

Research Article:**EFFECT OF DUAL RELEASE ANTIFUNGAL PAD ON POSTHARVEST QUALITY AND SHELF LIFE OF ACID LIME UNDER AMBIENT STORAGE CONDITIONS**

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ABSTRACT

Acid lime (*Citrus aurantifolia* Christm.) is an important commercial citrus fruit crop in Nepal next to mandarin. It is a non-climacteric and perishable type, having a short shelf life, and quality deteriorates rapidly after harvest. This study was conducted to evaluate the effect of sulfur dioxide (SO₂) generating antifungal pads containing different concentrations of sodium metabisulfite on the postharvest quality and storage life of acid lime, and to identify the most suitable antifungal pad dose for storage. Altogether, nine treatments of SO₂ pads (0.00, 1.25, 2.50, 3.75, 5.00, 6.25, 7.50, 8.75, and 10.00 g) were evaluated in a completely randomized design (CRD) with three replications. Fruits of uniform size (30-40 g) were packaged at modified atmospheric condition and stored at 32±2°C with 75±5% relative humidity. Physicochemical parameters were assessed at 1, 8, 15, 22, and 29 days after storage (DAS). Titratable acidity (TA) and total soluble solids (TSS) declined at higher doses (above 7.50 g). Results revealed that SO₂ pad doses ranging from 2.5 g to 3.75 g were the most effective to reduce physiological weight loss (6.21% and 6.97%, respectively). Juice recovery percentage was highest at 3.75 g (24.70%) and 2.50 g (24.4%), while the lowest was observed at 10.00 g SO₂. The highest freshness (4.65 score), and longest shelf life (33.80 days) of the acid lime fruits were observed at 2.50 g SO₂ dose. Overall, lower SO₂ doses (2.5-3.75 g) maintained postharvest quality and extended the shelf life of acid lime approximately by 14 days under ambient storage conditions.

Keywords: *Citrus aurantifolia*, Physicochemical properties, physiological loss in weight, sodium metabisulphite, sulphur dioxide, total soluble solids

INTRODUCTION

Acid lime (*Citrus aurantifolia* Christm.) is an important citrus fruit crop ranking in the second position after mandarin in Nepal (Poudel, 2021). The total area of cultivation is estimated to be 48,329 ha, with a total production of 318,939 metric tons and productivity of 9.39 MT ha⁻¹ (MoALD, 2024). Fruits are non-climacteric and highly perishable in nature, with a short shelf life (one to two weeks) depending on environmental conditions (Rokaya et al., 2016). Joshi et al. (2020) reported that postharvest losses for citrus fruits in Nepal vary between 20-25% and these occur at various stages of the value chain. These losses are largely due to the highly perishable nature of citrus fruits, along with physiological activities such as high transpiration and respiration rates, postharvest microbial infections, and improper handling practices, including immediate packaging and transportation without proper removal of field heat (Adhikari & G.C.,

2021; Haider et al., 2021). Consequently, such postharvest losses significantly reduce farmers' income by reducing fruit marketability and limiting their availability during the off season (Shrestha et al., 2024).

In the past, various strategies have been investigated to minimize postharvest losses in citrus fruits. Techniques such as modified atmosphere packaging (MAP) and application of edible coatings such as oils, waxes, and safer chemical treatments have also been reported to improve postharvest shelf life and quality (D.C. et al., 2021; Joshi et al., 2020; Shrestha et al., 2024). Additionally, different conventional packaging materials including plastic crates, bamboo baskets, and wooden boxes are commonly used for the handling and storage of citrus fruits in Nepal (Poudel, 2021).

Sulfur dioxide (SO₂) has long been used in postharvest handling to inhibit decay organisms and extend storage life (Sabir & Sabir, 2009). SO₂ generating antifungal pads, first developed in California in the 1960s, release SO₂ by reaction of sodium metabisulfite with moisture and are effective against fungal pathogens (Cantin et al., 2011; Henriquez & Pinochet, 2016). Commercial pads are broadly classified as slow-release or dual-release. Dual-release pads emit a rapid, high dose during the first 24-48 hours (sterilization phase) followed by a prolonged low-dose release lasting up to several weeks (export/maintenance phase) (Ahmed et al., 2018; de Aguiar et al., 2023; Higuchi et al., 2024).

Despite their efficacy, SO₂ pads can cause phytotoxicity and quality defects at high doses (e.g., bleaching, browning, and secondary infections), which has led to restrictions in some markets (Cantín et al., 2011; Daniel-Swartland et al., 2024). Nonetheless, low-dose SO₂ treatments remain attractive because they are easy to apply, cost-effective, and pose lower health risks than field fungicides (Ahmed et al., 2018).

Antifungal pads, particularly sulfur dioxide (SO₂) generating pads, have been extensively studied in grapes for extending shelf life in previous studies (Ahmed et al., 2018). Different treatments have been evaluated for controlling postharvest decay in banana, lemon, litchi, apple, raspberry, blueberry, and fig in other countries (Cantín et al., 2011; Daniel Swartland et al., 2024; Saito & Xiao, 2017). However, study on the application of SO₂ generating pads for the postharvest management of acid lime is not undertaken yet in Nepal. Therefore, this research was conducted to study the effect of dual release antifungal pads on the postharvest quality and shelf life of acid lime and to identify the most suitable dose of SO₂ generating antifungal pads for growers and other stakeholders under ambient storage conditions in the mid-hill region.

RESEARCH METHODS

Research site

This research was conducted at Soil Minilab, Agriculture Knowledge Center (AKC), Tamghas Gulmi (latitude 27° 40' N, longitude 85° 19' E, 1838 meters above sea level). *Sunkagati-1* variety of acid lime was used for experimental purpose. Uniform sized (30-40 g), healthy, and well-matured lime fruit samples were harvested using a clipper, keeping a small pedicel intact on each fruit. The harvested fruits were then sorted, graded, collected in crates and transported from Dhurkot Rural Municipality, Gulmi, a potential citrus-producing zone, to Soil Minilab, AKC, Gulmi, in the last week of February, 2025. The transported fruits were then washed with distilled water and air-dried under shade for three hours.

Experimental setup

The experimental setup consisted of nine treatments of SO₂ pads (0.00 g control, 1.25 g, 2.50 g, 3.75 g, 5.00 g, 6.25 g, 7.50 g, 8.75 g, and 10.00 g). This experiment was laid out in a completely randomized design (CRD) with three replications. Altogether, there were 27 experimental units, each containing 30 fruits (10 non-destructive and 20 destructive). Fruits were kept in the modified atmospheric bag (thickness of 50 microns and dimensions of 40 cm × 40 cm) containing antifungal pads without perforated holes. Antifungal pads (Company: High Tech International, India) of thickness 100 microns were purchased from the market. Fruits were placed at the bottom of the modified atmospheric bag and antifungal pads were stapled inside the bag, over the fruits without directly touching them. The packaging material used in this research acted as a barrier for gas circulation and distribution around the fruits. The experiment was conducted from last week of February to last week of March 2025. The maximum and minimum temperature of the research site were 34°C and 29°C respectively. The maximum relative humidity was 80% whereas the minimum was 70% throughout the experimental period.

Parameter measured

This study measured six physiochemical properties of acid lime in total. Titrable acidity (TA) and total soluble solids (TSS) were measured to check the chemical properties of the fruits. Physiological loss in weight (PLW), juice recovery percentage, freshness (1-5), and shelf life were recorded to track physical changes appeared in fruits over time.

Titration Acidity (TA)

The acidity of the fruits from each treatment were estimated at seven days interval for five times throughout the research. A total of 10 ml of clear juice from each treatment was taken and titration was done against standard 0.1N of sodium hydroxide (NaOH) using phenolphthalein as an indicator as described by Joshi et al., (2020). The TA of fruit was then calculated with the help of following formula.

$$\text{TA (\%)} = \frac{\text{ml of NaOH used} \times \text{acid factor (i.e. 0.0064 for citric acid)}}{\text{volume (ml) of juice used}} \times 100\%$$

Total Soluble Solids (TSS)

TSS was determined using a digital hand-held refractometer (Model: ERMA, Japan) and was expressed in °Brix. First, juice was extracted from each fruit and placed on the prism of the refractometer. The prism was cleaned with 99.9 % ethanol followed by distilled water using a soft cloth. Juice was extracted from two randomly selected fruits from the destructive samples. The refractometer was calibrated before recording each observation.

Physiological Loss in Weight (PLW%)

Physiological loss in weight was recorded from 10 fruits (non-destructive) sample at seven days interval. A digital sensitive balance (Model: CY 224C, Company: Aczet) was used to measure the fruit weight. The PLW (%) was calculated according to the formula (Rokaya et al., 2016).

$$\text{PLW (\%)} = \frac{\text{weight of the initial fruits (g)} - \text{weight of the fruits at designated time (g)}}{\text{weight of the initial fruits (g)}} \times 100\%$$

Juice recovery (%)

Juice was extracted by squeezing via manual hand-held juice squeezer. The volume of juice was measured (mL/fruit) using measuring cylinder. Average juice percentage per fruit was obtained from the following formula as given by Joshi et al. (2020).

$$\text{Juice Recovery (\%)} = \frac{\text{Juice weight per fruit (g)}}{\text{Individual fruit weight (g)}} \times 100\%$$

Freshness

Freshness of the fruits was rated by a panel of five judges on the basis of fruit color, texture, and aroma using a hedonic rating scale of 1-5 as described by Rokaya et al. (2016), where 1- very low freshness (spoiled or unacceptable), 2- low freshness (slightly spoiled, noticeable deterioration), 3- moderate freshness (acceptable but not ideal), 4- good freshness (minor changes but still fresh), 5- excellent freshness (very fresh). Freshness was assessed at the last day of storage. Fruits scoring a minimum of 3 out of 5 were regarded as acceptable from a consumer point of view.

Shelf life

Shelf life of the fruit was counted as number of days after storage of fruits. It was done by the visual assessment of the quality of the fruits and decay loss from non-destructive samples. Shelf life of each fruit was recorded and noted individually. At last, average shelf life was calculated by dividing the sum of shelf life of individual fruits by number of fruits in non-destructive sample.

Data collection and analysis

Statistical analysis for the data was carried out by using R-Studio software (Version 4.4.1, website: <https://cran.r-project.org/bin/windows/base/old/4.4.1/>). Analysis of variance (ANOVA) was conducted to determine significant differences among treatment means, and the least significant difference (LSD) test was applied at the 5% level of significance ($p \leq 0.05$).

RESULTS AND DISCUSSION

Titration Acidity (TA)

The TA of acid lime fruit was not significantly influenced by the different doses of dual release antifungal SO₂ pads during the early storage period (1 DAS, 8 DAS, and 15 DAS). However, significant variation among treatments was observed at 22 DAS ($p < 0.01$) and 29 DAS ($p < 0.001$).

Across the treatments, a general decline in TA was observed over the 29 DAS. At 29 DAS, the control (0.00 g) and lower SO₂ doses (1.25 g and 2.50 g) retained comparatively higher TA values of 6.27%, 6.10%, and 6.12% respectively, and were statistically similar to each other. In contrast, the higher SO₂ doses of 8.75 g and 10.00 g recorded the lowest TA values of 5.36% and 5.33% respectively at 29 DAS, which were significantly lower than the control and lower dose treatments (≤ 3.75 g), and were statistically similar to each other.

The decrease in TA with increasing the concentration of SO₂ observed in this study is associated with negative metabolic effects of SO₂ present in antifungal pad. On increasing SO₂ concentration, malic acid content decreases due to binding of malic acid with SO₂ and oxidation of malic acid to oxaloacetic acid (Salur-can et al., 2016). Inserra (2017) also conducted similar research in apricot and reported negative role of SO₂ concentration in TA content of fruit during postharvest storage. However, Ahmed et al. (2018) found no significant effect of SO₂ pads on the TA of table grapes under cold storage, which disagree with our findings. The SO₂ dose used by Ahmed et al. (2018) may have been lower than those used in the present study, and therefore did not cause a noticeable reduction in TA. These differences suggest that the effect of SO₂ on TA is dependent on both the fruit types and the dose of SO₂ applied.

Total Soluble Solids (TSS)

The TSS content of acid lime fruit showed no significant differences among treatments at 1, 8, and 15 DAS. Significant differences appeared at 22 DAS ($p < 0.01$) and 29 DAS ($p < 0.05$), showing that the effect of SO₂ pad doses on TSS became visible only as storage period advanced. Overall, TSS increased in all treatments throughout the 29 days storage period. At 29 DAS, the highest TSS was recorded in fruits treated with lower SO₂ doses, particularly 2.50 g (7.90 °Brix), 1.25 g (7.86 °Brix), and the control (7.85 °Brix), which were all statistically similar to each other. On the other hand, the highest dose of 10 g recorded the significantly lowest TSS values of 7.43 °Brix.

The increase in TSS of acid lime observed across all treatments during the 29-day storage period is consistent with previous reports in lemon (Kayesh et al., 2018), and in papaya (Farouk Idnan et al., 2012), where TSS was found increasing with advancing storage duration due to moisture loss, starch hydrolysis, and the concentration of soluble solids within the fruit tissue. The lower TSS at higher SO₂ doses might be due to the inhibitory effect of elevated SO₂ concentrations on the respiratory and enzymatic processes of the fruit. According to Hamzaoglu et al. (2018), SO₂ at higher concentrations inhibits the activity of key respiratory enzymes, which slows down the breakdown of organic acids into simpler sugar compounds, thereby limiting the accumulation of soluble solids in the fruit tissue. Furthermore, the binding of SO₂ with sugar intermediates and its interference with glycolytic pathways may also contribute to the reduced TSS at elevated doses. These findings are consistent with the results of the TA in the present study, where higher SO₂ doses also caused greater reduction in organic acid content.

Table 1. Effect of dual release antifungal pad on TA (%) and TSS (°Brix) of acid lime in different storage periods

Antifungal Pad (g)	Titrable Acidity (TA), %					Total Soluble Solids (TSS), °Brix				
	Days After Storage (DAS)					Days After Storage (DAS)				
	1	8	15	22	29	1	8	15	22	29
0.00	7.26	7.03	6.83	6.50 ^a	6.27 ^a	6.33	6.93	7.44	7.66 ^a	7.85 ^a
1.25	7.34	6.95	6.57	6.32 ^{ab}	6.10 ^a	6.54	6.76	7.57	7.73 ^a	7.86 ^a
2.50	7.35	7.16	7.01	6.46 ^a	6.12 ^{ab}	6.63	6.83	7.13	7.70 ^a	7.90 ^a
3.75	7.26	6.79	6.17	6.11 ^{ab}	6.07 ^{ab}	6.56	7.00	7.31	7.63 ^a	7.80 ^a
5.00	7.47	7.00	6.66	6.30 ^{ab}	6.20 ^{ab}	6.46	7.06	7.60	7.50 ^a	7.73 ^a
6.25	6.64	6.18	6.08	5.95 ^{bc}	5.80 ^{bc}	6.86	7.13	7.66	7.46 ^a	7.83 ^a
7.50	6.74	6.23	6.10	5.90 ^{bc}	5.51 ^{cd}	6.70	7.00	7.53	7.68 ^a	7.81 ^a
8.75	7.06	6.35	5.98	5.51 ^c	5.36 ^d	6.06	6.66	7.43	7.46 ^a	7.76 ^a
10.00	6.80	6.16	5.80	5.56 ^c	5.33 ^d	6.16	6.46	7.03	7.10 ^b	7.43 ^b
SE _m (±)	0.56	0.29	0.28	0.16	0.13	0.38	0.44	0.36	0.10	0.09
F-test	NS	NS	NS	**	***	NS	NS	NS	**	*
LSD (0.05)	1.69	0.87	0.86	0.48	0.41	1.14	1.31	1.08	0.28	0.25
CV (%)	13.88	7.65	7.88	4.65	4.10	10.31	11.15	8.52	2.21	1.88
Grand mean	7.10	6.65	6.36	6.07	5.86	6.48	6.87	7.41	7.55	7.77

Note: DAS=Days After Storage, SEm(±) = Standard Error of Mean; LSD=Least Significant Difference, CV=Coefficient of Variation, Different letters in the column are significantly different at $p < 0.05$. NS, *, **, *** non-significant, significant at 5%, 1% and 0.1%, respectively

Physiological Loss in Weight (PLW%)

No significant effect of different doses of antifungal pads on PLW was observed until the 15th DAS (Table 2). PLW was significantly increased from 2.50 g to 10.00 g treatments with the advancement of the storage periods. The highest PLW was recorded in the 10.00 g treatment (7.84% and 8.06%), while the lowest (5.95% and 6.21%) was observed at 2.50 g treatment at 22 DAS and 29 DAS respectively. The fruits treated with higher doses (above 7.50 g) showed higher PLW% at both DAS.

The significantly lower PLW values observed at 2.50-3.75 g indicate that lower pad doses were more effective in reducing weight loss of acid lime fruits. This reduction may be attributed to retardation in the process of respiration and transpiration by closing of lenticels and stomata of the cell wall of the fruits accompanied by effective suppression of decay causing microorganisms (Higuchi et al., 2024). In contrast, both the control and higher doses resulted in significantly greater PLW throughout the storage periods. In fruits treated with higher SO₂ doses (above 7.50 g), excessive SO₂ release may have exerted phytotoxic effects on the peel tissues, leading to disruption of cell membrane integrity and increased electrolyte leakage, which in turn accelerated moisture loss from the fruit surface (Saito et al., 2020). In the control, the absence of any protective treatment allowed unrestricted moisture diffusion through the peel, and rapid water loss accompanied by subsequent shrinkage of the fruit surface likely contributed to the higher PLW recorded throughout the storage period. These findings are consistent with the observations as reported by Ali et al. (2024).

Juice recovery percentage (%)

Juice recovery percentage declined progressively across all treatments throughout the storage periods (Table 2), indicating that postharvest water loss inversely affects the extractable juice content of acid lime fruits. No statistically significant differences in juice recovery was observed among treatments up to 22 DAS. However, significant differences were noticed by 29 DAS. At 29 DAS, the highest juice recovery was recorded in fruits treated with 3.75 g (24.74%), followed by 2.50 g (24.40%), while the lowest was observed in the 10.00 g treatment (19.71%). These data suggest that the cumulative effect of antifungal pad doses on fruit physiology becomes pronounced during the later stages of storage.

The higher juice retention in lower dose treatments (≤ 3.75 g) may be attributed to the controlled release of SO₂ gases, which adequately suppressed postharvest pathogens without inducing phytotoxic effects on fruit tissues. At lower SO₂ doses (2.50 and 3.75 g), the amount of SO₂ gas released inside the modified atmospheric packaging (MAP) was enough to partially slow down respiratory enzyme activity and reduce the overall metabolic rate of the fruit, but was not sufficient to extensively reinforce the integrity of cellular organelles and cytoplasm homogeneity, resulting in a comparatively less rigid cellular structure of the juice sacs of acid lime, which facilitated the release of a greater volume of juice upon extraction (Higuchi et al., 2024).

According to Zoffoli et al. (2008) higher SO₂ doses (≥ 5.00 g) increased the effective surface area of emitting material, leading to excessive diffusion of volatile compounds into fruit tissues. Such over exposure has been associated with membrane lipid peroxidation, cellular damage, and accelerated water loss collectively reducing the amount of recoverable juice. The observed decline in juice recovery at higher doses in this study therefore reflects a dose-dependent phytotoxic response rather than a beneficial preservation effect. These findings agree with those of Ahmed et al. (2018), who reported that elevated concentrations of postharvest treatments can compromise tissue integrity in citrus fruits, resulting in reduced juice content.

Table 2. Effect of dual release antifungal pad on PLW (%) and juice recovery % of acid lime in different storage periods

Antifungal Pad (g)	Physiological Loss in Weight (PLW%)				Juice Recovery (%)				
	Days After Storage (DAS)				Days After Storage (DAS)				
	8	15	22	29	1	8	15	22	29
0.00	4.56	5.77	7.20 ^{ab}	8.00 ^a	52.57	48.77	43.52	31.54	23.77 ^{ab}
1.25	4.45	4.49	6.85 ^{abc}	7.79 ^{ab}	44.35	48.77	33.92	27.04	22.85 ^{ab}
2.50	3.80	5.29	5.95 ^c	6.21 ^d	49.62	45.87	41.21	35.55	24.40 ^a
3.75	4.24	5.51	5.99 ^c	6.97 ^c	45.04	37.44	27.89	26.45	24.74 ^a
5.00	4.62	6.48	6.62 ^{bc}	7.27 ^{bc}	46.82	40.51	36.24	31.88	23.82 ^{ab}
6.25	4.65	5.51	7.00 ^{abc}	7.58 ^{ab}	48.08	39.52	40.03	30.61	22.54 ^{abc}
7.50	5.13	6.79	7.30 ^{ab}	7.77 ^{ab}	45.30	36.17	32.47	30.85	21.32 ^{bc}
8.75	5.24	5.96	7.46 ^{ab}	7.95 ^a	43.60	34.85	30.13	24.51	21.89 ^{abc}
10.00	6.23	6.81	7.84 ^a	8.06 ^a	45.12	33.30	32.23	27.88	19.71 ^c
SE _m (±)	1.06	1.13	0.39	0.17	5.93	7.75	6.54	5.14	0.90
F-test	NS	NS	**	***	NS	NS	NS	NS	*
LSD (0.05)	3.15	3.37	0.96	0.54	17.64	23.04	19.46	15.30	2.68
CV (%)	38.58	33.67	8.03	4.12	22.00	33.70	32.13	30.13	6.86
Grand mean	4.77	5.84	6.91	7.51	46.72	39.85	35.29	29.59	22.78

Note: DAS=Days After Storage, SE_m(±) = Standard Error of Mean; LSD=Least Significant Difference, CV=Coefficient of Variation, Different letters in the column are significantly different at $p<0.05$. NS, *, **, *** non-significant, significant at 5%, 1% and 0.1%, respectively

Freshness

The freshness of the acid lime fruits rated during storage under different treatments is presented in Fig. 1 (a). At 29 DAS, the maximum and equal (4.65 score) freshness of the acid lime fruit was observed in 1.25g and 2.50 g, which is statistically similar with control (4.32 score) and 3.75 g (4.32 score). As the SO₂ dose increased beyond 3.75 g, rating of freshness declined progressively. The lowest freshness rating was recorded at the highest dose of 10.00 g (1.32), which was significantly different from all other treatments.

In principle, SO₂ generating pads release SO₂ gas in a controlled manner, which is sufficient to inhibit fungal inoculum and maintain the physicochemical and sensory characteristics of fruits. However, at higher SO₂ doses, rapid shrinkage and discoloration of the peel were observed along with poor sensory characteristics, and similar results have been reported by de Aguiar et al. (2023). In this study, 1.25 and 2.50 g antifungal pads showed the highest freshness score, while 10.00 g treatment showed the lowest. This may be due to the rapid absorption of water vapor released during fruit respiration, as well as bleaching, skin injury, and unpleasant changes in fruit flavor and color caused by excessive SO₂ gas at higher doses. Conversely, lower doses did not cause such adverse effects, resulting in improved fruit appearance and sensory quality. These findings agree with the results of previous researchers (Lurie et al. 2006, Zutahy et al. 2008).

Shelf life

The effect of different doses of antifungal pad on shelf life of acid lime is mentioned in Fig. 1 (b). The shelf life of acid lime fruit also varied significantly among SO₂ pad doses. The longest shelf life (33.80 days), was recorded at 2.50 g which was significantly higher than all other treatments. The control (0.00g), 1.25 g, 3.75 g, and 5.00 g were possessed statistically similar to the 2.50 g treatment and values were 27.40, 27.00, 26.60, and 25.00 days respectively. As the SO₂ dose increased further, shelf life declined steadily. Treatments of 5.00 g, 6.25 g, 7.50 g, and 8.75 g exhibited progressively shorter shelf life. The shortest shelf life was observed at the highest dose of 10.00 g (19.80 days), which was significantly lower than the 2.50 g treatment. The present findings shows that excessive SO₂ doses negatively influenced the storage life of acid lime fruit.

The effective suppression of decay organisms and delayed senescence might be the reason for giving maximum shelf life at lower dose (2.50 g). In contrast, higher doses probably caused increased SO₂ uptake by peel or tissue, including membrane damage, oxidative stress and peel injury that result in the loss of quality of fruits along with lower shelf life (Huang et al., 2024). Gao et al. (2002) have also reported that the excessive SO₂ concentration was more significant in decreasing the shelf life of fruits.

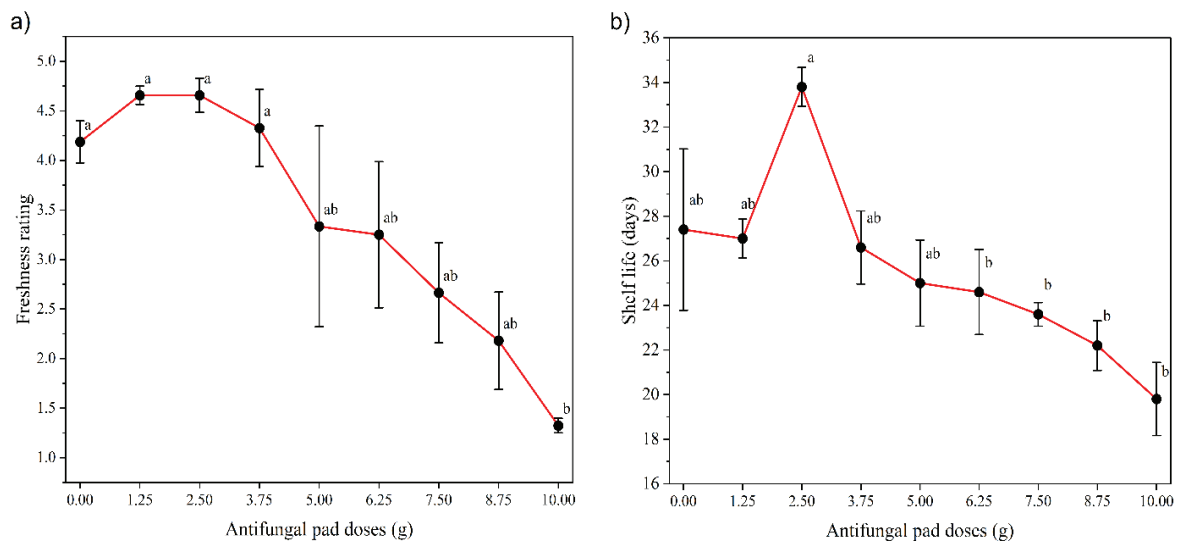


Fig. 1. Freshness rating (1-5 score) (a) Freshness rating, 1- Very low freshness (spoiled or unacceptable), 2- Low freshness (slightly spoiled, noticeable deterioration), 3- Moderate freshness (acceptable but not ideal), 4- Good freshness (minor changes but still fresh), 5- Excellent freshness (very fresh); (b) shelf life, days of acid lime at different doses of antifungal pad (g) at 29 DAS

CONCLUSION

The present study showed a significant influence of dual-release SO₂ generating antifungal pads on the physicochemical parameters of acid lime. Among the tested treatments, lower doses (less than 5.00 g) were found to be most effective in preserving TA and TSS, reducing PLW %, and maintaining higher juice recovery percentage. In contrast, doses above 5.00 g accelerated the rate of change of these parameters and negatively affected fruit quality. The highest freshness score (4.65) and shelf life (33.80 days) were recorded in fruits treated with the 2.50 g antifungal pad. Therefore, a 2.50-3.75 g pad dose can be considered most effective to maintain postharvest quality and extend the shelf life of acid lime under ambient storage conditions. Further studies can be conducted to validate the present findings by taking more

parameters such as measurement of transpiration rate, respiration rate, microorganisms, malic acid content, and electrolyte leakage from the fruits.

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AUTHOR CONTRIBUTIONS

KK: Conceptualization, Methodology, Investigation, Data curation, Writing – original draft; **RHT:** Supervision, Writing – review & editing; **CR:** Writing – review & editing; **BP:** Investigation, Data curation; **GK:** Investigation, Data curation; **SK:** Visualization.

CONFLICT OF INTEREST

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

ETHICAL APPROVAL AND PERMITS

Not applicable.

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