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Standardisation of Active Modified Atmosphere Storage in Indi Lime (Citrus aurantifolia Swingle) Fruits

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Abstract

Indi lime (*Citrus aurantifolia* Swingle), commonly known as Kagzi lime, is an important citrus fruit cultivated widely in the northern districts of Karnataka, particularly in the Indi region of Vijayapura. Despite its economic and nutritional importance, lime fruits are highly perishable and suffer considerable postharvest losses due to rapid physiological deterioration, microbial decay and improper storage conditions. Modified Atmosphere Packaging (MAP) is a promising postharvest technology that alters the gaseous environment surrounding the produce to reduce respiration, delay senescence and extend storage life. The present study was conducted during the year 2023–24 at the Department of Postharvest Management, College of Horticulture, University of Horticultural Sciences, Bengaluru, to standardize active modified atmosphere storage conditions for Indi lime fruits. The experiment was laid out in a Completely Randomized Design with five treatments and four replications using LDPE bags (250 µm) with different gas compositions *viz.*, passive MAP (control), 4% O_2 + 2% CO_2 + 94% N_2, 6% O_2 + 4% CO_2 + 90% N_2, 8% O_2 + 6% CO_2 + 86% N_2 and 10% O_2 + 8% CO_2 + 82% N_2. Fruits were stored at 10 ± 2°C and evaluated at 10-day intervals for physiological, biochemical and sensory parameters. Results revealed that active MAP significantly influenced fruit quality during storage. Treatment T_4 (8% O_2 + 6% CO_2 + 86% N_2) was found to be the most effective in maintaining fruit quality by reducing physiological loss in weight, preserving firmness and colour, maintaining moisture content, lowering respiration rate and delaying biochemical changes compared to passive MAP. The treatment also recorded better sensory acceptability and reduced decay incidence. Thus, indi lime fruits stored under T_4 (8% O_2 + 6% CO_2 + 86% N_2) conditions maintained acceptable quality for up to 60 days of cold storage, followed by a short shelf life under ambient conditions.

INTRODUCTION

Indi lime (*Citrus aurantifolia* Swingle) belonging to the family Rutaceae, is an important citrus fruit widely cultivated in the tropical and subtropical regions of India. Among the citrus fruits, lime ranks third after mandarin and sweet orange in terms of commercial importance. India is one of the major producers of lime globally and the crop plays an significant role in the horticultural economy (Liu et al., 2012). The Indi region of Vijayapura district in Karnataka (16.82° N latitude and 76.18° E longitude) is particularly known for the cultivation of high-quality Kagzi lime, which possesses desirable attributes such as thin peel, high juice content, characteristic aroma and high vitamin C content. In Karnataka, on an average Kagzi lime cultivated in area of about 13.1 thousand hectares with an annual production of 3,06,210 metric tons (NHB, 2018). Notably, more than half of the total production in Vijayapura district comes from the Indi taluk alone. Owing to its unique qualities, Indi lime has received a Geographical Indication (GI) tag, highlighting its regional importance (KSLDB, 2025).

Lime fruits are widely used in beverages, culinary preparations, pickles and food processing industries (Ranganna, 1986). In addition to culinary importance, they are highly valued for their medicinal and nutritional properties, particularly their high vitamin C content (Salunkhe and Kadam, 1995). It exhibits several health promoting properties, including anti-cancer, anti-inflammatory, anti-diabetic, anti-bacterial

and antifungal activities (Abakpa and Adenaike, 2021). Despite these benefits, lime fruits are highly perishable and susceptible to rapid quality deterioration during storage. Postharvest losses occur due to moisture loss, respiration, microbial decay, mechanical damage during transportation and improper storage conditions (Kader, 2002). These factors significantly reduce the shelf life and market quality of the fruits.

To minimize these losses, appropriate postharvest handling practices are essential for maintaining quality and extending shelf life, which depend on proper handling, treatment, storage and transportation of harvested produce. One such solution for this is Modified Atmosphere Packaging (MAP) (Florkowski et al., 2014). MAP involves modifying the composition of gases surrounding the produce, typically by reducing oxygen levels and increasing carbon dioxide concentration, which helps to slowdown respiration and microbial growth (Sandya, 2010). The technique can be applied either passively, where the atmosphere develops naturally due to the respiration of produce within the package, or actively by flushing the package with a predetermined gas mixture. It also been widely reported to delay ripening, reduce weight loss, maintain firmness and preserve colour and nutritional quality in several fruits (Wardowsky *et al*., 1973). However, the optimal gas composition varies depending on the crop type and the storage conditions.

Modern consumers prefer fruits that are fresh, convenient and of high quality. Modified Atmosphere Packaging (MAP) helps to preserve the nutritional content and sensory attributes of fruits while, significantly extending their shelf life (Wills et al., 2016). By prolonging longer availability across the different regions, MAP supports growers and consumers by reducing postharvest losses and enhancing market opportunities. Therefore, evaluating the MAP for Indi lime becomes essential to determine its potential in maintaining quality, minimizing losses and ensuring a consistent supply of market-acceptable fruits. However, limited information is available regarding the suitable modified atmosphere composition for prolonged storage of Indi lime. Hence, the present investigation was undertaken to standardize active modified atmosphere storage conditions for Indi lime fruits and to evaluate their effects on physiological, biochemical and sensory characteristics during storage.

MATERIALS AND METHODS

The present investigation entitled **“Standardisation of Active Modified Atmospheric Storage in Indi Lime (***Citrus aurantifolia* **Swingle) fruits”** was conducted at the Department of Postharvest Management, College of Horticulture, University of Horticultural Sciences, Bengaluru during the year 2023–24. Fresh lime fruits (cv. Kagzi) were harvested at the mature stage and sorted to remove damaged, diseased and misshapen fruits and graded for uniform size, shape and colour. Then the fruits were washed using **200 ppm sodium hypochlorite solution**for surface sanitation and subsequently air-dried for five hours to remove surface moisture. The experiment was conducted using 250 g fruits per package **in LDPE bags (250 µm thickness)** under five treatments with four replications in a **Completely Randomized Design (CRD).** The packaged fruits were stored under cold storage conditions at a temperature of 10 ± 2°C and evaluated at every 10-day interval. The study consisted of five treatments; *viz.,* Passive MAP (without gas flushing) (T_1); 4% O_2 + 2% CO_2 + 94% N_2 (T_2); 6% O_2 + 4% CO_2 + 90% N_2 (T_3); 8% O_2 + 6% CO_2 + 86% N_2

(T_4) and 10% O_2 + 8% CO_2 + 82% N_2 (T_5). These treatments were evaluated to determine the effect of different modified atmosphere composition on the storage quality and shelf life of Indi lime fruits. Observations were recorded on various physiological, biochemical and sensory parameters including physiological loss in weight (%), moisture content (%), fruit firmness (N), colour values (L*, a*, b*), total soluble solids (°Brix), titratable acidity (%), ascorbic acid content (mg 100 ml^{-1}), antioxidant activity (FRAP method), respiration rate (mg CO_2 kg^{-1} h^{-1}), fruit decay (%), sensory evaluation using 9-point hedonic scale, as well as storage and shelf life of fruits. Then the recorded data were statistically analysed using a Completely Randomized Design at 1% level of significance to determine the effect of different modified atmosphere treatments on the quality attributes and storage performance of Indi lime fruits.

The moisture content of fruits was determined at regular intervals by using four grams of finely chopped peel from each sample in a Sartorius electronic moisture analyser (Model MA 35). Fruit firmness was assessed by penetrating each sample with a 5 mm cylindrical probe moving at a speed of 2 mm/s, followed by an automatic return. The probe was set to penetrate 5 mm deep, with the pre-test and post-test speeds adjusted to 1 mm/s and 10 mm/s, respectively. The measurements were performed using a Texture Analyser (Model TA.HD Plus, Stable Micro Systems, UK). The colour of the fruits was evaluated using a portable colourimeter spectrophotometer (Lovibond LC 100, Model RM200, The Tintometer Ltd., Salisbury, UK). Colour measurements were recorded based on the CIE Lab* colour system, where *L** indicates lightness on a scale from 0 (pure black) to 100 (pure white). The *a** and *b** values represent the hue: positive a* values indicate red tones, while negative *a** values indicate green; similarly, positive b* values correspond to yellow and negative *b** values to blue, with both ranging from 60 to +60.

Physiological loss in weight was recorded using a high-precision electronic weighing balance (Sartorius GmbH, Goettingen, Germany; Model GE812) at 10-day intervals throughout the storage period. These readings were used to calculate the cumulative PLW, which was expressed as the percentage of weight loss using the following formula:

$$\text{Physiological loss in weight (\%)} = \frac{\text{Initial weight - Final weight}}{\text{Initial weight}} \times 100$$

The titratable acidity of lime fruit juice was determined using the titration method. For this, 1ml of the sample was diluted with 25 mL of distilled water to obtain a uniform solution. The diluted sample was then titrated against 0.1N sodium hydroxide (NaOH) solution with 2-3 drops of phenolphthalein as the indicator. The endpoint of the titration was identified by the appearence of a light pink colour. The titratable acidity was calculated and expressed as a percentage of citric acid equivalent (AOAC, 1990).

$$\text{Titratable acidity (\%)} = \frac{T \times E \times N \times V_1 \times 100}{V_2 \times 1000 \times W}$$

Ascorbic acid content of the sample was estimated titrimetrically using 2, 6-dichlorophenol indophenol dye. The one-gram sample was diluted with 4% oxalic acid. Then, 25 ml of an aliquot taken from the

sample was titrated against 2,6-dichlorophenol indophenol. The results are expressed as milligrams of ascorbic acid per 100 g of the sample. (A0AC, 2006)

$$\text{Ascorbic acid content (mg 100ml}^{-1}) = \frac{0.5 \times V_2 \times 100 \times 100}{V_1 \times 5 \times \text{weight of sample}}$$

The respiration rate of the lime fruits with different gas compositions was measured after taking them out of the packages during their storage. The fruits were weighed enclosed in a hermetic container for specified time and head space gas concentration of CO_2 was measured by piercing the probe of an auto oxygen/carbon dioxide analyser (Make: Quantek, Model: 902D Dual track) into the container through the septa fixed on the lid of the container and direct reading was noted down from the instrument screen. The respiration rate was calculated in mg kg^{-1} h^{-1} by using the formula:

$$\text{Respiration rate(mg kg}^{-1}\text{h}^{-1}) = \frac{\%\ CO_2 \text{ x Container volume (ml) x 60}}{\text{[Fruits weight (kg)] x [Enclosing time (min)] x 100}}$$

The incidence of decay in lime fruits was evaluated visually and expressed as total decay. Fruits showing any external signs of rotting, such as mould growth, were classified as external decayed fruits. These fruits were recorded and removed from the lot. The percentage of fruits affected by decay was then calculated using the following formula:

$$\text{Decay incidence (\%)} = \frac{\text{Number of discarded fruits at each sampling date}}{\text{Total number of fruits in treatment}} \text{ x100}$$

The total soluble solids of lime fruits were measured using a hand refractometer (Erma Optical Works Ltd., Tokyo, Japan; range 0–32°B) and readings were adjusted to 20°C and expressed as °Brix (Ranganna, 1986). The total antioxidant activity of lime fruits was determined using the FRAP method explained by Benzie and Strain (1996). Organoleptic evaluation of lime fruits was conducted based on colour, texture, taste, aroma and overall acceptability by a panel of ten semi-trained judges, where lime juice was diluted in a 1:3 (lime Juice and water) using a nine-point Hedonic scale as laid out by Amerine *et al*. (1965). Shelf life of fruit was determined after removing the lime fruits from low temperature storage (10±2^{o}C) and observing their quality under ambient conditions until they became unfit for composition.

RESULTS AND DISCUSSION

The physicochemical properties of fresh lime fruits were evaluated prior to the application of any postharvest treatments in order to establish the initial quality parameters and baseline data for the study (Table 1). The analysis revealed that the fruits had an average fruit weight of 47.7 g with juice content of 48.96% and TSS of 6.5°Brix indicating moderate sweetness and good juice yield. The fruits had moisture content of 83.9%, which reflects the high water content typical of citrus fruits and contributes to their perishability. The titratable acidity of 8.15%, antioxidant activity was found to be 75 mg AAE 100ml-^{1} while ascorbic acid content of 32 mg 100 ml⁻¹, demonstrating that lime fruits are a good source of natural

antioxidants and vitamin C. The colour parameters, namely *lightness* (*L**), *redness* (*a**) and *yellowness* (*b**) were found to be 53.9, – 13.6 and 31.25 respectively, indicate the typical greenish-yellow appearance of mature lime fruits. The respiration rate of the fruits was observed as 17.1 mg CO_2 kg^{-1} h^{-1} at 25 °C, suggesting a relatively active metabolic rate under ambient conditions, which contributes to faster postharvest deterioration. Additionally, the fruit texture measured 51.8 N, reflecting acceptable firmness at the time of harvest. Based on these initial quality attributes, the shelf life of fresh lime fruits under ambient storage conditions was recorded as approximately 7 days, highlighting the highly perishable nature of the fruit and the need for appropriate postharvest handling and storage techniques to extend its marketable life. Similar reports were noted by Kader (2002), Florkowski et al. (2014) and Ranganna (1986) in fruit crops.

Table 1
Physio-chemical properties of Fresh Indi lime (*Citrus aurantifolia* Swingle) fruits used for the experiment

Sl. No.	Parameter	Values
1	Fruit weight (g)	47.70
2	Juice (%)	48.96
3	TSS (°B)	6.50
4	Moisture (%)	83.90
5	Lightness (*L**) value	53.90
6	Redness (*a**) value	-13.6
7	Yellowness (*b**) value	31.25
8	Respiration rate (mg CO_2 kg^{-1} h^{-1})	17.10
9	Texture (N)	51.80
10	Titratable acidity (%)	8.15
11	Antioxidants (mg AAE $100g^{-1}$)	75.00
12	Ascorbic acid ($mg100g^{-1}$)	32.00
13	Shelf life (No. of days)	7.00

Physiological weight loss increased progressively during the storage period in all treatments (Table 2). Among the different atmospheric conditions, fruits stored under T_4 (8% O_2 + 6% CO_2) recorded the lowest PLW with values of 0.40, 0.90, 1.60, 2.30, 2.90 and 3.50 per cent on the 10, 20, 30, 40, 50 and 60th days of storage, respectively (Plate 1–6). The reduced weight loss under this treatment indicates the effectiveness of modified atmosphere in reducing metabolic activity such as respiration and transpiration. These findings are in agreement with earlier reports on citrus fruits stored under controlled atmospheric conditions (Strano et al., 2022). In contrast, the highest weight loss was observed in T_1 (Passive MAP),

reaching 7.03% at 60 days of storage, which could be attributed to higher transpiration and respiration. A similar rapid decline under non-modified storage was reported in Kaghzi lime (Hayat et al., 2017). Physiological loss in weight (PLW) is closely correlated with storage temperature, relative humidity and the type of packaging used, in addition to the inherent metabolic activities of the fruits. Higher storage temperatures accelerate respiration and transpiration rates, leading to increased moisture loss and consequent reduction in fruit weight. Similarly, low relative humidity increases the vapour pressure deficit between the fruit surface and the surrounding air, thereby promoting greater water loss through transpiration and ultimately contributing to higher PLW during storage.

Table 2
Effect of active modified atmosphere package on physiological loss in weight (%) of Indi lime fruits under low temperature storage (10 ± 2°C)

Physiological loss in weight (%)						
Treatments	**10 DAS**	**20 DAS**	**30 DAS**	**40 DAS**	**50 DAS**	**60 DAS**
T_1 (Passive MAP)	0.900^{a}	1.625^{a}	2.800^{a}	4.000^{a}	5.300^{a}	7.025^{a}
T_2 (4% O_2 + 2% CO_2)	0.700^{ab}	1.200^{ab}	2.100^{ab}	3.200^{b}	4.100^{b}	5.000^{b}
T_3 (6% O_2 + 4% CO_2)	0.600^{b}	1.100^{ab}	1.900^{b}	2.800^{bc}	3.600^{c}	4.400^{c}
T_4 (8% O_2 + 6% CO_2)	0.400^{b}	0.900^{b}	1.600^{b}	2.300^{d}	2.900^{d}	3.500^{e}
T_5 (10% O_2 + 8% CO_2)	0.500^{b}	1.000^{b}	1.800^{b}	2.600^{cd}	3.300^{c}	3.900^{d}
Mean	0.62	1.17	2.04	2.98	3.84	0.151
S. Em±	0.091	0.204	0.241	0.143	0.103	0.107
CD @ 5%	0.275	-	0.726	0.430	0.311	0.323
CD @ 1%	0.380	-	1.004	0.594	0.430	0.446
F-test	*	**NS**	*	**	**	**
* Significant at 5% level * * Significant at 1% level NS: Non significance						
DAS: Days after storage						

Table 3
Effect of active modified atmosphere package on moisture (%) of Indi lime fruits under low temperature storage (10 ± 2°C)

Moisture (%)							
Treatments	**Initial**	**10 DAS**	**20 DAS**	**30 DAS**	**40 DAS**	**50 DAS**	**60 DAS**
T_1 (Passive MAP)	83.900	83.438^{c}	82.850^{c}	81.838^{c}	80.825^{d}	79.738^{e}	78.313^{e}
T_2 (4% O_2 + 2% CO_2)	83.900	83.613^{bc}	83.188^{b}	82.425^{b}	81.513^{c}	80.750^{d}	79.988^{d}
T_3 (6% O_2 + 4% CO_2)	83.900	83.688^{ab}	83.275^{ab}	82.600^{ab}	81.838^{b}	81.175^{c}	80.500^{c}
T_4 (8% O_2 + 6% CO_2)	83.900	83.863^{a}	83.438^{a}	82.850^{a}	82.263^{a}	81.763^{a}	81.250^{a}
T_5 (10% O_2 + 8% CO_2)	83.900	83.775^{ab}	83.363^{ab}	82.675^{ab}	82.013^{b}	81.425^{b}	80.925^{b}
Mean	83.90	83.68	83.22	82.48	81.69	80.97	80.20
S. Em±	--	0.072	0.061	0.081	0.069	0.077	0.082
CD @ 5%	--	0.218	0.184	0.244	0.208	0.233	0.247
CD @ 1%	--	0.302	0.254	0.337	0.287	0.322	0.341
F-test	--	**	**	**	**	**	**
* Significant at 5% level * * Significant at 1% level NS: Non significance							
DAS: Days after storage							

The initial moisture content of fresh lime fruits was 83.90 per cent, which gradually declined during the storage period across all the treatments. On the 40th day of storage, the highest moisture content (82.26%) was recorded in fruits stored under T_4 (8% O_2 +6% CO_2), followed by T_5 (10% O_2 + 8% CO_2) with 82.01 per cent, suggesting that a moderate O_2–CO_2 ratio helps in reducing moisture loss by lowering the respiration and transportation rate without causing physiological stress to fruits. Comparable reductions in moisture loss under MAP have been reported in grapefruit stored under modified atmospheres (Chaudhary et al., 2015). While the lowest (80.82%) moisture content was observed in fruits under passive T_1 (MAP) at 40th day, which could be attributed to relatively higher metabolic activity and water loss. By the end of 60 days of storage, the maximum moisture content (81.25%) was still maintained in T_4 (8% O_2 + 6% CO_2) followed by T_5 (10% O_2 + 8% CO_2) (80.93%), whereas the minimum moisture content (78.31%) was recorded in T_1 (passive MAP). The mean moisture content across treatments declined from 83.90 per cent (initial) to 80.20 per cent after 60 days of storage, indicating a steady loss of moisture with time of storage. These findings are similar to Kaghzi lime under non-modified storage (Hayat et al., 2017) and in citrus fruits (Strano et al., 2022).

The initial texture of fresh lime fruits was recorded as 51.80 N, which showed a continuous decline during storage in all the treatments (Table 4). On the 40th day of storage, the highest texture firmness (48.20 N)

was observed in fruits stored under T_4 (8% O_2 + 6% CO_2), followed by T_5 (10% O_2 + 8% CO_2) at about 47.70 N and T_3 (6% O_2 + 4% CO_2) at 47.58 N. The retention of higher firmness under these modified atmosphere conditions indicates that reduced oxygen and elevated carbon dioxide levels slow down metabolic activity and delay the degradation of cell wall components responsible for fruit softening. In contrast, the lowest texture value (43.80 N) was recorded in fruits under passive MAP (T_1). Similarly, firmness reduction under conventional storage has been reported in citrus fruits stored without atmospheric modification (Porat et al., 2004). By the end of 60 days of storage, fruits packed in T_4 (8% O_2 + 6% CO_2) retained the highest firmness (45.60 N), followed by T_5 (44.50 N) and T_3 (44.20 N), whereas the lowest firmness (38.00 N) was observed in T_1 (passive MAP) indicating that reduced O_2 level combined with elevated CO_2 concentration helps in reducing enzymatic breakdown of cell wall components, thereby maintaining structural integrity of fruit tissue. These observations were consistent with the role of MAP in delaying softening in citrus (Baldwin et al., 2011). The balanced gas ratio minimizes firmness loss without inducing stress responses. Valero and Serrano (2010) also noted that modified atmospheres helps to maintain textural integrity by reducing respiration and delaying structural degradation in fruit tissues.

Table 4
Effect of active modified atmosphere package on the texture of Indi lime fruits under low temperature storage (10 ± 2^{o}C)

Texture (N)							
Treatments	**0 DAS**	**10 DAS**	**20 DAS**	**30 DAS**	**40 DAS**	**50 DAS**	**60 DAS**
T_1 (Passive MAP)	51.800	50.625^{d}	48.375^{d}	46.100^{d}	43.800^{d}	41.200^{e}	38.000^{e}
T_2 (4% O_2 + 2% CO_2)	51.800	51.000^{c}	49.800^{c}	48.175^{c}	46.200^{c}	44.400^{d}	42.025^{d}
T_3 (6% O_2 + 4% CO_2)	51.800	51.400^{ab}	50.200^{b}	49.025^{b}	47.575^{b}	46.025^{c}	44.200^{c}
T_4 (8% O_2 + 6% CO_2)	51.800	51.600^{a}	50.800^{a}	49.600^{a}	48.200^{a}	47.000^{a}	45.600^{a}
T_5 (10% O_2 + 8% CO_2)	51.800	51.325^{b}	50.400^{b}	49.200^{b}	47.700^{b}	46.425^{b}	44.500^{b}
Mean	51.800	51.190	49.915	48.420	46.695	45.010	42.865
S. Em±	--	0.077	0.104	0.106	0.090	0.085	0.074
CD @ 5%	--	0.232	0.313	0.320	0.272	0.257	0.223
CD @ 1%	--	0.321	0.433	0.442	0.376	0.355	0.308
F-test	--	**	**	**	**	**	**
* Significant at 5% level * * Significant at 1% level NS: Non significance							
DAS: Days after storage							

Colour is an important quality attribute that significantly influences the appearance, freshness and consumer acceptability of lime fruits (Table 5). The *L** value indicates darkness or lightness of fruit

surface ranging from 0 (dark) to 100 (light). The *a** coordinate varies from − 120 to + 120, representing greenness and redness, respectively. Meanwhile, the *b** values ranges from − 120 to + 120, indicate blueness with negative numbers and yellowness with positive numbers. The initial *L** value of fresh lime fruits was 53.90, which gradually increased during storage across all the treatments, indicating progressive colour change associated with ripening and chlorophyll degradation. At the end of 60 days of storage. The highest *L** value (76.00) was recorded in fruits stored under Passive MAP (T_1), followed by T_2 (4% O_2 + 2% CO_2) with 71.20, while the lowest *L** value (66.43) was noted in T_4 (8% O_2 + 6% CO_2) this was due to faster chlorophyll degradation and senescence. Similar observations in citrus fruits has shown that modified atmospheres suppress chlorophyll degradation and delays colour deterioration (Rodrigo and Zacarías, 2007). Additionally, the reduced respiration rate under MAP contributes to better retention of visual quality (Pathare et al., 2013). These findings align with report of Ben-Yehoshua (2005), who reported that limiting gas exchange helps to maintain external appearance, confirming that active MAP is effective in preserving colour and extending the marketability of fresh lime fruits.

The *a** value of fresh lime fruits increased (became less negative) during storage, indicating a reduction in green colour intensity and progression towards yellowing, with the fastest colour change was observed in T_1 (Passive MAP), where the a* value increased from − 13.60 to − 1.80 by 60 DAS after storage (Table 6). This rapid change can be attributed to accelerated chlorophyll degradation and fruit senescence in T_1 under passive storage conditions. In contrast, the lowest change in *a** value (–7.98) was recorded in T_4 (8% O_2 + 6% CO_2), demonstrating that reduced O_2 and elevated CO_2 levels delayed pigment breakdown and helped to maintain the green colour of fruit. These results demonstrate that, modified atmosphere condition can slow the biochemical processes responsible for colour change during storage. Similar delayed chlorophyll under modified atmospheres has been reported in citrus, where lower oxygen slows down chlorophyll degradation and associated with colour transition (Rodrigo and Zacarías, 2007). Additionally, the reduced respiration rates under modified atmosphere storage helps to maintain the visual quality and delay senescence during storage (Kader, 2002). These findings also align with observations of Gross (1987), who reported that carotenoid accumulation increases as chlorophyll content declines during ripening, leading to visible colour changes.

The *b** values (+ yellow/ - blue) of fresh lime fruits increased progressively during storage in all the treatments, indicating a gradual shift towards higher yellowness due to carotenoid accumulation and chlorophyll degradation during ripening and senescence (Table 7). The most rapid increase in *b** value was observed in T_1 (Passive MAP) from 31.25 to 59.60 by 60 DAS as senescence advanced. This rapid rise indicates accelerated senescence and pigment transformation under passive storage conditions. In contrast, fruits stored under T_4 (8% O_2 + 6% CO_2) showed the slowest increase in *b** value, reaching 48.20 at 60 DAS, demonstrating that reduced O_2 and elevated CO_2 levels delayed colour transformation by slowing pigment degradation and oxidative reaction associated with ripening. Similar trends have been reported in citrus fruit, where modified atmospheric conditions suppress chlorophyll loss and delay increases in *b** values (Rodrigo and Zacarías, 2007), Furthermore, reduced respiration rate under MAP can delay carotenoid synthesis associated with ripening (Matsumoto *et al*., 2009). These results are consistent with the findings of Dhuique-Mayer et al. (2005), who reported that colour changes in citrus fruit intensify

as senescence progresses, confirming that active MAP helps to maintain visual quality and thereby extending the marketability of fresh lime fruits during storage.

The respiration rate of fresh lime fruits increased steadily during storage across all the treatments, reflecting the progression of metabolic activity and senescence (Table 8). The highest increase was observed in T_1 (Passive MAP) from 17.10 to 42.50 mg CO_2 kg^{-1} h^{-1} by 60 DAS due to unrestricted oxygen availability, which accelerates metabolic activity and promotes physiological deterioration. Higher O_2 levels enhance the oxidative breakdown of substrates resulted in higher heat and CO_2 production, consequently increased respiration, leading to faster physiological deterioration, as noted in citrus stored under ambient conditions (Kader, 2002). In contrast, fruits stored under T_4 (8% O_2 + 6% CO_2) exhibited the lowest increase in respiration rate, reaching only 26.00 mg CO_2 kg^{-1} h^{-1} by end of storage, indicating that reduced O_2 combined with elevated CO_2 effectively suppressed respiration by limiting electron transport process and inhibiting the metabolic enzyme activity. The balanced gas composition slows down the respiration without inducing anaerobic stress, thereby helping to maintain fruit quality during storage. Elevated CO_2 levels are known to reduce ethylene synthesis and delay metabolic changes in citrus, thereby improving the storage stability (Porat et al., 2016). Similarly, reduced O_2 has been reported to lower respiratory demand and prolongs the postharvest life by slowing biochemical reactions associated with ripening and senescence (Saltveit, 2019).

Table 8
Effect of active modified atmosphere package on the Respiration rate of Indi lime fruits under low temperature storage (10 ± 2^{o}C)

Respiration rate (mg CO_2 kg^{-1} h^{-1})							
Treatments	**Initial**	**10 DAS**	**20 DAS**	**30 DAS**	**40 DAS**	**50 DAS**	**60 DAS**
T_1 (Passive MAP)	17.100	22.000^{a}	25.500^{a}	29.000^{a}	33.000^{a}	38.500^{a}	42.500^{a}
T_2 (4% O_2 + 2% CO_2)	17.100	17.500^{b}	18.200^{b}	18.975^{b}	20.200^{b}	26.000^{b}	30.200^{b}
T_3 (6% O_2 + 4% CO_2)	17.100	17.400^{b}	18.000^{c}	18.800^{bc}	19.800^{c}	23.500^{c}	27.000^{c}
T_4 (8% O_2 + 6% CO_2)	17.100	17.300^{b}	17.900^{c}	18.700^{c}	19.700^{c}	22.500^{e}	26.000^{e}
T_5 (10% O_2 + 8% CO_2)	17.100	17.600^{b}	18.125^{c}	18.900^{c}	19.900^{c}	23.000^{d}	26.500^{d}
Mean	17.100	18.360	19.545	20.875	22.520	26.700	30.440
S. Em±	--	0.111	0.090	0.074	0.063	0.061	0.077
CD @ 5%	--	0.335	0.272	0.223	0.191	0.183	0.233
CD @ 1%	--	0.463	0.376	0.308	0.264	0.252	0.323
F-test	--	**	**	**	**	**	**
Note: *b** Value (+ yellow/ - blue)							
* Significant at 5% level * * Significant at 1% level NS: Non significance							
DAS: Days after storage							

The highest TSS was consistently recorded in Passive MAP (T_1), reaching 8.90°B at 60 days of storage (Table 9). This rapid increase may be attributed to higher respiration and moisture loss under unrestricted atmospheric conditions, where elevated O_2 availability stimulates oxidative respiration, enhancing the conversion of stored polysaccharides and organic acids into simple sugars, thereby increasing the TSS levels. Simultaneously, the absence of CO_2 enrichment fails to suppress respiratory enzyme activity, resulting in faster metabolic turnover and accelerated ripening. Similar increases in TSS have been reported in citrus fruits stored without atmospheric modification, where rapid senescence leads to greater accumulation of soluble solids during storage (Ladaniya, 2008). In contrast, lowest TSS value was observed in T_5 (10% O_2 + 8% CO_2) with 7.60°B indicating that reduced O_2 and elevated CO_2 slowed metabolic activity and delayed biochemical changes associated with ripening, helping to maintain the internal quality and extend the storage life of lime fruits.

Table 9

Effect of active modified atmosphere package on TSS (^{0}B) of Indi lime fruits under low temperature storage (10 ± 2^{o}C)

TSS (^{0}B)							
Treatments	**Initial**	**10 DAS**	**20 DAS**	**30 DAS**	**40 DAS**	**50 DAS**	**60 DAS**
T_1 (Passive MAP)	6.500	6.900^a	7.250^a	7.700^a	8.100^a	8.450^a	8.900^a
T_2 (4% O_2 + 2% CO_2)	6.500	6.725^b	6.900^c	7.200^c	7.500^c	7.850^c	8.200^c
T_3 (6% O_2 + 4% CO_2)	6.500	6.775^{ab}	7.050^b	7.350^b	7.675^b	8.100^b	8.500^b
T_4 (8% O_2 + 6% CO_2)	6.500	6.675^b	6.800^c	7.000^d	7.100^e	7.400^d	7.700^d
T_5 (10% O_2 + 8% CO_2)	6.500	6.700^b	6.850^c	7.050^d	7.250^d	7.500^d	7.600^d
Mean	6.500	6.755	6.970	7.260	7.525	7.860	8.180
S. Em±	--	0.041	0.034	0.037	0.040	0.037	0.041
CD @ 5%	--	0.125	0.103	0.110	0.122	0.110	0.123
CD @ 1%	--	0.172	0.142	0.152	0.168	0.152	0.170
F-test	--	*	**	**	**	**	**
* Significant at 5% level * * Significant at 1% level NS: Non significance							
DAS: Days after storage							

The titratable acidity of fresh lime fruits declined gradually during storage in all the treatments reflecting the utilization of organic acids in respiratory metabolism during the storage period (Table 10). The lowest TA was consistently recorded in Passive MAP (T_1), reaching 6.40 per cent at 60 days, while the highest TA occurred in T_4 (8% O_2 + 6% CO_2) with 7.60 per cent. The highest retention of acidity under modified atmosphere conditions indicates that reduced oxygen and elevated carbon dioxide levels slow down respiratory metabolism and delay the utilization of organic acids, thereby helping to preserve fruit quality during storage. Similarly, the ascorbic acid content at 60 days was recorded in T_4 (8% O_2 + 6% CO_2) with 29.5mg100ml^{-1} with the highest retention of about 92.22 per cent followed by T_5 (10% O_2 + 8% CO_2) and T_3 (6% O_2 + 4% CO_2), while the lowest ascorbic acid content was found in Passive MAP (T_1) with 17.5 mg100ml^{-1} corresponding to the least retention of 54.68 per cent. The better retention of ascorbic acid under modified atmosphere conditions may be attributed to reduced oxidative degradation and slower metabolic activity. Similar trend was observed in antioxidant activity, the highest antioxidant content was recorded in T_4 (8% O_2 + 6% CO_2) with 67.0 mgAAE 100 ml^{-1} at 60 days of storage, whereas the lowest was found in Passive MAP (T_1) with 48.0 mgAAE 100 ml^{-1}. These results indicate that modified atmosphere storage effectively slows down oxidative reactions and metabolic degradation, thereby helping to retain bioactive compounds and maintain the nutritional quality of lime fruits during prolonged storage.

Table 10
Effect of active modified atmosphere package on Titratable acidity of Indi lime fruits under low temperature storage (10 ± 2^{o}C)

Titratable acidity (%)							
Treatments	**Initial**	**10 DAS**	**20 DAS**	**30 DAS**	**40 DAS**	**50 DAS**	**60 DAS**
T_1 (Passive MAP)	8.15	7.900^{b}	7.600^{c}	7.300^{d}	7.000^{d}	6.700^{d}	6.400^{d}
T_2 (4% O_2 + 2% CO_2)	8.15	8.000^{b}	7.800^{b}	7.600^{c}	7.400^{c}	7.200^{c}	7.000^{c}
T_3 (6% O_2 + 4% CO_2)	8.15	8.050^{a}	7.900^{ab}	7.750^{b}	7.600^{b}	7.450^{b}	7.300^{b}
T_4 (8% O_2 + 6% CO_2)	8.15	8.100^{a}	8.000^{a}	7.900^{a}	7.800^{a}	7.700^{a}	7.600^{a}
T_5 (10% O_2 + 8% CO_2)	8.15	8.075^{a}	7.975^{a}	7.875^{a}	7.775^{a}	7.675^{a}	7.575^{a}
Mean	8.15	8.025	7.855	7.685	7.515	7.345	7.175
S. Em±	--	0.036	0.038	0.036	0.038	0.036	0.038
CD @ 5%	--	0.108	0.115	0.108	0.115	0.108	0.115
CD @ 1%	--	0.150	0.159	0.150	0.159	0.150	0.159
F-test	--	*	**	**	**	**	**
* Significant at 5% level * * Significant at 1% level NS: Non significance							

The ascorbic acid content of fresh lime fruits declined steadily during storage in all treatments. The fastest reduction was observed in T_1 (Passive MAP) from 32.00 to 17.50 mg100ml^{-1} by 60 DAS with the least retention of 54.68 per cent (Table 11). This rapid declined may be attributed to higher oxygen availability under passive conditions, which accelerates the oxidative degradation of vitamin C during respiration and senescence. Similar reductions in ascorbic acid content under ambient storage conditions have been reported in citrus fruits due to increased enzymatic oxidation and metabolic activity (Lee and Kader, 2000). In contrast, fruits stored under T_4 (8% O_2 + 6% CO_2) retained the highest ascorbic acid (29.50 mg100ml^{-1}), indicating that reduced oxygen and elevated carbon dioxide concentration effectively slowed oxidative reactions and metabolic degradation. Among the MAP treatments, T_4 (8% O_2 + 6% CO_2) proved to be most effective with highest retention of about 92.22 per cent, followed by T_5 (10% O_2 + 8% CO_2) and T_3 (6% O_2 + 4% CO_2). This suggests that a balanced gas atmosphere, coupled with low temperature, minimal physical injury and reduced physiological stress helps to maintain vitamin C stability by suppressing respiration and limiting exposure to oxidative stress. These findings align with Porat et al. (2005), who reported that MAP preserves internal fruit quality by slowing biochemical deterioration during storage and in citrus fruit (Dhuique-Mayer et al., 2007).

Table 11
Effect of active modified atmosphere package on ascorbic acid content of Indi lime fruits under low temperature storage (10 ± 2°C)

Ascorbic acid (mg 100ml^{-1})								
Treatments	**Initial**	**10 DAS**	**20 DAS**	**30 DAS**	**40 DAS**	**50 DAS**	**60 DAS**	**Retention (%)**
T_1 (Passive MAP)	32.000	29.500^{d}	26.500^{e}	23.525^{e}	21.000^{e}	19.000^{e}	17.500^{e}	54.68
T_2 (4% O_2 + 2% CO_2)	32.000	30.800^{c}	29.500^{d}	28.000^{d}	26.500^{d}	25.000^{d}	23.800^{d}	74.38
T_3 (6% O_2 + 4% CO_2)	32.000	31.200^{b}	30.475^{c}	29.800^{c}	29.000^{c}	28.200^{c}	27.500^{c}	85.93
T_4 (8% O_2 + 6% CO_2)	32.000	31.625^{a}	31.225^{a}	30.800^{a}	30.425^{a}	30.000^{a}	29.500^{a}	92.22
T_5 (10% O_2 + 8% CO_2)	32.000	31.525^{a}	30.775^{b}	30.425^{b}	29.800^{b}	29.300^{b}	28.800^{b}	90.00
Mean	32.000	30.930	29.695	28.510	27.345	26.300	25.420	79.44
S. Em±	--	0.077	0.088	0.085	0.074	0.077	0.071	-
C.D. @ 1%	--	0.321	0.366	0.355	0.308	0.323	0.295	-
C.D. @ 5%	--		0.265	0.257	0.223	0.233	0.213	-
F-test	--	**	**	**	**	**	**	-

* Significant at 5% level * * Significant at 1% level NS: Non significance

Total antioxidant content of fresh lime fruits declined steadily during storage in all treatments, with the largest decrease in T_1 (Passive MAP) from 75.10 to 48.00 mgAAE 100ml^{-1} by 60 DAS due to faster oxidative degradation under normal oxygen conditions, which accelerates metabolic activity and the action of oxidative enzymes during fruit senescence (Table 12). Similar reductions in antioxidant capacity during storage have been reported in citrus as senescence and oxidative enzymes increase lead to the degradation of bioactive compounds (Dhuique-Mayer et al., 2005). In contrast, fruits stored under T_4 (8% O_2 + 6% CO_2) exhibited the slowest decline, in antioxidant content, retaining 67.00 mgAAE 100ml^{-1}, indicating that reduced O_2 and elevated CO_2 limited the oxidative reactions. Among MAP treatments, T_4 (8% O_2 + 6% CO_2) maintained the highest antioxidant levels, followed by T_5 (10% O_2 + 8% CO_2) and T_3 (6% O_2 + 4% CO_2), suggesting that balanced gas composition helps to suppress respiration and reduce the formation of reactive oxygen species, thereby protecting antioxidant compounds during storage. Modified atmosphere storage has been shown to preserve phenolic compounds, moisture and essential vitamins and minerals, thereby enhancing the antioxidant stability in citrus fruits during storage (Baldwin et al.,

2012). In addition, reduced oxygen levels slow enzymatic oxidation by inhibiting oxidative enzymes responsible for phenolic degradation (Gil et al., 1999).

Table 12
Effect of active modified atmosphere package on Total Antioxidant (mg AAE 100ml-1) content of Indi lime fruits under low temperature storage (10 ± 2°C)

Total Antioxidant (mg AAE 100ml-1)							
Treatments	**Initial**	**10 DAS**	**20 DAS**	**30 DAS**	**40 DAS**	**50 DAS**	**60 DAS**
T_1 (Passive MAP)	75.100	72.500^{d}	70.000^{d}	66.500^{d}	61.000^{e}	55.000^{d}	48.000^{e}
T_2 (4% O_2 + 2% CO_2)	75.100	72.000^{e}	69.500^{c}	66.000^{e}	61.500^{d}	55.000^{d}	48.500^{d}
T_3 (6% O_2 + 4% CO_2)	75.100	73.500^{c}	72.000^{e}	70.500^{c}	68.000^{c}	64.500^{c}	60.000^{c}
T_4 (8% O_2 + 6% CO_2)	75.100	74.200^{a}	73.500^{a}	72.000^{a}	71.000^{a}	69.500^{a}	67.000^{a}
T_5 (10% O_2 + 8% CO_2)	75.100	74.000^{b}	72.975^{b}	71.500^{b}	70.000^{b}	68.000^{b}	65.000^{b}
Mean	75.100	73.240	71.595	69.300	66.300	62.400	57.700
S. Em±	--	0.048	0.053	0.041	0.075	0.080	0.093
CD @ 5%	--	0.146	0.159	0.123	0.227	0.240	0.281
CD @ 1%	--	0.201	0.220	0.170	0.314	0.332	0.388
F-test	--	**	**	**	**	**	**
* Significant at 5% level * * Significant at 1% level NS: Non significance							
DAS: Days after storage							

The sensory attributes of lime fruits, namely colour, texture, taste, aroma and overall acceptability, were evaluated using a nine-point hedonic scale, where 9 = like extremely and 1 = dislike extremely, by a semi-trained sensory panel (Table 13–21, Fig. 1). The sensory quality of lime fruits gradually decreased with prolonged storage under all treatments; however, fruits stored under modified atmosphere conditions retained higher hedonic scores for all attributes compared to the control throughout the storage period.

Table 13
Effect of active modified atmosphere package on sensory quality (colour) of Indi lime fruits under low temperature storage (10 ± 2^{o}C)

Colour						
Treatments	**10 DAS**	**20 DAS**	**30 DAS**	**40 DAS**	**50 DAS**	**60 DAS**
T_1 (Passive MAP)	8	8	8	7	6	6
T_2 (4% O_2 + 2% CO_2)	9	9	8	8	8	7
T_3 (6% O_2 + 4% CO_2)	9	9	9	8	8	8
T_4 (8% O_2 + 6% CO_2)	9	9	9	9	9	8
T_5 (10% O_2 + 8% CO_2)	9	9	9	9	9	8
Mode	9	9	9	8	8	8

Among the different sensory parameters, colour scores declined progressively with advancement of storage period across all treatments (Table 13). Fruits stored under active MAP treatments (T_2–T_5) consistently retained higher colour scores compared to passive MAP (T_1) throughout storage. Among the treatments, T_4 (8% O_2 + 6% CO_2) and T_5 (10% O_2 + 8% CO_2) recorded the highest colour retention up to 50 DAS, followed by T_3 (6% O_2 + 4% CO_2). The modal colour score remained 9 during 10–30 DAS, decreased to 8 at 40–60 DAS, indicating gradual colour deterioration of colour with prolonged storage. Overall, higher CO_2 concentration combined with moderated O_2 levels were more effective in maintaining colour quality during storage, as these conditions delay pigment degradation and reduce surface yellowing of lime fruits. These results are in conformity to Lab value which demonstrated objectively and agrees with findings that modified atmospheres slow colour changes in citrus by suppressing chlorophyll degradation and delaying senescence (Rodrigo and Zacarías, 2007).

Fruits stored under active MAP treatments (T_2–T_5) maintained significantly higher aroma scores compared to passive MAP (T_1) throughout the storage period, due to faster respiration and loss of volatile compounds under normal atmospheric condition, which accelerates senescence and reduce sensory quality (Table 14). Among the treatments, T_4 (8% O_2 + 6% CO_2) and T_5 (10% O_2 + 8% CO_2) were found to be the most effective in retaining aroma, recording the highest scores up to 40 DAS. The modal aroma score was remained 9 during 10–20 DAS and gradually decreased to 8 from 30 to 60 DAS, indicating a gradual loss of aroma with prolonged storage duration. These results are similar with findings of citrus fruits, where modified atmospheres storage helps to maintain aroma by reducing metabolic activity and limiting volatile loss during storage (Tietel et al., 2010).

Table 14
Effect of active modified atmosphere package on sensory quality (aroma) of Indi lime fruits under low temperature storage (10 ± 2^{o}C)

Aroma						
Treatments	**10 DAS**	**20 DAS**	**30 DAS**	**40 DAS**	**50 DAS**	**60 DAS**
T_1 (Passive MAP)	8	8	8	8	7	6
T_2 (4% O_2 + 2% CO_2)	9	9	8	8	8	8
T_3 (6% O_2 + 4% CO_2)	9	9	8	8	8	8
T_4 (8% O_2 + 6% CO_2)	9	9	9	8	8	8
T_5 (10% O_2 + 8% CO_2)	9	9	9	9	8	8
Mode	9	9	8	8	8	8
Note: N = 10						
N: Total number of semi-trained panel members for sensory evaluation						
DAS: Days after storage						

Fruits stored under active MAP treatments (T_2–T_5) consistently exhibited higher taste scores compared to those stored under passive MAP (T_1) throughout the storage period. The decline in taste quality under passive MAP may be attributed to higher respiration rates and faster biochemical deterioration under normal atmospheric conditions, which lead to rapid depletion of sugars, organic acids and flavour compounds (Table 15). Among the treatments, T_4 (8% O_2 + 6% CO_2) and T_5 (10% O_2 + 8% CO_2) were found to be most effective in retaining taste, maintaining the highest scores up to 40 DAS. The modal taste score remained 9 during 10–30 DAS and gradually decreased to 8 from 40 to 60 DAS, indicating a progressive decline in taste with prolonged storage. These conditions help slow respiration and biochemical deterioration, thereby maintaining the balance of sugars, acids and flavour compounds responsible for desirable taste. Similar observations have been reported in citrus, where modified atmospheres maintained better taste quality during storage (Porat et al., 2005).

Table 15
Effect of active modified atmosphere package on sensory quality (Taste) of Indi lime fruits under low temperature storage (10 ± 2^{o}C)

Taste						
Treatments	**10 DAS**	**20 DAS**	**30 DAS**	**40 DAS**	**50 DAS**	**60 DAS**
T_1 (Passive MAP)	8	8	8	7	7	6
T_2 (4% O_2 + 2% CO_2)	9	9	8	8	8	8
T_3 (6% O_2 + 4% CO_2)	9	9	9	8	8	8
T_4 (8% O_2 + 6% CO_2)	9	9	9	9	8	8
T_5 (10% O_2 + 8% CO_2)	9	9	9	9	8	8
Mode	9	9	9	8	8	8

Fruits stored under active MAP treatments (T_2–T_5) maintained superior texture compared to passive MAP (T_1) throughout the storage period. The faster decline in texture under passive MAP can be attributed to higher respiration rates and increased cellular breakdown under normal atmospheric conditions, which accelerate fruit softening (Table 16). Among the treatments, T_4(8% O_2 + 6% CO_2) showed the best texture retention, maintaining the highest scores up to 50 DAS, followed closely by T_3 (6% O_2 + 4% CO_2) and T_5 (10% O_2 + 8% CO_2). The modal texture score remained 9 from 10 to 40 DAS and declined to 8 during 50 and 60 DAS, indicating gradual softening of fruits with prolonged storage, this reduced oxygen and elevated CO_2 slowed softening by minimizing respiration and cellular breakdown. Similar findings were reported that modified atmospheres helps to preserve firmness and texture in citrus during storage by delaying physiological deterioration during storage (Baldwin et al., 2012).

Table 16
Effect of active modified atmosphere package on sensory quality (Texture) of Indi lime fruits under low temperature storage (10 ± 2^{o}C)

Texture						
Treatments	**10 DAS**	**20 DAS**	**30 DAS**	**40 DAS**	**50 DAS**	**60 DAS**
T_1 (Passive MAP)	8	8	8	8	7	6
T_2 (4% O_2 + 2% CO_2)	9	9	9	8	8	8
T_3 (6% O_2 + 4% CO_2)	9	9	9	9	8	8
T_4 (8% O_2 + 6% CO_2)	9	9	9	9	9	8
T_5 (10% O_2 + 8% CO_2)	9	9	9	9	8	8
Mode	9	9	9	9	8	8
Note: N = 10						
N: Total number of semi-trained panel members for sensory evaluation						
DAS: Days after storage						

Overall acceptability of lime fruits decreased progressively with increase in storage duration in all treatments. However, fruits stored under active modified atmosphere conditions exhibited slower deterioration and maintained higher acceptability scores compared to those stored under passive MAP (Table 17). Among the treatments T_4 (8% O_2 + 6% CO_2) and T_5 (10% O_2 + 8% CO_2) performed best, retaining higher consumer acceptability up to 50 DAS. The modal score was 9 up to 40 DAS, which gradually declined to 8 at 50 and 60 DAS, indicating a gradual reduction in overall quality during extended storage. The better acceptability observed under modified atmosphere conditions may be attributed to slower physiological and biochemical deterioration, improved retention of colour, texture, taste and aroma and reduced respiration rates during storage. Similar findings have been reported in citrus fruits (Porat et al., 2005).

Table 17
Effect of active modified atmosphere package on sensory quality (Overall acceptability) of Indi lime fruits under low temperature storage (10 ± 2^{o}C)

Overall acceptability						
Treatments	**10 DAS**	**20 DAS**	**30 DAS**	**40 DAS**	**50 DAS**	**60 DAS**
T_1 (Passive MAP)	8	8	8	7	7	6
T_2 (4% O_2 + 2% CO_2)	9	9	8	8	8	7
T_3 (6% O_2 + 4% CO_2)	9	9	9	9	8	8
T_4 (8% O_2 + 6% CO_2)	9	9	9	9	9	8
T_5 (10% O_2 + 8% CO_2)	9	9	9	9	9	8
Mode	9	9	9	9	8	8
Note: N = 10						
N: Total number of semi-trained panel members for sensory evaluation						
DAS: Days after storage						

The storage life of lime fruits at low temperature (10 ± 2°C) remained constant at 60 days in the T_4 (8% O_2 + 6% CO_2) and T_5 (10% O_2 + 8% CO_2) and 40 days in the T_3 (6% O_2 + 4% CO_2) and T_2 (4% O_2 + 2% CO_2) and the least was recorded in Passive MAP (T_1). At the beginning of storage, all the treatments recorded a shelf-life score of 7 days under ambient condition after removal from cold storage (Table 18). By 20–30 DAS, the shelf life slightly declined to 6–6.5 days across the treatments. At 40 DAS, fruits stored under T_1 recorded a shelf life of 3 days, whereas T_2, T_3, T_4 and T_5 recorded 5 days. At 50 DAS, T_1 showed only 2 days of shelf life, T_2 and T_3 had 2.5 days and T4 and T5 has retained 4 days. By 60 DAS, the lowest shelf life (1 day) was recorded in T_1, while T_4 and T_5 still maintained a shelf life of 3 days under ambient conditions. Overall, the data indicate that MAP treatments, especially T_4 (8% O_2 + 6% CO_2) and T_5 (10% O_2 + 8% CO_2), were most effective in extending the storage and shelf life of lime fruits under ambient conditions compared to Passive MAP (T_1). This may be attributed to reduced respiration, delayed senescence and lower microbial decay during storage and marketing. Similar findings were reported in citrus (Porat et al., 2005).

Conclusion

The study demonstrated that active modified atmosphere packaging significantly improves the storage life and quality of Indi lime fruits. Among the treatments tested, 8% O_2 + 6% CO_2 + 86% N_2 (T_4) proved to be the most effective gas composition for maintaining fruit quality during storage. This gas composition

maintained higher firmness, moisture, acidity, antioxidants, vitamins and mineral content throughout 60 days of storage. Along with it also recorded the lowest respiration rate, weight loss and decay percentage. Overall, active MAP extended both storage and shelf life, ensuring better marketability and consumer acceptability. Therefore, 8 per cent O_2 + 6 per cent CO_2 can be recommended as the ideal packaging atmosphere for long-term storage of Indi lime fruits.

Declarations

Author Contribution

K.B.D. conceptualized and designed the study, conducted the experiments, collected and analyzed the data, and wrote the original manuscript draft. H.C.K. and K.R.V. supervised the research work and contributed to methodology development and data interpretation. V.R. assisted in experimental planning and technical guidance. D.S.A. contributed to data analysis and manuscript editing. R.H. provided critical review and overall guidance for the study. All authors reviewed and approved the final manuscript.

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Tables 5, 6 and 7

Tables 5, 6 and 7 are available in the Supplementary Files section.

Plates

Plates are available in the Supplementary Files section.

Figures

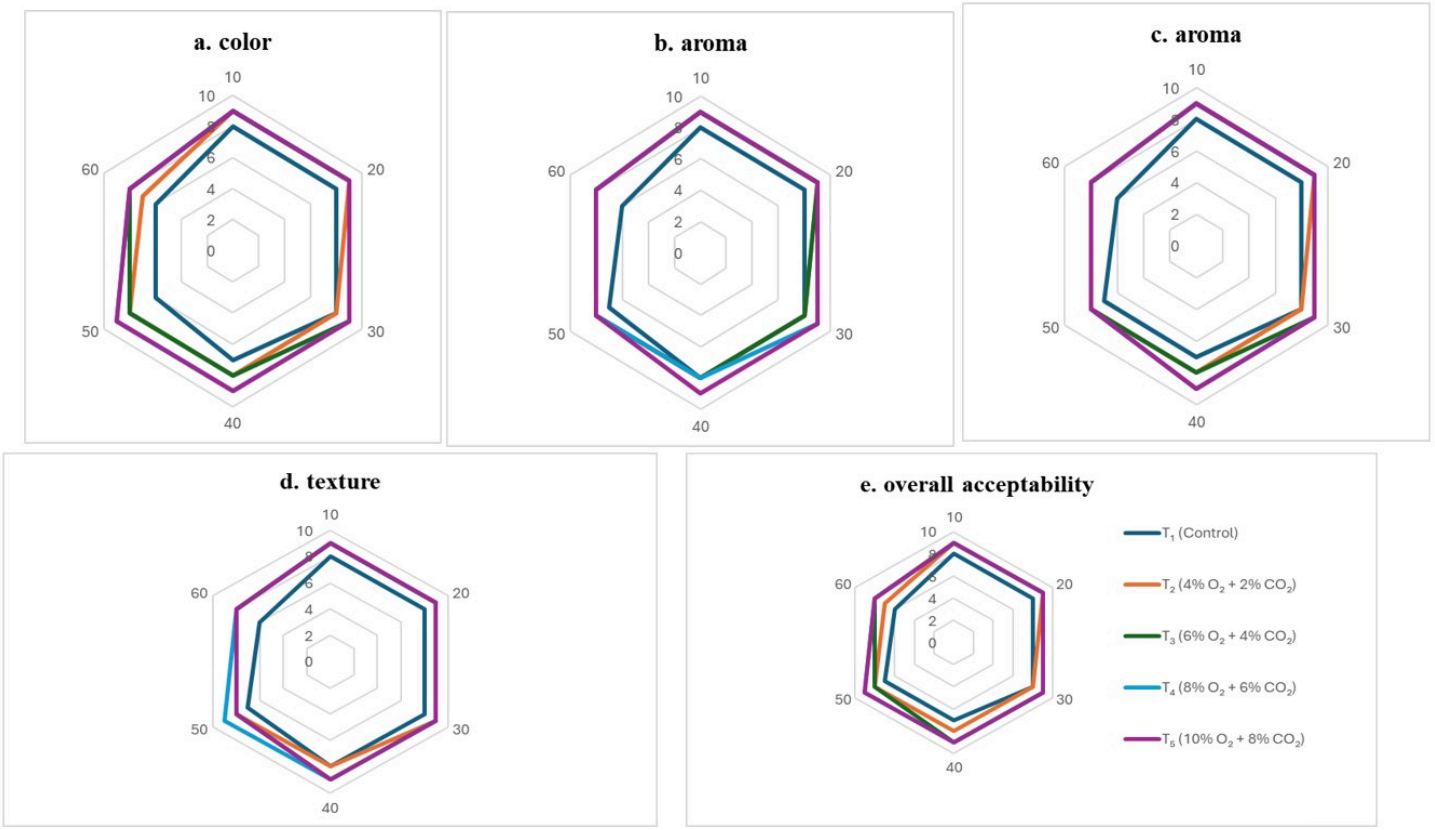


Figure 1

Effect of active modified atmosphere package on Sensory parameter (9-point hedonic scale) a. color, b. aroma, c. aroma, d. texture and e. overall acceptability of Indi lime fruits under low temperature storage (10±2^{o}C)

Supplementary Files

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- Tables56and7.docx
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