



# Application of Microbubble Technology for Improved Efficiency and Reduction in Treatment Time of 1-Methylcyclopropene for Postharvest Ripening Delay of Banana

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## Abstract

This research is aimed at evaluating feasibility of using 1-methylcyclopropene microbubbles (1-MCP-MBs) as an alternative postharvest treatment for delaying the ripening of bananas with performance comparison of treating bananas with gaseous fumigation using conventional treatments and without treatment. The effects of immersion time (5, 10, and 15 min), 1-MCP concentration (500, 1000, and 1500 ppb), and microbubble generation pressure (4, 5, and 6 kg/cm<sup>2</sup>) were tested systematically for 10 days storage period. The results showed the high efficacy of 1-methylcyclopropene microbubbles (1-MCP-MBs) in control of fruit ripening and preventing weight loss when compared with the conventional fumigation with gaseous 1-MCP. The optimal conditions for treating were 1-MCP at 500 ppb, an immersion duration of 5 min, and a generation pressure of 5 kg/cm<sup>2</sup>. These situations were able to create stable microbubble formation with a high specific surface area resulting in increased adhesion of 1-MCP to the fruit peel. The optimized storage condition resulted in weight loss of  $1.68 \pm 0.07\%$  during storage for 10 days in comparison to the control weight loss of  $3.14 \pm 0.56\%$ . Moreover, the treatment using the 1-MCP resulted in a good preservation of the chloroplast integrity and chlorophyll stability, and thus fruit freshness was maintained for over 10 days. Contrastingly, fruits in the control group experienced severe senescing and ripening in 6–8 days. The overall results indicated high potential for 1-MCP-MB technology to be applied as a postharvest technology that can increase competitiveness of banana exports in terms of cost, time, and reduced chemical usage by improved operational efficiency.

**Keywords:** 1-MCP, Banana, Microbubble technology, Postharvest life, Ripening delay

## INTRODUCTION

Thailand earns a large amount of revenue as a nation from export of agricultural goods such as rubber, vegetables and fruits [1]. Its strategic geographical position, as well as the well-developed transportation infrastructures, allows for the production and distribution of these products on a large scale and efficiently. Among these commodities, the banana is an economically important fruit crop with a significant contribution of both the domestic trade value and international export markets, especially to Japan and China [2].

Despite the commercial importance, the limited shelf life and rapid postharvest physiological deterioration of the fruit pose critical problems to obtain quality over long distance transportation. These limitations significantly reduce its potential for export and competitiveness in the market. Therefore, effective strategies to inhibit ripening are very important to preserve quality and extend marketable life of fruits. Several postharvest technologies have been developed to delay the process of ripening such as bagging of fruit, edible coatings and ethylene scavenging system [3], [4], [5], [6], [7]. Additionally, the use of 1-methylcyclopropene (1-MCP) has been widely known as an efficient ethylene action inhibitor, which inhibits ethylene perception thereby retarding ripening while preserving postharvest quality over prolonged storage [8].

Fumigation using 1-MCP is very popular in agriculture to inhibit ethylene-induced ripening of agricultural produce [9]. As a nontoxic, colorless and odorless gas, 1-MCP is highly active even in low concentrations. However successful fumigation requires airtight chambers to prevent gas leakage and the exposure period is usually 1 to 24 hours. These operational constraints add extra costs because of the specialization of fumigation facilities, environmental controls and long processing times [10]. Although aqueous solutions of 1-MCP have been introduced for applications in immersing or spraying, this method requires the use of considerable volumes of water and chemical agents. At the commercial level, these requirements significantly increase the cost of operation, especially water supply infrastructure and wastewater treatment costs.

To overcome the limitations, present for the conventional application of 1-MCP, microbubbles (MBs) technology has been suggested as an alternative delivery platform through the production of 1-methylcyclopropene-microbubbles (1-MCP-MBs) [11], [12]. Microbubbles have unique physicochemical properties such as a high specific surface area and a long sticking time in the aqueous phase, which boosts the interfacial interactions of gases and liquids [13]. These attributes allow continuous and homogeneous contact between 1-MCP-MBs and the fruit surface, which could enhance the efficiency of the utilization of active compounds and reduce the amount of chemicals usage and the operating cost. Therefore, this research investigated the effects of 1-MCP-MBs on the inhibition of banana ripening compared to the conventional immersion and fumigation methods. While previous studies [14] showed the basic efficacy, the present study further examined important engineering factors, such as the pressure for generating bubbles and the immersion time. The combined effect of the concentration of 1-MCP, generation pressure and immersion time was systematically examined to determine the optimal operating conditions and enhance treatment efficiency.



## LITERATURE REVIEW

### 1. Delaying Ripening in Agricultural Produce

Postharvest physiological activities in fresh produce, namely metabolic respiration and ethylene biosynthesis are the most important mechanism causing natural senescence and quality degradation. This phenomenon is sharply manifested in climacteric fruits such as bananas, mangoes and tomatoes. These species are characterized by the existence of a clear burst of respiration and a simultaneous increase of autocatalytic ethylene production throughout the ripening phase. As a master signaling hormone, ethylene is responsible for the regulation of genes associated with the ripening process, in which a cascade of biochemical and physical changes is triggered. These include degradation of chlorophyll, conversion of starch into soluble sugars by enzymatic action and the systematic reduction of textural firmness and pericarp color [15], [16]. Furthermore, ethylene as a key regulator of fruit transpiration and integrity as well as ripening. Ethylene induces increased activity of cell wall-degrading enzymes, including pectin methyl esterase (PME) and polygalacturonase (PG), which causes a breakdown of the cell wall, weakens the ability to hold water and promotes water loss [17], [18]. Moreover, high ethylene-induced respiration helps to accelerate weight loss by stimulating the metabolism of substrates and oxidizing carbon dioxide and water vapor. Consequently, treating fruits with 1-MCP, an ethylene perception inhibitor, delays ripening and also helps to maintain fruit surface integrity to minimize postharvest weight loss.

Current postharvest management strategies focus on the reduction of metabolic rates and the blocking of the molecular perception mechanisms of ethylene. Common interventions include the application of chemical inhibitors, temperature control, and the utilization of modified or controlled atmosphere storage [19]. Although, 1-methylcyclopropene (1-MCP) has become a leading antagonistic agent because the compound has a high affinity with ethylene receptors. By irreversibly combining with these receptors, 1-MCP manage to block the ethylene signal pathway effectively, therefore greatly reducing the internal respiration speed and endogenous ethylene evolution. Despite the efficacy of conventional gaseous 1-MCP fumigation it is limited by significant operational constraints. The process requires hermetically sealed spaces to avoid leakage of gases and takes a long time for exposure ranging between 12 to 24 hours. These requirements lead not only to an escalation of energy costs and logistical costs due to the need for temperature control housing, they also hamper the throughput efficiency of industrial scale supply chains. While the potential of aqueous delivery system (immersing or spraying) has been developed to replace it, they are frequently faced with challenges in terms of water consumption, high chemical discharge, and particularly, high complexities associated with wastewater remediation. Recent advancements have put forward the concept of combining 1-MCP with microbubble (MB) technology, both of which provide a novelty approach to postharvest preservation technology [14], [20], [21]. By capitalizing on the peculiarities of the interface properties and enhanced mass transfer possibilities of bubbles at the microscopic scale; it is expected with this hybrid technology to improve the storage life and to postpone the deterioration in quality more efficiently than with traditional methods.

### 2. Microbubble Generation

Microbubble (MB) technology has been receiving growing interest in a broad range of fields such as biomedical engineering, nanotechnology, advanced agriculture and industrial wastewater treatment. Normally in 50 to 200

micrometers in diameter, microbubbles have unique physicochemical properties that make them fundamentally different from conventional bubbles. These include high gas dissolution efficiency, high surface area to volume ratio and high residence time in the liquid phase due to low buoyant velocity. In postharvest application such features allow a platform for efficient gas delivery improving mass transfer of inhibitory compounds including 1-MCP and more uniform and sustainable adsorption on the fruit surface compared to more conventional fumigation or aqueous treatment. Microbubble generation technologies can be broadly divided into four main categories according to microbubble generation mechanisms, such as fluid flow induced fragmentation methods, ultrasonic cavitation, electrochemical generation and mechanical vibration [22], [23], [24]. Considering these, hydrodynamic or fluid flow systems are especially suitable for agricultural and industrial scale deployment, for their simplicity of operation, capacity for scalability and energy efficiency. Various designs have been developed to optimize the formation of bubbles, such as swirling flow systems based on centrifugal shear [25], pressurized dissolution techniques based on the release of supersaturated gas-liquid mixtures [26] and ejector or venturi designs that utilize high-velocity flow and shear fragmentation of gas [27], [28]. In this study, the concept of a combination of venturi type generator with pressurized dissolution is proposed. The venturi type has the advantage of structural simplicity and constant system performance, working on the basis of fluid acceleration in a constricted throat with a consequent localization of pressure drop and extreme shear forces. These hydrodynamic conditions are very effective in fragmenting 1-MCP gas into a dense suspension of stable microbubbles. Coupled with the pressure regulation unit, the system increases the gas solubility and concentration in the bubbles. This design enhances the uniform distribution and surface interaction of 1-MCP throughout the banana peel. This approach minimizes chemical waste production and facilitates integration into a closed-loop water circulation system.

## **METHODS**

### **1. Experimental Setup**

The experimental design was determined to appreciate the effectiveness of the use of 1-MCP-MBs in delaying the ripening of bananas in terms of weight loss and physical changes. Three treatment groups were studied: (1) a control group that was not exposed to 1-MCP, (2) a conventional fumigation group that was exposed to gaseous 1-MCP for 24 hours, and (3) a microbubble assisted group that was exposed to 1-MCP-MBs immersion for different treatment times.

The configuration of the 1-MCP-MBs generation system is shown in figure 1. First, aqueous solutions with predetermined concentrations of 1-MCP were prepared. Compressed air was passed through a flow controller into a storage chamber to generate 1-MCP gas at the desired concentration. The produced gas was then fed into a microbubble generator (venturi-type) that was installed along the primary water line. Within the generator, hydrodynamic shear forces separated the gas stream into micro-scale bubbles to form 1-MCP-MBs. The gas-liquid mixture was then circulated through a pressure tank by a pump to stabilize the system before being released into the plastic tank. A recirculating water configuration was used to improve operational efficiency. Flow rates were controlled and monitored by control valves and rotameters, while a cooling unit was used to keep the water temperature constant during the experiment. The detailed operational parameters, in terms of 1-MCP concentration, immersion duration, and generation pressure, are shown in table 1. After treatment, the individual

bananas were placed in zip lock bags and left under ambient conditions. Physical attributes and differences in weight were measured every day for 10 days storage period.

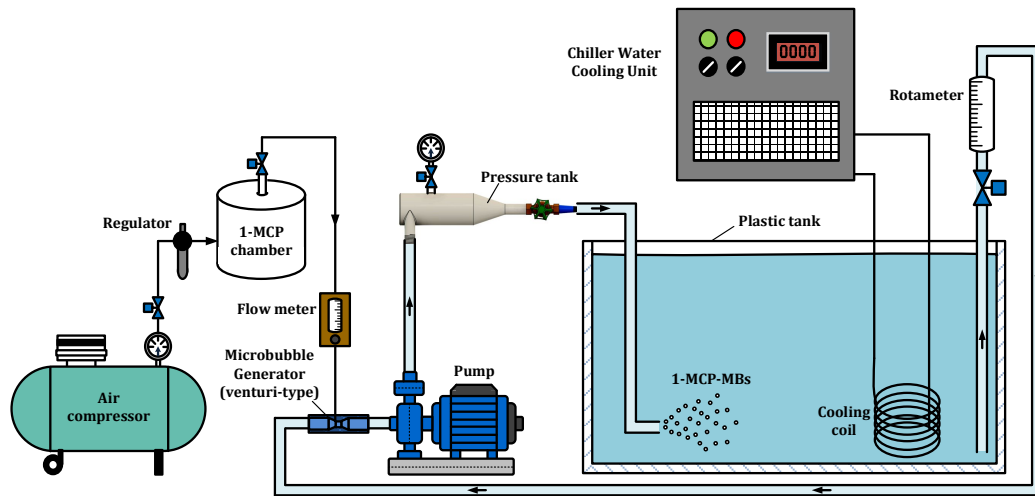


Figure 1: Schematic diagram of the experimental setup

Table 1: Experimental conditions

| Parameters                         | Values                         |
|------------------------------------|--------------------------------|
| Water pressure                     | 4, 5, and 6 kg/cm <sup>2</sup> |
| Concentration of 1-MCP             | 500, 1000, and 1500 ppb        |
| Duration of immersion in 1-MCP-MBs | 5, 10, and 15 min              |
| Storage duration                   | 10 days                        |
| Storage conditions                 | Ambient temperature            |

## 2. Determination of Weight Loss

Changes in the weight of bananas were recorded using a high precision digital analytical balance. Weight loss was determined using the difference between the initial weight and the weight at each sampling interval. For standardized comparison, the starting weight of each sample was used as the reference of 100%, and the percentage of residual weight was calculated using the following equation (1):

$$\text{Weight Loss (\%)} = \frac{W_o - W_t}{W_o} \times 100 \quad (1)$$

where  $W_o$  is the initial weight of the sample and  $W_t$  is recorded weight of the sample every 24-hour interval over the 10-day storage period. In addition, each measurement was repeated three times for each experimental condition, and the results are presented as mean  $\pm$  standard deviation (SD).

## RESULTS AND DISCUSSION

Figure 2 shows the variation in banana weight over 10 days of storage, keeping the starting weight at 100% (Day 0). The analysis includes an untreated control, 24 hours of 1-MCP gaseous fumigation, and 5 min 1-MCP-MBs immersion treatment at a concentration of 500 ppb.

A steady decline in weight was observed in all treatment groups throughout the storage period, primarily attributed to postharvest transpiration and respiration processes. However, the magnitude of weight loss varied significantly among treatments. The control samples showed the highest weight reduction, with the residual weight decreasing from 100% to 96.86%, representing a total weight loss of  $3.14 \pm 0.56\%$  after 10 days of storage. This tendency suggests continued ripening in nature with a loss of moisture. Bananas that were subjected to 1-MCP for 24 hours showed a lower rate of weight loss compared to the control group. The inhibition of ethylene receptor activity by 1-MCP probably contributed to the decreased rate of respiration and moisture loss. Despite this effect, the weight gradually lowered to 97.52% at Day 10, indicating a reduction of  $2.48 \pm 0.30\%$ . On the other hand, the 1-MCP-MBs immersion treatment (5 min) produced the best weight retention, showing a final weight measure of 98.32% and a weight loss of  $1.68 \pm 0.07\%$ .

The superior performance of this treatment may be attributed to improved dispersion and contact efficiency of 1-MCP, facilitated by microbubble technology. The small bubble size and high interfacial area likely provide a more homogeneous contact between the active compound and the fruit surface, helping to counteract physiological water loss and ripening to a greater extent and for a longer time than commonly used fumigation, despite the much shorter exposure time. In conclusion, the present research findings highlight the potential of 1-MCP-MBs application as an efficient approach to extend the shelf life of bananas.

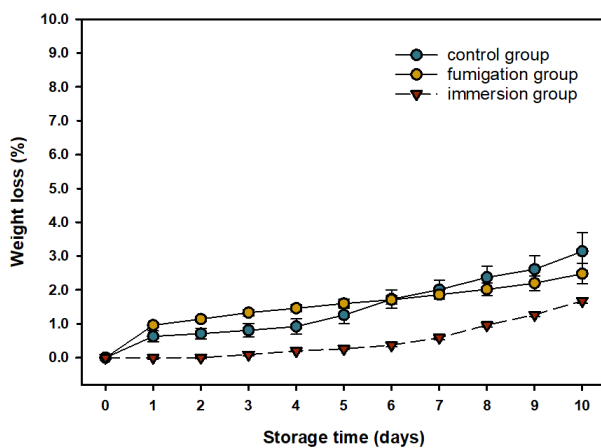


Figure 2: Weight loss of banana at different ripening delay methods

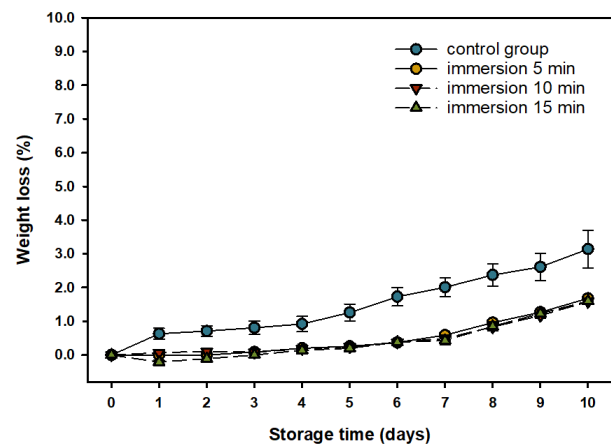


Figure 3: Weight loss of banana at different immersion time

From the comparative results of banana ripening inhibition, the immersion of 1-MCP-MBs showed better results. Consequently, the impact of the immersion time (5, 10, and 15 min) on weight change was studied to find the optimal processing time by using a constant 1-MCP concentration of 500 ppb and a generation pressure of  $5 \text{ kg/cm}^2$ .

As shown in figure 3, an increasing trend was noted in weight loss among experimental groups in terms of storage period, which conforms to the normal postharvest transpiration behavior. However, the results showed that bananas treated with 1-MCP-MBs for 5, 10, and 15 min have remarkably similar weight profiles over the 10 days interval. On the last day of storage, the weight loss recorded was  $1.68 \pm 0.07\%$ ,  $1.58 \pm 0.05\%$ , and  $1.60 \pm 0.03\%$  for 5-, 10-, and 15-min treatments, respectively. These results indicate that varying the immersion time in this range does not have a significant effect on the rate of weight loss. From engineering perspective, the time when immersion happens to obtain appropriate performance of the adhesion mechanism of microbubbles is rather short by 5 to 15 min for the immersion of 1-MCP on the surface of the fruit can be easily achieved. This indicates that the shorter time of 5 min is enough for the desired inhibitory effect with major advantages from the viewpoint of throughput and operational efficiency in industrial applications.

After determining that an immersion time of 5 to 15 min was the optimal range for delaying ripening, an immersion time of 5 min was chosen for subsequent experiments to optimize processing efficiency. This exposure time was then used to test the effect of different concentrations of 1-MCP: 500, 1000, and 1500 ppb on the suppression of the ripening process.

The changes in the weight of bananas stored for 10 days after immersion in 1-MCP-MBs at a generation pressure of  $5 \text{ kg/cm}^2$  are shown in figure 4. A gradual increase in weight loss was observed in all groups over time, indicating normal postharvest water loss and respiratory activities. The control fruit showed the greatest increase in weight loss, reaching up to  $3.14 \pm 0.56\%$  by Day 10, representing continuous ethylene-induced ripening. The application of 1-MCP through microbubble immersion reduced the degree of weight loss in all treated groups. Among the concentrations experimented, a concentration of 500 ppb resulted in the greatest retention ( $1.68 \pm 0.07\%$ ), showing effective inhibition in the physiological response by ethylene. However, extending the concentration to 1000 or 1500 ppb did not yield any further improvement in weight retention. This observation suggests that under the current microbubble-assisted delivery conditions, a concentration of 500 ppb is sufficient to achieve functional saturation of the available ethylene receptors, and additional 1-MCP does not provide measurable additional benefits.

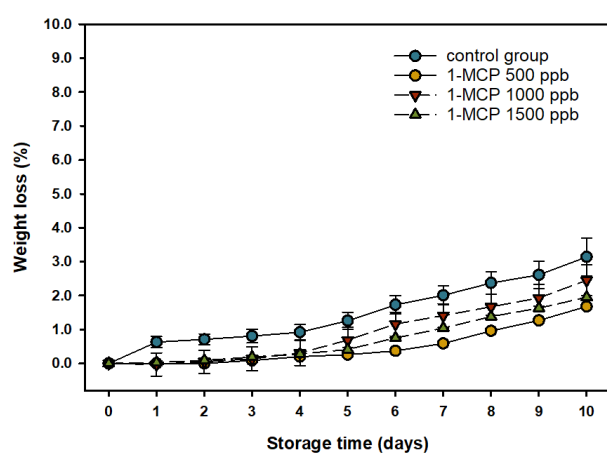


Figure 4: Weight loss of banana at different 1-MCP concentration

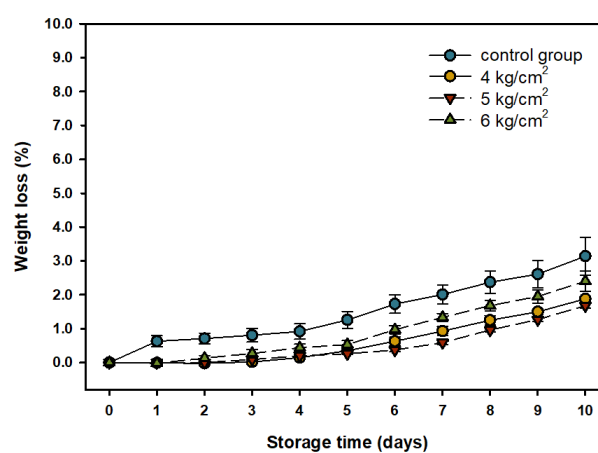


Figure 5: Weight loss of banana at different water pressure for microbubble generation

Following the identification of 500 ppb as an effective concentration of 1-MCP for limiting ripening and the occurrence of weight loss, the influence of water pressure during the generation of microbubbles was further studied at 4, 5, and 6 kg/cm<sup>2</sup>, while other parameters were kept constant, and the immersion time was set to 5 min.

Figure 5 shows that weight loss increased at a progressive rate in all groups during the 10 days storage duration, which agrees with normal postharvest moisture evaporation and respiratory activities. Despite this general trend, the amount of weight reduction was a function of generation pressure. At Day 10 of storage, the group treated at 5 kg/cm<sup>2</sup> showed the lowest weight loss at  $1.68 \pm 0.07\%$ , compared to  $1.80 \pm 0.08\%$  and  $2.40 \pm 0.03\%$  for the 4 and 6 kg/cm<sup>2</sup> groups, respectively. This intermediate pressure probably created favorable conditions of formation and dispersion of bubbles in the aqueous phase. Therefore, at 5 kg/cm<sup>2</sup> generation pressure, the parameters of bubbles size, distribution and stability provided the greatest gas-liquid interface, which facilitates the effective transfer of 1-MCP onto the banana peel. These resulted in an increased capacity to inhibit ethylene-induced physiological responses and consequently ripening was much more delayed than under other pressure conditions. From the results, it is concluded that this pressure created microbubbles that were stable and allowed for maximum adhesion of 1-MCP to the fruit peel, so 5 kg/cm<sup>2</sup> was identified as the optimal operating condition of the proposed delivery system.

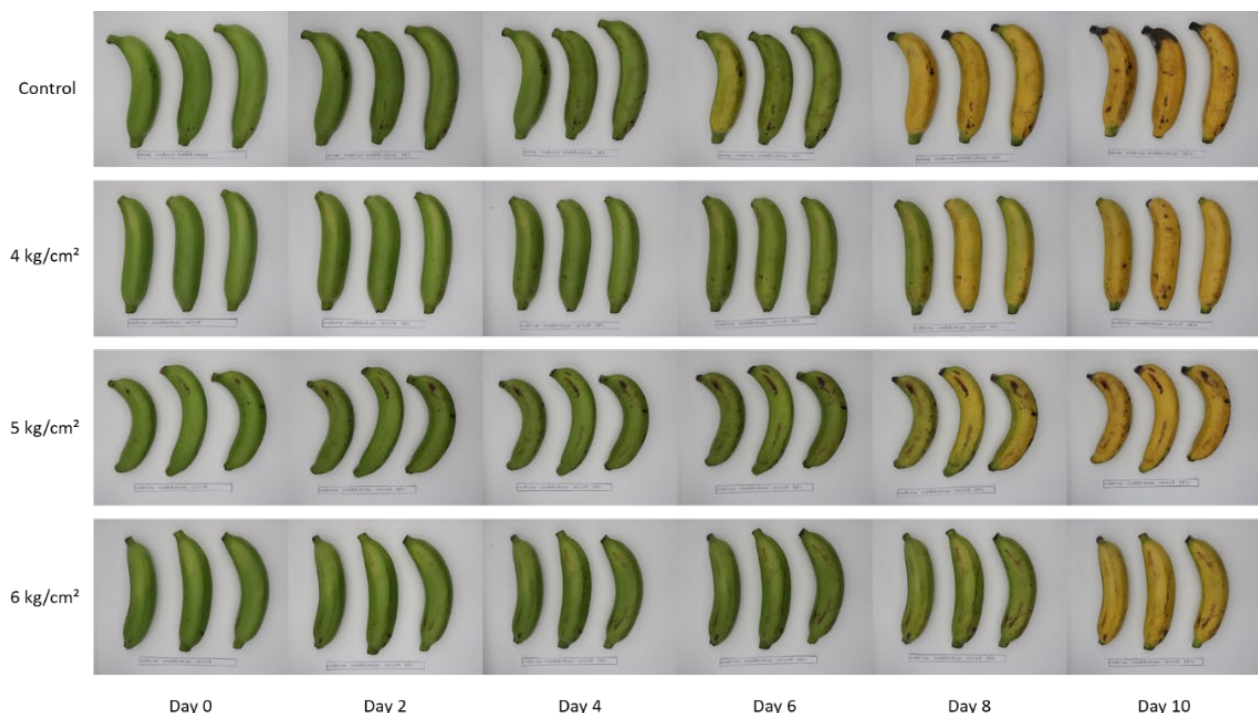


Figure 6: Change in peel color of banana during storage at room temperature for 10 days

Figure 6 shows the changes in peel color of bananas kept at ambient temperature for a period of 10 days. The analysis is based on both the untreated control and the immersion treatments (500 ppb concentration, 5 min) with 1-MCP-MBs at pressures of 4, 5, and 6 kg/cm<sup>2</sup>. On Day 0, the peels of all samples were a uniform green, which is characteristic of the unripe stage. Throughout the storage period, the control fruit showed a significant color



change from green to yellow and the formation of brown spots between Days 8 and 10. The pattern observed is in line with the climacteric fruits increase in ethylene production and the triggering of a senescence response. On the other hand, bananas treated with 1-MCP-MBs showed a lower rate of degreening under all pressure conditions. It is interesting to note that the treatment given at  $5 \text{ kg/cm}^2$  retained a green peel color for the longest period, showing little yellowing by Day 10. The slowed degradation of chlorophylls suggests the effective suppression of ethylene-mediated ripening, which agrees with the previously mentioned reduced weight loss. The higher response at  $5 \text{ kg/cm}^2$  might be due to more favorable properties of bubble formation at this pressure. An intermediate operating pressure could facilitate the even dispersion of bubbles and provide sufficient gas-liquid interaction, which would enhance the interaction between 1-MCP and the fruit surface. This interaction may, in turn, be responsible for a much more consistent inhibition of ethylene perception and a slowed ripening process.

## CONCLUSION

This study examined the use of 1-MCP-MBs as an alternative to delay postharvest ripening of bananas. By investigating treatment methods, immersion duration, 1-MCP concentration and microbubble generation pressure, practical operating conditions were found:

1. Immersion in 1-MCP-MBs resulted in a more consistent ripening progression and weight loss than the untreated control and conventional 24 hours gaseous fumigation. The presence of the microbubbles system seems to enhance contact between 1-MCP and the fruit surface to deliver effective treatment in a shorter exposure period.
2. A comparative analysis of immersion times (5, 10, and 15 min) showed no significant difference in weight loss prevention. Under the tested conditions, 5 min of treatment was sufficient to achieve the desired inhibitory effect while also reducing processing time.
3. A concentration of 500 ppb was sufficient to repress ripening-related responses. An increase in dosage to 1000 or 1500 ppb did not yield further measurable improvements, suggesting that the effective interaction between 1-MCP and ethylene receptors may be nearing the saturation point at 500 ppb under the management of microbubbles.
4. Of the different evaluated pressures, the pressure of  $5 \text{ kg/cm}^2$  led to the most stable control of weight loss and peel color development. This condition must promote favorable bubble formation and dispersion characteristics, which help in the efficient gas and liquid interaction in the treatment process.
5. The combination of 500 ppb 1-MCP, immersion for 5 min, and generation of  $5 \text{ kg/cm}^2$  pressure was correlated to delayed peel yellowing and reduced mass loss throughout 10 days of storage, while control fruit reached visible senescence between Day 6 and Day 8.

In summary, the application of 1-MCP with microbubbles is a time efficient alternative to conventional fumigation. The results offer a basis for further evaluation for commercial-scale post-harvest handling conditions.

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