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Application of the salicylic/low molecular weight chitosan-iodine complex and calcium nitrate for Edaw longan to delay the ripening process and prolong the post-harvest shelf life of fruits

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Abstract. Longan (*Dimocarpus longan*) is a tropical fruit widely cultivated in many Asian countries. However, its short shelf life makes it prone to quality deterioration during storage and transportation, especially during the peak harvest. In this study, we present a pre-harvest treatment method by spraying the mixture of salicylic acid/low molecular weight chitosan-iodine (SA/LMWCS-I_2) complex and $Ca(NO_3)_2$ solution on Edaw longan trees during fruit setting period to delay fruit ripening and extend the post-harvest shelf life of longan fruits. The SA/LMWCS-I_2 complex was prepared by dissolving LMWCS in SA and subsequently complexing it with an I_2 solution. The formation of a complex between LMWCS and I_2 was confirmed through X-ray diffraction analysis. Experimental results indicated that four pre-harvest treatments with the SA/LMWCS-I_2 complex at concentrations of 260, 325, and 433 mg/L combined with a 5,000 mg/L $Ca(NO_3)_2$ solution delayed the ripening of Edaw longan fruits by 6–10 days. Additionally, these treatments increased fruit weight by 10–15 % compared to the control treatment. Furthermore, the quality of longan fruit treated with the SA/LMWCS-I_2 complex combined with $Ca(NO_3)_2$ solution was improved during post-harvest storage, with a shelf life of 6–8 days at ambient temperature, compared to only 4 days for the control treatment. Thus, pre-harvest application of the SA/LMWCS-I_2 complex mixed with $Ca(NO_3)_2$ solution not only delays fruit ripening, i.e., extends the harvest period but also increases the shelf life of Edaw longan fruits, offering a promising approach to improving economic efficiency in longan production.

Keywords: Edaw longan, iodine, low molecular weight chitosan, pre-harvest, preservation, salicylic acid.

Classification numbers: 1.3.1, 1.4.2, 1.4.5.

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1. INTRODUCTION

Fruit production in agriculture is typically seasonal. A surplus in supply often occurs during harvest time when fruits ripen simultaneously, leading to a significant drop in product prices. Therefore, extending the harvest period not only increases farmers' profitability but also balances supply and demand in agricultural production [1]. Longan (*Dimocarpus longan* Lour.), a common fruit cultivated in Viet Nam [2], experiences a similar situation during its harvest season. This subtropical fruit tree belonging to the Sapindaceae family, thrives in monsoon regions such as China, Taiwan, Thailand, Viet Nam, Laos, Indonesia, Queensland (Australia), and Florida (USA) [3]. The Edaw longan (also known as Edor longan) trees are a Thai-origin variety with a fruit development period of 4–4.5 months and a nearly 12-month gap between harvests. Its yield ranges from 20–30 tons/ha, depending on the tree's age [4]. In Viet Nam, longan trees are cultivated on approximately 800,000 hectares, with an annual production of 600,000 tons. In 2003, longan fruit export revenue reached USD 1.4 million, with major export markets including China, Australia, and Japan [3]. Longan fruits have a sweet flavor and are nutritious. The nutritional composition per 100g of edible longan includes 1.31 g protein, 0.1 g lipid, 15.14 g total carbohydrates, 1.1 g crude fiber, 84 g ascorbic acid, and essential minerals such as calcium, iron, magnesium, manganese, and phosphorus [5].

The Edaw longan has a short harvest season, typically concentrated from late June to early July, which places significant pressure on the market to consume large quantities of fruit within a short time. Its natural shelf life is limited to 5–7 days, posing challenges in transportation and storage, leading to price reductions and lower farmer profits. Therefore, research on the application of novel materials for pre-treatment of Edaw longan to extend the harvest period, enhance fresh fruit quality, and prolong shelf life is expected to provide significant economic benefits for both producers and consumers.

In agriculture, among the materials studied for modulating the physiological properties of crops, chitosan (CS), a biopolymer, has garnered significant attention. CS is biocompatible, biodegradable, antibacterial, non-toxic, and derived from seafood waste such as shrimp and crab shells [6]. Structurally, CS is poly β-(1,4) N-acetyl-d-glucosamine, produced via the deacetylation of chitin [7]. In agriculture, CS serves as a bio-fungicide, bactericide, and antiviral agent while enhancing plant defense mechanisms against pathogens [8, 9]. CS has potential applications in pre-harvest treatment, not only improving the nutritional value of fruits [10, 11] but also delaying the ripening process [12]. Recent studies highlight the effectiveness of combining CS with other compounds, such as Ca^{2+} salt [10], salicylic acid (SA) [13], or CS-SA-Ca^{2+} mixtures [14] for pre-harvest treatments. These methods prolong ripening, enhance hardness, reduce weight loss, improve antioxidant capacity, and maintain fruit quality during storage. Fruit ripening is commonly assessed through parameters like total soluble solids (TSS), starch content, and titratable acidity (TA). During ripening, TSS typically increases, while starch and TA content decline [15]. Kumarihami *et al.* (2021) reported that treating 'Garmrok' kiwifruit three times with CS at 100 and 500 mg/L reduced TSS and maintained significantly higher TA compared to the control treatment at harvest. The treatment also increased fruit weight, inhibited ethylene production, and elevated total polyphenol (TP) and lignin content in cell walls, thereby enhancing fruit pericarp hardness and extending shelf life [12]. Similarly, Ahmed *et al.* (2022) found that pre-harvest treatments of date palm fruits with 3 % Ca^{2+} salt or a 1 % CS-2 mM SA mixture resulted in lower TSS content and significantly higher TP content than the control treatment at harvest [14]. In another study by Cui *et al.* (2020), pre-harvest treatment of apricots with chitosan oligosaccharide (COS) or COS-SA delayed on-tree ripening by reducing TSS and increasing TA.

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Furthermore, post-harvest treated apricots exhibited a slower deterioration rate, reduced browning, and enhanced antioxidant capacity due to the increased production of antioxidant-related enzymes [16].

SA is a plant phytohormone that regulates various physiological and biochemical processes, particularly during fruit ripening and senescence. SA influences ethylene production, color, and the activity of enzymes responsible for flavor-specific compounds. Recent studies have revealed that exogenous SA application can alter numerous physiological and aging processes in plants, including the activation of antioxidant enzymes, regulation of metabolic pathways, reduction of water loss, enhancement of hardness, and maintenance of product quality during storage [17]. Studies have demonstrated that pre-harvest treatment with SA delays ripening extends post-harvest shelf life, and preserves fruit quality on several crops like grapes [18], strawberries [19], apples [20], raspberries [21], and tomatoes [22]. Despite its relatively low water solubility (2.2 g/L at 25 °C) [23], SA can protonate $–NH_2$ groups, enabling the dissolution of CS in aqueous solutions [24]. Aqueous solutions of CS and SA are known to enhance plant growth, regulate physiological processes, and control plant diseases [24].

In this study, SA was utilized to dissolve low molecular weight chitosan (LMWCS), followed by the formation of a complex with iodine (I_2). The SA/LMWCS-I_2 complex combined with $Ca(NO_3)_2$ was applied as a pre-harvest treatment on Edaw longan trees to regulate physiological processes and delay fruit ripening. The CS-I_2 complex enhances antifungal activity against pathogens affecting both the trees and the longan fruits, creating a safe, disease-free product while reducing microbial-induced fruit decay during storage. CS-I_2 is a colorless, irreversible complex with superior antiseptic and wound-healing properties compared to the polyvinylpyrrolidone-I_2 complex [25, 26]. The CS-I_2 complex has been recognized as a safe chemical that is applicable as an antiseptic solution in medicine and edible coatings for preserving fruits [27, 28]. In our previous research, the COS-I_2 complex demonstrated high *in vitro* efficacy against *Pantoea stewartii*, the pathogen responsible for bronzing disease in Thailand jackfruit. Specifically, at concentrations of 425–500 mg/L, the COS-I_2 complex formed inhibition zones ranging from 5.3 to 13.3 mm, while COS alone showed no direct bactericidal effect at the same concentrations [29]. Additionally, the addition of Ca^{2+} salt has been established as an effective approach to delay ripening and reduce the softening of fruits. This effect is attributed to its regulation of abscisic acid synthesis, a hormone that interacts with ethylene in fruits and participates in sugar accumulation and starch degradation. This process reduces cell breakdown and minimizes fruit spoilage [30, 31].

The application of the SA/LMWCS-I_2 complex and the addition of $Ca(NO_3)_2$ in the pre-harvest treatment of longan trees is expected to create synergy to enhance the biological effectiveness between the substances, specifically to slow down the ripening process of the fruit, control diseases on the tree and fruit to extend the harvest season and prolong the post-harvest storage period to improve economic efficiency for farmers.

2. MATERIALS AND METHODS

2.1. Materials

CS with molecular weight (M_w) ~135 kDa, DD ~92.7 % (Suntze Chemical, Viet Nam). Chemicals used in the experiment were of analytical grade, including I_2, SA, H_2O_2 30 %, C_2H_5OH 99.7 %, NaOH, $Ca(NO_3)_2.4H_2O$ (Xilong, China).

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2.2. Methods

Preparation of LMWCS: LMWCS was prepared by degradation of CS using H_2O_2 according to the method of Tran *et al.* (2024) [32]. Specifically, 10 g of CS powder was dissolved in 100 mL of 1 % H_2O_2 in 30 min and stirred thoroughly. After three days, the CS/H_2O_2 mixture was filtered and washed with H_2O and then dried to obtain the LMWCS powder.

Preparation of SA/LMWCS-I_2 complex: The SA/LMWCS-I_2 complex was synthesized according to the method of Huang *et al.* (2017) [13] and Du *et al.* (2023) [33]. Specifically, 10g LMWCS powder was soaked in 190 mL H_2O for 4 h, then 2 g SA was added, and the mixture was stirred until the LMWCS was completely dissolved. 10 mL of 10 % I_2 solution dissolved in C_2H_5OH was added to the SA/LMWCS mixture, and then stirred until a homogeneous solution was obtained. This resulted in 200 mL of SA/LMWCS-I_2 complex solution containing 1 % SA, 5 % LMWCS, and 0.5 % I_2 (w/v).

Characterization of materials: The M_w was determined by gel permeation chromatography (GPC) spectroscopy on a GPC LC-20AD (Shimazu, Japan). The DD was analyzed using a Fourier transform infrared (FTIR) spectrometer on an FTIR 8400 S (Shimadzu, Japan) in the wavenumber range of 4000−400 cm^{-1}. The DD was calculated by the formula (1) [34]:

$$DD\ (\%) = 100 - \frac{A_{1655}}{A_{3450}} \times 115 \quad (1)$$

where A_{1655} and A_{3450} are the absorbance intensities at 1655 cm^{-1} (the –C=O bond) and 3450 cm^{-1} (the O–H or N–H bonds), respectively.

The crystalline structure was analyzed by X-ray diffraction (XRD) using a D8 Advance diffractometer (Bruker, Germany). The SA/LMWCS-I_2 complex powder was prepared for XRD measurement by the precipitation method in C_2H_5OH. The volume ratio of sample:C_2H_5OH was 3:1, and 2 % NaOH solution was used to adjust the pH of the mixture to ~7. The mixture was stirred and allowed to settle for 2 h. The precipitate was then filtered through filter paper, washed with C_2H_5OH, and dried at 60 °C to a constant weight.

Pre-harvest treatment of Edaw longan: The experiment was conducted at the Phu Quy Edor Longan Cooperative, Ba Ria Vung Tau Province, Viet Nam. The trial was arranged in a completely randomized block design (CRBD) with 05 treatments, replicated 03 times. Each replication included one ~07-year-old longan tree with a relatively uniform canopy diameter. The treatments were designed as follows:

Control: Non-treated.

T1: Treated with 5.000 mg/L $Ca(NO_3)_2$.

T2: Treated with 260 mg/L SA/LMWCS-I_2 + 5.000 mg/L $Ca(NO_3)_2$.

T3: Treated with 325 mg/L SA/LMWCS-I_2 + 5.000 mg/L $Ca(NO_3)_2$.

T4: Treated with 433 mg/L SA/LMWCS-I_2 + 5.000 mg/L $Ca(NO_3)_2$.

The flowering treatment of longan was carried out on January 10, 2023, by spraying ~50 g of $KClO_3/m^2$ foliage. The longan fruit was fully set after 35 days of flowering. The materials were treated by spraying evenly on leaves and fruits. The first spraying was done 45 days after the fruit set (DAS), with the final spraying occurring 15 days before harvest. The interval between sprays was ~40 days, and the spray flow was ~800 liters/ha, using a Mitsu Power 12 MS-08 electric sprayer, which delivered a fine mist at 80 psi pressure with a flow rate of 3.6 liters per minute.

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Spraying is done in the morning when it is not raining, spraying evenly wet leaves and fruits. Once the fruits in the control treatment reached maturity, the treatments were harvested and repeated every two days to analyze maturity-related parameters. For each treatment, ~3 kg of longan fruits from three different points/tree were selected for the analysis of TSS and TA content, and the average weight and diameter of fruits.

The TSS and TA content of longan fruits were determined according to the method of Chen *et al.* (2020) [35]. Specifically, 10 g of longan pulp was homogenized and centrifuged at 10,000 rpm for 20 min. The supernatant was used to analyze TSS content using an Atago PAL-1 refractometer (Atago, Japan), and TA content was determined by titration with 0.1 M NaOH solution.

Postharvest longan storage experiment: In this experiment, longan fruits of uniform size, free from physical damage and fungal infection were selected for each treatment to monitor quality changes during storage. After being washed and air-dried, the fruits were packed in a perforated carton box lined with paper to store at ambient temperature (~30 °C). The evaluated parameters included fruit weight and diameter were determined after harvest, along with changes during storage in terms of hardness, microbial density, lignin content, weight loss, browning index, TSS and TP content, and respiration rate, which were determined at 0, 2, 4, 6, and 8 days of storage.

Fruit weight and size were measured using a digital electronic balance with an accuracy of ± 0.01 g and a digital caliper with a precision of 0.01 mm, respectively. The hardness of the longan pericarp was measured using the handheld hardness tester FHT-15 (Total Meter, China). To determine the microbial density on the fruit pericarp, 03 longan fruits were shaken and washed with sterile saline. The obtained solution was then diluted and added to a petri dish containing PDA medium, then incubated at room temperature. The microbial density was determined after 72 h by plate count method [36]. The lignin content was determined according to the method of Deng *et al.* (2015) [37]. Specifically, 2 g dried longan pericarp powder, after being dried at 100 °C to a constant weight and finely ground, was mixed with 20 mL of boiling water. Once the solution cooled, 25 mL of 86 % H_2SO_4 solution was added for hydrolysis at room temperature for 4 h. The mixture was then diluted with 250 mL of distilled water and boiled for 1 h. After cooling, it was filtered and thoroughly washed to remove H_2SO_4. The remaining residue was insoluble lignin, which was dried to a constant weight and calculated using the formula (2):

$$\text{Lignin content (\%)} = 100 \times \frac{m}{m_0} \quad (2)$$

where m and m_0 (g) are the weight of the lignin and the initial sample weight, respectively.

The weight loss was calculated using the formula (3):

$$\text{Weight loss (\%)} = 100 \times \frac{m_0 - m}{m_0} \quad (3)$$

where m_0 and m (g) are the initial weight and the weight at the inspection date, respectively.

The browning index was determined by measuring the browned area of the fruit pericarp using the following scale: 1 – No browning, 2 – Slight browning, 3 – Browning area < ¼, 4 – Browning area ≥ ¼ and < ½, 5 – Browning area ≥ ½. The browning index was calculated with the formula (4) [38]: Browning index = ∑(browning scale × proportion of corresponding fruit in each class). The TP content was determined using the Folin-Ciocalteu method, with gallic acid as the standard [39]. The CO_2 and C_2H_4 concentrations were measured using gas chromatography (GC) as follows: Thirty uniform, longan fruits without any signs of bruising or spoilage were selected, weighed, and placed into a 5-liter airtight plastic container. After 60 minutes of incubation, a 5

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mL gas-tight syringe was used to collect gas samples and inject it into a SCION 456-GC (SCION, Netherlands) to determine the concentrations of CO_2 (mL/kg/h) and C_2H_4 (µL/kg/h).

Statistical analysis: The experiment was carried out in triplicate, and the average values were used for analysis. The data were statistically analyzed using IRRISTAT 5.0 software and Microsoft Excel 365. Analysis of variance was performed, and treatment means were compared using the least significant difference test at a significance level of $p < 0.05$. The results are presented as mean ± standard error.

3. RESULTS AND DISCUSSION

3.1. Preparation of LMWCS and the SA/LMWCS-I_2 complex

After 72 h, M_w of the initial CS ~135 kDa decreased to ~50 kDa after oxidative hydrolysis with 1 % H_2O_2 solution, as shown in the GPC chromatogram in Figure 1. This result was consistent with our previous study, where a 1 % H_2O_2 solution was used to hydrolyze oxidized CS with an initial M_w of 130 kDa, resulting in CS with an M_w of ~45 kDa after 72 h [32]. Moreover, the use of a 1 % H_2O_2 solution in the degradation of CS produced LMWCS with a smaller M_w without significantly altering the DD (90.4 % compared to 92.7 %).

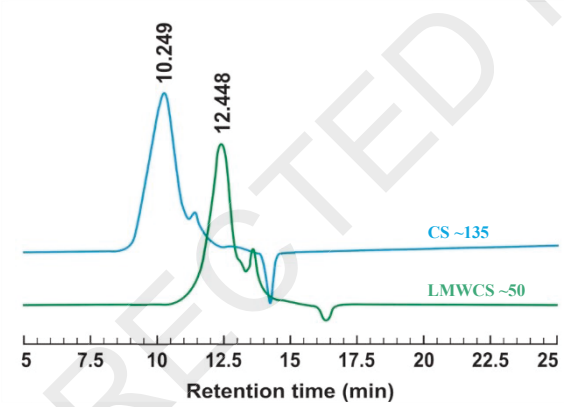

Figure 1. GPC chromatogram of original CS and LMWCS.

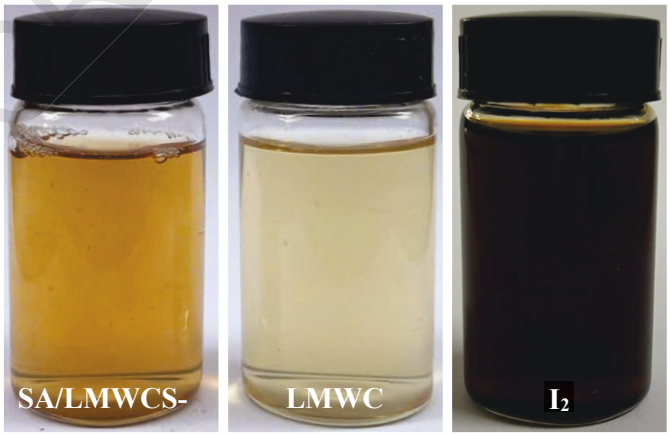

Figure 2. Photographs of the SA/LMWCS-I_2 complex, LMWCS, I_2 solution.

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The images of the SA/LMWCS-I_2 complex, LMWCS, and I_2 solutions are shown in Figure 2. The SA/LMWCS-I_2 complex solution appeared darker compared to the light-yellow color of the LMWCS solution and had lost the characteristic brownish-purple color of the I_2 solution due to the formation of the complex.

The XRD patterns of the SA/LMWCS-I_2 complex and LMWCS in Figure 3 showed that LMWCS had two characteristic peaks at 2θ ~10.54° and 20.10° [32, 40]. This indicated that when a 1 % H_2O_2 solution was used as an oxidizing agent, the crystalline properties of LMWCS remained almost unchanged [32, 41]. In the XRD pattern of the SA/LMWCS-I_2 complex, the peak at 2θ ~10.54° almost disappeared, and the peak at 2θ ~20.10° showed a decrease in intensity, it might be due to the interaction between the –NH_2 and –OH groups in LMWCS with I_2, leading to the formation of the complex and reducing the crystalline property, as reported in previous studies [33, 41]. These results confirmed the formation of a complex between LMWCS dissolved in SA and I_2.

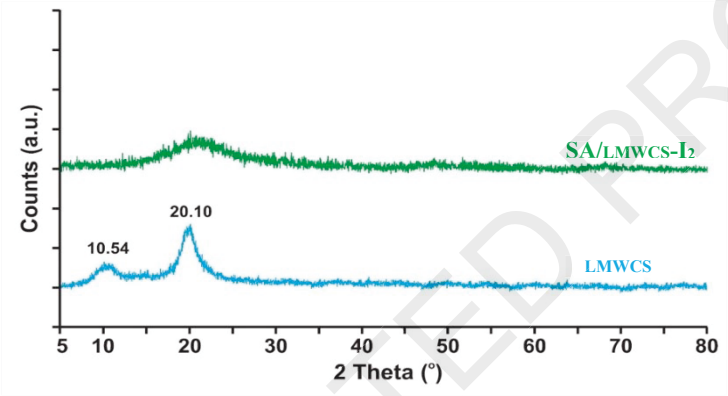

Figure 3. XRD patterns of the SA/LMWCS-I_2 complex and LMWCS.

3.2. Pretreated on Edaw longan

The longan fruits in the control treatment began to ripen 135 DAS. The results of TSS and TA content in longan fruits are presented in Table 1. At ripening, the TSS and TA content of the longan fruits in the control treatment were 19.6 % and 0.125 %, respectively. The longan fruits of the T1 treatment showed a statistically significant lower TSS content (17.7 %), while TA content (0.135 %) was higher but not significantly higher than that of the control treatment. On the 139th DAS, the longan fruits in treatment T1 had TSS and TA content equivalent to those of the control treatment. This result was consistent with the study by Ahmed *et al.* (2022), where pre-treatment of 'Khenizi' fruits with a 3 % Ca^{2+} salt solution reduced TSS content [14]. Thus, pre-treatment with $Ca(NO_3)_2$ delayed the ripening of Edaw longan fruits by 4 days compared to non-treatment.

For the treatments pretreated by the SA/LMWCS-I_2 complex combined with $Ca(NO_3)_2$ solution, the ripening process of longan fruits was delayed by 6 to 10 days, depending on the concentration of the complex used. At 135 DAS, the longan fruits in treatments T2, T3, and T4 showed a statistically significant higher TSS content and lower TA content compared to the control treatment. After 141 DAS, the TSS and TA content of the longan fruits in the T2 treatment became equivalent to that of the control treatment at ripening, and for treatments T3 and T4, it was 145 DAS. Previous studies have reported that using CS [12] or SA [42] inhibited ethylene production, delayed fruit ripening, and prolonged post-harvest storage life. Kumarihami *et al.* (2021) studied pre-harvest treatment of kiwi with CS at 500–1,000 mg/L. The results showed a lower TSS content at harvest compared to the control treatment (6.0 % vs. 6.2 %) [12]. Gayed *et*

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al. (2017) demonstrated that pre-treatment with a 2 % Ca^{2+} salt solution combined with 0.5 % or 1 % CS reduced the TSS content of peach fruits to 11.87% and 11.40 %, lower than that of the control treatment at 12.63 % [10]. Another study by Ahmed *et al.* (2022) reported that pre-harvest treatment with a 1 % CS and 2 mM SA mixture reduced the TSS content of date palm fruits compared to the control treatment (24.12% compared to 26.21 %) [14]. This study presented novel findings by using the SA/LMWCS-I_2 complex in combination with $Ca(NO_3)_2$ to integrate the properties of individual substances such as inhibiting ethylene production and enhancing antimicrobial properties, thereby slowing down the ripening process of longan fruits.

Table 1. Effect of pre-harvest treated on TSS and TA content of Edaw longan fruits.

Monitoring indicators	Treatments	DAS					
		135	137	139	141	143	145
TSS (%)	Control	$19.6^{a} \pm 0.6$	-	-	-	-	-
	T1	$17.7^{b} \pm 0.4$	$18.8^{a} \pm 0.4$	$19.7^{a} \pm 0.3$	-	-	-
	T2	$17.2^{b} \pm 0.2$	$18.4^{a} \pm 0.5$	$19.1^{a} \pm 0.4$	$19.7^{ns} \pm 0.3$	-	-
	T3	$15.3^{c} \pm 0.1$	$16.5^{b} \pm 0.3$	$17.6^{b} \pm 0.1$	$18.4^{ns} \pm 0.2$	$19.1^{ns} \pm 0.4$	$19.6^{ns} \pm 0.4$
	T4	$15.6^{c} \pm 0.7$	$16.6^{b} \pm 0.5$	$17.3^{b} \pm 0.7$	$18.4^{ns} \pm 0.5$	$19.2^{ns} \pm 0.5$	$19.5^{ns} \pm 0.4$
$LSD_{0.05}$		1.70	1.59	1.45	1.59	1.90	2.28
TA (%)	Control	$0.125^{ns} \pm 0.002$	-	-	-	-	-
	T1	$0.135^{ns} \pm 0.005$	$0.130^{ns} \pm 0.006$	$0.123^{ns} \pm 0.004$	-	-	-
	T2	$0.134^{ns} \pm 0.006$	$0.131^{ns} \pm 0.006$	$0.128^{ns} \pm 0.005$	$0.124^{ns} \pm 0.005$	-	-
	T3	$0.144^{ns} \pm 0.008$	$0.141^{ns} \pm 0.008$	$0.135^{ns} \pm 0.008$	$0.130^{ns} \pm 0.008$	$0.126^{ns} \pm 0.007$	$0.123^{ns} \pm 0.006$
	T4	$0.142^{ns} \pm 0.006$	$0.140^{ns} \pm 0.006$	$0.137^{ns} \pm 0.007$	$0.131^{ns} \pm 0.006$	$0.126^{ns} \pm 0.005$	$0.123^{ns} \pm 0.004$
$LSD_{0.05}$		0.020	0.023	0.022	0.029	0.032	0.028

Note: The mean values in a column with the same letter are not significantly different at $P < 0.05$.

The results regarding the average weight and diameter of the longan fruits in Table 2 indicated that, in addition to delaying ripening, pre-harvest treated with the SA/LMWCS-I_2 complex combined with $Ca(NO_3)_2$ also enhanced the fruits' weight and size. Compared to the control, all treatments significantly increased both fruit weight and diameter. T1 resulted in a slight but statistically significant increase in fruit weight, whereas T3 and T4 showed more pronounced effects, with fruit weights significantly higher than both the control and T1 treatments. Notably, longan fruits in the T4 treatment had a significantly larger average diameter compared to the control. This effect might be attributed to the regulatory and growth-promoting properties of SA and LMWCS, which have been shown to stimulate the development of various crops such as wheat, soybean, corn, and coffee [43–47]. Furthermore, the supplementation with $Ca(NO_3)_2$ provided essential nutrients crucial for plant growth. Specifically, Ca enhanced cell wall and membrane structures, while N served as a vital macronutrient necessary for plant development [48].

Table 2. Effect of pre-harvest treated on average weight and diameter of Edaw longan fruits.

Treatments	Weight (g)	Diameter (cm)
Control	$14.65^{a} \pm 0.18$	$2.27^{a} \pm 0.02$
T1	$15.53^{b} \pm 0.23$	$2.31^{ab} \pm 0.02$
T2	$16.12^{bc} \pm 0.24$	$2.34^{ab} \pm 0.04$
T3	$16.41^{c} \pm 0.23$	$2.37^{ab} \pm 0.03$
T4	$16.85^{c} \pm 0.26$	$2.39^{b} \pm 0.03$
$LSD_{0.05}$	0.81	0.10

Note: The mean values in a column with the same letter are not significantly different at $P < 0.05$.

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3.2. Preserving Edaw longan fruits

At the time of ripening (control – 135 DAS, T1 – 139 DAS, T2 – 141 DAS, and T3 and T4 – 145 DAS), hardness, microbial density, and lignin content in the fruit pericarp changed over storage time at room temperature, as shown in Table 3. Longan fruits in treatment T1 had higher hardness than that of the control treatment, although lignin content was almost unchanged. Notably, fruit hardness in T1 showed a statistically significant higher from day 2 to day 6 of storage. According to Vicente *et al.* (2009), the application of Ca to plants enhanced the hardness of the fruit pericarp by being transported through the xylem, where it cross-links with pectic polysaccharide chains [49]. Longan fruits pretreated with the SA/LMWCS-I_2 complex and $Ca(NO_3)_2$ exhibited a statistically significant higher hardness than both the control and T1 treatments. Jogaiah *et al.* also confirmed that CS increased lignin content in fruits [50]. Thus, the synergistic effect of these active compounds increased the fruit hardness at harvest. Overall, both fruit hardness and lignin content in all treatments tended to decrease over the storage period, which might be due to microbial damage. Additionally, lignin content in the pericarp of longan fruits decreased, likely due to the polymerization of proanthocyanidins and lignin [51]. Regarding microbial density, the control and T1 treatments exhibited high microbial densities of 4.16 and 4.18 log cfu/mL, respectively. In T2, T3, and T4, the microbial density was statistically significantly lower compared to the control. Specifically, microbial density in T2 decreased by ~60 % (3.73 log cfu/mL), and by ~80 % in treatments T3 (3.46 log cfu/mL) and T4 (3.42 log cfu/mL), demonstrating the antimicrobial efficacy or the potential of the SA/LMWCS-I_2 complex to stimulate the production of plant defense enzymes. Longan fruits pretreated with the SA/LMWCS-I_2 complex and $Ca(NO_3)_2$ resulted in a longer shelf life of 6–8 days compared to 4 days in the control and T1 treatments. The results also indicated that when microbial density exceeded 5.2 log cfu/g, longan fruits suffered damage due to microbial destruction.

Table 3. Effect of pre-harvest treated on hardness, microbial density, and lignin content of Edaw longan fruits during storage.

Monitoring indicators	Treatments	Days				
		0	2	4	6	8
Hardness (N)	Control	$17.67^{a} \pm 0.09$	$17.22^{a} \pm 0.14$	$15.51^{a} \pm 0.12$	$6.86^{a} \pm 0.09$	-
	T1	$17.64^{a} \pm 0.17$	$17.54^{b} \pm 0.14$	$16.84^{b} \pm 0.01$	$8.57^{b} \pm 0.07$	-
	T2	$18.12^{b} \pm 0.17$	$18.01^{c} \pm 0.15$	$17.35^{c} \pm 0.13$	$16.54^{c} \pm 0.17$	$9.54^{a} \pm 0.20$
	T3	$18.95^{c} \pm 0.15$	$18.54^{d} \pm 0.07$	$18.16^{d} \pm 0.09$	$17.41^{d} \pm 0.21$	$16.47^{b} \pm 0.17$
	T4	$19.01^{c} \pm 0.16$	$18.61^{d} \pm 0.07$	$18.22^{d} \pm 0.23$	$17.43^{d} \pm 0.12$	$16.48^{b} \pm 0.05$
$LSD_{0.05}$		0.41	0.31	0.31	0.35	0.64
Microbial density (log cfu/g)	Control	$4.16^{a} \pm 0.17$	$4.21^{a} \pm 0.16$	$4.37^{a} \pm 0.12$	$5.23^{a} \pm 0.06$	-
	T1	$4.18^{a} \pm 0.09$	$4.21^{a} \pm 0.09$	$4.30^{a} \pm 0.10$	$5.21^{a} \pm 0.27$	-
	T2	$3.73^{b} \pm 0.08$	$3.82^{ab} \pm 0.05$	$4.03^{ab} \pm 0.04$	$4.80^{ab} \pm 0.18$	$5.23^{ns} \pm 0.13$
	T3	$3.46^{b} \pm 0.17$	$3.58^{b} \pm 0.08$	$3.73^{b} \pm 0.09$	$4.55^{b} \pm 0.16$	$4.68^{ns} \pm 0.17$
	T4	$3.42^{b} \pm 0.03$	$3.53^{b} \pm 0.17$	$3.65^{b} \pm 0.14$	$4.53^{b} \pm 0.11$	$4.65^{ns} \pm 0.09$
$LSD_{0.05}$		0.39	0.42	0.36	0.60	0.58
Lignin (%)	Control	$8.52^{ns} \pm 0.09$	$8.47^{ns} \pm 0.08$	$8.35^{ns} \pm 0.04$	$8.28^{ns} \pm 0.06$	-
	T1	$8.57^{ns} \pm 0.04$	$8.45^{ns} \pm 0.07$	$8.34^{ns} \pm 0.05$	$8.30^{ns} \pm 0.05$	-
	T2	$8.73^{ns} \pm 0.16$	$8.68^{ns} \pm 0.16$	$8.51^{ns} \pm 0.04$	$8.37^{ns} \pm 0.04$	$8.32^{ns} \pm 0.04$
	T3	$8.94^{ns} \pm 0.24$	$8.83^{ns} \pm 0.25$	$8.72^{ns} \pm 0.24$	$8.48^{ns} \pm 0.16$	$8.40^{ns} \pm 0.17$

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	T4	$9.03^{ns} \pm 0.14$	$8.86^{ns} \pm 0.09$	$8.73^{ns} \pm 0.10$	$8.50^{ns} \pm 0.07$	$8.42^{ns} \pm 0.07$
$LSD_{0.05}$		0.51	0.49	0.40	0.30	0.40

Note: The mean values in a column with the same letter are not significantly different at $P < 0.05$.

The weight loss, browning index, TSS, and TP contents of longan fruits during storage are presented in Table 4. TP content was calculated by the regression equation: $y = 0.0473x - 0.0193$ ($R^2 = 0.9972$), where x is absorbance and y is GA content (2.5–15 mg/L). Table 4 illustrated the increasing trends of weight loss and browning index in longan fruits during storage. The weight loss was due to the dehydration of longan fruit during storage at room temperature, whereas the rise in browning index was likely due to the polymerization of proanthocyanidin and lignin, leading to the formation of brown pigments in the pericarp [51]. The TSS content in longan fruits increased by more than 20 % after 02 days of storage and decreased in the following days. This initial rise could be explained by the hydrolysis of starch into sugars as the fruit continues to ripen, whereas the subsequent decrease results from complete starch conversion and increased respiration, which consumes carbohydrates and reduces TSS levels [52, 53]. The weight loss, browning index, and TSS content in longan fruits pretreated with the SA/LMWCS-I_2 complex and $Ca(NO_3)_2$ progressed more slowly, and showed statistically significant differences compared to the control and T1 treatments after 4 days of storage. This suggests that the combination of pre-treatment compounds might stimulate the production of enzymes that inhibited oxidation [54], thereby delaying senescence and microbial degradation [16]. Furthermore, T3 and T4 treatments exhibited the highest TP content at harvest, reaching 8.85 and 8.90 mg GAE/g, respectively, compared to 7.06 mg GAE/g in the control treatment. In contrast, the TP content in the T1 treatment did not change noticeably compared to the control treatment. These results indicated that pretreated with the SA/LMWCS-I_2 complex and $Ca(NO_3)_2$ promoted TP accumulation in the fruit and slowed TP degradation during storage, possibly by inhibiting pigment breakdown in the pericarp, thereby maintaining higher TP levels [55]. These results aligned with Cui *et al.* (2020), who reported similar effects when treating apricots with CS and SA [16].

Table 4. Effect of pre-harvest treated on weight loss, browning index, TSS content, and TP content of Edaw longan fruits during storage.

Monitoring indicators	Treatments	Days				
		0	2	4	6	8
Weight loss (%)	Control	$0.00^{ns} \pm 0.00$	$1.64^{a} \pm 0.02$	$2.42^{a} \pm 0.04$	$3.52^{a} \pm 0.03$	$0.00^{c} \pm 0.00$
	T1	$0.00^{ns} \pm 0.00$	$1.61^{a} \pm 0.13$	$2.33^{a} \pm 0.18$	$3.48^{a} \pm 0.20$	$0.00^{c} \pm 0.00$
	T2	$0.00^{ns} \pm 0.00$	$1.20^{b} \pm 0.20$	$1.67^{b} \pm 0.16$	$2.15^{b} \pm 0.10$	$2.34^{a} \pm 0.05$
	T3	$0.00^{ns} \pm 0.00$	$0.26^{c} \pm 0.02$	$0.42^{c} \pm 0.06$	$0.98^{c} \pm 0.06$	$1.66^{b} \pm 0.06$
	T4	$0.00^{ns} \pm 0.00$	$0.29^{c} \pm 0.01$	$0.38^{c} \pm 0.02$	$0.97^{c} \pm 0.02$	$1.62^{b} \pm 0.05$
$LSD_{0.05}$		0.00	0.38	0.40	0.36	0.15
Browing index	Control	$1.0^{ns} \pm 0.0$	$1.3^{ns} \pm 0.3$	$2.0^{a} \pm 0.0$	$3.0^{a} \pm 0.0$	$4.7^{a} \pm 0.3$
	T1	$1.0^{ns} \pm 0.0$	$1.3^{ns} \pm 0.3$	$1.7^{a} \pm 0.3$	$2.7^{a} \pm 0.3$	$3.7^{a} \pm 0.3$
	T2	$1.0^{ns} \pm 0.0$	$1.0^{ns} \pm 0.0$	$1.0^{b} \pm 0.0$	$1.3^{b} \pm 0.3$	$1.7^{b} \pm 0.3$
	T3	$1.0^{ns} \pm 0.0$	$1.0^{ns} \pm 0.0$	$1.0^{b} \pm 0.0$	$1.3^{b} \pm 0.3$	$1.3^{b} \pm 0.3$
	T4	$1.0^{ns} \pm 0.0$	$1.0^{ns} \pm 0.0$	$1.0^{b} \pm 0.0$	$1.3^{b} \pm 0.3$	$1.3^{b} \pm 0.3$
$LSD_{0.05}$		0.00	0.73	0.49	1.06	1.11
TSS (%)	Control	$19.6^{ns} \pm 0.2$	$20.1^{ns} \pm 0.2$	$18.9^{b} \pm 0.1$	$17.6^{a} \pm 0.1$	$0.0^{a} \pm 0.0$

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	T1	$19.7^{ns} \pm 0.2$	$20.5^{ns} \pm 0.2$	$18.5^{a} \pm 0.1$	$17.5^{a} \pm 0.3$	$0.0^{a} \pm 0.0$
	T2	$19.7^{ns} \pm 0.1$	$20.4^{ns} \pm 0.2$	$19.8^{c} \pm 0.1$	$18.6^{b} \pm 0.0$	$17.8^{b} \pm 0.1$
	T3	$19.6^{ns} \pm 0.3$	$20.2^{ns} \pm 0.1$	$19.9^{cd} \pm 0.1$	$19.1^{bc} \pm 0.1$	$18.4^{c} \pm 0.2$
	T4	$19.5^{ns} \pm 0.2$	$20.3^{ns} \pm 0.0$	$20.2^{d} \pm 0.1$	$19.2^{c} \pm 0.2$	$18.6^{c} \pm 0.2$
$LSD_{0.05}$		0.51	0.40	0.32	0.51	0.42
TP (%)	Control	$7.06^{a} \pm 0.17$	$6.76^{a} \pm 0.04$	$6.12^{a} \pm 0.10$	$5.24^{a} \pm 0.19$	$0.00^{a} \pm 0.00$
	T1	$7.12^{a} \pm 0.21$	$6.82^{a} \pm 0.13$	$6.34^{a} \pm 0.10$	$5.29^{a} \pm 0.09$	$0.00^{a} \pm 0.00$
	T2	$8.50^{b} \pm 0.21$	$8.34^{b} \pm 0.16$	$7.62^{b} \pm 0.20$	$7.02^{b} \pm 0.20$	$5.65^{b} \pm 0.09$
	T3	$8.85^{b} \pm 0.03$	$8.76^{c} \pm 0.07$	$8.16^{c} \pm 0.14$	$7.46^{bc} \pm 0.08$	$6.98^{c} \pm 0.23$
	T4	$8.90^{b} \pm 0.17$	$8.77^{c} \pm 0.13$	$8.23^{c} \pm 0.11$	$7.62^{c} \pm 0.13$	$7.14^{c} \pm 0.17$
$LSD_{0.05}$		0.59	0.33	0.41	0.46	0.46

Note: The mean values in a column with the same letter are not significantly different at $P < 0.05$.

The respiration rate of longan fruit, a key factor in ripening and senescence, was illustrated in Table 5. In general, longans pretreated with SA/LMWCS-I_2 complex and $Ca(NO_3)_2$ exhibited a statistically significant reduction in respiration rate compared to both the control and T1. The combination of SA and CS has been shown to activate enzymes that inhibited ethylene biosynthesis, thereby delaying fruit ripening [12, 14].

Experimental results indicated that the pretreated Edaw longans with the SA/LMWCS-I_2 complex combined with $Ca(NO_3)_2$ extended the harvest period by 6–10 days while maintaining fruit hardness, increasing TP content, and notably reducing microbial density on the fruit pericarp compared to the control treatment. Additionally, this method slowed the respiration rate, minimized weight loss, and prolonged the postharvest storage life of longan fruits.

Table 5. Effect of pre-harvest treated on the respiration rate of Edaw longan fruits during storage.

Monitoring indicators	Treatments	Days				
		0	2	4	6	8
CO_2 (mL/kg/h)	Control	$72.62^{a} \pm 0.31$	$138.15^{a} \pm 0.65$	$185.51^{a} \pm 0.51$	$0.00^{a} \pm 0.00$	$0.00^{a} \pm 0.00$
	T1	$73.24^{a} \pm 0.24$	$135.68^{b} \pm 0.76$	$186.25^{a} \pm 1.30$	$0.00^{a} \pm 0.00$	$0.00^{a} \pm 0.00$
	T2	$70.54^{b} \pm 0.17$	$95.45^{c} \pm 0.22$	$136.54^{b} \pm 1.05$	$195.98^{b} \pm 1.13$	$0.00^{a} \pm 0.00$
	T3	$68.62^{c} \pm 0.60$	$76.68^{d} \pm 0.19$	$98.57^{c} \pm 0.77$	$118.95^{c} \pm 0.26$	$145.98^{b} \pm 1.16$
	T4	$68.42^{c} \pm 0.71$	$77.65^{d} \pm 1.14$	$96.87^{c} \pm 0.76$	$109.98^{d} \pm 1.73$	$141.69^{c} \pm 1.38$
$LSD_{0.05}$		1.64	2.37	3.34	3.09	2.72
C_2O_4 (µL/kg/h)	Control	$0.24^{ns} \pm 0.02$	$0.65^{ab} \pm 0.07$	$22.42^{a} \pm 0.49$	$0.00^{c} \pm 0.00$	$0.00^{b} \pm 0.00$
	T1	$0.23^{ns} \pm 0.03$	$0.76^{a} \pm 0.07$	$22.51^{a} \pm 0.41$	$0.00^{c} \pm 0.00$	$0.00^{b} \pm 0.00$
	T2	$0.21^{ns} \pm 0.02$	$0.45^{b} \pm 0.06$	$18.45^{b} \pm 0.28$	$23.58^{a} \pm 0.66$	$0.00^{b} \pm 0.00$
	T3	$0.17^{ns} \pm 0.03$	$0.38^{b} \pm 0.04$	$7.84^{c} \pm 0.41$	$12.64^{b} \pm 0.32$	$19.15^{a} \pm 0.49$
	T4	$0.18^{ns} \pm 0.02$	$0.37^{b} \pm 0.03$	$7.57^{c} \pm 0.34$	$12.57^{b} \pm 0.65$	$18.87^{a} \pm 0.69$
$LSD_{0.05}$		0.09	0.20	1.43	1.56	1.38

Note: The mean values in a column with the same letter are not significantly different at $P < 0.05$.

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4. CONCLUSION

The preparation and application of the SA/LMWCS-I_2 complex combined with $Ca(NO_3)_2$ for pre-treating Edaw longans have proven effective in delaying ripening, enhancing quality ingredients, and reducing microbial load in fruits, thereby extending postharvest storage life. Furthermore, the fruit weight of longan fruits treated by the SA/LMWCS-I_2 and $Ca(NO_3)_2$ increased by 10–15 % than that of the control treatment. Therefore, this method is considered an effective approach, contributing to addressing the issue of price reduction or difficult sales during the peak harvest season of longan and potentially application to other crop varieties.

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Declaration of competing interest. The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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