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Enhancing Postharvest Quality of Cavendish Bananas (*Musa acuminata*) with *Lactobacillus* sp.

Denrel T. Hernando*[AB]

[A] BS Agriculture Program, Faculty of Agriculture and Life Sciences, Davao Oriental State University, City of Mati, Davao Oriental, 8200 Philippines
[B] University of Southeastern Philippines, Tagum-Mabini Campus, Apokon, Tagum City, 8100 Philippines

*Corresponding author; email: denreldorsu18@gmail.com

Abstract

Cavendish bananas are among the most widely cultivated and consumed varieties worldwide, valued for their sweetness, texture, and versatility. However, postharvest diseases, particularly crown rot caused by *Fusarium* and *Colletotrichum* spp., present significant challenges, resulting in substantial losses in both quality and yield. Traditional management relies on synthetic chemicals, such as prochloraz and calcium hypochlorite; however, concerns over pesticide residues, environmental impact, and consumer preference for low-chemical produce have driven the search for safer alternatives. Lactic acid bacteria, particularly *Lactobacillus* sp., have shown promise in agriculture due to their ability to produce organic acids, such as lactic acid, which suppress pathogens and enhance fruit quality. This study investigated the efficacy of *Lactobacillus* sp. as a postharvest treatment for Cavendish bananas, comparing it with conventional chemical treatments. The main objectives were to evaluate fruit quality, crown rot incidence, sensory attributes, and economic viability. Results demonstrated that bananas treated with *Lactobacillus* sp. (10 ml.L^{-1} water) achieved a high select quality (SQ) rating of 94.25%, closely comparable to 94.65% observed in synthetic chemical-treated fruits. Untreated bananas and those treated with calcium hypochlorite exhibited lower quality and a higher incidence of crown rot. Sensory evaluation revealed no significant differences in odor, aroma, flavor, texture, or overall acceptability across treatments, indicating that *Lactobacillus* sp. does not compromise sensory qualities. Economic analysis further highlighted the benefits of this biological treatment, with *Lactobacillus* sp. yielding the highest return on investment (61.7%), outperforming synthetic chemicals at 37.5% ROI. These findings highlight Lactobacillus sp. as a cost-effective and sustainable alternative to traditional fungicides, offering comparable fruit quality and profitability while reducing chemical reliance. This approach aligns with consumer demand for low-chemical produce, particularly in markets such as Japan, and supports environmentally sustainable postharvest disease management.

Keywords: biocontrol, economics, pathogens, residues, sustainability

Introduction

Banana (*Musa acuminata*) is a staple food crop for millions worldwide and one of the most important tropical fruits due to its significant economic value and nutritional benefits (Choudhary and Kaur, 2023; Handayani et al., 2024; Nasution et al., 2025). According to the Food and Agriculture Organization (FAO, 2025), bananas, comprising over 1,000 varieties, are among the most widely produced, traded, and consumed fruits globally, playing a crucial role in food security and income generation, especially in low-income, food-deficit countries such as the Philippines, while India and China lead in domestic production. In India, bananas are cultivated year-round across nearly all states, with tissue-cultured Cavendish varieties significantly boosting output, contributing 32.6% of total fruit production from just 11.1% of the cultivated fruit area (Mitra, 2014). The Cavendish variety dominates international trade, accounting for nearly half of global banana production at approximately 50 million tonnes annually, with worldwide trade volumes reaching around 20 million tonnes per year (FAO, 2025). In 2024, the Philippines ranked as the leading banana exporter in Asia and fourth globally, exporting 2.278 million tonnes, following Ecuador (5.757 million tonnes), Guatemala (2.591 million tonnes), and Colombia (2.327 million tonnes) (FAO, 2025). Within the country, the Cavendish variety accounted for the largest share of total production, with 1.13 million metric tons representing 50.5% of national output (PSA, 2025). The Davao Region

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remained the primary production hub, contributing 821.75 thousand metric tons or 36.8% of total domestic production (PSA, 2025). According to the Philippines Export Statistics (TradeImeX®, 2024), banana exports reached USD 1.22 billion in 2023–2024, with Japan (USD 562.58 million), China (USD 359.76 million), and South Korea (USD 164.53 million) as top importers. The main export destinations continue to be Japan, China, South Korea, and the Middle East (TradeImeX®, 2024). As a key export commodity, the postharvest handling of Cavendish bananas is critical to preserving quality during transport and ensuring extended shelf life for global markets.

Despite its global importance, the Cavendish banana faces significant postharvest challenges that compromise its marketability and consumer acceptability, including rapid ripening, mechanical damage, fungal decay, and reduced shelf life—often worsened by improper handling and inadequate storage conditions (Ssekyanzi and Park, 2023). Quality deterioration during transport also leads to major economic losses (Al-Dairi et al., 2023). To address these issues, various strategies have been explored to improve postharvest quality, such as the use of heat units as a harvesting criterion, which has been shown to support optimal shelf life and fruit quality (Abdurrohim et al., 2018), and the application of chemical treatments. However, standard commercial treatments commonly rely on synthetic chemicals, raising concerns about food safety, environmental impact, and economic feasibility (Al-Dairi et al., 2023). This underscores the urgent need to develop and adopt natural, eco-friendly alternatives to preserve the postharvest quality of bananas.

Recent studies suggest that *Lactobacillus*, a genus of lactic acid bacteria commonly associated with fermentation, may offer promising benefits for postharvest management (Badea et al., 2022; Gajendran and Rajamani, 2024; Lys, 2025). Known for their antimicrobial and antifungal properties, *Lactobacillus* strains have been applied to fruits like strawberries, apples, and citrus to delay spoilage and improve shelf stability (Badea et al., 2022; Nasrollahzadeh et al., 2022). In bananas, *Lactobacillus* plantarum has shown potential in reducing fungal infections and enhancing physicochemical properties (Chari, 2021). As a bio-based solution, the application of *Lactobacillus* could offer a sustainable alternative to chemical preservatives, particularly in tropical fruits that are highly perishable.

This study aimed to investigate the impact of *Lactobacillus* sp. application on the postharvest quality of Cavendish bananas, with a particular focus on fruit firmness, color, organoleptic properties (taste, aroma, texture), and total soluble solids (TSS). Additionally, it sought to evaluate the economic viability of using *Lactobacillus* compared to commercial synthetic products currently used in banana postharvest handling. By comparing biological and synthetic treatments, the research intends to provide practical insights for improving postharvest strategies in banana production.

The significance of this research lies in its potential to contribute to sustainable agriculture and the production of value-added bananas. While earlier studies have demonstrated the antimicrobial properties of *Lactobacillus* spp. on various fruits (Alimi et al., 2023; Sharma and Lee, 2025), there remains a lack of in-depth, locally relevant research specifically targeting Cavendish bananas within the Philippine postharvest supply chain. Davao, as a central banana-producing region, faces unique logistical and environmental challenges that affect fruit quality during storage and export. Additionally, the economic comparison between microbial and synthetic treatments remains underexplored. There is a clear need to validate the efficacy and cost-effectiveness of *Lactobacillus* applications under actual production and export conditions. By addressing these gaps, this study could help reduce postharvest losses, enhance fruit quality, and provide an accessible, natural alternative to synthetic chemicals for banana growers and exporters in tropical regions.

Materials and Methods

Study Location and Experimental Design

The study was conducted at Packing House 096, located in Tacor, Santo Tomas, Davao del Norte, Philippines, from January to June 2023. This facility serves as one of the primary postharvest handling and packaging centers for Cavendish bananas (*Musa acuminata*, AAA Group) intended for export. The research site was strategically selected due to its adherence to export-quality standards and its proximity to major banana production areas in the Davao Region, ensuring that the experimental setup closely reflected the actual operational environment of commercial banana handling.

The experimental design was specifically formulated to simulate postharvest handling conditions of Cavendish bananas destined for the Japanese export market, which requires stringent quality control and precise temperature management throughout the supply chain. The simulation encompassed all critical stages of the export handling continuum, including

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harvesting, washing, grading, packing, transport simulation, storage, ripening, and shelf-life evaluation. To closely replicate commercial conditions, transport and storage simulations were conducted for 10 to 15 days, reflecting the average duration between harvest and arrival at Japanese ports. During this period, the fruit samples were maintained under controlled laboratory conditions that simulated typical export parameters, including temperature (13–15°C), relative humidity (85%–90%), and airflow conditions comparable to those in refrigerated container settings. Following the simulated transport and storage phase, bananas underwent controlled ripening procedures using calibrated ethylene gas exposure (100–150 ppm) to achieve uniform ripening consistent with export ripening protocols. Subsequently, shelf-life assessments were carried out under ambient laboratory conditions (27±2°C and 70%–80% RH) to evaluate postharvest quality deterioration and marketable life. This comprehensive simulation ensured that all experimental treatments were evaluated under standardized and reproducible conditions, accurately reflecting the handling, storage, and distribution environments encountered by Cavendish bananas exported from the Philippines to Japan.

Preparation of Lactobacillus sp. Treatment

The *Lactobacillus* sp. culture used in this study was obtained from a commercially available probiotic formulation widely utilized in agricultural and postharvest applications. The product contained a consortium of lactic acid bacteria suspended in a nutrient-stabilized aqueous medium, formulated to enhance microbial balance and suppress postharvest pathogens naturally present on fruit surfaces.

For treatment preparation, 10 mL of the commercial probiotic formulation was diluted in 1 L of sterile distilled water to achieve the working concentration used for banana postharvest treatment. The solution was freshly prepared before each application to maintain high bacterial viability and metabolic activity. To ensure product stability, the formulation was kept in its original sealed and light-protected packaging and stored at 4–8°C when not in use. Each container was properly labeled, displaying the batch number, manufacturing date, expiration date, and handling instructions as provided by the manufacturer.

The prepared *Lactobacillus* suspension was applied to the fruit immediately after harvest and before packing. The dipping method was employed, wherein each banana hand was immersed in the treatment solution for 3–5 minutes to ensure complete surface contact. Excess solution was allowed to drain naturally under ambient laboratory conditions (27±2°C) before the fruit was air-dried for approximately 30 minutes on sanitized racks lined with absorbent paper. This process ensured uniform microbial coating and minimized residual moisture that could affect crown integrity or promote secondary contamination.

All treated fruits were subsequently subjected to simulated export handling procedures, including storage, transport, ripening, and shelf-life evaluation, to determine the effectiveness of the *Lactobacillus*-based treatment under conditions closely replicating the commercial handling of Cavendish bananas intended for export.

Bacterial Viability Confirmation

To verify the viability and purity of the *Lactobacillus* sp. culture used in the postharvest treatments, microbiological assays were conducted before each experimental application. The viability test ensured that the bacterial population within the probiotic formulation was metabolically active and capable of growth under standard laboratory conditions.

Nutrient agar (NA) was used as the growth medium for culturing and enumeration. The medium was prepared by dissolving 28 g of commercially available NA powder per 1 L of distilled water, in accordance with the manufacturer's instructions. The pH was adjusted to 7.0±0.1 using 1 N NaOH or HCl as needed. The prepared medium was dispensed into 500 mL Erlenmeyer flasks, sterilized by autoclaving at 121°C and 15 psi for 15 minutes, and then cooled to 45–50°C in a water bath. Approximately 15–20 mL of molten NA was aseptically poured into sterile Petri dishes (90 mm diameter) under a laminar airflow hood. Once solidified, the plates were stored inverted at 4°C to prevent condensation and were used within 7 days of preparation.

For inoculation, a 200 μL aliquot of the probiotic suspension was transferred aseptically onto the surface of the NA plate. The inoculum was spread evenly using a sterilized L-shaped glass rod (resembling a hockey stick) that had been previously dipped in 70% ethanol and flamed. The inoculated plates were incubated inverted at 37°C for 24–48 hours to allow visible colony development. Following incubation, colony-forming units (CFUs) were enumerated using a digital colony counter, and colony morphology, including color, size, shape, and elevation, was recorded to verify consistency with *Lactobacillus*-type growth characteristics.

A representative single, well-isolated colony exhibiting typical *Lactobacillus* morphology (small,

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round, convex, cream-white) was then sub-cultured onto freshly prepared NA slants for purification and preserved at 4°C for short-term maintenance.

Further phenotypic characterization of the bacterial isolate was performed through Gram staining and catalase testing following the procedures described by Cappuccino and Sherman (2014). Gram staining was conducted on 48 hour old cultures fixed on clean glass slides, stained sequentially with crystal violet, Gram's iodine, 95% ethanol, and safranin, and examined under a compound light microscope at 1000× magnification (oil immersion). The isolate exhibited the characteristic Gram-positive, non-spore-forming, rod-shaped morphology consistent with *Lactobacillus* species. For catalase testing, a small portion of the bacterial colony was transferred to a clean glass slide, and one drop of 3% hydrogen peroxide (H_2O_2) was added. The absence or minimal production of gas bubbles indicated a catalase-negative reaction, confirming the presumptive identification of the isolate as a member of the genus *Lactobacillus*.

All microbiological procedures were conducted under aseptic conditions within a Class II biosafety cabinet to prevent contamination and ensure reproducibility of results. All microbiological assays were performed in triplicate to ensure the accuracy, precision, and reproducibility of results. Each batch of nutrient agar and all inoculated plates was assigned a unique identification code that included the date of preparation, the batch number of the probiotic formulation, and the analyst's initials for proper traceability. Laboratory instruments, such as pipettes and incubators, were calibrated and verified for accuracy before use in accordance with the standard operating procedures of the laboratory facility.

During culture preparation and incubation, sterile techniques were strictly observed within a Class II biosafety cabinet to minimize the risk of cross-contamination. All glassware and culture tools were autoclaved before use, and ethanol-based disinfection was conducted before and after each procedure. Negative control plates (uninoculated NA) were included in every experimental run to confirm sterility of the medium and aseptic handling.

After incubation, colony-forming units (CFUs) were counted manually and verified using a digital colony counter. For quantitative consistency, only plates exhibiting 30–300 colonies were considered valid for enumeration. CFU counts were expressed as mean ± standard deviation (SD) across replicates. A minimum CFU density of 10^6–10^8 CFU.mL^{-1} in the probiotic suspension was considered indicative of satisfactory bacterial viability for postharvest treatment use, consistent with typical *Lactobacillus* viability standards reported in literature.

All data were recorded immediately in preformatted laboratory notebooks and electronic spreadsheets to reduce transcription errors. Each entry included detailed notes on media lot number, incubation duration, culture appearance, and any deviations from the expected colony morphology. Raw data sheets were reviewed and signed by the laboratory analyst, then verified by the project's principal investigator, before being encoded.

To ensure data integrity, the results of Gram staining and catalase testing were independently verified by two analysts, and micrographs of representative stained preparations were archived as supporting documentation. All waste materials were sterilized by autoclaving before disposal, in accordance with the laboratory's biosafety and environmental management protocols. This systematic quality assurance framework ensured that the bacterial viability assessment of *Lactobacillus* sp. was performed under controlled, traceable, and validated laboratory conditions, thereby guaranteeing the reliability of subsequent postharvest treatment experiments.

Postharvest Quality Assessment

Postharvest quality assessment was conducted to determine the physicochemical, sensory, and pathological responses of Cavendish banana (*Musa acuminata*, AAA Group) fruits subjected to different postharvest treatments during storage. Evaluation parameters included fruit firmness, peel color, total soluble solids (TSS), organoleptic properties, and crown rot incidence and severity.

A total of 120 banana hands of uniform size, maturity stage (75%–80% full maturity, light green peel), and free from visible defects were used for the experiment. The samples were randomly divided into four treatment groups, each consisting of 30 banana hands, corresponding to the experimental treatments: untreated control, chemical standard, *Lactobacillus* sp. treatment, and combined or alternative treatment, as applicable. Each treatment was replicated three times, with 10 hands per replicate, to ensure statistical validity.

Quality assessments were performed at 0, 3, 6, and 9 days after harvest (DAH) to monitor temporal changes in fruit characteristics during the storage period. All measurements were conducted at ambient laboratory conditions (27±2°C and 70%–80% RH)

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under uniform lighting to minimize observer bias and environmental variation.

Fruit Firmness and Peel Color

Fruit firmness was evaluated manually using the finger pressure test and validated through visual and tactile assessments, following standard postharvest evaluation guidelines for banana quality (as adapted from the Bureau of Plant Industry's Banana Export Protocol). Firmness ratings were expressed using a qualitative 5-point scale, where 1= very soft and 5= firm and unripe. Peel color was assessed visually by comparing each sample to a standard banana color chart (1–7 scale), where 1= dark green and 7= fully yellow, as per international grading standards (Chiquita Banana Color Reference Scale). Trained assessors performed evaluations to ensure consistency and reduce subjectivity.

Organoleptic Evaluation

Sensory or organoleptic properties, including taste, aroma, texture, and overall acceptability, were assessed by a trained panel of five evaluators experienced in fruit quality testing. Before evaluation, panelists underwent orientation on the use of a 9-point hedonic scale, where 1= Dislike extremely; 2= Dislike very much; 3= Dislike moderately; 4 = Dislike slightly; 5= Neither like nor dislike; 6= Like slightly; 7= Like moderately; 8= ike very much; 9= Like extremely.

Samples were presented in coded, randomized order under controlled sensory laboratory conditions to minimize bias. Evaluations were conducted under neutral white lighting, and panelists were provided with room-temperature water between samples to cleanse their palate. Mean hedonic scores were computed for each attribute and treatment at every sampling interval.

Measurement of Total Soluble Solids (TSS)

The total soluble solids (TSS) content was measured to estimate the sugar concentration in the banana pulp. For each sample, a representative portion of the pulp was homogenized using a sterile mortar and pestle, and the juice was extracted by gentle filtration through clean muslin cloth. A drop of the filtrate was placed on the prism of a calibrated analog refractometer (ATAGO, Japan), and the reading in °Brix was recorded once the scale stabilized. The refractometer was calibrated with distilled water (0 °Brix) before every measurement session. Between samples, the prism was rinsed with distilled water and wiped dry with lint-free tissue paper to prevent cross-contamination and ensure measurement accuracy. Each reading was performed in triplicate, and the mean value was used for data analysis.

Crown Rot Incidence and Severity

Crown rot development was carefully monitored throughout the storage and ripening period. The crown region of each banana hand was visually examined for symptoms such as browning, softening, mycelial growth, and tissue decay. Disease severity was rated using a 0–4 Crown Rot Severity Scale adapted from the standard evaluation system of a private banana export company. A score of **0** indicated no visible infection; **1** represented slight browning of crown tissues; **2** denoted moderate browning accompanied by minor fungal growth; **3** described extensive discoloration with moderate fungal colonization; and **4** corresponded to severe infection covering the entire crown area and extending into the finger attachment. The crown rot incidence, expressed as a percentage, was determined by calculating the proportion of banana hands exhibiting moderate to severe infection (scores of 2 or higher) relative to the total number of hands assessed in each treatment. This value was then multiplied by 100 to obtain the percentage of infected samples.

Two trained evaluators independently performed all disease assessments, and mean values were computed to minimize observer bias. Representative photographs were taken at each assessment interval to document the progression of crown rot symptoms and to serve as visual confirmation of the scoring accuracy.

Economic Analysis

The economic viability of the postharvest treatments was evaluated to determine the financial feasibility of using *Lactobacillus* sp. as an alternative to conventional chemical controls. A comprehensive accounting of all input costs was conducted, including both material costs (such as chemicals, probiotic formulation, packaging materials, water, and other consumables) and labor costs (such as handling, application, and monitoring during the postharvest period). All expenses were recorded in Philippine pesos and corresponded to actual expenditure incurred throughout the experimental period.

The net return for each treatment was calculated as the difference between total revenue from marketable banana sales and total costs of inputs and labor associated with that treatment. Marketable banana sales were determined by multiplying the number of saleable banana hands by the unit price per kilogram or per hand at prevailing market rates during the study period.

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The return on investment (ROI) was computed to quantify the financial efficiency of each postharvest treatment. ROI was calculated by dividing the net profit (net return) by the total cost of investment and expressing the result as a percentage. In practical terms, this was determined by taking the net sales generated from each treatment, dividing it by the total treatment cost, and multiplying the quotient by 100 to express it as a percentage. This approach allowed a direct comparative analysis of the profitability of *Lactobacillus* sp. treatment relative to conventional chemical controls, highlighting the potential economic benefits of adopting microbial-based postharvest management strategies.

Two independent evaluators cross-checked all economic calculations to ensure accuracy, and sensitivity analysis was performed to assess how variations in input costs or market prices could influence the ROI. This rigorous approach provided a robust and transparent assessment of the economic feasibility of probiotic-based postharvest treatments for Cavendish bananas intended for export.

Statistical Analysis

All collected data were subjected to comprehensive statistical analysis using SPSS (Statistical Package for the Social Sciences) and R-Studio software to ensure accuracy and reliability of results. Before conducting inferential tests, data was examined for normality and homogeneity of variances to determine the appropriate statistical procedures.

One-way Analysis of Variance (ANOVA) was employed to evaluate the effects of treatments on the measured parameters and to identify statistically significant differences among treatment means. When significant differences were detected, Fisher's Least Significant Difference (LSD) test with Bonferroni correction was applied to control for Type I error and to determine which specific treatment pairs differed significantly.

For quality parameters that did not meet the assumptions of normality, particularly organoleptic or sensory scores, the non-parametric Kruskal–Wallis test was performed as an alternative to ANOVA. This allowed for the comparison of median values among treatments under non-normal data distributions.

In addition, descriptive statistics, including mean, standard deviation, and range, were computed to summarize and interpret the data on total soluble solids (TSS) and sensory evaluation. These statistical summaries provided a clear overview of the variability and central tendency of the measured postharvest quality attributes. All statistical tests were evaluated at a 5% level of significance ($p<0.05$).

Results and Discussion

Gram Staining and Catalase Testing of ***Lactobacillus*** *sp.*

To further characterize *Lactobacillus* sp., both Gram staining and a catalase test were performed using a 48-hour pure culture. The Gram staining results revealed that the bacterial cells of *Lactobacillus* sp. stained purple under the microscope (see Figure 1), indicating that the organism is a Gram-positive bacterium. This outcome is due to the thick peptidoglycan layer in the cell wall, which retains the crystal violet stain.

In addition to Gram staining, a catalase test was performed to further characterize the *Lactobacillus*

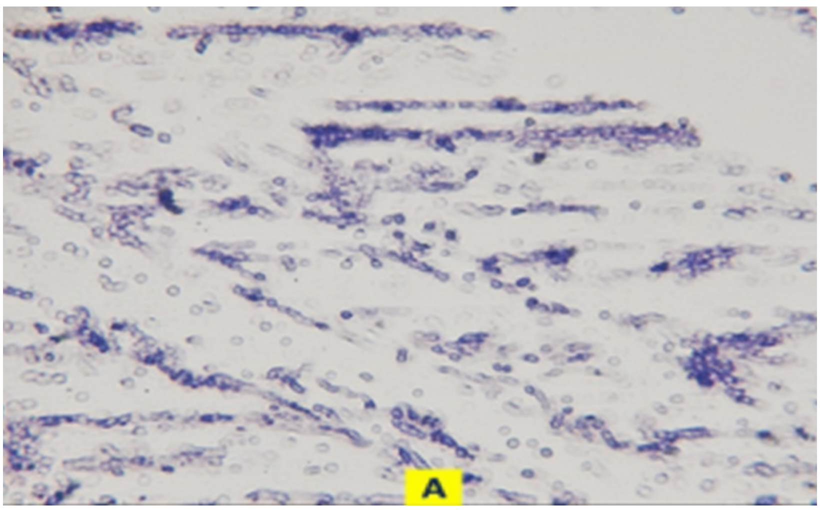

Figure 1. Gram staining of 48 hour *Lactobacillus* sp. culture showing Gram-positive cells (1000X)

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sp. isolate. A small amount of a 48-hour-old culture grown on Nutrient Agar was aseptically transferred to the center of a clean glass slide using a sterilized inoculating loop. A 3% hydrogen peroxide (H_2O_2) solution was added directly to the bacterial smear. No bubble formation was observed, indicating a catalase-negative reaction, which is consistent with the known characteristics of *Lactobacillus* species. The absence of catalase activity confirms that the isolate lacks the enzyme catalase, which in other bacteria rapidly decomposes hydrogen peroxide into water and oxygen.

As a member of the lactic acid bacteria (LAB) group, *Lactobacillus* sp. is non-spore-forming and primarily metabolizes organic acids such as lactic acid, acetic acid, and succinic acid (Muhammad, 2021). LAB strains are widely recognized for their antibacterial, antifungal, and probiotic properties, contributing to their diverse biological functions (Abouloifa et al., 2022; Simões et al., 2022; Mahjoory et al., 2023). The catalase-negative nature of *Lactobacillus* sp. is a crucial phenotypic trait that distinguishes it from catalase-positive bacteria and is particularly relevant to its survival and activity in low-oxygen environments, such as the interior of fruits during postharvest storage.

These gram-positive, catalase-negative properties make *Lactobacillus* sp. a highly effective natural agent for preserving fruit quality. By offering an eco-friendly alternative to chemical preservatives, *Lactobacillus* contributes to more sustainable postharvest management. Its ability to naturally inhibit the growth of harmful microorganisms while promoting a balanced microbial environment further enhances its role in extending the shelf life and improving the appearance of harvested fruits.

Postharvest Quality Assessment

Select quality (SQ) reading

The percent quality (SQ) readings of the banana fruits were assessed to verify and correlate with the incidence of crown rot (see Figure 2). Fruits treated with *Lactobacillus* sp. (10 ml.L^{-1} water) showed a high-quality rating of 94.25%, which was comparable to the 94.65% SQ observed in fruits treated with synthetic chemicals (Prochloraz) (see Table 1). Both treatments also exhibited minimal incidence of crown rot. In contrast, untreated fruits and those treated with calcium hypochlorite (positive control) displayed lower quality ratings of 80.91% and 85.32%, respectively. These results demonstrate that *Lactobacillus* sp. treatment yields fruit quality like that of synthetic chemicals, making it an effective alternative for postharvest management.

The percent select quality (SQ) readings revealed that bananas treated with *Lactobacillus* sp. (10 ml.L^{-1} water) maintained high postharvest quality, achieving a 94.25% SQ rating, which was statistically comparable to fruits treated with synthetic chemicals (94.65%). These results underscore the potential of *Lactobacillus* sp. as a biological alternative to conventional fungicides in maintaining fruit quality and reducing postharvest disease, particularly crown rot. The effectiveness of *Lactobacillus* in enhancing postharvest quality may be attributed to its ability to produce organic acids such as lactic acid, which lowers pH and suppresses spoilage organisms (Badea et al., 2022). Similar findings were reported that lactic acid bacteria reduced fungal decay in fruits by producing antimicrobial compounds and competing for nutrients (Ibrahim et al., 2021). In contrast, lower-quality readings were observed in untreated fruits (80.91%) and those treated with calcium hypochlorite (85.32%), reflecting a higher incidence of crown rot, which highlights the limitations of traditional disinfectants. These results align with previous studies demonstrating that biological control agents, including *Pseudomonas* spp., *Bacillus subtilis*, and *Metschnikowia fructicola*, are not only effective in controlling postharvest diseases but also represent a safer and more sustainable strategy for postharvest management (Sellitto et al., 2021).

Table 1. Percent quality reading of the sampled boxes with the different treatments

Treatments	No. of samples	% Select quality*
Water only (Negative control)	16	80.91^{c}
Calcium hypochlorite (Positive control)	16	85.32^{b}
Synthetic chemical (Prochloraz)	16	94.65^{a}
Lactobacillus sp. (10 ml.L^{-1} water)	16	94.25^{a}
% CV = 7.2		

Notes: *Values followed by the same letter are not significantly different in Kruskal-Wallis and Post-hoc analysis at a 5% level of significance.

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Total soluble solids

The total soluble solids (TSS) content of the banana samples from each treatment group was measured to evaluate whether the application of *Lactobacillus* sp. had any influence on the internal quality of the fruit. The results indicated no significant differences in TSS levels across all treatments (see Table 2), suggesting that none of the postharvest applications, including *Lactobacillus* sp., synthetic chemicals, calcium hypochlorite, or the untreated control, had a measurable impact on this parameter. TSS, commonly expressed in degrees Brix, is an important indicator of fruit sweetness and overall internal quality (Kumudham and Shakir, 2024). The findings imply that the use of *Lactobacillus* sp. as a biological postharvest treatment does not alter the fruit's inherent sweetness or soluble sugar content. Therefore, while *Lactobacillus* sp. effectively supports external fruit quality and disease reduction, it does so without compromising the internal quality characteristics such as TSS.

The total soluble solids (TSS) content, a key indicator of fruit sweetness and internal quality, showed no significant differences among the Cavendish banana fruits subjected to different postharvest treatments, including *Lactobacillus* sp., synthetic chemical, calcium hypochlorite, and the untreated control. This result suggests that while these treatments influence external fruit quality and disease resistance, they do not significantly affect internal biochemical attributes, such as sugar content (Table 2). Similar findings were reported by Thangavelu et al. (2024), who observed that biological control treatments in bananas did not compromise internal fruit characteristics such as TSS. Moreover, Osei-Kwarteng et al. (2024) emphasized that postharvest treatments aimed at disease control must preserve internal quality to maintain consumer acceptability, a finding that aligns with the present study's results. Thus, the application of *Lactobacillus* sp. as a postharvest biocontrol agent appears to keep the fruit's natural sweetness and soluble sugar levels, affirming its suitability as an alternative to chemical treatments without sacrificing internal fruit quality.

Organoleptic Evaluation

The organoleptic evaluation aimed to determine the sensory acceptability of Cavendish bananas treated with different postharvest applications, focusing on key attributes such as odor and aroma, flavor, texture, and overall acceptability. Using a panel of trained evaluators and a standardized score sheet, ripe banana fingers were randomly coded to eliminate bias. Each panelist used palate cleansers between tastings to ensure accurate and independent evaluations of each sample. As shown in Table 3, no significant differences were observed among the treatments in terms of all sensory parameters. Bananas treated with *Lactobacillus* sp. (10 ml.L^{-1} water) received consistent median ratings of 7 for odor and aroma and 8 for

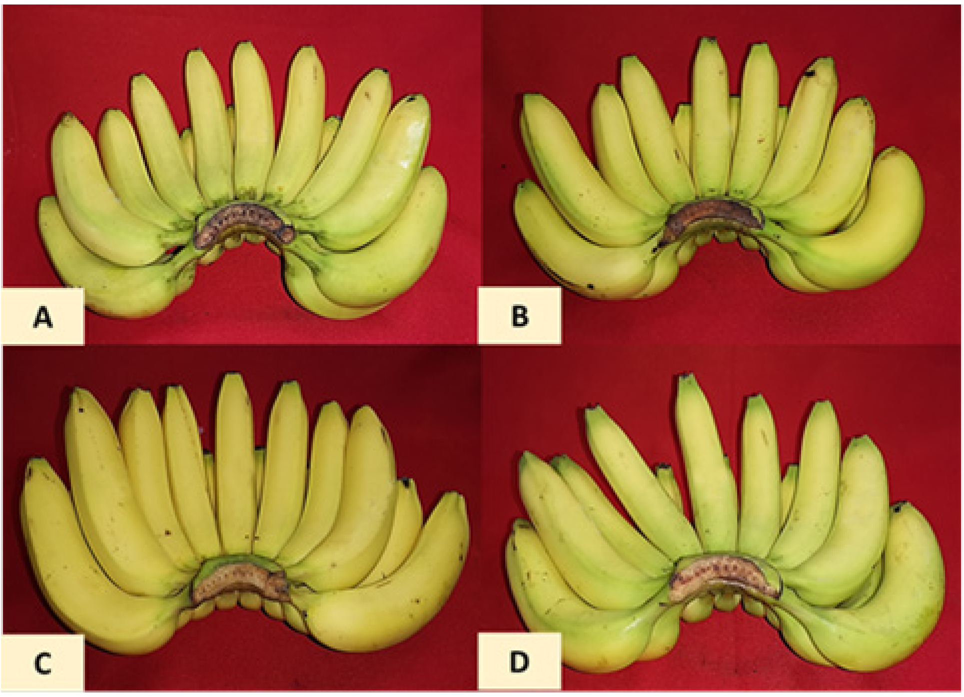

Figure 2. Sampled banana hands in the quality reading. (A) water only (negative control); (B). calcium hypochlorite (positive control); synthetic chemical (Prochloraz) (C); *Lactobacillus* sp. (10 ml.L^{-1} water) (D).

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flavor, texture, and overall acceptability, identical to those treated with the synthetic chemical Prochloraz and calcium hypochlorite. Even the untreated control showed acceptable scores, though slightly lower. These results suggest that *Lactobacillus* sp. does not negatively impact the sensory quality of bananas and performs comparably to conventional treatments. This reinforces its potential as a viable, natural alternative in postharvest management, offering both disease suppression and consumer-acceptable fruit quality.

The organoleptic evaluation of Cavendish bananas treated with various postharvest applications revealed no significant differences in sensory attributes, including odor and aroma, flavor, texture, and overall acceptability, among the treatments. As shown in Table 3, bananas treated with *Lactobacillus* sp. (10 ml.L^{-1} water) received median scores of 7 for odor and aroma and 8 for flavor, texture, and overall acceptability, ratings identical to those given to fruits treated with synthetic chemicals and calcium hypochlorite. The untreated control also received acceptable, though slightly lower, scores across all attributes. These findings indicate that the application of *Lactobacillus* sp. does not negatively affect the sensory quality of bananas and is equally acceptable to consumers as conventional chemical treatments. Lactic acid bacteria maintain the organoleptic quality of fruit while enhancing microbial safety. Therefore, *Lactobacillus* sp. presents a promising, natural alternative for postharvest treatment that ensures both disease suppression and high consumer acceptability.

Cost and Return Analysis

The cost and return analysis assessed the economic viability of each postharvest treatment by considering labor, material, and product costs. As shown in Table 4, *Lactobacillus* sp. (10 ml.L^{-1} water) yielded the highest return on investment (ROI) at 61.7%, with net sales of PHP 1,402.30 (USD 24.31) per box. This treatment incurred a minimal cost of PHP 2.40 (USD 0.04), resulting in a significant profit margin compared to other treatments. In contrast, the water-only control and calcium hypochlorite treatments showed negative returns, with the former incurring a substantial loss of PHP 1,758.90 or USD 30.060 (ROI of -77.5%) and the latter a negative ROI of -10.8%, primarily due to product rejection caused by quality issues. The synthetic chemical treatment (prochloraz) yielded a positive ROI of 37.5%, with net sales of PHP 972.20 (approximately USD 16.92). These findings suggest that *Lactobacillus* sp. is not only a

Table 2. Total soluble solids (TSS) readings of Cavendish banana fruits treated with different postharvest applications at two ripening stages (Color 5.0 and 6.0)

Treatments	TSS (°Brix) color 5.0	TSS (°Brix) color 6.0
Water only (Negative control)	17.66[a]	19.22[a]
Calcium hypochlorite (Positive control)	19.32[a]	20.74[a]
Synthetic chemical (Prochloraz)	19.04[a]	20.00[a]
Lactobacillus sp. (10 ml.L^{-1} water)	19.10[a]	20.48[a]
CV = 5.5%		

Notes: Values represent the mean of 20 fruit samples per treatment. Superscript letters ([a]) indicate no significant differences among treatments (p>0.05, one-way ANOVA).

Table 3. Median sensory evaluation scores of Cavendish bananas treated with different postharvest applications based on odor and aroma, flavor, texture, and overall acceptability

Treatments	Odor and aroma	Flavor	Texture	Overall acceptability
Water only (Negative control)	7[a]	7[a]	7[a]	7[a]
Calcium hypochlorite (Positive control)	7[a]	8[a]	8[a]	8[a]
Synthetic chemical (Prochloraz)	7[a]	8[a]	8[a]	8[a]
Lactobacillus sp. (10 ml.L^{-1} water)	7[a]	8[a]	8[a]	8[a]
% CV = 8.9				

Notes: Values represent the median of scores from five trained panelists per treatment. Superscript letters ([a]) indicate no significant differences among treatments (p>0.05, Kruskal-Wallis test). Values are based on the use of a **9-point hedonic scale**, where 1= Dislike extremely; 2= Dislike very much; 3= Dislike moderately; 4= Dislike slightly; 5= Neither like nor dislike; 6= Like slightly; 7= Like moderately; 8= Like very much; 9= Like extremely.

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Table 4. Cost and return analysis of different postharvest treatments for Cavendish bananas

Treatment	Estimated labor cost (PHP)	Estimated material cost (PHP)	Treatment cost (PHP)	Total cost incurred (PHP)	Farm gate sales (PHP)	Net sales (PHP)	% ROI
Water only (Negative control)	333.3	1936.0	0.0	2269.3	510.4	-1758.9	-77.5
Calcium hypochlorite (Positive control)	333.3	1936.0	0.6	2269.9	2024.0	-245.9	-10.8
Synthetic chemical (Prochloraz)	333.3	1936.0	322.5	2591.8	3564.0	972.2	37.5
Lactobacillus sp. (10 ml.L^{-1} water)	333.3	1936.0	2.4	2271.7	3674.0	1402.3	61.7

Notes: PHP = Philippine pesos.

cost-effective alternative but also more profitable than both synthetic chemicals and traditional methods. The analysis used a farm-gate price of USD 5 (≈ PHP 275) per box, excluding hauling, shipping, and other logistical costs. Therefore, this baseline may not reflect the actual return on investment for exporters, as export requirements and associated expenses can significantly impact profitability. Thus, *Lactobacillus* sp. demonstrated the lowest treatment cost and the highest profitability, with a return of PHP 0.62 (approximately USD 0.01) for every PHP spent. In contrast, the calcium hypochlorite treatment's negative ROI was due to quality-related rejections.

These findings underscore the economic advantage of using *Lactobacillus* sp. as a cost-effective and profitable postharvest treatment. Comparable studies, such as that by Lys (2025), have shown that biological treatments using lactic acid bacteria can significantly reduce postharvest decay while minimizing input costs, leading to improved economic outcomes for producers. Moreover, with increasing international concerns over maximum residue limits (MRLs) and the inconsistent pesticide regulations across countries, the use of synthetic chemicals presents a growing risk in global agricultural trade. In this context, *Lactobacillus* sp. offers not only a competitive cost advantage but also greater compliance with evolving international food safety standards, serving as a natural and residue-free alternative. This makes it a strategically viable option for banana exporters aiming to meet both market demands and regulatory requirements.

Japan is one of the leading markets with increasing demand for low-chemical Cavendish bananas, as it promotes natural farming practices. The market prioritizes products that are either free from synthetic chemicals or contain minimal chemical use, while still maintaining high-quality standards at reasonable prices. In line with this, exploring the potential of *Lactobacillus sp.* as a postharvest treatment for Cavendish bananas aligns with these market preferences. The use of *Lactobacillus sp.* as a biological control to manage crown rot offers a sustainable and environmentally friendly approach to postharvest disease management. This method not only supports business continuity by adapting to changing market demands but also ensures food safety for banana consumers of all ages. Additionally, it offers a consumer-friendly solution that can have a positive impact on the environment by reducing reliance on synthetic chemicals.

Conclusions

Postharvest application of *Lactobacillus* sp. significantly enhances the quality of Cavendish bananas, as indicated by improvements in fruit firmness, a reduced incidence of crown rot, and the maintenance of desirable organoleptic properties (taste, aroma, texture), with outcomes comparable to those achieved by synthetic chemical treatments. No alteration in total soluble solids (TSS) was detected, indicating that internal sweetness was preserved. Economic analysis revealed that the highest return on investment was attained using *Lactobacillus* sp., surpassing conventional chemical approaches and establishing its viability as a cost-effective alternative in postharvest management. It is recommended that *Lactobacillus* sp. be further investigated as a practical alternative for postharvest treatment, especially in markets where low-chemical produce is preferred. Optimization of application parameters, such as concentration and frequency, should be pursued to maximize efficacy and economic benefit, and evaluation of long-term effects during extended storage periods is warranted. Adoption by banana producers in regions with stringent pesticide residue

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regulations is also advised, as *Lactobacillus* sp. presents a natural, environmentally friendly solution that aligns with consumer preferences for chemical-free produce.

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