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Evaluation of a chitosan and sodium benzoate-based coating to preserve the postharvest quality of jackfruit (*Artocarpus heterophyllus* L.)

Evaluación de un recubrimiento a base de quitosano y benzoato de sodio para conservar la calidad postcosecha del fruto de yaca (*Artocarpus heterophyllus* L.)

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Abstract

The conservation of jackfruit (*Artocarpus heterophyllus* L.) is essential for its successful commercialization due to its high perishability and susceptibility to postharvest diseases, particularly those caused by *Rhizopus stolonifer*. This study evaluated the effectiveness of a chitosan and sodium benzoate-based coating, classified as Generally Recognized as Safe (GRAS), in extending the fruit's shelf life. A two-stage storage regime (10 °C for 5 days, followed by 25 °C) was implemented, and physicochemical parameters, respiration rate (CO_2 production), and ethylene emission were monitored. The results demonstrated that the coating inhibited *R. stolonifer* development, maintained fruit firmness, and extended shelf life to 17 days. Additionally, the treatment enhanced peroxidase (POD) activity, a key enzyme in the fruit's defense mechanism. These findings highlight the coating's potential as a sustainable postharvest conservation strategy for jackfruit.

Keywords: Climacteric fruit, Defense mechanisms, GRAS substances, Peroxidase activity, Refrigeration.

Resumen

La conservación de la yaca (*Artocarpus heterophyllus* L.) es esencial para su comercialización exitosa debido a su alta perecibilidad y susceptibilidad a enfermedades postcosecha, particularmente aquellas causadas por *Rhizopus stolonifer*. Este estudio evaluó la efectividad de un recubrimiento a base de quitosano y benzoato de sodio, clasificado como Generalmente Reconocido como Seguro (GRAS, por sus siglas en inglés), para extender la vida útil de la fruta. Se implementó un régimen de almacenamiento de dos etapas (10 °C durante 5 días, seguido de 25 °C), y se monitorearon los parámetros fisicoquímicos, la tasa de respiración (producción de CO_2) y la emisión de etileno. Los resultados demostraron que el recubrimiento inhibió el desarrollo de *R. stolonifer*, mantuvo la firmeza de la fruta y extendió la vida útil a 17 días. Además, el tratamiento mejoró la actividad de la peroxidasa (POD), enzima clave en el mecanismo de defensa de la fruta. Estos hallazgos resaltan el potencial del recubrimiento como una estrategia de conservación postcosecha sustentable para la yaca.

Palabras clave: Fruto climatérico, Mecanismos de defensa, Sustancias GRAS, Actividad de la peroxidasa, Refrigeración.

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1 Introduction

Jackfruit (*Artocarpus heterophyllus* L.) is a climacteric tropical fruit with high postharvest perishability, primarily due to ethylene-induced ripening and susceptibility to fungal infections such as those caused by *Rhizopus stolonifer* (Coronado-Partida *et al*., 2021). In Mexico, Nayarit is the leading producer, with an annual output of approximately 29,375 tons, of which 80% is exported to the United States (SIAP, 2023). Given the fruit's economic importance, technologies that enhance its shelf life and preserve quality are critical for minimizing losses. Conventional postharvest treatments, such as hot water immersion and chemical fungicides, have shown limited success, with the latter raising regulatory and consumer concerns due to potential residues (FDA, 2022). Consequently, bioactive compounds such as chitosan and sodium benzoate have emerged as promising alternatives for postharvest preservation. These compounds combine antimicrobial activity with the ability to form semipermeable coatings that modulate gas exchange, thereby decelerating ripening processes. Chitosan (a cationic biopolymer derived from chitin) exhibits broad-spectrum antimicrobial properties and forms cohesive, semipermeable films that act as physical barriers. When applied as an edible coating, chitosan creates a modified microenvironment around the fruit surface, attenuating respiratory activity by restricting O_2 influx and CO_2 efflux. Given the oxygen-dependent nature of ethylene biosynthesis, this localized hypoxia downregulates ethylene production, effectively extending postharvest shelf life (Gutiérrez-Martínez *et al*., 2018; Martínez-Batista *et al*., 2024). This mechanism is particularly relevant for climacteric fruits like jackfruit, which exhibit a pronounced surge in ethylene and CO_2 production during the climacteric phase. This metabolic shift triggers coordinated physiological changes, including cell wall degradation (mediated by polygalacturonase and pectin methylesterase activity), tissue softening, and biosynthesis of volatile aromatic compounds and pigments (Singh *et al*., 2018). Unmitigated, these processes (driven by elevated respiration rates) accelerate quality deterioration through enzymatic and oxidative spoilage pathways.

Technologies like controlled atmospheres and edible coatings have proven useful for regulating these gases, thereby extending the fruit's shelf life (Jha *et al*., 2012). Sodium benzoate, classified as GRAS by the FDA, has emerged as a viable alternative to conventional fungicides. This compound offers advantages such as high solubility, low cost, and ease of application in packaging facilities (Palou *et al*., 2018). Furthermore, it has been shown to be effective in combination with chitosan for controlling *R. stolonifer*, inhibiting mycelial growth and reducing spore production (Coronado-Partida *et al*., 2023). Its use as an edible coating helps maintain firmness, color, and the fruit's nutritional properties during storage (Mahmood *et al*., 2022).

Refrigeration is one of the most effective strategies for postharvest fruit preservation (Inestroza-Lizardo *et al*., 2016). By lowering the temperature, metabolic processes such as respiration and ethylene production slow down, delaying ripening and deterioration. However, it must be tailored to the specific characteristics of each fruit to avoid chilling injuries, such as cuticle blemishes or firmness loss (Wang *et al*., 2013). Combining refrigeration with edible coatings and controlled atmospheres can enhance the benefits of these techniques (Mahajan and Goswami, 2004). This study evaluated the effect of a chitosan and sodium benzoate-based coating on the preservation of jackfruit stored at temperatures of 10 °C and 25 °C. Physicochemical properties, physiological activity, and peroxidase (POD) enzyme activity associated with plant defense were characterized. This approach aims to contribute to the development of more sustainable and effective strategies for the postharvest conservation of jackfruit.

2 Materials and methods

2.1 Plant material

Jackfruit (*Artocarpus heterophyllus* L.) at physiological maturity, free from mechanical damage and with uniform appearance, were obtained from the municipality of San Blas, Nayarit, Mexico. The fruits were transported to the Agricultural Parasitology Laboratory at the Universidad Autónoma de Nayarit.

2.2 Treatment

A low molecular weight chitosan (Chi) solution (Sigma-Aldrich, MO, USA) at a concentration of 3% (w/v) was prepared in 2% (v/v) acetic acid (EMSURE-USA). The solutions were stirred for 24 hours, and the pH was adjusted to 5.6 using 1N NaOH. Subsequently, 0.1 mL of Tween 80 (Sigma-Aldrich, MO, USA) was added as a surfactant. A sodium benzoate (SB) solution (Deiman, Mexico) at a concentration of 2.5% (w/v) in sterile distilled water was also prepared (Coronado-Partida *et al*., 2023).

The treatments were divided into eight groups: Treatment I: Fruits kept at standard room temperature (25 ±2 °C) without inoculation or additional treatments. Treatment II: Fruits maintained at 25 ±2 °C after inoculation. Treatment III: Fruits initially stored at low temperature (10 ±2 °C) for 5 days and then transferred to 25 ±2 °C. Treatment IV: Inoculated fruits stored at 10 ± 2 °C for 5 days and then transferred to 25 ±2 °C. Treatment V: Fruits treated with Chi-BS and stored at 25 ±2 °C. Treatment VI: Fruits treated with Chi-BS, initially stored at 10 ±2 °C for 5 days, and then maintained at 25 ±2 °C. Treatment VII: Inoculated fruits treated with Chi-BS and stored at 25 ±2 °C. Treatment VIII: Inoculated fruits treated with Chi-BS, stored at 10 ±2 °C for 5 days, and then transferred to 25 ±2 °C.

2.2.1 *Artificial inoculation*

The fruits designated for inoculation were first washed with a 2% (v/v) sodium hypochlorite solution for two minutes to disinfect the surface. They were then rinsed with potable water and left to air dry at room temperature. After disinfection, five wounds were carefully made on the fruit surface using a sterile needle. Each wound was inoculated with 20 μL of a *R. stolonifer* spore suspension (previously isolated and identified) at a concentration of 10^6 conidia mL^{-1}.

2.3 *Physicochemical parameters*

2.3.1 *Physiological weight loss*

Weight loss was determined as a percentage using the equation [(A-B) / A] x 100 (Northover and Zhou, 2002), where A represents the initial weight of the jackfruit before treatment, and B represents the weight of the fruit every 24 hours.

2.3.2 *Firmness*

Firmness was measured using a penetrometer (Shimpo, FGE-100X) equipped with a 10 mm diameter probe. Penetration tests were conducted at five points along the fruit (ends and middle) with the peel intact. The resistance force to penetration was recorded and expressed in Newtons (N).

2.3.3 *Total soluble solids (TSS)*

The jackfruit pulp was homogenized and filtered through a Whatman No. 1 filter paper. Soluble solids were determined using a digital refractometer (Abbé HI 96801), and the results were reported in °Brix (AOAC, 2005).

2.3.4 *Titratable acidity*

A 5 g fruit sample was titrated with 0.1 M NaOH, using 0.1% phenolphthalein as an indicator. Results were calculated and expressed as the percentage of malic acid per 100 g of fresh weight (Ali *et al.*, 2011).

2.4 *Physiological parameters*

Respiration rate: Respiration rate was measured daily until the fruit reached senescence using a portable ethylene and CO_2 analyzer (F-900, CID Bio Science, Inc.). Ethylene production was expressed in μL kg^{-1} h^{-1}, and CO_2 production was expressed in mL CO_2 kg^{-1} h^{-1}.

2.5 *Enzymatic activity*

Enzymatic activity was evaluated every 24 hours after applying the Chi-SB treatment to the jackfruit. The enzyme extract was obtained from the fruit's cuticle using the methodology described by Chen *et al.*, (2000). POD activity: The expression of peroxidase (POD) activity was assessed using the method proposed by Chance and Maehly (1955) with minor modifications. Briefly, 0.5 mL of crude extract (supernatant) was mixed with 2 mL of guaiacol buffer solution and incubated for 5 minutes at 30 ±2 ºC. Then, 1 mL of H_2O_2 was added, and absorbance was measured at 460 nm every 5 seconds for 90 seconds using a UV/visible spectrophotometer (VE-6000T-VELAB). Enzyme activity was expressed as U mg^{-1} of protein. Protein content was determined using the Bradford method (1976).

2.6 *Statistical analysis*

A multifactorial design with completely randomized blocks was used. One factor was the coating treatment, another was the storage temperature, and the blocks were the storage days. Data were analyzed using analysis of variance (ANOVA), and mean comparisons were performed with Tukey's test ($p \leq 0.05$) using IBM SPSS Statistics software.

3 Results and discussion

3.1 *Physicochemical parameters*

Table 1 shows that fruits treated solely with the coating achieved a shelf life of 14 days, compared to the control group, which lasted only 7 days. Fruits in the control group exhibited lower firmness, reduced titratable acidity, and a more advanced ripening stage, making them more susceptible to *R. stolonifer* infection. In this group, fruits inoculated, on the fifth day displayed pathogen growth. In contrast, fruits that were inoculated and treated with the coating achieved a shelf life of up to 9 days, demonstrating the antifungal efficacy of the treatment.

Table 1. Evaluation of TSS, titratable acidity and firmness during storage of jackfruit treated with Chi-SB with and without *R. stolonifer* inoculation stored at 25 ±2 °C.

Treatment	Days	TSS (°Brix)	Titratable acidity (%)	Firmness (N)
Control	0	5.12 ± 0.22 a	0.95 ± 0.10 a	330 ± 1.24 a
	7	38.95± 0.98 b	0.56 ± 0.08 b	179 ± 1.33 b
Control (inoculated)	0	7.65± 0.54 a	1.06 ± 0.06 a	308 ± 3.11 a
	5	37.7± 0.58 b	0.74 ± 0.11 b	12 ± 2.58 b
Chi-SB	0	5.55± 0.55 a	1.14 ± 0.09 a	287 ± 1.91 a
	14	25.7± 1.05 b	0.68 ± 0.01 b	244 ± 1.96 b
Chi-BS (inoculated)	0	4.99± 0.46 a	1.01 ± 0.05 a	320 ± 1.84 a
	9	24.55± 0.56 b	0.54 ± 0.02 b	220 ± 1.28 b

The values are the means of three replicates. Different letters within a column indicate significant differences between treatments ($p \leq 0.05$).

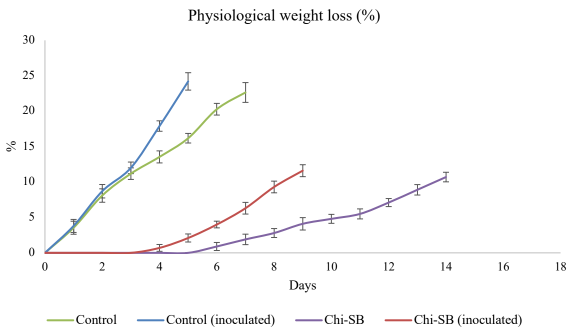

Figure 1. Physiological weight loss of jackfruit stored at 25 ±2 °C.

Figure 1 presents data on the physiological weight loss (PWL) of the analyzed fruits. Control fruits, both inoculated and non-inoculated, exhibited significant weight loss, with reductions of 24% and 22%, respectively, in less than five days. In contrast, fruits treated with the coating maintained their weight over a longer period, recording only a 10% loss by day 14. PWL is directly associated with metabolic processes such as cellular respiration, which induce physiological and structural changes in fruit tissues. According to Vieira *et al.* (2016), coatings made with chitosan and essential oils have proven effective in mitigating weight loss in fruits. For the treated jackfruit, the reduced PWL is attributed to the properties of chitosan, whose hydrophobic structure and polymeric matrix strengthen the cell wall, increase mechanical resistance, and form a barrier that limits water loss (Tokatli and Demirdöven, 2020). Furthermore, sodium benzoate, a widely used antimicrobial compound in the food industry, plays a critical role in preserving fruit quality. This compound inhibits the growth of microorganisms responsible for the degradation of plant tissue, helping maintain cell integrity and reducing transpiration and weight loss during storage. Previous studies have demonstrated the efficacy of sodium benzoate in reducing microbial activity and preserving physical properties such as firmness and weight in food matrices (Montesinos-Herrero *et al.*, 2016). Therefore, the inclusion of sodium benzoate in postharvest treatments is proposed as an effective strategy to optimize the conservation of fresh fruits, minimizing losses associated with handling and prolonged storage.

In fruits refrigerated for 5 days at 10 °C, a deceleration in the ripening process was observed, highlighting the positive impact of low temperatures on fruit preservation. Control fruits, both inoculated and non-inoculated, exhibited faster ripening indices compared to treated fruits. This difference was reflected in the total soluble solids (TSS) values, where treated fruits had up to 50% less TSS compared to the control group on the fifth day of storage (Table 2). Firmness values also confirmed these differences, demonstrating better preservation in the treated fruits. Subsequently, after 5 days of storage at 10 °C, the fruits were transferred to 25 °C. Fruits treated with the Chi-SB coating achieved a shelf life of 17 days, while those treated and inoculated with *R. stolonifer* maintained a shelf life of 12 days. These results demonstrate that combining an initial storage period at 10 °C with postharvest treatment, followed by storage at 25 °C, is an effective strategy for preserving jackfruit. Similarly, Ramos-Bell *et al.*, (2024) reported that the application of chitosan and salicylic acid in blueberries preserved quality during postharvest storage. At 4 °C, treated fruits exhibited less firmness degradation compared to the control group, while at room temperature (25 °C), the combined treatment significantly reduced weight loss, achieving 11% in treated fruits versus 22% in the control. During refrigeration, weight loss ranged from 5.25% to 6.45%, with no significant differences between treated and control groups. Furthermore, the treatment decreased the rate of changes in soluble solids, pH, and titratable acidity, contributing to maintaining an optimal balance in the sensory quality of the fruit.

Table 2. Evaluation of TSS, titratable acidity and firmness during storage of jackfruit treated with Chi-SB with and without inoculation stored at 10 °C for 5 days and subsequently at 25 ±2 °C with *R. stolonifer*.

Treatment	Days	TSS (°Brix)	Titratable acidity (%)	Firmness (N)
Control	0	6.2 ± 1.08 a	1.01 ± 0.07 a	317 ± 2.54 a
	5	18.05 ± 0.64 b	0.89 ± 0.02 b	280 ± 1.11 b
	10	31.3 ± 0.85 c	0.68 ± 0.06 c	209 ± 1.58 c
Control (inoculated)	0	7.45 ± 0.72 a	0.953 ± 0.06 a	280 ± 1.24 a
	5	25.88 ± 0.89 b	0.78 ± 0.01 b	241 ± 1.26 b
	9	35.44 ± 0.58 c	0.56± 0.02 c	9 ± 0.96 c
Chi-SB	0	5.75 ± 0.63 a	1.02± 0.07 a	325 ± 0.82 a
	5	10.3 ± 0.83 b	0.89 ± 0.01 b	290 ± 1.31 b
	17	26.2 ± 0.78 c	0.68 ± 0.06 c	254 ± 0.73 c
Chi-SB (inoculated)	0	4.9 ± 0.61 a	0.95 ± 0.07 a	309 ± 0.97 a
	5	10.45 ± 0.43 b	0.78 ± 0.03 b	270 ± 1.11 b
	12	28 ± 0.47 c	0.56 ± 0.01 c	235 ± 1.22 c

The values are the means of three replicates. Different letters within a column indicate significant differences between treatments ($p \leq 0.05$).

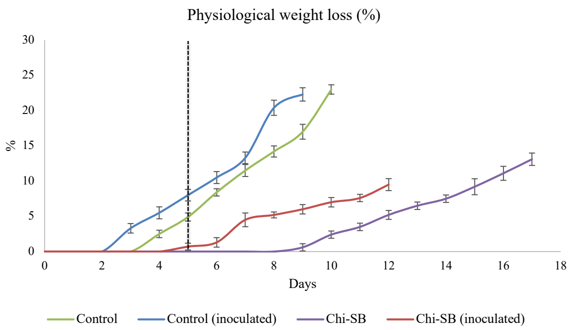

Figure 2. Physiological weight loss of jackfruit stored at 10 °C for 5 days and then stored at 25 °C.

Fruits stored at 10 °C for 5 days and treated with the coating did not show significant weight loss until they were transferred to storage at 25 °C, where the ripening process began. These results, shown in Figure 2, indicate that the treatment extended the fruit's shelf life up to 17 days. In contrast, control fruits stored at 10 °C experienced weight loss even during refrigeration, and after being transferred to 25 °C, they exhibited a 23% weight loss by day 9. Herrera-González *et al*., (2022) demonstrated that a 1.5% chitosan coating significantly reduced physiological weight loss ($p \leq 0.05$) in 'Hass' avocados compared to untreated fruit. This effect was linked to chitosan's formation of a semipermeable film, which mitigates the water potential gradient between the fruit and its environment, thereby suppressing transpiration and evaporative water loss. Similarly, Costantini *et al*., (2018) observed that chitosan nanoparticles reduced weight loss and improved firmness retention in strawberries stored both at 5 °C and room temperature, relative to controls. Both studies attribute these outcomes to chitosan's barrier properties, which restrict gas exchange and transpiration, thus slowing postharvest metabolic activity.

3.2 Physiological parameters

The respiration rate of jackfruit treated with the Chi-SB formulation was evaluated. Control fruits artificially inoculated with *R. stolonifer* and stored at 25 °C exhibited a climacteric peak on day 3, followed by a decrease in respiration rate accompanied by signs of soft rot. In contrast, uninoculated control fruits reached their climacteric peak on day 5, with a maximum value of 149.6 mL CO_2 kg^{-1} h^{-1}, after which a progressive decline associated with fruit senescence was observed. Mata-Montes de Oca *et al*., (2007) reported similar behavior in jackfruit stored at 20 °C, with the climacteric peak occurring on day 7 and a maximum CO_2 production of 98.7 mL CO_2 kg^{-1}h^{-1}. Fruits treated with Chi-SB and inoculated with the pathogen reached their maximum CO_2 production on day 6, with values of 110 mL CO_2 kg^{-1}h^{-1}. In fruits treated solely with the formulation, the climacteric peak occurred on day 8, with a maximum production of 155.8 mL CO_2 kg^{-1}h^{-1} (Fig. 3). These results indicate that the Chi-SB treatment alters the respiratory dynamics of the fruits by delaying the climacteric peak, contributing to an extended shelf life, particularly in the absence of pathogen infection. In previous studies, Nolasco-González *et al*., (2021) evaluated the effect of commercial coatings on jackfruit, observing a significant reduction in ethylene production and respiration rate (CO_2). This effect was attributed to the barrier properties of the coating, which limit gas exchange and modify the fruit's internal atmosphere, slowing metabolism and the ripening process. Additionally, it was highlighted that refrigeration at 8 °C has a considerable impact on reducing respiration and ethylene production, reinforcing the effectiveness of postharvest treatments in preserving fruit quality.

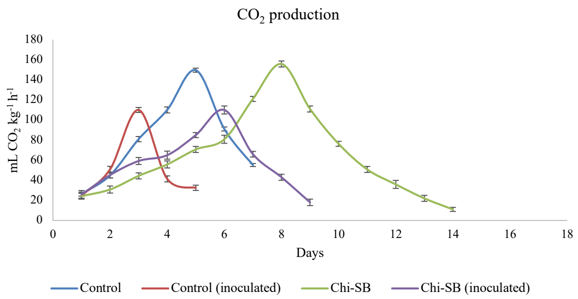

Figure 3. CO_2 production rate in control and Chi-SB-treated jackfruit with and without *R. stolonifer* inoculation stored at 25 ±2 °C.

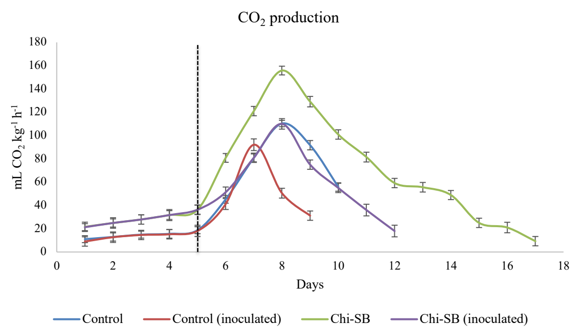

Figure 4. CO_2 production rate in control and Chi-SB-treated jackfruit with and without *R. stolonifer* inoculation stored at 10 °C for 5 days and then stored at 25 ±2 °C.

In fruits stored at 10 °C for the first five days (Fig. 4), the rate of CO_2 production remained controlled, demonstrating that refrigeration regulates this physiological process. Upon transferring the fruits to storage conditions at 25 °C, control fruits inoculated with the pathogen reached a climacteric peak on day 4, with a CO_2 production of 44.2 mL CO_2 kg^{-1}h^{-1}. Uninoculated control fruits exhibited their peak on day 5, with a production of 45 mL CO_2 kg^{-1}h^{-1}.

In contrast, fruits treated solely with the coating showed controlled CO_2 production, reaching their climacteric peak on day 8 with a maximum value of 155.8 mL CO_2 kg^{-1}h^{-1}, followed by a progressive decline to 9.3 mL CO_2 kg^{-1}h^{-1} on day 17. Similarly, fruits treated with the coating and inoculated with the pathogen exhibited a climacteric peak on day 8 (three days after being stored at 25 °C), with CO_2 production of 110 mL CO_2 kg^{-1}h^{-1}, followed by a rapid decline in CO_2 production. These results indicate that artificial inoculation with the fungus affects the ripening process, accelerating respiration and associated metabolism. The action of the Chi-SB formulation on the respiratory rate can be explained by its influence on the ethylene biosynthetic pathway. The formulation creates a modified atmosphere that suppresses ethylene production by inhibiting the expression of the enzymes 1-aminocyclopropane-1-carboxylate synthase (ACC synthase) and 1-aminocyclopropane-1-carboxylate oxidase (ACC oxidase). The latter is oxygen-dependent, limiting ethylene synthesis and thus reducing both O_2 consumption and CO_2 production (do Nascimento Sousa *et al.*, 2020).

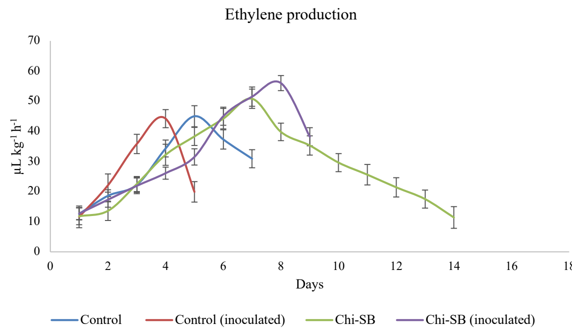

Figure 5. Ethylene production rate in control and Chi-SB-treated jackfruit with and without *R. stolonifer* inoculation stored at 25 ±2 °C.

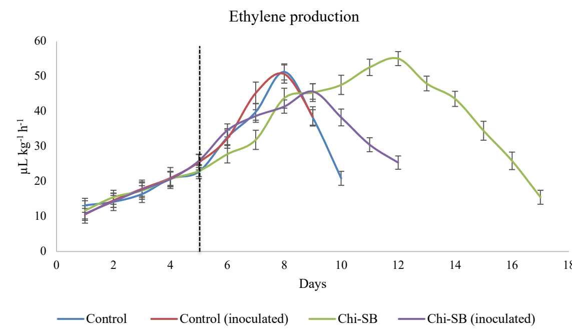

Figure 6. Ethylene production rate in control and Chi-SB-treated jackfruit with and without *R. stolonifer* inoculation stored at 10 °C for 5 days and then stored at 25 ±2 °C.

The production of ethylene in fruits under different treatment and storage conditions was evaluated (Figs. 5 and 6). In control fruits artificially inoculated with *R. stolonifer*, the highest ethylene production was recorded on day 4, reaching 19.9 μL kg^{-1} h^{-1}. In contrast, uninoculated control fruits exhibited peak ethylene production on day 6, with a value of 45 μL kg^{-1} h^{-1}. Mata-Montes de Oca *et al.*, (2007) reported that jackfruit stored at 20 °C reached 63.7 μL kg^{-1} h^{-1} on day 4. Fruits treated with Chi-SB and inoculated with the pathogen exhibited a climacteric ethylene production peak on day 8, reaching 56 μL kg^{-1} h^{-1}. Meanwhile, fruits treated solely with the formulation achieved maximum ethylene production on day 7, recording 51.5 μL kg^{-1} h^{-1} before entering senescence and becoming susceptible to fungal invasion. Ramos-Guerrero *et al.*, (2019) reported that the application of edible coatings composed of chitosan controlled the respiration rate in soursop fruits by forming a physical barrier, which regulated this process and reduced ethylene production. In fruits stored at 10 °C, the ethylene production rate remained steady during refrigeration. However, after transferring to 25 °C, fruits treated solely with Chi-SB reached maximum ethylene production on day 12 (55.1 μL kg^{-1} h^{-1}), followed by a decline. Similarly, coated fruits inoculated with *R. stolonifer* exhibited a production peak of 45.7 μL kg^{-1} h^{-1} on day 9, which was followed by a decrease and the appearance of infection signs.

These metabolic changes are associated with the presence of compounds such as chitosan and sodium benzoate on the fruit surface, which modify the internal atmosphere, alter ethylene production, and prolong the fruit's shelf life. Chitosan-based coatings have proven to be an effective strategy for controlling ethylene in postharvest fruits, contributing to extended shelf life and quality preservation. Chitosan, a natural polysaccharide with antimicrobial and antioxidant properties, acts as a physical barrier that limits the diffusion of gases like ethylene, slowing the ripening and senescence processes. Additionally, chitosan has been reported to interact with reactive oxygen species (ROS) and ethylene metabolism, promoting antioxidant enzyme activity and reducing endogenous ethylene production (Hernández-Muñoz *et al*., 2008; Xing *et al*., 2020). This is particularly beneficial for climacteric fruits, where ethylene plays a central role in regulating ripening. Recent studies highlight that chitosan coatings applied to fruits such as bananas and tomatoes can significantly delay their decomposition, maintaining firmness, color, and nutritional value during storage (Ali *et al*., 2021). Jackfruit, being a climacteric fruit, is characterized by a high ethylene production rate, making it highly perishable and susceptible to pathogen invasion during storage.

3.3 Enzymatic activity

Figure 7 illustrates the effect of the Chi-BS treatment on peroxidase (POD) activity. Fruits treated and inoculated with *R. stolonifer* exhibited significantly higher POD activity compared to controls ($p \leq 0.05$). An increase in enzymatic activity was observed in fruits treated solely with Chi-BS on day 4, while fruits treated and artificially inoculated with the pathogen reached maximum POD activity on day 8. In contrast, the control group showed an increase in enzymatic activity up to day 6, followed by a decline associated with the onset of senescence, indicating a lower concentration of POD. Plant peroxidases, also referred to as Class III peroxidases, are monomeric enzymes essential to various physiological processes. Their functions include lignification, auxin metabolism, and protein assembly in the cell wall. Furthermore, these enzymes play a critical role in the plant antioxidant system, contributing to recognition and defense against abiotic stressors such as drought and tolerance to high salt concentrations (Shah *et al*., 2021).

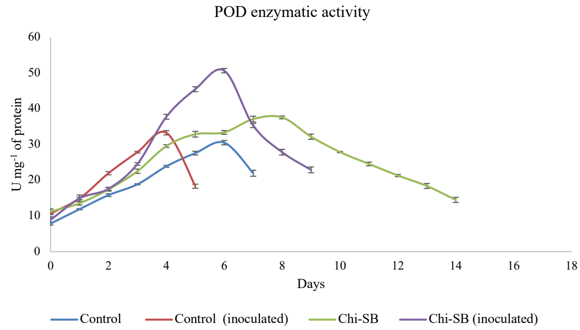

Figure 7. Effect of Chi-SB treatment on POD activity in *R. stolonifer*-inoculated and non-inoculated jackfruit stored at 25 ±2 °C.

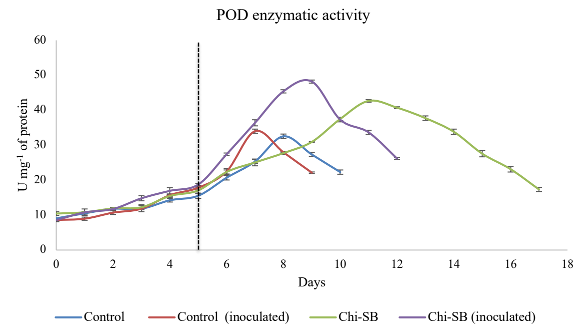

Figure 8. Effect of Chi-SB treatment on POD activity in jackfruit inoculated and non-inoculated with *R. stolonifer* stored at 10 °C for 5 days and then stored at 25 ±2 °C.

Figure 8 shows POD enzyme activity in fruits stored at 10 °C for the first five days, during which no significant differences in activity were observed. However, after transferring the fruits to storage conditions at 25 °C, a progressive increase in POD activity was noted in coated fruits, reaching its peak on day 9 for treated and inoculated fruits and on day 11 for fruits treated only with the coating. In contrast, control fruits exhibited their highest enzymatic activity on day 7 for inoculated fruits and day 8 for uninoculated fruits. These results suggest that the applied treatment, combined with changes in storage conditions, facilitated an adaptive response in treated fruits, prolonging POD activity compared to the control fruits. The increase in POD activity in fruits exposed to biotic stress suggests a response induced by pathogen invasion. This stress activates the synthesis of reactive oxygen species (ROS), such as superoxide radicals (O_2^-) and hydrogen peroxide (H_2O_2). According to Lo'ay *et al*., (2019), fungal infection stimulates POD activity, promoting H_2O_2 production. This compound catalyzes the polymerization of phenolic compounds to form lignin and suberin in the cell wall, creating a structural barrier that restricts pathogen spread in the fruit tissues. Ackah *et al*., (2022) reported that POD activity in wounded fruit treated with chitosan increased by 99% compared to the wounded control fruit on day 3, concluding that chitosan effectively regulates the formation and elimination of ROS, preventing oxidative stress while maintaining fruit quality under wound-induced stress. H_2O_2 generated by POD can serve as a substrate for other peroxidases, act as an antimicrobial agent, or trigger hypersensitivity reactions that activate defense mechanisms in the fruit (Nie *et al*., 2020). Additionally, H_2O_2 can diffuse intracellularly and activate defense-related genes, leading to programmed cell death (Davison *et al*., 2002).

Conclusions

This study demonstrates that the combined use of a chitosan-sodium benzoate coating and a two-stage storage regime effectively extends the postharvest shelf life of jackfruit. The treatment not only inhibited the development of *Rhizopus stolonifer* but also preserved critical quality parameters such as firmness and weight. Additionally, the coating enhanced peroxidase activity, highlighting its role in the fruit's defense mechanisms. These findings present a sustainable and practical solution for reducing postharvest losses, thereby improving the marketability and economic value of jackfruit.

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