trimmed coconuts that were stored at 5-8°C while submerged in various chemical solutions.

Treated solution	Storage time (day)	Total plate count (CFU/g)	Yeasts and mold count (CFU/g)
Control	0	3.98×10^3	ND
	3	1.58×10^4	ND
	6	3.16×10^4	ND
	9	NA	ND
	15	NA	< 25
10% CA	3	29.8	ND
	6	79	ND
	9	1.99×10^2	ND
	15	3.16×10^3	< 25
20% CA	3	25	ND
	6	63.1	ND
	9	3.16×10^2	ND
	15	1.58×10^3	< 25
10% NaCl	3	31	ND
	6	5.01×10^2	ND
	9	12.59×10^3	ND
	15	NA	< 25
20% NaCl	3	39.8	ND
	6	3.98×10^2	ND
	9	2.51×10^3	ND
	15	7.94×10^4	< 25
80 ppm PAA	3	31.6	ND
	6	1.28×10^3	ND
	9	6.31×10^4	ND
	15	NA	< 25

Note: NA: Not assessed since external quality fell below the marketability criteria. ND means not detected. When less than 25 colonies were found on the plate, the data were classified as < 25 CFU/g.

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Citric acid has been shown to be more effective than lactic acid in reducing mesophilic bacterial populations, which is attributed to the presence of multiple carboxyl groups (–COOH) that enhance its antimicrobial activity [44]. In the present study, NaCl and PAA demonstrated antimicrobial effects comparable to citric acid; however, their effectiveness was highly dependent on treatment concentration and immersion duration. NaCl inhibits microbial growth primarily by lowering water activity (a_w) through osmotic dehydration, thereby restricting the availability of free water required for microbial metabolism. Growth of yeasts and molds is suppressed at a_w values below 0.60, while most bacteria are unable to proliferate at a_w below 0.91 [45]. Moreover, NaCl concentrations exceeding 8.5% have been reported to inhibit pathogenic bacteria such as *Escherichia coli* O157:H7 [46]. These mechanisms likely contributed to the delayed microbial growth observed in NaCl-treated coconuts during refrigerated storage.

Peracetic acid exerts its antimicrobial action through strong oxidative reactions that disrupt microbial cell membranes and inactivate essential enzymes [47]. Although PAA is recognized as a broad-spectrum disinfectant, its efficacy in reducing native microflora varies according to commodity type, tissue structure, and surface properties [48]. Effective microbial control therefore requires careful optimization of both sanitizer concentration and exposure time [48, 49]. In the present study, PAA suppressed total plate counts for only the first six days of refrigerated storage. In addition, treatment with 80 ppm PAA caused visible surface damage to the coconut, which likely facilitated subsequent bacterial contamination. Similar deterioration of tissue integrity following excessive oxidant exposure has been reported for other fruits [42, 48] (Fan et al., 2008; Petri et al., 2021), emphasizing the need to balance antimicrobial efficacy with the preservation of product surface integrity.

The limited effectiveness of PAA observed in this study may also be associated with insufficient contact time between the sanitizer solution and the coconut surface, underscoring the importance of optimizing treatment parameters to achieve sustained microbial control. Furthermore, non-chemical interventions such as high-intensity ultrasound, blanching [50], and modified atmosphere packaging [25] have been reported to preserve quality attributes and extend the shelf life of minimally processed fruits. These approaches represent promising alternatives for maintaining the microbiological and physicochemical quality of trimmed coconuts during cold storage while minimizing reliance on chemical sanitizers.

CONCLUSIONS

This study demonstrated that chemical pretreatment significantly affects the postharvest quality of trimmed aromatic coconuts stored at 5–8°C. Among the tested treatments, citric acid was consistently more effective than sodium chloride and peroxyacetic acid in suppressing enzymatic browning, maintaining mesocarp lightness, preserving physicochemical attributes, and reducing microbial growth. In particular, the 20% CA treatment resulted in the highest L* values, the lowest browning index, and the lowest total plate counts throughout the 15-day storage period. Sodium chloride provided moderate protection against browning and microbial proliferation but was less effective than citric acid, while peroxyacetic acid showed only short-term antimicrobial effects and was associated with accelerated discoloration, limiting its suitability for prolonged storage. Therefore, immersion in 20% citric acid for 5 min is recommended as an effective postharvest strategy to extend shelf life and maintain the visual, physicochemical, and microbiological quality of trimmed aromatic coconuts under refrigerated conditions. These findings offer practical guidance for improving postharvest handling and enhancing the marketability of fresh coconut products.

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