Agric Res J **61** (3): 332-339, *June* 2024
DOI: 10.5958/2395-146X.2024.00043.0

ORGANIC AND IN-ORGANIC COATINGS FOR IMPROVING POST-HARVEST QUALITY AND SHELF LIFE OF 'RANGPUR LIME' (*Citrus limonia* Osbeck)

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ABSTRACT

Rangpur lime serves as a crucial rootstock for mandarin cultivation and holds potential for processing industries. The preservation of fruit quality during transportation and storage is vital. Coating agents play a significant role in extending the shelf life and maintaining the quality of produce. This investigation explores the practical application of various organic coatings to enhance the post-harvest quality and shelf life of Rangpur lime fruits. The study employed a range of treatments over a 16-day storage period, including uncoated fruits (T_1), guava leaf extract (GLE) at 15% combined with lemon extract (LE) at 5% (T_2), GLE at 30% with LE at 10% (T_3), GLE at 45% with LE at 15% (T_4), potassium permanganate ($KMnO_4$) at 4 g with calcium chloride ($CaCl_2$) at 1% (T_5), $KMnO_4$ at 8 g with $CaCl_2$ at 2% (T_6), silver nitrate ($AgNO_3$) at 2% (T_7), $AgNO_3$ at 4% (T_8), and bamboo leaves (T_9). Among all treatments, T_4 (GLE at 45% + LE at 15%) emerged as the most effective organic coating, significantly preserving acidity, total soluble solids (TSS), and vitamin C content. Notably, the fruits treated with bamboo leaves and those coated with 8 g of $KMnO_4$ plus 2% $CaCl_2$ exhibited superior external appearance. This study demonstrates that treatments T_4 (GLE at 45% + LE at 15%) and T_9 (bamboo leaves) are effective coating materials for maintaining the post-harvest quality of Rangpur lime fruits under ambient storage conditions.

Key Words: Fruit quality, Guava leaf extract, Lemon leaf extract, PLW

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Citrus is one of the most significant fruit crops in India, comprising a diverse array of species, varieties, and cultivars. Among these, Rangpur lime (*Citrus limonia* Osbeck) is particularly renowned on a global scale. Believed to be a hybrid of lemon and mandarin, Rangpur lime is thought to have originated in India (Acevedo, 2012). It is extensively utilized in Argentina and Brazil, where it serves as a vital citrus rootstock. The origins of this lime can be traced back to India, with seedling plants found in nearly every country that cultivates citrus. Primarily cultivated in the Bombay-Deccan region, Rangpur lime has remarkably adapted to the expansive agricultural landscapes of northern, western, and southern India. Its capacity for healthy growth, salt tolerance, and resistance to citrus greening and tristeza makes it an ideal rootstock for mandarin and sweet orange varieties in India (Dilip *et al.*, 2017). Furthermore, the juice extracted from Rangpur lime has applications in natural cosmetics, serving as a topical skin lotion, hair rinse, and mouthwash (Randhawa and Srivastava, 1986). Additionally, Rangpur limes continue to play a vital role in Indian cuisine; for instance, mandarin juice, a popular beverage in the country, is frequently enhanced with the addition of Rangpur lime juice. Despite its importance, there has been a notable lack of research focused on the enhancement of postharvest quality for Rangpur lime. This article aims to delve into this underexplored area, providing insights that are not widely known to the general public but for which an increasing body of information is becoming available.

Coating agents play a crucial role in reducing gaseous exchange by forming a protective layer on the surface of fruits. This layer significantly decreases oxygen uptake, thereby helping to maintain the quality of the produce (Tesfay *et al.*, 2017). Organic coatings are often preferred over inorganic options due to their sustainability, eco-friendliness, and safety. Furthermore, bio-coatings can be enhanced with bioactive compounds, nutrients, and vitamins, thereby increasing the nutritional value of fruits and vegetables. The incorporation of natural antimicrobial agents into these coatings can also bolster their effectiveness in preventing microbial spoilage (Ungureanu *et al.*, 2023). In addition to minimizing moisture loss (Pham *et al.*, 2023), organic coatings improve the appearance and texture of the produce during storage (Jafarzadeh *et al.*, 2021).

Plant extracts, such as those derived from guava leaves, lemon, and bamboo, are cost-effective and abundantly available, making them popular choices for postharvest treatments. This study aims to evaluate the efficacy of plant extracts in maintaining the physicochemical properties and extending the

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Date of receipt: 05.05.2023, Date of acceptance: 18.05.2024

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shelf life of fruits during the postharvest period. Guava leaf extract is recognized as a natural preservative due to its antimicrobial, antioxidant, and antibacterial properties (Naseer *et al.*, 2018). The acidity of lemon effectively suppresses bacterial growth, contributing to the preservation of fruits and vegetables. Additionally, bamboo leaves and shoots provide a rich source of antioxidants, including phenolic compounds, as well as essential minerals such as selenium, copper, zinc, iron, and manganese (Nirmala, 2018). Inorganic coatings also play a crucial role in maintaining fruit quality. For instance, exogenous calcium stabilizes the cell wall and protects it from enzymatic breakdown (White and Broadley, 2003). Potassium permanganate, known for its ethylene-absorbing properties, is utilized to enhance storage duration. Moreover, silver nitrate ($AgNO_3$) treatments can effectively reduce postharvest losses and extend the shelf life of fruits. These interventions work by minimizing microbial contamination and preventing cellular disorganization. Despite these advancements, substantial postharvest losses persist, largely due to the high costs of sophisticated treatments and a general lack of awareness among producers. Many Indian farmers, who are primarily smallholders, find these methods financially prohibitive. Therefore, there is an urgent need to standardize alternative, low-cost solutions that are accessible, economically viable, and practical (Pandey *et al.*, 2010). The use of plant extracts, particularly guava leaf and lemon extract coatings, has gained global interest as they effectively retain quality under standard laboratory conditions while being readily available and cost-effective. Given these considerations, this study aims to address the existing research gap by developing eco-friendly and easily accessible methods for extending the shelf life of Rangpur lime, both for domestic use and long-distance transportation. Thus, this analysis serves as a comparative study to identify effective skin-coating emulsions that can preserve the quality of Rangpur lime fruits postharvest and prolong their shelf life.

MATERIALS AND METHODS

The present investigation was conducted in the Department of Fruit Science at the College of Horticulture and Forestry, Central Agricultural University (Imphal), Pasighat, Arunachal Pradesh, India. Fully matured Rangpur lime fruits were collected from a dedicated cultivation block within the college premises. The fruit samples were thoroughly washed and dried using tissue paper to remove any surface moisture prior to coating treatment. Mature Assam lemon fruits, intended for lemon extract preparation, were also sourced from the experimental lemon field located on campus. The chemicals used in this study, including potassium permanganate ($KMnO_4$) and calcium chloride ($CaCl_2$), were obtained from HIMEDIA Pvt. Ltd., while silver nitrate ($AgNO_3$) was procured from SRL Pvt. Ltd.

Treatment details

A total of nine treatments were employed in this study. The treatments included a non-treated control (T_1: No coating) and the following combinations: T_2 (Guava Leaf Extract (GLE) at 15% + Lemon Extract (LE) at 5%), T_3 (GLE at 30% + LE at 10%), T_4 (GLE at 45% + LE at 15%), T_5 ($KMnO_4$ at 4 g + $CaCl_2$ at 1%), T_6 ($KMnO_4$ at 8 g + $CaCl_2$ at 2%), T_7 ($AgNO_3$ at 2%), T_8 ($AgNO_3$ at 4%), and T_9 (Bamboo leaves). Observations on the lime fruits subjected to various treatments were recorded in accordance with established guidelines for each parameter. Assessments were made at four-day intervals, continuing over a total storage period of 16 days.

Preparation and application of botanical extract and chemical solutions

Guava leaf powder was purchased from the market and combined with 1000 cc of distilled water. Extracts of 15%, 30%, and 45% concentrations were prepared by dissolving 150 g, 300 g, and 450 g of the raw guava leaf powder in a 500 ml beaker, adding distilled water incrementally until a final volume of 200 ml was reached for each concentration. Lemon extract preparations (5%, 10%, and 15%) followed a similar procedure. The resulting guava leaf extract (GLE) and lemon extract (LE) were transferred to beakers sealed with aluminum foil, filtered using Whatman's filter paper No. 2, and refrigerated for future use. On a sterile surface, the fruit samples were divided into four groups, with three replications assigned to each treatment. Potassium permanganate ($KMnO_4$) was prepared in sachets at concentrations of 4 g and 8 g, while solutions of calcium chloride ($CaCl_2$) at 1% and 2%, and silver nitrate ($AgNO_3$) at 2% and 4% were also prepared for fruit coating. The GLE, LE, and chemical solutions were sprayed onto the cleaned fruit surfaces. The fruits were then systematically arranged in naturally ventilated Corrugated Fiber Board (CFB) boxes. For treatment T_9, a double layer of fresh bamboo leaves was used to cover the fruits on both sides, and these were also placed in naturally ventilated CFB boxes.

Biochemical estimation of fruits

a. Total soluble solids

The total soluble solids (TSS) of the fruit juice were measured using a hand refractometer (ERMA, Tokyo, Japan). A drop of lime juice was placed on the refractometer's prism, and the instrument provided the TSS readings, expressed in degrees Brix (°Brix).

b. Titratable acidity

Rangpur lime juice (5 ml) was diluted with 20 ml of distilled water. A 5 ml aliquot of this diluted juice was then titrated against a 0.1 N NaOH solution, using phenolphthalein as an indicator. The endpoint was indicated by the appearance of a light pink colour. The percentage of titratable acidity was calculated using the following formula (AOAC, 2002):

$$\text{Acidity (\%)} = \frac{\text{Titre value x N of NaOH x Vol. made up x Eq.weight of acid}}{\text{Vol.of aliquot x Vol.of sample taken x 1000}} \times 100$$

c. Total sugars

The total sugars content was estimated using the Anthrone method as described by Hedge and Hofreiter (1962). The results were calculated using the following formula and expressed as a percentage (%):

$$\text{Amount of sugars present in 100mg of sample} = \frac{\text{mg of glucose}}{\text{Volume of the sample taken}} \times 100$$

d. Reducing sugars

Sugars were extracted by macerating 100 mg of the sample with 5 ml of 80% ethanol. The mixture was centrifuged at 3000 rpm for 5 minutes. Water was then added to dissolve the extracted sugars. An aliquot of 0.2 ml was taken and diluted to 2 ml with distilled water. Subsequently, 1 ml of alkaline copper tartrate reagent was added to each tube. The tubes were placed in boiling water for 10 minutes, then allowed to cool. After cooling, 1 ml of arsenomolybdic acid reagent was added to each tube, and the final volume was adjusted to 10 ml with distilled water. The contents were incubated at room temperature for 10 minutes. After the incubation period, the absorbance of each sample was measured against a blank solution using a UV-visible spectrophotometer at 620 nm. The concentration of reducing sugars in the sample was calculated from the slope of a standard curve for reducing sugars. The percentage of reducing sugars was calculated using the following formula:

Absorbance corresponds to 0.1 ml of test = X mg glucose

$$\text{10 ml contains} = \frac{x}{0.1} \text{ 10 mg of glucose}$$

$$= \text{\% of reducing sugar}$$

e. Non-reducing sugars

The non-reducing sugars content was determined by subtracting the reducing sugars content from the total sugars content. The values were expressed as a percentage (%):

Non reducing sugars content = (Total sugars - Reducing sugars) x 0.95

f. Vitamin C

As recommended by Jagota and Dani (1982), 2 g of the sample was combined with 6% metaphosphoric acid (MPA) and centrifuged at 5000 rpm for 10 minutes. The final volume was adjusted to 4 ml with distilled water. An aliquot of 0.1 ml was diluted to 1.2 ml with 3% MPA. Then, 0.4 cc of Folin-Ciocalteu reagent was added to each tube, and the mixture was thoroughly blended. The tubes were subsequently centrifuged for 10 minutes at 3000 rpm. After centrifugation, the supernatant was measured at 760 nm in a UV-visible spectrophotometer against a blank solution. The vitamin C concentration was calculated using the following formula:

$$\text{Vitamin C} \left(\frac{\text{mg}}{\text{100g}}\right) = \frac{\text{total volume of the sample x conc. of Vit C x 100 x 1}}{\text{Weight of the sample x amount of sample x 100}}$$

Physiological loss in weight (PLW)

The weight of five fruits per replication was recorded using an electronic weighing balance. The percentage of physiological weight loss (PLW) was calculated using the following formula (Singh *et al.*, 2022):

$$\text{PLW (\%)} = \frac{\text{Initial fresh weight of fruit-Weight of fruit after storage}}{\text{Initial fresh weight of fruit}} \times 100$$

External colour

The colour of Rangpur lime fruits was assessed using the citrus descriptor developed by the International Plant Genetic Resources Institute (IPGRI, 1999). This descriptor list serves as a globally recognized framework for documenting data on plant genetic resources, providing an international “language” for colour classification. The external colour of the fruits was recorded at various intervals and documented according to the IPGRI descriptor guidelines.

Statistical analysis

The experiment was conducted in triplicate using a Completely Randomized Design (CRD). The data were analyzed using the Duncan Multiple Range Test (DMRT) with WASP 2.0 software (Jangam and Thali, 2004). Significant differences between treatments were indicated by different letters, with a significance level set at $p \leq 0.05$.

RESULTS AND DISCUSSION

Fruit biochemical estimation

Total soluble solids (TSS)

One of the key metrics used to assess fruit quality is total soluble solids (TSS). Our results (Table 1) indicate

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that TSS content increased with extended storage time across all treatments, except for T_4 and the fruits placed in bamboo leaves. The maximum TSS was observed in untreated fruits (T_1), with values rising from 8.60 °Brix on the 4th day to 9.30 °Brix on the 16th day. On the other hand, the lowest TSS were recorded in T_4 fruits treated with guava leaf extract (GLE) at 45% and lemon extract (LE) at 15%, which showed TSS values of 6.30 °Brix on the 4th day and 7.60 °Brix on the 16th day. The data suggest that fruits treated with guava leaf and lemon extracts maintained a lower rate of TSS increase compared to the control, indicating better quality preservation. This slower increase in TSS can be attributed to reduced metabolic activity through respiration in treated fruits, as opposed to the higher metabolic rates observed in untreated fruits (Jholgiker and Reddy, 2007). Wills *et al.* (2007) noted that the acidic composition of lemon juice helps prevent physiological changes and delays the ripening process in treated fruits. They further explained that the acid serves as an energy reserve for the fruit, and as metabolic activities increase, this can lead to fruit deterioration. This deterioration may result from intensified aging processes that elevate respiration rates. Additionally, the decline in moisture content is likely due to water loss from transpiration and evaporation, as well as starch hydrolysis. The increase in TSS in control fruits can be attributed to the breakdown of complex polymers into simple sugars by hydrolytic enzymes during the ripening process (Paul *et al.*, 2024).

Titratable acidity

The acidity of lime fruits increased over a storage duration of up to 16 days. Fruits treated with T_3 (Guava Leaf Extract (GLE) at 30% and Lemon Extract (LE) at 10%) exhibited the highest acidity throughout the storage period, ranging from 0.79% to 0.85%. This was followed by T_6 ($KMnO_4$ at 8 g + $CaCl_2$ at 2%), which showed acidity levels from 0.71% to 0.81% at the 16-day mark (Table 1). The preservation of higher acidity in lime fruits can be attributed to reduced oxygen availability in the later stages of storage. This increase is likely due to organic acids involved in respiration that remain unoxidized (Bisen *et al.*, 2012). The phenolic compounds in guava leaves, along with the acidic composition of lemon juice, may play a significant role in reducing respiration and transpiration in fruits, thereby limiting the conversion of starch to sugars and maintaining acidity during storage. Additionally, the metabolic activities of microorganisms during storage can lead to a decrease in fruit pH, potentially converting sugar compounds into alcohols and acids (Tabikha *et al.*, 2010). Coating with guava leaf extract exhibits antioxidant and antimicrobial properties, resulting in a reduction of respiration rates, catabolic processes, and enzymatic activities. This ultimately delays fruit

Table 1. Influence of organic and inorganic coatings on Total Soluble Solids (TSS), Titratable Acidity and Vitamin C content in Rangpur lime fruits

Treatments	Total Soluble Solids (TSS) (°Brix)				Titratable Acidity (%)				Vitamin C (mg/100g)			
	4 DAT*	8 DAT	12 DAT	16 DAT	4 DAT	8 DAT	12 DAT	16 DAT	4 DAT	8 DAT	12 DAT	16 DAT
T_1	8.60^{a}±0.27	8.90^{a}±0.25	9.20^{a}±0.36	9.30^{a}±0.05	0.63^{c}±0.01	0.68^{de}±0.02	0.71^{cd}±0.02	0.70^{f}±0.02	18.90^{de}±0.18	20.78^{g}±0.56	24.02^{f}±0.82	31.63^{e}±0.68
T_2	7.40^{de}±0.02	7.57^{c}±0.19	8.00^{cd}±0.33	8.20^{c}±0.10	0.73^{b}±0.03	0.73^{c}±0.02	0.71^{cd}±0.02	0.77^{cd}±0.03	19.01^{cd}±0.65	22.09^{f}±0.45	31.70^{c}±1.00	38.75^{b}±1.04
T_3	7.17^{e}±0.16	8.00^{b}±0.04	8.20^{bc}±0.35	8.20^{c}±0.08	0.79^{a}±0.03	0.83^{a}±0.01	0.84^{a}±0.02	0.85^{a}±0.02	19.94^{c}±0.84	23.59^{cde}±0.29	28.89^{d}±1.19	36.90^{c}±1.53
T_4	6.30^{f}±0.19	6.90^{d}±0.12	7.21^{e}±0.29	7.60^{d}±0.27	0.63^{c}±0.01	0.69^{d}±0.02	0.72^{c}±0.02	0.75^{de}±0.03	20.92^{b}±0.71	26.43^{b}±0.21	33.97^{b}±1.22	37.09^{bc}±0.40
T_5	7.43^{de}±0.11	7.51^{c}±0.22	7.80^{cd}±0.08	8.10^{c}±0.09	0.65^{c}±0.02	0.74^{c}±0.01	0.77^{b}±0.01	0.80^{bc}±0.01	17.97e^{f}±0.58	23.92^{cd}±0.45	28.15^{de}±0.38	34.07^{d}±0.73
T_6	7.60^{cd}±0.29	7.90^{b}±0.14	7.93^{cd}±0.19	8.50^{b}±0.27	0.74^{b}±0.03	0.75^{bc}±0.03	0.79^{b}±0.03	0.81^{bc}±0.03	17.23^{f}±0.41	23.40^{de}±0.73	28.61^{d}±0.72	30.25^{e}±1.06
T_7	7.90^{bc}±0.34	8.07^{b}±0.17	8.50^{b}±0.20	8.60^{b}±0.06	0.63^{c}±0.01	0.78^{b}±0.03	0.80^{b}±0.01	0.82^{ab}±0.01	18.28d^{e}±0.21	24.27^{c}±0.56	28.69^{d}±0.20	33.38^{d}±0.18
T_8	6.50^{f}±0.26	7.50^{c}±0.01	7.70^{d}±0.13	8.20^{c}±0.07	0.65^{c}±0.02	0.71^{cd}±0.03	0.72^{c}±0.01	0.73^{ef}±0.02	18.77d^{e}±0.37	23.03^{e}±0.47	26.72^{e}±0.84	34.67^{d}±0.90
T_9	8.18^{b}±0.35	6.60^{d}±0.23	7.07^{e}±0.15	7.30^{e}±0.26	0.74^{b}±0.01	0.65^{e}±0.02	0.68^{d}±0.02	0.79^{bc}±0.02	22.95^{a}±0.70	28.11^{a}±0.25	35.66^{a}±0.86	46.79^{a}±1.43
SEm±	0.14	0.10	0.14	0.14	0.01	0.02	0.01	0.01	0.32	0.27	0.50	0.56
CD (p≤0.05)	0.41	0.29	0.43	0.28	0.03	0.04	0.03	0.03	0.98	0.82	1.49	1.68

*DAT: Days after treatment

T_1: No coating, T_2: Guava Leaf Extract (GLE) at 15% + Lemon Extract (LE) at 5%, T_3: GLE at 30% + LE at 10%, T_4: GLE at 45% + LE at 15%, T_5: $KMnO_4$ at 4 g + $CaCl_2$ at 1%, T_6: $KMnO_4$ at 8 g + $CaCl_2$ at 2%, T_7: $AgNO_3$ at 2%, T_8: $AgNO_3$ at 4%, T_9: Bamboo leaves ripening, which helps preserve fruit pH and titratable acidity (Alqahtani *et al.*, 2023a). The acidity retained in $CaCl_2$-coated fruits may be due to the chemical's role in delaying ripening, reducing decay losses, minimizing disease incidence, and prolonging shelf life (Gao *et al.*, 2020). Our findings support the results of Alqahtani *et al.* (2023b) and Kumar *et al.* (2021), who observed similar effects in *barhi* dates and bell peppers, respectively.

Vitamin C

Vitamin C plays a crucial role in human nutrition, serving as a potent antioxidant, enhancing immune function, and contributing to plant defense mechanisms. Fruits are the primary source of vitamin C (ascorbic acid) in the human diet. This study assessed the changes in vitamin C levels in Rangpur lime fruits during storage. Fruits wrapped in bamboo leaves exhibited the highest concentration of vitamin C, recorded at 22.95 mg/100 g on the 4th day, and continued to show the highest concentration at 46.79 mg/100 g after 16 days of storage (Table 1). All treatment groups, including the control, demonstrated an increase in vitamin C levels, rising from 18.90 mg/100 g to 31.63 mg/100 g between the 4th and 16th days of storage. The observed increase in vitamin C content may be attributed to the ongoing synthesis of L-ascorbic acid from its precursor, glucose-6-phosphate. The loss of vitamin C in fruits could be linked to the enzymatic degradation of ascorbic acid during ripening. Overripe fruits with damaged skin are particularly susceptible to rapid conversion of ascorbic acid to dehydroascorbic acid due to the activity of the enzyme ascorbinase (Chandra *et al.*, 2012). These findings are consistent with previous research on *Kagzi* lime fruits by Bisen and Pandey (2008) and Jadhao *et al.* (2008). Similarly, Gameel (2012) reported that ascorbic acid content was significantly higher in lemon fruits treated with jasmine oil or garlic extract. The fluctuations in ascorbic acid levels may also be influenced by metabolic changes and the increased acidity resulting from the application of guava leaf and lemon extracts, bamboo leaves, and other coating compounds.

Total sugars

Total sugars concentration in fruits is a key indicator for monitoring the ripening process and assessing shelf life. During ripening, the breakdown of starch reserves significantly influences sugar content. The graphical representation in Fig. 1 shows that the maximum concentration of total sugars in lime fruits was 2.04%, observed in T_9 on the 12th day, with similar findings in T_4 fruits. On the same day, treated fruits exhibited sugar content ranging from 1.47% to 2.04%, with T_6 showing the lowest levels. By the 16th day, the highest total sugars concentration was recorded in T_9 at 1.85%, while T_8 showed the lowest at 0.98%, compared to the other treated lime fruits. Throughout the 16-day storage period, fruits in T_9 consistently maintained the highest total sugars levels. In this experiment, total sugars increased until the 12th day of storage, after which it began to decline with further storage. Kaur and Singh (2020) similarly reported a gradual increase in total sugars content until the 14th day of storage, followed by a decrease after the 21st day in guava fruits. Comparable results were noted by Jodhani and Nataraj (2021), who suggested that coatings such as lemon peel extract and aloe gel may delay respiration rates, thereby slowing the production and utilization of metabolites and reducing the conversion of complex carbohydrates to sugars.

Reducing and non-reducing sugars

In the current study, the concentrations of both reducing and non-reducing sugars in Rangpur lime fruits increased with storage time until the 12th day. Coated lime fruits exhibited a more rapid increase in reducing sugars levels compared to control fruits, which did not show similar growth patterns. The rapid rise in reducing sugars content from the 4th to the 12th day of storage (Fig. 2) ranged from 0.25% to 0.32% in control fruits. On the 12th day, the highest concentration was recorded in T_4 at 0.38%, followed closely by T_9 at 0.37%. In contrast, the lowest concentration (0.29%) was observed in fruits treated with guava leaf and lemon extract. The reducing sugars content in treated fruits continued to increase until the 12th day but began to decline towards the end

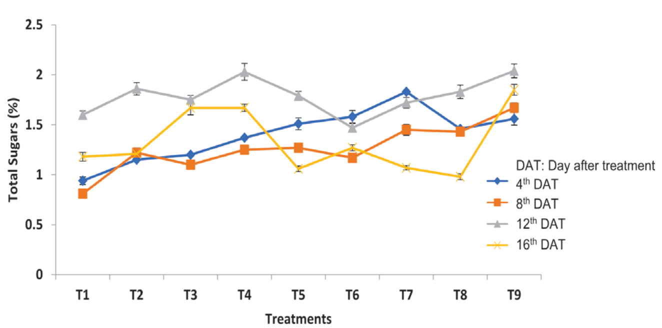

Fig. 1. Influence of organic and inorganic coatings on total sugars content in Rangpur lime fruits

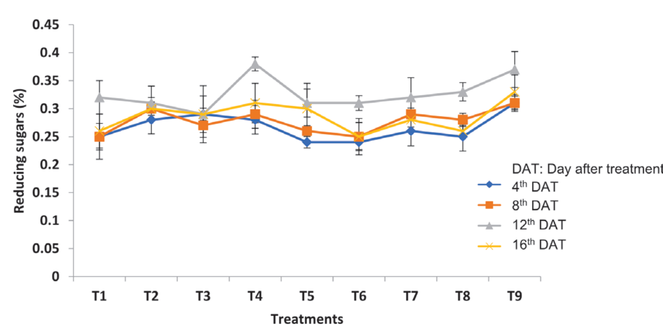

Fig. 2. Influence of organic and inorganic coatings on reducing sugars content in Rangpur lime fruits

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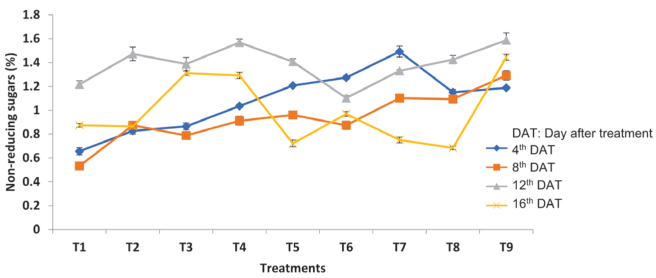

Fig. 3. Influence of organic and inorganic coatings on non-reducing sugars content in Rangpur lime fruits

of the storage period. By the 16th day, the maximum reducing sugars content was noted in T_9 at 0.33%, followed by T_4 at 0.31%.

During the storage of Rangpur lime fruits, non-reducing sugars levels (Fig. 3) also increased in both coated and control fruits. On the 4th day of storage, untreated fruits showed a non-reducing sugars content of 0.66%. In comparison to other chemical characteristics in treated lime fruits, the increase in non-reducing sugars was notably slower and less consistent. It declined on the 8th day, increased again on the 12th day, and then decreased toward the end of the storage period. On the 8th day, the lowest non-reducing sugars content was recorded in T_1 at 0.53%. On the other hand, the highest level was observed in T_9 at 1.59% on the 12th day. The observed increases in both reducing and non-reducing sugars during storage can be attributed to the conversion of starch into sugars, as confirmed by Maqbool *et al.* (2011). Furthermore, the effectiveness of guava leaf extract and lemon extract in enhancing reducing sugars content has been documented in studies on banana by Tabassum *et al.* (2018).

Physiological loss in weight (PLW)

Weight loss refers to the loss of water and essential nutrients from fresh produce after harvest, negatively impacting the quality and marketability of fruits and vegetables. Typically, the percentage of physiological weight loss (PLW) in fruits increases with extended storage duration; initially, this increase is gradual, but it accelerates over time (Table 2). This observation aligns with findings by Poudel *et al.* (2021) regarding Assam lemon fruits. In the case of Rangpur lime, post-harvest treatments utilizing guava leaf extract and lemon extract significantly reduced physiological weight loss. Specifically, fruits treated with T_4 (guava leaf extract at 45% and lemon extract at 15%) exhibited the lowest PLW, ranging from 5.72% to 11.93% during the storage period (Table 2). In contrast, control fruits experienced the highest weight loss, ranging from 13.43% to 21.93% over 16 days. The weight loss in fresh fruit during storage is primarily attributed to respiration and transpiration processes. Transpiration occurs through lenticels in the fruit's pericarp, driven by the vapour pressure differential between the internal fruit environment and the external atmosphere. According to Cosme Silva *et al.* (2017), coating techniques create a barrier on the fruit surface that minimizes moisture loss, thereby preserving the quality and appearance of the fruits. Our findings indicate that coatings of guava and lemon extracts effectively reduced the rate of water loss from Rangpur limes during storage. Given that water is crucial for maintaining fruit quality, shelf life, and market value, minimizing water loss during storage is essential

Table 2. Influence of organic and inorganic coatings on physiological loss in weight and external colour in Rangpur lime fruits

Treatments	Physiological loss in weight (%)				External colour			
	4 DAT	8 DAT	12 DAT	16 DAT	4 DAT	8 DAT	12 DAT	16 DAT
T_1	$13.43^{a}\pm0.24$	$16.68^{a}\pm0.21$	$19.33^{a}\pm0.46$	$21.93^{a}\pm0.89$	LY+LO**	LY+Y	Y+DY	DY+LO
T_2	$6.10^{h}\pm0.07$	$7.75^{g}\pm0.04$	$12.40^{d}\pm0.33$	$14.27^{e}\pm0.23$	Y+LO	DY+O	Y+LO	DO+LY
T_3	$6.40^{g}\pm0.15$	$9.07^{f}\pm0.36$	$11.55^{e}\pm0.35$	$16.40^{c}\pm0.32$	LY+LO	DY+LY	DY+LO	O+Y
T_4	$5.72^{i}\pm0.150$	$8.02^{g}\pm0.195$	$10.40^{f}\pm0.216$	$11.93^{f}\pm0.32$	LY+DO	DY+O	DY+O	DO+Y
T_5	$7.49^{e}\pm0.08$	$8.03^{g}\pm0.09$	$11.10^{e}\pm0.17$	$15.20^{d}\pm0.37$	DY+LO	LO+LY	Y+LO	DY+LO
T_6	$10.92^{c}\pm0.08$	$12.48^{c}\pm0.20$	$15.33^{c}\pm0.20$	$18.17^{b}\pm0.672$	O+DY	O+LY	DO+Y	DO+Y
T_7	$10.46^{d}\pm0.057$	$11.40^{d}\pm0.319$	$15.00^{c}\pm0.41$	$18.53^{b}\pm0.301$	LY+Y	Y+LO	O+Y	PO+LY
T_8	$12.58^{b}\pm0.11$	$13.45^{b}\pm0.44$	$16.22^{b}\pm1.72$	$18.73^{b}\pm0.506$	LY+LO	DY+O	O+DY	DY+O
T_9	$6.89^{f}\pm0.21$	$9.60^{e}\pm0.02$	$12.92^{d}\pm0.54$	$15.27^{d}\pm0.46$	DY+LO	LO+O	O+DY	DO+O
SEm±	0.08	0.14	0.38	0.28	-			
C.D ($p\leq0.05$)	0.24	0.43	0.58	0.85				

*DAT: Days after treatment

T_1: No coating, T_2: Guava Leaf Extract (GLE) at 15% + Lemon Extract (LE) at 5%, T_3: GLE at 30% + LE at 10%, T_4: GLE at 45% + LE at 15%, T_5: $KMnO_4$ at 4 g + $CaCl_2$ at 1%, T_6: $KMnO_4$ at 8 g + $CaCl_2$ at 2%, T_7: $AgNO_3$ at 2%, T_8: $AgNO_3$ at 4%, T_9: Bamboo leaves

**Y: Yellow, O: Orange, LY: Light yellow, LO: Light orange, DY: Dark yellow, DO: Dark orange, PO: Pink orange

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for optimal fruit preservation.

External fruit colour

Fruits coated with a combination of guava leaf extract (GLE 45%) and lemon extract (LE 15%), as well as those treated with $KMnO_4$ (4 and 8 g), $CaCl_2$ (1 and 2%), and $AgNO_3$ (2 and 4%), were able to maintain their natural orange colour for up to 16 days of storage, which is favourable for consumer perception of marketable products (Table 2). This retention of colour can be attributed to delayed senescence, reduced metabolic and enzymatic activity, and diminished breakdown of colour pigments (carotenoids), which collectively slow down colour changes. However, by the end of the 16-day storage period, fruits treated with $AgNO_3$ exhibited a brownish exterior colour. This discoloration may result from skin damage caused by the preservative chemical, which can lead to tissue weakening and alterations in colour pigment, ultimately affecting the fruit's outer appearance. Similar observations were reported by Dalal *et al.* (1987), who found that mustard oil emulsion treatment in *baramasi* lemons resulted in significant physiological weight loss, decreased firmness, and noticeable variations in fruit shape and colour.

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CONCLUSION

In conclusion, the present study demonstrated that both fresh bamboo leaves and the coating of guava leaf extract (GLE 45%) combined with lemon extract (LE 15%) are effective in maintaining the quality and extending the storage life of Rangpur lime fruits over a 16-day period. These treatments not only preserved key quality attributes, such as total soluble solids, acidity, and vitamin C content, but also significantly reduced physiological weight loss and maintained the fruit's natural colour. Given the widespread availability of bamboo leaves in the Northeastern regions of India, this treatment presents a practical solution that farmers, vendors, and transporters can readily adopt for long-distance transportation and storage of Rangpur limes. The findings highlight the potential for these eco-friendly approaches to be further explored by researchers for other perishable commodities, thereby contributing to enhanced post-harvest management practices in the agricultural sector.

Authors contribution: Conceptualization and designing of the research work (BVS; PKN); Execution of lab experiments and data collection (BVS, LS); Analysis of data and interpretation (BVS, PKN, SS); Preparation of manuscript (BVS, PKN, SS, WL).

Conflicts of interest: Authors declare that they have no conflicts of interest.

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