

Formulation and characterization of ethanol–lemongrass oil emitters as antimicrobial active packaging

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Abstract. The application of appropriate postharvest technologies is essential to reduce deterioration and maintain the quality of fresh tropical fruits. Active packaging is an effective approach that enables the controlled release of antimicrobial agents to suppress fungal growth. This study developed an ethanol–lemongrass oil emitter (ELE) formulated with ethanol, silica dioxide, sodium stearate, and lemongrass (*Cymbopogon citratus*) essential oil at concentrations of 0 MIC, 0.5 × MIC, 1 × MIC, and 2 × MIC. Increasing essential oil concentration enhanced antifungal activity against *Aspergillus niger*, with the 2 × MIC formulation combined with an emitter mass of 2.5 g achieving complete fungal inhibition during storage. The antifungal effect was dose-dependent, as higher concentrations resulted in greater suppression of mycelial growth. Analysis of mass changes indicated that weight loss was mainly due to the volatilization of ethanol and essential oil components, rather than moisture absorption. The incorporation of silica dioxide and sodium stearate helped maintain the formulation's hydrophobic properties and ensure stable vapor release throughout storage. Overall, the ELE demonstrated strong antifungal efficacy and consistent controlled-release performance, highlighting its potential application for extending the shelf life of fresh tropical fruits.

1 Introduction

Tropical fruits grow in high-temperature regions and contribute substantially to global fruit diversity. Developing countries account for approximately 90% of total tropical fruit production, and most tropical fruits are highly nutritious, rich in vitamins, minerals, and phytochemical compounds [1]. However, postharvest losses and short shelf life remain significant challenges during storage, transportation, and marketing. Their high moisture content, typically ranging from 70% to 90% on a wet-weight basis, makes them highly perishable and susceptible to fungal spoilage [2].

The implementation of appropriate postharvest technologies has become crucial in reducing quality degradation and extending shelf life. Conventional preservation methods are often insufficient to address these challenges, highlighting the need for innovative approaches such as active packaging. Ethanol is recognized as a safe compound for food applications under the Generally Recognized as Safe (GRAS) classification. Ethanol offers several advantages in active packaging systems, particularly its high volatility, which makes it suitable as a vapor-phase agent in emitter-based formulations. In addition, ethanol vapor acts as an antimicrobial and antifungal agent by inhibiting ethylene action, minimizing discoloration and tissue senescence, and enhancing product aroma [3]. The use of ethanol-emitting sachets enables controlled release of ethanol vapor into the package headspace,

providing effective microbial inhibition without direct contact with the food product while minimizing undesirable sensory effects [4]. Ethanol vapor-releasing sachets have been incorporated into packaging systems for various fresh fruits, where the released vapor has been shown to reduce postharvest decay in Chinese bayberry, mulberry, and loquat [5,6,7]. However, the direct use of ethanol may produce an undesirable alcoholic odor that negatively affects sensory quality. Lemongrass essential oil is considered a suitable masking agent, providing a pleasant, sweet citrus aroma and containing bioactive compounds, such as geranial and neral, with antimicrobial properties [8]. Despite its known limitations, such as rapid volatilization and potential sensory impact at high concentrations, these challenges are addressed through controlled-release emitter formulation.

In addition to its antimicrobial function, the ethanol emitter can interact with moisture because silica dioxide (SiO₂) is hygroscopic. When ethanol volatilizes in the packaging headspace, it may lower internal temperature and cause condensation, increasing relative humidity around the product. SiO₂ functions as a moisture and gas adsorbent while serving as a carrier matrix for active agents in films or sachets, thereby contributing to the stabilization of the packaging microenvironment [9]. Although active packaging technologies using ethanol or essential oils have been widely explored, studies on controlled-release systems combining ethanol and lemongrass oil emitters (ELEs) remain limited.

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Therefore, this study was designed to develop and characterize an ELE-based active packaging system with antimicrobial activity. The Research included determining the minimum inhibitory concentration (MIC), evaluating antifungal activity against *Aspergillus niger*, and analyzing water uptake behavior to understand the volatilization dynamics of the emitter during storage. Further optimization is required to enhance the efficiency and applicability of ELE systems for postharvest active packaging applications.

2 Materials and Methods

2.1 Materials

The materials used in this study included 95% ethanol, sodium stearate, silica dioxide (SiO₂), commercial lemongrass (*Cymbopogon citratus*) essential oil, distilled water, and MG/LDPE paper. Potato Dextrose Agar (PDA), a pure culture of *Aspergillus niger* ATCC 6275, and sterile paper discs were used for microbiological analysis. The equipment consisted of beaker glasses, a hotplate, an analytical balance, a hot sealer, spatulas, an incubator, a vortex mixer (Stuart), Petri dishes, micropipettes, test tubes, glass rods, a Bunsen burner, and a 40-mesh sieve.

2.2 Determination of Minimum Inhibitory Concentration (MIC) of Lemongrass Oil and Optimal Dosage of Ethanol-Lemongrass Oil Emitters

The MIC of lemongrass essential oil was determined using a macrodilution method on solid media, as described by De-Montijo-Prieto et al. [10]. A stock solution of essential oil (288 mg/mL in 98% ethanol) was serially diluted in distilled water containing 0.5% Tween-80 to yield concentrations ranging from 18 to 0.56 mg/mL. Five milliliters of each dilution were mixed with 15 mL molten PDA, homogenized using a vortex mixer, poured into Petri dishes, and allowed to solidify. Plates were inoculated with 5 µL of *A. niger* suspension (10⁶ CFU/mL) at the center and incubated at 30 °C for 7 days. The positive control consisted of PDA with 0.5% Tween-80 inoculated with *A. niger*, while the negative control contained PDA with 0.5% Tween-80 without inoculation. MIC was defined as the lowest concentration that completely inhibited visible hyphal growth.

The optimal emitter dosage was determined using the same in vitro procedure described for the antifungal evaluation of ELE sachets, following the method of Colín-Chávez et al. [11], with modifications in the emitter mass. The ELE powder was prepared at three different dosages (0.5 g, 1.0 g, and 2.5 g), sealed in MG/LDPE sachets, and attached to the inner lid of inoculated PDA plates to assess the effect of mass variation on vapor-phase antifungal activity.

2.3 Preparation of Ethanol-Lemongrass Oil Emitters (ELE)

ELEs were prepared by mixing sodium stearate, lemongrass essential oil, and distilled water, followed by heating the mixture to 70 °C. Ethanol was added to form a uniform gel matrix [5]. Sodium stearate was used as a gel-forming agent to regulate ethanol release by binding ethanol within the matrix, thereby enabling gradual evaporation and reducing potential sensory residue [7]. Essential oil concentrations of 0.5, 1, and 2 MIC were incorporated. After homogenization, SiO₂ was gradually added until a dry powder was obtained. SiO₂ acted as a stabilizing filler within the powder matrix, helping maintain low moisture interaction during storage [9]. The mixture was cooled, weighed to 2.5 g, and packed into MG/LDPE sachets (2 × 6 cm). All sachets were heat-sealed and stored at room temperature.

2.4 Evaluation of Antifungal Activity of Ethanol Lemongrass Oil Emitter (ELE)

The antifungal activity of ELE sachets was evaluated in vitro against *A. niger* following the method of Colín-Chávez et al. [11]. PDA plates were inoculated with a 6-mm fungal disc, and ELE sachets were attached to the inner lid surface. Plates were sealed with parafilm and incubated at 25–28 °C for nine days. Treatments included ELE formulations and a negative control (no sachet). Relative inhibition (RI) was calculated using:

$$RI (\%) = \left(\frac{C-T}{C} \right) \times 100 \quad (1)$$

Where *C* and *T* represent the mycelial diameters of the control and treatment, all experiments were performed in triplicate.

2.5 Water Uptake Test

Water uptake was measured following the method of Susanti and Putri [12], with modifications. A desiccator containing distilled water was used to establish 100% relative humidity (RH). Samples (control and ELE) were placed vertically without contact with water and kept at room temperature. Samples were weighed every 24 hours until reaching a constant weight. Water uptake was calculated using:

$$\text{Water uptake } (\%) = \left(\frac{W_t - W_o}{W_o} \right) \times 100 \quad (2)$$

where *W_o* is the initial weight, and *W_t* is the weight at time *t*. All tests were conducted in triplicate.

2.6 Statistical Analysis

Data were tabulated in Microsoft Excel 2016 and analyzed using ANOVA in IBM SPSS Statistics 20.0. When significant differences occurred, Tukey's post hoc test was applied at *p* < 0.05.

3 Results and discussion

3.1 Preliminary Study

A preliminary experiment was conducted to determine the Minimum Inhibitory Concentration (MIC) of lemongrass (*Cymbopogon citratus*) essential

oil as the basis for formulating the active packaging system and to establish the optimal emitter powder dosage for inhibiting fungal growth. This stage was necessary to ensure that the combination of ethanol and lemongrass oil achieved maximum antimicrobial effectiveness. The MIC analysis revealed that the development of *Aspergillus niger* colonies was completely inhibited at a lemongrass oil concentration of 2.25 mg/mL (Figure 1).

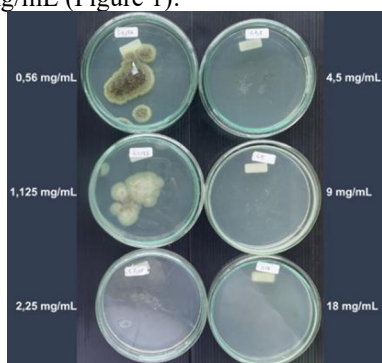


Figure 1. Growth inhibition of *Aspergillus niger* at different concentrations of lemongrass oil for determining the MIC. Complete inhibition was observed at 2.25 mg/mL, which was identified as the MIC value.

According to previous studies [14], lemongrass oil extracts tested against several fungal genera, including *Aspergillus*, *Botrytis*, *Candida*, and *Penicillium*, exhibited MIC values ranging from 0.09 to 3.96 mg/mL, with an average of 2.02 mg/mL. The relatively low MIC value of 2.25 mg/mL obtained in this study indicates the high biological activity of lemongrass oil even at low concentrations, making it suitable for application in active packaging systems without the risk of imparting excessive aroma.

The antimicrobial activity of lemongrass essential oil is attributed to its bioactive components, particularly citral, geraniol, and neral. Citral compounds found in lemongrass primarily exert their antifungal effects by targeting sporulation and growth-related genes involved in ergosterol biosynthesis associated with fungal pathogenesis, leading to reactive oxygen species (ROS) accumulation in target cells and subsequent destruction of the fungal cell membrane [15]. These bioactive components cause membrane perforation and damage to the fungal cell wall. Citral and geraniol inhibit key enzymes in the ergosterol biosynthetic pathway, a vital component of fungal cell membranes. This inhibition reduces membrane fluidity and causes lipid disorganization, thereby preventing mycelial growth and conidial germination [13]. Furthermore, lemongrass oil has been shown to inhibit biofilm formation by *Aspergillus niger* and *Candida albicans* and to reduce the production of mycotoxins such as aflatoxin [16].

Based on these findings, the MIC value of 2.25 mg/mL was used as a reference for determining the formulation range of the emitter (0, 0.5, 1, and 2 MIC) in the subsequent stage to evaluate the effectiveness of the combination between lemongrass oil concentration and emitter powder mass in the active packaging system. The antifungal efficacy of lemongrass oil was assessed further by varying the ethanol emitter mass to determine the optimal dose for active packaging applications. The results presented in Figure 2 show that

the highest antifungal activity was achieved at the combination of 2 MIC and 2.5 g emitter, which completely inhibited the growth of *Aspergillus niger*, while treatments without lemongrass oil exhibited only mild fungistatic effects.

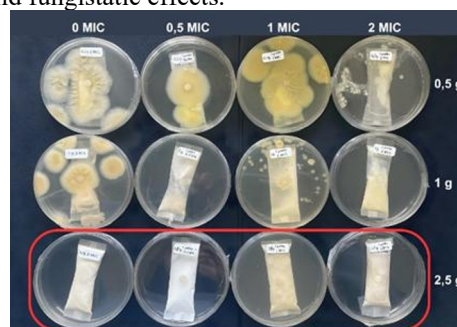


Figure 2. Growth of *A. niger* under different ethanol emitter weights (0.5, 1, and 2.5 g) and lemongrass oil concentrations (0, 0.5, 1, and 2 MIC). The 2.5 g emitter showed the most potent inhibition.

Increasing the emitter mass directly affected the amount of ethanol vapor released into the microatmosphere within the incubation chamber, thereby enhancing the diffusion rate of active compounds from lemongrass oil. Previous literature reported that the mass or load of the ethanol carrier material is a critical factor in determining the antimicrobial vapor pressure in active packaging systems, with the optimal emitter dosage ranging from 2 to 3 g of ethanol-releasing powder [17]. This dosage is sufficient to generate an effective vapor pressure for microbial inhibition without causing condensation or altering the product aroma. In addition to the effect of emitter mass, lemongrass oil concentration also contributed significantly to the system's overall effectiveness. The integration of essential oil into the ethanol-based releasing system increased the efficiency of active compound transfer via co-evaporation, allowing citral components to be evenly distributed throughout the package micro-atmosphere [18]. This process produced a dose-dependent antifungal effect, as observed in the 2 MIC treatment, which exhibited the widest inhibition zone. A higher emitter mass strengthened ethanol volatilization capacity, while increasing lemongrass oil concentration enhanced the biochemical potency of citral in disrupting fungal cell structures. The combination of these two factors produced a significant fungistatic-to-fungicidal effect, indicating that the ELE system has strong potential as an effective natural active packaging technology for fungal control in tropical fruits during storage.

3.2 Antifungal Activity of Ethanol Lemongrass Oil Emitter (ELE)

The antifungal activity analysis showed a distinct trend in the changes of *Aspergillus niger* colony diameter at different ELE concentrations over the observation period. As shown in Figure 3, the control exhibited the most significant colony growth throughout the incubation period, whereas treatments with higher ELE concentrations showed markedly smaller colony diameters. This trend indicates that increasing the

concentration of lemongrass oil in the ELE system significantly enhances its antifungal activity, thereby slowing fungal hyphal growth in the culture medium.

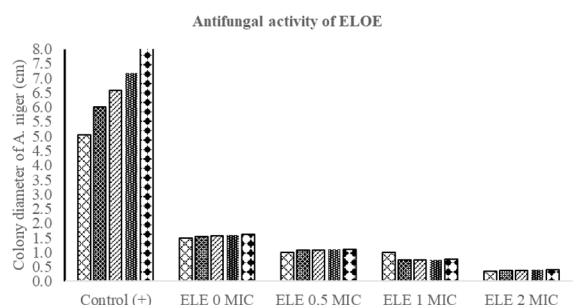


Figure 3. Effect of ELE concentration and storage duration on colony diameter of *A. niger* (Day 3, Day 5, Day 7, and Day 9)

The reduction in colony diameter was consistent with the bioactive characteristics of lemongrass (*Cymbopogon citratus*) essential oil, particularly citral (geranial and neral), which disrupts cell membrane integrity, increases lipid permeability, causes ion leakage, and inhibits mitochondrial respiration [13]. These findings agree with previous work showing that lemongrass oil containing more than 70% citral exhibited MIC values of 0.6–0.8 $\mu\text{L}/\text{mL}$ against *Aspergillus* spp., with fungistatic effects at low doses and fungicidal effects at higher doses [19]. In this context, ethanol acts as a carrier agent for volatile compounds, facilitating diffusion and maintaining the stability of citral vapor during the observation period, while also contributing a mild antifungal effect. Ethanol vapor has been reported to inhibit mycelial growth and suppress pathogenic enzyme activity during postharvest fungal infections [7]. Although the inhibitory effect of ethanol was lower than that of lemongrass oil, it still played an important role as a volatile agent with mild antifungal activity.

The decrease in colony diameter at higher ELE concentrations indicates a synergistic effect between citral's chemical toxicity and the sustained diffusion of antifungal vapors, enabling the ELE system to suppress *A. niger* growth effectively through day 9 of the observation period. The decreasing trend in colony diameter was further supported by the calculated relative inhibition percentage (%RI), which quantifies the relationship between emitter concentration and antifungal activity (Table 1). The mean inhibition values ranged from 63% to 88%, with higher emitter concentrations resulting in more potent inhibition, consistent with the colony diameter observations. The low standard deviation ($\text{SD} < 5\%$) indicated high consistency among replicates. The increase in %RI on day 9 demonstrated that the ELE system maintained stable antifungal effectiveness throughout the observation period.

Table 1. Relative inhibition (%RI) of *Aspergillus niger* during storage

Day	% Relative Inhibition			
	EE	ELE 0,5 MIC	ELE 1 MIC	ELE 2 MIC
3	63.02 ± 2.07	71.74 ± 3.90	72.03 ± 5.27	83.65 ± 1.99
5	67.55 ± 2.37	74.96 ± 3.56	80.04 ± 4.56	85.15 ± 1.73
6	69.94 ± 2.64	76.88 ± 3.57	81.50 ± 4.61	86.36 ± 1.64
7	72.03 ± 1.21	78.46 ± 2.88	82.89 ± 2.52	87.27 ± 1.88
9	74.35 ± 3.07	80.42 ± 3.98	84.24 ± 2.97	88.46 ± 2.57

Values are presented as mean \pm SD ($n = 3$). Different superscript letters in the same row indicate significant differences (Tukey HSD, $p < 0.05$). Increasing emitter concentration (ELE) resulted in significantly higher inhibition percentages against *Aspergillus niger*.

The increasing trend of %RI values indicated that the antifungal activity of the ELE system improved with higher concentrations of lemongrass oil. This suggests that citral compounds in lemongrass oil exhibit a dose-dependent inhibitory effect, with greater citral release into the microatmosphere exerting stronger toxic pressure on fungal cells [20]. These results agree with reports stating that lemongrass oil is among the most potent fungicidal essential oils against postharvest pathogens such as *Botrytis cinerea* and *Aspergillus flavus*, owing to its stable volatility and dominance of oxygenated components [8].

This effectiveness aligns with the principle of controlled-release packaging, in which volatile compounds are gradually released to maintain antimicrobial activity over an extended period. The findings also support reports that the combination of ethanol and essential oils possesses high potential as a natural biocontrol agent suitable for food applications [21]. Therefore, the ELE system can be developed as a natural-based active packaging technology capable of extending the shelf life of tropical fruits by effectively controlling fungal growth during storage.

3.3 Effect of Concentration on Water Uptake Behavior of ELE Compared to Control ($\text{SiO}_2 + \text{Na Stearat}$)

The water-uptake analysis was conducted to determine the material's ability to adsorb or release water vapor during storage. Positive values indicate water adsorption, while negative values represent the release of water vapor or volatile compounds (desorption). This parameter is essential for evaluating the effectiveness of the active packaging system in controlling moisture levels during storage. The observed percentage of water vapor uptake (Fig. 4) showed distinct differences between the control ($\text{SiO}_2 + \text{sodium stearate}$) and all ELE treatments throughout the storage period.

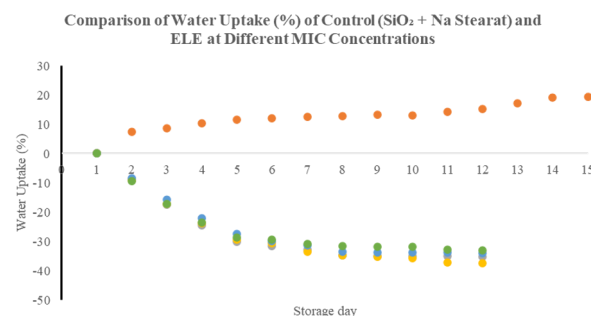


Figure 4. Water uptake (%) of the control ($\text{SiO}_2 + \text{sodium stearate}$) compared with ELE formulations at different MIC levels (0 MIC, 0.5 MIC, 1 MIC, and 2 MIC) during 15 days of storage.

The water uptake in the control sample ($\text{SiO}_2 + \text{sodium stearate}$) increased, reaching 19% at the end of storage, indicating that the control material exhibited hygroscopic behavior and absorbed water vapor from

the surrounding environment. Amorphous silica (SiO₂) has a high adsorption capacity for water vapor and can be readily regenerated, making it a widely used adsorbent [22]. According to Calabrese et al. [23], under high relative humidity conditions (RH > 60%), water molecules begin to penetrate the pores of SiO₂ particles through capillary condensation. This process occurs because the partial pressure of water vapor approaches saturation, allowing water molecules to acquire sufficient energy to diffuse through pore walls and form water layers within the silica structure, which then accumulate on the SiO₂ surface. This condition increases water adsorption capacity, as reflected by the positive uptake values in the control treatment. When adsorption reaches equilibrium, it indicates that the material has reached its maximum adsorption capacity [24]. Meanwhile, sodium stearate serves as a weak binder that maintains the mechanical stability of the SiO₂ powder but does not inhibit water vapor adsorption [25].

In contrast, all ELE treatments exhibited negative uptake values from the first day, ranging from -15% to -37%. This indicates that the emitter system tended to release ethanol vapor, thereby lowering relative humidity in the packaging space. This pattern suggests that the passive system (control) tended to absorb moisture, while the active system (emitter) stabilized internal humidity by desorbing volatile compounds. The process occurs due to the ethanol concentration gradient between the inside of the sachet and the surrounding air, which drives the permeation of the active compounds. The release rate gradually decreased as the gradient diminished. This finding is supported by the negative % water uptake values, confirming a gradual release of ethanol vapor that slowed down once equilibrium was reached in the ethanol vapor concentration within the desiccator chamber. The ethanol emitter operates via a controlled-release mechanism, gradually emitting ethanol vapor into the package's headspace. The emitter is prepared by adsorbing ethanol onto SiO₂ powder; when placed in a high-humidity environment, water vapor is adsorbed by the carrier (SiO₂), replacing ethanol molecules on its surface and triggering ethanol release [26].

Table 2. Mean sample weight (g) of Control (SiO₂ + Na Stearate) and ethanol emitters during 15 days of storage.

Day	Control (SiO ₂ + Na Stearate)	EE	ELE 0.5 MIC	ELE 1 MIC	ELE 2 MIC
0	1.20 ± 0.01 ^a	2.62 ± 0.01 ^b	2.62 ± 0.00 ^b	2.62 ± 0.01 ^b	2.62 ± 0.01 ^b
1	1.29 ± 0.01 ^a	2.38 ± 0.02 ^b	2.37 ± 0.02 ^b	2.38 ± 0.03 ^b	2.36 ± 0.03 ^b
2	1.30 ± 0.00 ^a	2.16 ± 0.03 ^b	2.17 ± 0.04 ^b	2.18 ± 0.04 ^b	2.16 ± 0.04 ^b
3	1.32 ± 0.01 ^a	1.97 ± 0.02 ^b	1.99 ± 0.05 ^b	2.00 ± 0.03 ^b	2.00 ± 0.04 ^b
4	1.34 ± 0.01 ^a	1.82 ± 0.03 ^b	1.85 ± 0.04 ^b	1.88 ± 0.05 ^b	1.88 ± 0.06 ^b
5	1.34 ± 0.00 ^a	1.79 ± 0.02 ^b	1.81 ± 0.03 ^b	1.81 ± 0.04 ^b	1.84 ± 0.05 ^b
6	1.35 ± 0.01 ^a	1.75 ± 0.03 ^b	1.74 ± 0.09 ^b	1.77 ± 0.06 ^b	1.81 ± 0.07 ^b
7	1.35 ± 0.01 ^a	1.70 ± 0.04 ^b	1.70 ± 0.10 ^b	1.73 ± 0.07 ^b	1.79 ± 0.08 ^b
8	1.36 ± 0.01 ^a	1.70 ± 0.05 ^b	1.70 ± 0.10 ^b	1.73 ± 0.08 ^b	1.79 ± 0.09 ^b
9	1.35 ± 0.01 ^a	1.69 ± 0.05 ^b	1.70 ± 0.11 ^b	1.73 ± 0.09 ^b	1.78 ± 0.09 ^b
10	1.36 ± 0.02 ^a	1.69 ± 0.06 ^b	1.64 ± 0.09 ^b	1.73 ± 0.09 ^b	1.77 ± 0.10 ^b
11	1.38 ± 0.01 ^a	1.69 ± 0.06 ^b	1.63 ± 0.09 ^b	1.72 ± 0.09 ^b	1.75 ± 0.10 ^b
12	1.40 ± 0.00	-	-	-	-
13	1.43 ± 0.01	-	-	-	-
14	1.43 ± 0.01	-	-	-	-
15	1.44 ± 0.01	-	-	-	-

Means followed by different superscript letters differ significantly according to Tukey's HSD test (p < 0.05).

The changes in sample weight during storage reflected the dynamic mechanisms of adsorption and desorption of water vapor and ethanol within the emitter

system. Table 1 presents the average sample weights (g) of the control (SiO₂ + sodium stearate) and various ELE concentrations during storage. In general, the control showed a consistent weight increase from day 0 to day 15, whereas all ELE treatments showed a gradual decrease in weight from day 1, stabilizing after day 6. Based on Tukey's post hoc test, treatments with different superscript letters indicated significant differences (p < 0.05) between the control (SiO₂ + sodium stearate) and all emitter treatments (0, 0.5, 1, and 2 MIC). The control sample showed an increase in weight during storage due to the adsorption of water vapor on its surface and within its pores [23]. In contrast, all emitter treatments showed a decrease in weight due to ethanol release from the system [24]. This contrasting behavior demonstrates an opposite mass exchange mechanism between the two systems, in which the control acts as a moisture adsorbent. At the same time, the emitter releases volatile compounds under high-humidity conditions [27].

In contrast, variations in lemongrass oil concentration did not significantly affect emitter weight. This finding corresponds to the physicochemical properties of lemongrass oil, which is hydrophobic, non-hygroscopic, and highly volatile. Non-polar monoterpene compounds such as citral, myrcene, and limonene in lemongrass oil are unable to interact with water molecules under humid conditions [28]. Lemongrass essential oil consists predominantly of hydrophobic and low-polarity volatile compounds, which limit its interaction with water molecules and explain its physicochemical stability under high relative humidity conditions. [29]. These results confirm that ambient humidity plays a dominant role in regulating the equilibrium between adsorption and desorption processes within the ethanol emitter active packaging system, while lemongrass oil concentration does not exert a significant influence.

Conclusion

The ethanol-lemongrass oil emitter (ELE) demonstrated high effectiveness as an antifungal active packaging system for extending the shelf life of tropical fruits and increasing the lemongrass oil concentration and emitter mass enhanced inhibition against *Aspergillus niger*, with the 2 MIC and 2.5 g formulations achieving complete growth suppression. The antifungal activity followed a dose-dependent trend, while weight loss during storage was mainly attributed to ethanol and essential oil volatilization rather than moisture absorption. The presence of silica dioxide and sodium stearate in the emitter matrix improved hydrophobicity and vapor stability, maintaining structural integrity throughout storage. These findings highlight the strong potential of the ELE system as an environmentally friendly controlled-release packaging technology for preserving quality and extending the postharvest shelf life of tropical fruits.

References

- [1] Altendorf, S., "Major tropical fruits market review," *FAO Food Outlook*, 1, 87–96 (2019). Available at: <https://openknowledge.fao.org/items/5a08d8ae-e960-4244-855f-b15dd41c4b3f>
- [2] Sneha, K.B., Indra, N., Vanitha, S., Saranya, S., Ramalakshmi, A., "Exploring non-chemical alternatives for the management of postharvest fungal diseases of major tropical fruits: Mango, banana, and papaya," *Physiological and Molecular Plant Pathology*, 134, 102460 (2024). <https://doi.org/10.1016/j.pmpp.2024.102460>
- [3] Utto, W., Preutikul, R., Malila, P., Noomhorm, A., & Bronlund, J. E., "Delaying microbial proliferation in freshly peeled shallots by active packaging incorporating ethanol vapour-controlled release sachets and low storage temperature," *Food Science and Technology International*, 24, 132–144 (2018). <https://doi.org/10.1177/1082013217741429>
- [4] Yildirim, S., Röcker, B., Pettersen, M. K., Nilsen-Nygaard, J., Ayhan, Z., Rutkaite, R., & Coma, V., "Active packaging applications for food," *Comprehensive Reviews in Food Science and Food Safety*, 17, 165–199 (2018). <https://doi.org/10.1111/1541-4337.12322>
- [5] Choosung, P., Utto, W., Boonyariththongchai, P., Wasusri, T., Wongs-Aree, C., "Ethanol vapor releasing sachet reduces decay and improves aroma attributes in mulberry fruit," *Food Packag. Shelf Life*, 22, 100398 (2019). <https://doi.org/10.1016/j.fpsl.2019.100398>
- [6] Mu, H., Gao, H., Chen, H., Fang, X., Han, Q., "A novel controlled release ethanol emitter: Preparation and effect on some postharvest quality parameters of Chinese bayberry during storage," *J. Sci. Food Agric.*, 97, 4929–4936 (2017). <https://doi.org/10.1002/jsfa.8369>
- [7] Wang, K., Cao, S., Di, Y., Liao, Y., Zheng, Y., "Effect of ethanol treatment on disease resistance against anthracnose rot in postharvest loquat fruit," *Sci. Hortic.*, 188, 115–121 (2015). <https://doi.org/10.1016/j.scienta.2015.03.014>
- [8] De Albuquerque Sousa, T.C., da Cunha, W.M., Rosas, A.L.G., Oppelt, C.Q., Gandra, E.A., Rombaldi, C.V., Meinhart, A.D., "Essential oils as natural sources for the control of *Botrytis cinerea*: Chemical composition and antifungal effect," *Food Biosci.*, 62, 105516 (2024). <https://doi.org/10.1016/j.fbio.2024.105516>
- [9] Zhang, W., Ahari, H., Zhang, Z., Jafari, S.M., "Role of silica (SiO₂) nano/micro-particles in the functionality of degradable packaging films/coatings and their application in food preservation," *Trends Food Sci. Technol.*, 133, 75–86 (2023). <https://doi.org/10.1016/j.tifs.2023.01.009>
- [10] De-Montijo-Prieto, S., Razola-Díaz, M.D., Gómez-Caravaca, A.M., Guerra-Hernández, E.J., Jiménez-Valera, M., García-Villanova, B., Ruiz-Bravo, A., Verardo, V., "Essential oils from fruit and vegetables, aromatic herbs, and spices: Composition, antioxidant, and antimicrobial activities," *Biology*, 10, 1091 (2021). <https://doi.org/10.3390/biology10111091>
- [11] Colín-Chávez, C., Virgen-Ortiz, J.J., Miranda-Ackerman, M.A., Hernández-Cristóbal, O., Martínez-Téllez, M.Á., Esquivel-Chávez, F., Gallegos-Santoyo, N.L., "Induction of defense mechanisms in avocado using Mexican oregano oil-based antifungal sachet," *Future Foods*, 6, 100171 (2022). <https://doi.org/10.1016/j.fufo.2022.100171>
- [12] Susanti, Y.I., Putri, W.D.R., "Pembuatan minuman serbuk markisa merah (*Passiflora edulis* f. *edulis* Sims) (kajian konsentrasi Tween 80 dan suhu pengeringan)," *J. Pangan Agroind.*, 2, 170–179 (2014).
- [13] Falcon, R.M.G., Fahrenbach, S.U., Feliciano, J.F., Flores, B.M.B., Dida-Agun, A.S., Domingo, E.J.V., Domingo, F.K.S., Duran, H.E.T., Dungala, D.B., Dychiao, G.R.K., Evangelista, P.E.D., Facon, H.E.L., FlorCruz, F.E.R., Florita, M.H.B., Giron, M.S.T., Yabes, A.M., "Antifungal properties of *Cymbopogon citratus* (DC.) Stapf—A scoping review," *S. Afr. J. Bot.*, 170, 425–442 (2024). <https://doi.org/10.1016/j.sajb.2024.05.042>
- [14] Tang, X., Shao, Y.L., Tang, Y.J., Zhou, W.W., "Antifungal activity of essential oil compounds (geraniol and citral) and inhibitory mechanisms on grain pathogens (*Aspergillus flavus* and *Aspergillus ochraceus*)," *Molecules*, 23, 2108 (2018). <https://doi.org/10.3390/molecules23092108>
- [15] Taweechaisupapong, S., Aieamsaard, J., Chitropas, P., Khunkitti, W., "Inhibitory effect of lemongrass oil and its major constituents on *Candida* biofilm and germ tube formation," *S. Afr. J. Bot.*, 81, 95–102 (2012). <https://doi.org/10.1016/j.sajb.2012.06.003>
- [16] Boudechicha, A., Aouf, A., Farouk, A., Ali, H.S., Elkhadragy, M.F., Yehia, H.M., Badr, A.N., "Microfluidizing technique application for Algerian *Cymbopogon citratus* (DC.) Stapf effects enhanced volatile content, antimicrobial, and anti-mycotoxigenic properties," *Molecules*, 28, 5367 (2023). <https://doi.org/10.3390/molecules28145367>
- [17] Ahvenainen, R., "Active and intelligent packaging: an introduction," in: *Novel Food Packaging Techniques* (ed. R. Ahvenainen), Woodhead Publishing, 5–21 (2003). <https://doi.org/10.1533/9781855737020.1.5>

- [18] Coles, R., McDowell, D., Kirwan, M.J., *Food and beverage packaging technology*, 3rd ed., Wiley-Blackwell, Hoboken, NJ (2020). Available at: <https://content.e-bookshelf.de/media/reading/L-600908-aab28a9882.pdf>
- [19] Lee, L.T., Martinazzo, A.P., de Souza Teodoro, C.E., Berbert, P.A., “Potential use of lemongrass essential oil as fungicide against *Aspergillus brasiliensis* and as post-harvest protectant of wheat,” *Acta Sci. Biol. Sci.*, **43**, 1–10 (2021). <https://doi.org/10.4025/actascibiolsoci.v43i1.56763>
- [20] Ekpenyong, C.E., Akpan, E.E., “Use of *Cymbopogon citratus* essential oil in food preservation: recent advances and future perspectives,” *Crit. Rev. Food Sci. Nutr.*, **57**, 2541–2559 (2017). <https://doi.org/10.1080/10408398.2015.1016140>
- [21] Fahrullah, F., Kisworo, D., Bulkaini, B., Wulandani, B.R.D., Yulianto, W., “Development of protein-based films with essential oil incorporation for edible packaging applications,” *J. Nutr. Food Secur.*, **10**, 19243 (2025). <https://doi.org/10.18502/jnfs.v10i3.19243>
- [22] Siddique, A., Sultan, M., “Performance evaluation of silica-gel based desiccant dehumidification unit for air-conditioning applications,” in: *Proc. 3rd Int. Conf. Energy Conservation and Efficiency (ICECE)*, Lahore, Pakistan, 1–5 (2019). <https://doi.org/10.1109/ECE.2019.8921281>
- [23] Calabrese, L., Mastronardo, E., Piperopoulos, E., Scionti, G., De Antonellis, S., Freni, A., Milone, C., “Effect of alternating humidity and dryness on the durability of adsorbent sheets used in open-cycle adsorption processes,” *Polym. Degrad. Stab.*, **234**, 111201 (2025). <https://doi.org/10.1016/j.polymdegradstab.2025.111201>
- [24] Kampawong, H., Utto, W., Pruthikul, R., “Effects of relative humidity on ethanol vapour releases from hydrophilic film-based sachet in active food packaging,” *Food Res.*, **5**, 89–94 (2021). [https://doi.org/10.26656/fr.2017.5\(5\).202](https://doi.org/10.26656/fr.2017.5(5).202)
- [25] Otoni, C.G., Espitia, P.J.P., Avena-Bustillos, R.J., McHugh, T.H., “Trends in antimicrobial food packaging systems: emitting sachets and absorbent pads,” *Food Res. Int.*, **83**, 60–73 (2016). <https://doi.org/10.1016/j.foodres.2016.02.018>
- [26] Nayik, G.A., Muzaffar, K., “Developments in packaging of fresh fruits – shelf life perspective: a review,” *Am. J. Food Sci. Nutr. Res.*, **1**, 34–39 (2014). Available at: https://www.researchgate.net/publication/269686308_Developments_in_Packaging_of_Fresh_Fruits-Shelf_Life_Perspective_A_Review.pdf
- [27] Kampawong, P., Singkhonrat, S., Utto, W., “Moisture sorption and vapor interaction of adsorbent materials in active packaging,” *Food Res.*, **5**, 202–210 (2017). [https://doi.org/10.26656/fr.2017.5\(5\).202](https://doi.org/10.26656/fr.2017.5(5).202)
- [28] Khasanah, L.U., Ariviani, S., Purwanto, E., Praseptianga, D., “Chemical composition and citral content of essential oil of lemongrass (*Cymbopogon citratus* (DC.) Stapf) leaf waste prepared with various production methods,” *J. Agric. Food Res.*, **19**, 101570 (2025). <https://doi.org/10.1016/j.jafr.2024.101570>
- [29] Rabbani, A., Khaliq, A., Mudgil, P., Maqsood, S., Nazir, A., “Recent advances in lemongrass essential oil: Food safety, preservation, and bioactivity in food systems,” *Compr. Rev. Food Sci. Food Saf.*, **25**, e70350 (2026). <https://doi.org/10.1111/1541-4337.70350>