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Valorization potential of hill lemon (*Citrus pseudolimon* Tan.) peel into functional candies through osmotic dehydration and sweetener selection

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Abstract

This study investigates the valorization of hill lemon peel, an underutilized citrus by-product, through the development of functional peel-based candies employing four sweetening systems (sucrose, jaggery, honey, and sorbitol) in conjunction with two osmotic dehydration approaches (slow and fast). The fresh peel exhibited pronounced acidity (pH 2.30), considerable ascorbic acid content (39.84 mg/100 g), pectin (1.70%), tannins (30.62%), and high antioxidant activity (89.46%), collectively indicating significant nutraceutical potential. Concurrently, the influence of osmotic techniques and sweetener type on product quality was systematically evaluated. Candies produced via slow osmotic treatment with jaggery and honey demonstrated superior retention of bioactive constituents, enhanced antioxidant activity, and improved sensory acceptability, whereas fast osmotic dehydration offered the advantage of reduced processing duration. Additionally, Fourier Transform Infrared (FTIR) spectroscopy confirmed improved structural integrity of functional groups in samples processed under slow osmosis, particularly those formulated with natural sweeteners such as honey. Storage stability assessment further revealed that glass containers effectively maintained physico-chemical characteristics, while aluminium pouches exhibited better preservation of sensory quality over a 90-day storage period. Overall, the findings demonstrate the potential of hill lemon peel as a functional ingredient for confectionery applications and highlight the efficacy of slow osmotic dehydration combined with natural sweeteners in developing nutritionally enriched, shelf-stable value-added products.

Keywords: Citrus peel, functional candies, hill lemon, natural sweeteners, osmotic dehydration

Introduction

Citrus fruits are among the most widely cultivated fruit crops globally, valued for their high nutritional content, functional bioactives, and versatile processing potential. The hill lemon is a lesser-known and underutilized citrus species predominantly found in the Himalayan and sub-Himalayan regions of India, especially in states such as Himachal Pradesh, Uttarakhand, and parts of Northeast India. Despite its rich nutritional and functional properties, it remains largely untapped for commercial processing and value addition. While its juice is consumed for its therapeutic and organoleptic qualities, the peel, often discarded as waste, constitutes a rich source of polyphenols, flavonoids, vitamins, minerals, dietary fibers, and essential oils (Rafiq *et al.*, 2018) [22]. Citrus peel accounts for nearly 50% of the total fruit mass after processing, contributing significantly to agro-industrial waste (Sharma *et al.*, 2022) [26]. Improper disposal of this biomass may lead to environmental and economic concerns (Rafiq *et al.*, 2018) [22]. Therefore, valorization of citrus by-products, particularly peel, has gained importance as a sustainable approach for the development of value-added products and efficient waste management (Andrade *et al.*, 2023) [1].

In recent years, considerable attention has been directed towards the utilization of citrus residues, including peel, for the extraction of bioactive compounds and the development of functional food ingredients. Citrus peel has been explored for various applications such as antioxidant extraction, dietary fiber enrichment in foods, development of biodegradable packaging materials, and nutraceutical formulations (Kaur *et al.*, 2025) [14, 15]. However, the use of citrus peel in confectionery products, particularly candies, has received relatively limited scientific attention. Candies offer a promising matrix for incorporating nutritionally

rich ingredients due to their extended shelf life, high consumer acceptability, and flexible texture and flavor characteristics. Osmotic dehydration is widely recognized as an effective technique for fruit preservation and candy preparation. The process involves partial removal of water from fruit tissues by immersion in hypertonic solutions, which simultaneously improves sensory attributes and extends shelf life (Kaur *et al.*, 2025) ^[14, 15]. The type and rate of osmotic treatment, including slow dehydration at ambient temperatures or fast dehydration at elevated temperatures, significantly influence the texture, flavor retention, and preservation of bioactive compounds in the final product (Yadav *et al.*, 2014) ^[36]. Conventionally, sucrose syrup is used as the primary osmotic medium in the candying process. However, increasing health concerns related to excessive sugar consumption, such as obesity, type-2 diabetes, and cardiovascular disorders, have encouraged the exploration of alternative sweeteners (Tandel, 2011) ^[31]. Natural sweeteners such as jaggery and honey are gaining popularity as healthier substitutes for refined sugar due to their additional nutritional components and antioxidant properties. These sweeteners can improve both the nutritional value and functional attributes of confectionery products (Mohanta *et al.*, 2021) ^[20]. In addition, sorbitol, a sugar alcohol widely used in low-calorie foods, is considered a functional sweetener due to its low glycemic index and non-cariogenic characteristics, making it suitable for diabetic and calorie-conscious consumers (Grembecka, 2015) ^[9]. Previous studies have also demonstrated the incorporation of citrus peel derivatives in different food systems and packaging materials, highlighting their functional and technological potential. However, systematic investigations focusing on the development of hill lemon peel-based candies using different sweeteners combined with varied osmotic dehydration techniques remain scarce. Therefore, the present study aims to explore the sustainable utilization of hill lemon peel for value addition. This study evaluates the effects of different osmotic syrups sugar, jaggery, honey, and sorbitol under both slow and fast osmotic dehydration techniques on the physical, chemical, bioactive, and molecular properties of hill lemon peel candies. The outcomes of this research may contribute to the efficient utilization of hill lemon processing residues while providing a potential alternative to conventional confectionery products.

Material and methods

Materials

Hill lemon fruits were harvested in November from the experimental farm of the Department of Fruit Science, College of Horticulture and Forestry, YSPUHF, Neri, Hamirpur, Himachal Pradesh, India (31.68° N, 76.52° E; 700 m amsl). Sweeteners such as Sucrose (Fortune), honey (Patanjali), jaggery (Good life) and sorbitol (Bioven) were used for the preparation of candy and procured from local market Hamirpur.

Preparation of Candy

Washed hill lemon peel cut into uniformly sliced with cutter and pricked using fork. The slices were blanched in a 2% alum solution for 5 minutes to enhance texture and microbial stability, followed by thorough rinsing with tap water to remove any residual alum. The pretreated slices were then subjected to osmotic dehydration using four

different hypertonic syrup solutions sugar syrup, jaggery syrup, honey syrup, and sorbitol syrup each containing 1% citric acid.

Two osmotic dehydration methods were employed. In the first method, the slices were initially steeped in syrup of 50°Brix for 24 hours, followed by an increase to 60°Brix for the next two days, and finally maintained at 70°Brix for seven additional days (slow method). In the second method, slices were steeped in syrup at 70°Brix and 50 °C for 6 hours using a water bath (fast method). In both methods, after the osmotic treatment, the syrups were drained, and the slices were rinsed to remove excess syrup before being subjected to air drying. The prepared hill lemon candies were packed in aluminium packaging and evaluated for their physico-chemical and sensory characteristics.

Physico-Chemical Analysis

The hill lemon peel and candies prepared from different sweeteners and osmotic dehydration methods were analyzed for different physico-chemical parameters. The Total Soluble Solids (TSS) analysed using a digital refractometer (ERMA, Model: MASTER-S10a) and expressed in °Brix, pH was determined using a pH meter (Labman LMPH-10), Titratable acidity, reducing, non-reducing and total sugars, pectin, Tannins, Non-Enzymatic Browning (NEB), ascorbic acid were quantified as per standard method given in Ranganna, (2020) ^[23]. Total Phenolic Content (TPC) was measured using the Folin-Ciocalteu method (Rizvi *et al.*, 2023) ^[25], and antioxidant activity was assessed via DPPH assay (Kedare & Singh, 2011) ^[16], expressed as mg GAE/100 g and % DPPH inhibition. Limonin and naringin contents were determined spectrophotometrically after chloroform and methanolic extraction, respectively, with absorbance read at 503 nm and 420 nm (Brekse and Ibarra, 2007; Huang *et al.*, 2018) ^[4, 10]. Candies were also analysed for weight reduction, solid gain (SG), water loss (WL) using formula cited in Ranganna, (2020) ^[23] and time taken to dry given tray load was calculated by recording the time (h).

Sensory Analysis

The sensory quality of peel candy was evaluated using a 9-point hedonic scale, following the standard procedures outlined by Ranganna (2020) ^[23]. In this scale, 1 indicated dislike extremely and 9 indicated like extremely. A total of 10 trained panellists from the department of Food Science and Technology were, participated in the evaluation. Sensory evaluations were conducted in triplicate on different days. The mean scores from three replications were used for statistical analysis.

Fourier-Transform Infrared (FT-IR) Spectroscopy

All the prepared candies were also characterized using Fourier-Transform Infrared (FTIR) spectroscopy (Agilent Cary 630 FTIR) for the determination of various functional groups, structural changes, and possible interactions between sweeteners and osmosis methods. The analysis was performed in the range of 4000-650cm⁻¹ with a total number of 140 scans per sample (Smith, 2011) ^[27].

Storage Study

The experiment was conducted using a factorial Completely Randomized Design (CRD). Candies prepared using the optimized sweetener and osmotic dehydration method were packaged in Aluminium Laminated pouches (AL) and high-

density polyethylene (HDPE) pouches and stored for three intervals (0, 45, and 90 days) with three replications. The juice samples were filled into sterilized glass bottles and stored at ambient temperature (26-32 °C). Physico-chemical and sensory analyses were carried out at periodic intervals during storage.

Statistical Analysis

All experiments were conducted in triplicate ($n = 3$), and the results are expressed as mean $\pm$ standard deviation. Statistical analysis was performed using one-way Analysis of Variance (ANOVA) to assess differences among standardization techniques, while two-way ANOVA was applied to evaluate the effects of storage conditions and storage period. Data were analyzed using OPSAT software, and differences were considered statistically significant at $p \leq 0.05$ (Varalakshmi, 2025)^[34].

Results and Discussion

Chemical Characterization of Hill Lemon Peel

The chemical characteristics of hill lemon peel are presented in Table 1. The peel exhibited a Total Soluble Solids (TSS) content of 7.98 ± 0.07 °Brix, indicating a moderate concentration of soluble sugars, organic acids, and other soluble constituents. The pH of the peel was found to be highly acidic (2.30 ± 0.05), which is typical for citrus fruits and contributes to their characteristic sour taste and preservation stability. The titratable acidity was $0.56 \pm 0.02\%$, mainly attributed to the presence of citric acid, which dominates the organic acid composition of citrus fruits and plays a significant role in determining flavor and fruit quality (Thakur *et al.*, 2025)^[32].

The reducing sugar and total sugar contents were $4.02 \pm 0.04\%$ and $6.19 \pm 0.02\%$, respectively, indicating that reducing sugars constitute a considerable proportion of the total sugars present in the peel. These moderate sugar levels contribute to the overall palatability of the fruit and help balance its natural acidity (Zayse *et al.*, 2022)^[37]. The pectin content was relatively high ($1.70 \pm 0.08\%$), suggesting the potential of hill lemon peel as a valuable natural source of pectin for food processing applications, including the formulation of gelling agents, stabilizers, and functional food products. Non-Enzymatic Browning (NEB), expressed as an absorbance value of 0.31 ± 0.01 at OD₄₄₀ nm, indicated a relatively low degree of browning reactions. This may be associated with the high acidity and comparatively lower reducing sugar content of the peel, both of which can influence Maillard reactions and other non-enzymatic browning processes during processing and storage. The ascorbic acid content was found to be appreciable (39.84 ± 0.09 mg/100 g), confirming the strong antioxidant potential of hill lemon peel. Ascorbic acid plays a vital role in enhancing the nutritional quality and oxidative stability of foods by functioning as a natural antioxidant and free radical scavenger (Lambani *et al.*, 2018; Thakur *et al.*, 2025)^[18, 32].

The tannin content was notably high ($30.62 \pm 0.05\%$), which may contribute to the astringent taste of the peel as well as its antioxidant properties. High tannin concentrations have also been associated with antimicrobial activity and several health-promoting effects in food systems (Ali *et al.*). The total phenolic content, expressed as gallic acid equivalent, was 5.28 ± 0.09 mg GAE/100 g, indicating the presence of significant bioactive compounds that contribute to the

antioxidant potential of citrus peel. Furthermore, the peel contained notable concentrations of limonin (11.54 ± 0.34 mg/100 g) and naringin (32.81 ± 0.32 mg/100 g). Limonin, a prominent citrus monoterpene compound, contributes to the characteristic citrus aroma and has been reported to exhibit several biological activities, including antimicrobial and anti-inflammatory properties. Naringin, a major citrus flavonoid, is responsible for the bitter taste of citrus peel and has been widely recognized for its antioxidant, anti-inflammatory, and cholesterol-lowering effects. The overall antioxidant activity of hill lemon peel was found to be substantially high ($89.46 \pm 0.84\%$), which may be attributed to the synergistic effects of various bioactive constituents such as ascorbic acid, phenolic compounds, tannins, and flavonoids present in the peel matrix. This strong antioxidant capacity highlights the potential of hill lemon peel as a promising natural source of antioxidants for use in functional foods and nutraceutical formulations (Attri and Manini 1996; Badiyala *et al.*, 2004; Thakur and Kumari 2022)^[2, 3, 17, 33].

Effect of osmotic dehydration methods and sweeteners on quality attributes of hill lemon peel candy

Physico-Chemical Parameters

The results clearly demonstrate that both osmotic dehydration technique and sweetener type significantly influenced the physicochemical quality of hill lemon peel candy, primarily through their effects on mass transfer phenomena. Slow osmotic dehydration consistently promoted higher water loss, solid gain and overall weight reduction, which can be attributed to prolonged exposure time allowing greater diffusion of moisture and solutes across cellular membranes. This aligns with the fundamental principles of osmotic dehydration, where time-dependent concentration gradients govern mass transfer efficiency (Rastogi *et al.*, 2002)^[24].

Among sweeteners, honey exhibited superior performance in terms of solid gain and total soluble solids, likely due to its high content of low-molecular-weight sugars such as glucose and fructose. These sugars enhance osmotic pressure and facilitate deeper solute penetration into plant tissues. In contrast, sorbitol showed comparatively lower efficiency, reflecting its different physicochemical behavior as a sugar alcohol (Liu *et al.*, 2025)^[19].

Although fast osmotic dehydration reduced processing time considerably, it resulted in slightly lower moisture removal and reduced retention of key nutrients. The rapid dehydration process likely limited sufficient equilibration between the osmotic medium and cellular fluids, thereby restricting mass transfer. Conversely, slow osmotic treatment, despite requiring longer drying periods, preserved structural integrity and improved candy yield, suggesting reduced cellular damage during gradual dehydration (Giannakourou *et al.*, 2020; Tan *et al.*, 2025)^[8, 30].

Changes in chemical attributes such as TSS, acidity and sugars further highlight the role of sweetener composition. Higher sugar and TSS levels in honey and jaggery-treated samples reflect their inherent composition, while slight increases in pH under fast osmotic conditions may be due to leaching of organic acids into the osmotic medium. Non-enzymatic browning was more pronounced in fast osmotic treatments, indicating that rapid moisture removal and increased concentration of reactants may accelerate Maillard reactions. This effect was particularly evident in jaggery-

based samples, which are rich in reducing sugars and reactive compounds (Yadav *et al.*, 2014; Kaur *et al.*, 2025) [36].

A key observation of this study is the superior retention [14, 15] of bioactive compounds under slow osmotic dehydration. Higher levels of ascorbic acid, phenolics and antioxidant activity suggest that gradual moisture removal minimizes oxidative and thermal degradation. Additionally, the use of natural sweeteners such as jaggery and honey further enhanced antioxidant properties due to their intrinsic bioactive constituents.

Sensory Attributes

Products obtained through slow osmotic dehydration consistently achieved higher scores for colour, texture and overall acceptability, indicating that gradual dehydration better preserves product quality. Improved colour retention under slow osmotic conditions suggests reduced non-enzymatic browning and better preservation of natural pigments. In contrast, slightly lower colour scores in fast osmotic treatments may be associated with rapid concentration of sugars, promoting browning reactions. Texture differences further highlight the importance of dehydration kinetics. Slow osmotic treatment resulted in a more desirable chewy texture, likely due to uniform solute infusion and better maintenance of cellular structure. Rapid dehydration, on the other hand, may cause surface hardening and uneven moisture distribution, negatively affecting texture. Sweetener type played a decisive role in taste perception. Jaggery and honey-based samples were preferred due to their complex flavour profiles, whereas sorbitol-treated samples were less acceptable, possibly due to their lower sweetness intensity and lack of characteristic flavour compounds (Giannakourou *et al.*, 2020; Freitas *et al.*, 2021; Tan *et al.*, 2025) [7, 8, 30].

Effect on Molecular Characterization (FTIR)

Fourier Transform Infrared (FTIR) spectroscopy provided insight into the molecular interactions and structural stability of hill lemon peel candy as influenced by osmotic dehydration methods and sweetener type. The spectra of all samples exhibited characteristic bands corresponding to major functional groups present in citrus peel, confirming that processing did not fundamentally alter the chemical composition but rather affected intermolecular interactions. A broad absorption band in the region of 3200-3400 cm^{-1} , attributed to O-H stretching vibrations, was prominent in all samples, indicating the presence of hydroxyl groups associated with carbohydrates, phenolics and residual moisture. Slightly higher intensity observed in slow osmotic treatments suggests improved retention of hydrophilic compounds and stronger hydrogen bonding interactions. This indicates that gradual dehydration better preserves moisture-associated functional groups and bioactive constituents (Rafiq *et al.*, 2018; Yadav *et al.*, 2014) [22, 36]. The peaks observed at 2920-2850 cm^{-1} correspond to C-H stretching vibrations of aliphatic groups, confirming the dominance of carbohydrate structures in the candy matrix. Variations in peak intensity among treatments reflect differences in sugar incorporation during osmotic processing. Higher intensities in sugar and jaggery-based samples suggest greater solute uptake, supporting the physicochemical findings of increased solid gain (Freitas *et al.*, 2021) [7].

The presence of absorption bands in the region of 1700-1600 cm^{-1} , associated with C=O stretching of carboxyl groups, indicates the retention of organic acids and pectin structures inherent to citrus peel. Minimal variation across treatments suggests that osmotic dehydration does not significantly modify these core components, reinforcing the view that the process is largely physical rather than chemical in nature (Chandel *et al.*, 2023) [5].

The carbohydrate fingerprint region (1200-1000 cm^{-1}) showed strong absorption in all samples, confirming the presence of polysaccharides and glycosidic linkages. More intense peaks in sucrose and jaggery treatments indicate enhanced incorporation of carbohydrate molecules into the peel matrix, whereas lower intensity in sorbitol-treated samples highlights its limited interaction with plant polysaccharides due to its sugar alcohol structure (Kaur *et al.*, 2025) [14, 15].

Importantly, differences between slow and fast osmotic dehydration were reflected mainly in peak intensity rather than the emergence of new functional groups. Slow osmotic treatments produced sharper and more defined peaks, suggesting more uniform solute diffusion and better structural organization within the tissue matrix. In contrast, fast osmotic dehydration may lead to less homogeneous distribution of solutes, affecting molecular interactions at the microstructural level. The interpretation of the functional group was done according to Stuart (2021) [28]. The enhanced peak definition and intensity observed in jaggery candy with slow osmotic treatments support the conclusion that gradual processing promotes better molecular stability and preservation of functional components. These findings complement the physicochemical and sensory results, confirming that improved product quality is closely linked to more stable and well-integrated molecular structures.

Effect of Packaging Materials and Storage Duration on Physico-Chemical Quality

The storage stability of jaggery-based hill lemon peel candy was markedly influenced by packaging material due to differences in moisture and oxygen barrier properties. Changes observed during storage primarily reflect ongoing physicochemical and oxidative processes within the product matrix, which are regulated by the interaction between packaging characteristics and environmental conditions.

A gradual decrease in moisture content across all packaging systems indicates continuous moisture migration driven by differences in water activity between the product and surrounding environment. Glass jars showed the lowest moisture levels, confirming their superior moisture barrier capacity. This can be attributed to the non-porous and impermeable nature of glass, which limits water vapor transmission compared to polymeric materials like HDPE (Sushila *et al.*, 2025) [29]. The corresponding increase in total solids and TSS further supports this mechanism, as moisture loss concentrates soluble constituents a phenomenon widely reported in stored fruit products (Jia *et al.*, 2024) [12].

The slight decline in titratable acidity and increase in pH suggest gradual degradation or interaction of organic acids during storage. These changes were less pronounced in glass containers, likely due to reduced oxygen ingress, which slows oxidative reactions responsible for acid breakdown. This highlights the importance of oxygen permeability in maintaining chemical stability, as also observed in citrus-based products (Kaur *et al.*, 2013) [13].

The increase in total and reducing sugars during storage can be explained by hydrolysis of sucrose and other complex carbohydrates into simpler sugars. This reaction is facilitated by residual moisture and acidic conditions within the product matrix, indicating that storage-induced transformations continue even in dehydrated systems (Jia *et al.*, 2024) ^[12].

Non-enzymatic browning increased significantly in all treatments, with higher values in glass-packaged samples. While glass effectively restricts moisture transfer, its transparency permits light exposure, which can accelerate Maillard reactions and caramelization. This demonstrates that protection against one deterioration factor (moisture) may simultaneously enhance another (light-induced browning), emphasizing the need for balanced packaging selection (Pham *et al.*, 2020) ^[21].

In contrast, degradation of bioactive compounds such as ascorbic acid, phenolics and antioxidant activity was more strongly influenced by oxygen and light exposure than by moisture changes. Aluminium pouches showed better retention of these compounds due to their excellent barrier properties against both oxygen and light. This reduced oxidative stress within the product, thereby slowing nutrient degradation, a trend consistent with earlier findings in dehydrated fruit systems (Del *et al.*, 2004; Yadav *et al.*, 2014) ^[6, 36].

Sensory Deterioration Patterns during Storage

Sensory quality of hill lemon peel candy declined during storage due to physicochemical and oxidative changes influenced by packaging properties. The extent of deterioration varied among packaging systems, emphasizing

the importance of barrier characteristics in maintaining product acceptability. Colour degradation was more pronounced in glass jars, whereas aluminium pouches showed better colour retention. This is mainly due to light-induced pigment degradation and increased non-enzymatic browning in transparent packaging, while aluminium effectively blocks light and slows these reactions. Similar observations were reported by Im *et al.*, (2024) ^[11], who noted that citrus peel-based candies are highly susceptible to colour changes due to oxidation and browning reactions during storage. Texture showed a moderate decline across treatments, likely due to moisture redistribution and sugar crystallization. Aluminium pouches maintained better texture, indicating that controlled moisture transfer helps preserve structural integrity and prevents excessive hardening. Comparable results were reported in orange peel candy by Kumar *et al.*, (2022) ^[17] where storage-induced hardening was linked to moisture loss and sugar recrystallization. Taste deterioration was associated with oxidation of flavour compounds and degradation of organic acids. Aluminium packaging again performed better, as its low oxygen permeability helps retain volatile flavour components. Overall acceptability decreased gradually but remained within acceptable limits. Aluminium pouches recorded the highest scores due to better retention of colour, texture and flavour, whereas glass packaging showed lower acceptability due to combined effects of light and oxygen exposure. This aligns with findings from Xiong *et al.*, (2025) ^[35], who emphasized that oxygen exposure significantly affects flavour stability and functional quality in citrus-based confectionery systems.

Table 1: Chemical characteristics of hill lemon (*Citrus pseudolimon* Tan) peel

Sr. No.	Parameters	Peel Mean $\pm$ SD*
1.	TSS ($^{\circ}$ B)	7.98 $\pm$ 0.07
2.	pH	2.30 $\pm$ 0.05
3.	Titrateable acidity (%)	0.56 $\pm$ 0.02
4.	Reducing sugar (%)	4.02 $\pm$ 0.04
5.	Total sugar (%)	6.19 $\pm$ 0.02
6.	Pectin (%)	1.70 $\pm$ 0.08
7.	Non-enzymatic browning (OD _{440nm})	0.31 $\pm$ 0.01
8.	Ascorbic acid (mg/100g)	39.84 $\pm$ 0.09
9.	Tannin (%)	30.62 $\pm$ 0.05
10.	Phenols (mg GAE/100g)	5.28 $\pm$ 0.09
11.	Limonin (mg/100g)	11.54 $\pm$ 0.34
12.	Naringin (mg/100g)	32.81 $\pm$ 0.32
13.	Antioxidants (%)	89.46 $\pm$ 0.84

SD* = Standard deviation

Table 2: Effect of osmosis dehydration method and different sweeteners on physico-chemical characteristics of hill lemon peel candy

Test Parameters	Method(M)	Sweeteners (S)			
		Sugar	Jaggery	Honey	Sorbitol
Weight reduction (%)	Slow	32.40 ^{Aa}	32.60 ^{Ba}	32.80 ^{ca}	32.20 ^{Da}
	Fast	30.20 ^{Ab}	30.60 ^{Bb}	30.80 ^{cb}	30.10 ^{cb}
Solid gain (%)	Slow	20.81 ^{Aa}	20.93 ^{Ba}	21.90 ^{ca}	20.68 ^{Da}
	Fast	20.62 ^{Aa}	20.53 ^{Ba}	21.55 ^{ca}	20.56 ^{Ba}
Water loss (%)	Slow	32.26 ^{Aa}	32.27 ^{Ba}	32.28 ^{ca}	32.13 ^{Da}
	Fast	30.03 ^{Ab}	30.02 ^{Bb}	30.05 ^{cb}	30.01 ^{Db}
Drying time (h)	Slow	143.67 ^{Aa}	145.00 ^{Ba}	146.00 ^{Ba}	142.00 ^{Da}
	Fast	122.00 ^{Ab}	123.00 ^{Ab}	124.00 ^{Bb}	120.00 ^{Db}
Candy yield (%)	Slow	70.12 ^{Aa}	70.28 ^{Ba}	70.34 ^{Ba}	69.98 ^{Da}
	Fast	68.10 ^{Ab}	68.25 ^{Bb}	68.76 ^{cb}	67.77 ^{Db}
Moisture (%)	Slow	13.13 ^{Aa}	13.40 ^{Ba}	13.33 ^{Ba}	12.05 ^{Da}

	Fast	11.19 ^{Ab}	11.42 ^{Bb}	11.56 ^{cb}	11.56 ^{cb}
Total solid (%)	Slow	86.87 ^{Ab}	86.60 ^{Bb}	86.67 ^{Bb}	86.95 ^{Ab}
	Fast	88.81 ^{Aa}	88.58 ^{Ba}	88.44 ^{Ba}	88.44 ^{Ba}
TSS (°B)	Slow	72.58 ^{Ab}	72.75 ^{Ab}	72.70 ^{Ab}	55.39 ^{Bb}
	Fast	70.15 ^{Aa}	71.06 ^{Aa}	70.37 ^{Aa}	53.75 ^{Ba}
Titratable acidity (%)	Slow	0.64 ^{Ab}	0.66 ^{Aa}	0.65 ^{Aa}	0.63 ^{Bb}
	Fast	0.58 ^{Ab}	0.61 ^{Aa}	0.60 ^{Aa}	0.57 ^{Bb}
pH	Slow	3.18 ^{Ba}	3.16 ^{Ba}	3.19 ^{Ba}	3.20 ^{Ba}
	Fast	3.46 ^{Aa}	3.48 ^{Aa}	3.47 ^{Aa}	3.45 ^{Aa}
Total sugars (%)	Slow	63.89 ^{Ab}	64.93 ^{Aa}	64.43 ^{Aa}	47.41 ^{Bb}
	Fast	61.35 ^{Ab}	63.33 ^{Aa}	62.46 ^{Aa}	44.52 ^{Bb}
Reducing sugars (%)	Slow	19.55 ^{Ab}	19.82 ^{Aa}	19.61 ^{Aa}	14.98 ^{Bb}
	Fast	17.58 ^{Ab}	18.85 ^{Aa}	18.66 ^{Aa}	12.08 ^{Bb}
Non enzymatic browning(OD _{420nm})	Slow	0.14 ^{Ab}	0.16 ^{Aa}	0.15 ^{Aa}	0.11 ^{Bb}
	Fast	0.20 ^{Ab}	0.22 ^{Aa}	0.21 ^{Aa}	0.17 ^{Bb}
Ascorbic Acid (mg/100g)	Slow	32.32 ^{ABa}	32.78 ^{Aa}	32.40 ^{ABa}	31.26 ^{Ba}
	Fast	26.07 ^{Ab}	27.28 ^{Ab}	27.17 ^{Ab}	25.35 ^{Bb}
Phenols (mgGAE/100g)	Slow	34.30 ^{ABa}	34.80 ^{Aa}	34.60 ^{ABa}	33.60 ^{Ba}
	Fast	31.30 ^{Ab}	31.80 ^{Ab}	31.50 ^{Ab}	30.80 ^{Bb}
Antioxidant activity (%)	Slow	81.79 ^{ABa}	82.92 ^{Aa}	82.83 ^{Aa}	80.79 ^{Ba}
	Fast	73.49 ^{Ab}	76.65 ^{Ab}	76.59 ^{Ab}	71.93 ^{Bb}

Lowercase letters compare means of preparation methods; uppercase letters compare means of different sweeteners; Values within rows sharing the same letters are not significantly different according to Duncan's LSD post-hoc analysis at $p \leq 0.05$.

Table 3: Effect of different packaging materials on the physico chemical characteristics of hill lemon peel candy during storage at ambient temperatures

Test Parameters	Packaging (P)	Storage interval (S)		
		0 day	45 day	90 day
Moisture (%)	HDPE Pouches	13.40 ^{Aa}	13.16 ^{Ab}	12.85 ^{Ac}
	Aluminium Pouches	13.40 ^{Aa}	13.29 ^{Bb}	13.10 ^{Bc}
	Glass Jars	13.40 ^{Aa}	13.06 ^{Cb}	12.65 ^{Cc}
Total Solids (%)	HDPE Pouches	86.60 ^{Ca}	86.84 ^{Cb}	87.15 ^{Cc}
	Aluminium Pouches	86.60 ^{Ba}	86.71 ^{Bb}	86.90 ^{Bc}
	Glass Jars	86.60 ^{Aa}	86.94 ^{Ab}	87.35 ^{Ac}
Total Soluble Solids (°B)	HDPE Pouches	72.75 ^{Ca}	73.00 ^{Cb}	73.27 ^{Cc}
	Aluminium Pouches	72.75 ^{Ba}	72.88 ^{Bb}	73.02 ^{Bc}
	Glass Jars	72.75 ^{Aa}	73.10 ^{Ab}	73.47 ^{Ac}
Titratable acidity (%)	HDPE Pouches	0.63 ^{Aa}	0.60 ^{Ab}	0.57 ^{Ac}
	Aluminium Pouches	0.63 ^{Ba}	0.59 ^{Bb}	0.55 ^{Bc}
	Glass Jars	0.63 ^{Ca}	0.61 ^{Cb}	0.59 ^{Cc}
pH	HDPE Pouches	3.25 ^{Ca}	3.29 ^{Cb}	3.33 ^{Cc}
	Aluminium Pouches	3.25 ^{Ba}	3.26 ^{Bb}	3.27 ^{Bc}
	Glass Jars	3.25 ^{Aa}	3.30 ^{Ab}	3.35 ^{Ac}
Total Sugars (%)	HDPE Pouches	64.93 ^{Ca}	65.50 ^{Cb}	66.49 ^{Cc}
	Aluminium Pouches	64.93 ^{Ba}	65.33 ^{Bb}	66.23 ^{Bc}
	Glass Jars	64.93 ^{Aa}	65.60 ^{Ab}	66.67 ^{Ac}
Reducing sugar (%)	HDPE Pouches	19.82 ^{Ca}	20.29 ^{Cb}	21.21 ^{Cc}
	Aluminium Pouches	19.82 ^{Ba}	20.13 ^{Bb}	21.88 ^{Bc}
	Glass Jars	19.82 ^{Aa}	20.44 ^{Ab}	21.67 ^{Ac}
Non-enzymatic browning (OD _{440nm})	HDPE Pouches	0.16 ^{Ba}	0.38 ^{Bb}	0.60 ^{Bc}
	Aluminium Pouches	0.16 ^{Aa}	0.29 ^{Ab}	0.42 ^{Ac}
	Glass Jars	0.16 ^{Ca}	0.45 ^{Cb}	0.74 ^{Cc}
Ascorbic acid (mg/100g)	HDPE Pouches	32.78 ^{Ba}	32.51 ^{Bb}	32.12 ^{Bc}
	Aluminium Pouches	32.78 ^{Aa}	32.66 ^{Ab}	32.50 ^{Ac}
	Glass Jars	32.78 ^{Ca}	32.39 ^{Cb}	31.96 ^{Cc}
Phenols (mg/100g)	HDPE Pouches	34.83 ^{Ba}	34.60 ^{Bb}	34.30 ^{Bc}
	Aluminium Pouches	34.83 ^{Aa}	34.69 ^{Ab}	34.52 ^{Ac}
	Glass Jars	34.83 ^{Ca}	34.51 ^{Cb}	34.14 ^{Cc}
Antioxidant activity (%)	HDPE Pouches	82.92 ^{Ba}	82.69 ^{Bb}	82.40 ^{Bc}
	Aluminium Pouches	82.92 ^{Aa}	82.79 ^{Ab}	82.63 ^{Ac}
	Glass Jars	82.92 ^{Ca}	82.61 ^{Cb}	82.27 ^{Cc}

Lowercase letters compare means of storage interval; Uppercase letters compare means of different packaging material; Values within rows sharing the same letters are not significantly different according to Duncan's LSD post-hoc analysis at $p \leq 0.05$.

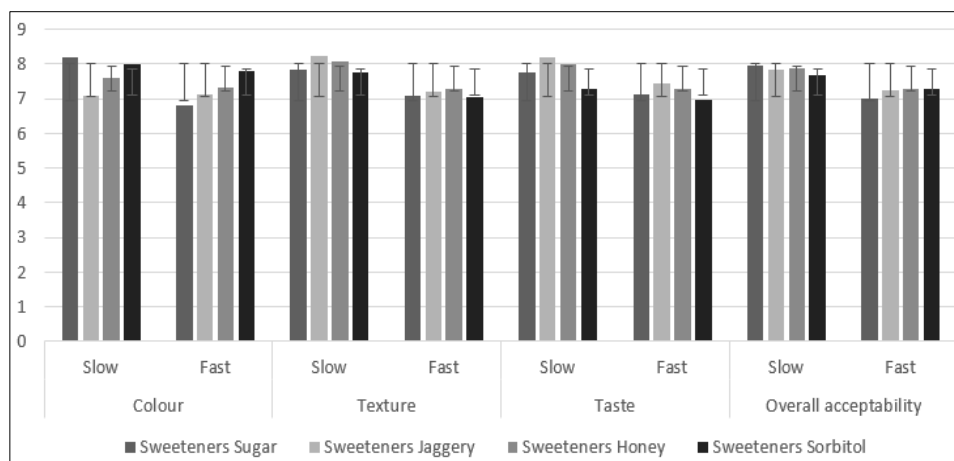


Fig 1: Sensory evaluation on 9-point hedonic scale of hill lemon peel candy prepared using different osmosis dehydration methods and sweeteners

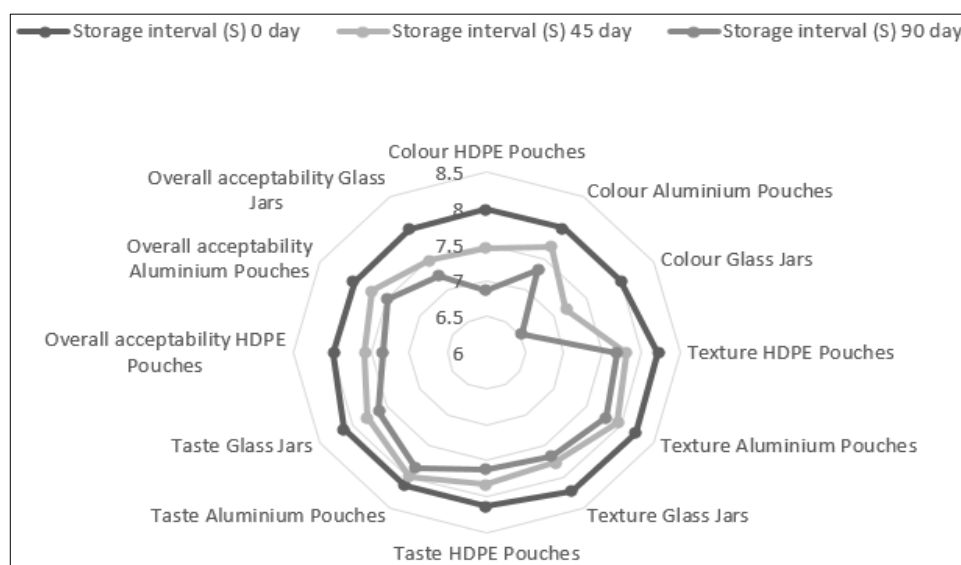


Fig 2: Effect of different packaging materials and sweeteners on the sensory scores (9-point Hedonic scale) of hill lemon peel candy during storage at ambient temperature

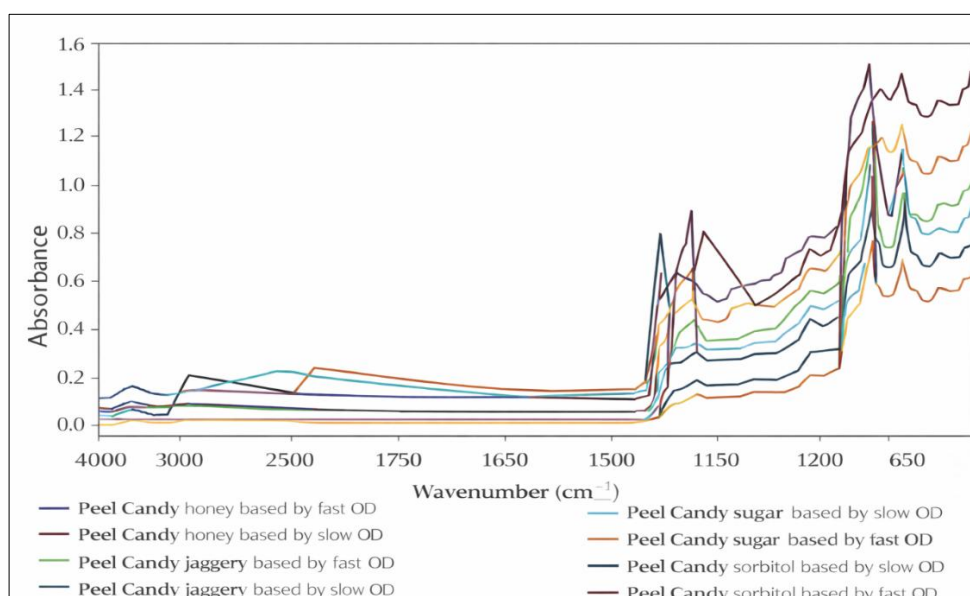


Fig 3: Fourier-transform infrared spectra of candy prepared with different osmosis dehydration methods and sweeteners

Conclusion

This study demonstrated that hill lemon peel is a valuable functional ingredient due to its high pectin, ascorbic acid,

phenolic content and strong antioxidant activity (89.46%). Slow osmotic dehydration was found to be more effective than fast osmosis, resulting in higher weight reduction, solid

gain and superior retention of bioactive compounds, including ascorbic acid and antioxidant activity. Jaggery and honey-based formulations further enhanced nutritional quality and sensory acceptability compared to sorbitol. FTIR analysis confirmed that osmotic dehydration primarily affected molecular interactions rather than chemical structure, with slow osmotic treatments showing better preservation of functional groups and structural stability. During storage, packaging material significantly influenced product stability. Glass jars effectively controlled moisture changes, whereas aluminium laminated pouches provided superior retention of bioactive compounds and sensory quality by minimizing oxygen and light-induced deterioration. Overall, slow osmotic dehydration combined with natural sweeteners (particularly jaggery) and aluminium packaging is recommended for producing high-quality hill lemon peel candy with improved nutritional value, sensory acceptability and shelf stability.

Declarations

Funding

This research received no external funding.

Conflicts of Interest

The authors declare no conflict of interest.

Ethical Approval

All procedures were conducted in accordance with the Declaration of Helsinki. Written informed consent was obtained from all participants prior to enrolment.

Data Availability Statement

The datasets generated and/or analyzed during the current study are available from the corresponding author upon reasonable request.

References

- Andrade MA, Barbosa CH, Shah MA, Ahmad N, Vilarinho F, Khwalidia K, *et al.* Citrus by-products: Valuable source of bioactive compounds for food applications. *Antioxidants*. 2023;12:38. DOI:10.3390/antiox12010038.
- Attri BL, Maini SB. Pectin from galgal (*Citrus pseudolimon* Tan.) peel. *Bioresour Technol*. 1996;55:89-91. DOI:10.1016/S0960-8524(96)90031-0.
- Badiyala SD, Sharma SK. Variability studies in galgal (*Citrus pseudolimon* Tanaka) in upper Shivaliks of Himachal Pradesh. *Indian J Hort*. 2004;61:105-108.
- Breksa AP III, Ibarra PJ Jr. Colorimetric method for the estimation of total limonoid aglycones and glucoside contents in citrus juices. *J Agric Food Chem*. 2007;55:5013-5017. DOI:10.1021/jf063731c.
- Chandel R, Kumar V, Kaur R, Kumar S, Gill MS, Sharma R, *et al.* Functionality enhancement of osmo-dried sand pear cubes using different sweeteners: quality, bioactive, textural, molecular, and structural characterization. *J Food Meas Charact*. 2023;17:3709-3721. DOI:10.1007/s11694-023-01894-9.
- Del Caro A, Piga A, Vacca V, Agabbio M. Changes of flavonoids, vitamin C and antioxidant capacity in minimally processed citrus segments and juices during storage. *Food Chem*. 2004;84:99-105. DOI:10.1016/S0308-8146(03)00180-8.
- Freitas HV, Dos Santos Filho AL, Rodrigues S, Abreu VKG, Narain N, Lemos TO, *et al.* Synbiotic açai juice (*Euterpe oleracea*) containing sucralose as noncaloric sweetener: processing optimization, bioactive compounds, and acceptance during storage. *J Food Sci*. 2021;86:730-739. DOI:10.1111/1750-3841.15617.
- Giannakourou MC, Lazou AE, Dermesonlouoglou EK. Optimization of osmotic dehydration of tomatoes in solutions of non-conventional sweeteners by response surface methodology and desirability approach. *Foods*. 2020;9:1393. DOI:10.3390/foods9101393.
- Grembecka M. Sugar alcohols—their role in the modern world of sweeteners: a review. *Eur Food Res Technol*. 2015;241:1-14. DOI:10.1007/s00217-015-2437-7.
- Huang R, Wu W, Shen S, Fan J, Chang Y, Chen S, *et al.* Evaluation of colorimetric methods for quantification of citrus flavonoids to avoid misuse. *Anal Methods*. 2018;10:2575-2587. DOI:10.1039/C8AY00661J.
- Im JH, Lee MK, Lee HI. Physicochemical and sensory properties and antioxidant activity of xylitol candies containing yuja (*Citrus junos*) peels or pulp. *Foods*. 2024;13:2396. DOI:10.3390/foods13152396.
- Jia X, Ren J, Fan G, Reineccius GA, Li X, Zhang N, *et al.* Citrus juice off-flavor during different processing and storage: review of odorants, formation pathways, and analytical techniques. *Crit Rev Food Sci Nutr*. 2024;64:3018-3043. DOI:10.1080/10408398.2022.2129581.
- Kaur K, Dhillon WS, Mahajan BV. Effect of different packaging materials and storage intervals on physical and biochemical characteristics of pear. *J Food Sci Technol*. 2013;50:147-152. DOI:10.1007/s13197-011-0317-0.
- Kaur R, Kumar V, Aggarwal P, Singh G. Valorization of citrus residue for the development of phytochemical enriched candy: textural, bioactive, molecular, and structural characterization. *Biomass Convers Biorefin*. 2025;15:2805-2816. DOI:10.1007/s13399-023-05069-w.
- Kaur S, Singh V, Verma P, Panesar PS. From citrus waste to value-added products: exploring biochemical routes for sustainable valorization. *Process Biochem*. 2025;158:81-98. DOI:10.1016/j.procbio.2025.08.009.
- Kedare SB, Singh RP. Genesis and development of DPPH method of antioxidant assay. *J Food Sci Technol*. 2011;48:412-422. DOI:10.1007/s13197-011-0251-1.
- Kumar R, Deb P, Dewangan RK, Pujari PK, Kumar A. Preparation and quality assessment of orange (*Citrus reticulata* L.) peel candy. *Pharma Innov J*. 2022;11:2958-2963.
- Lambani N, Malik SK, Kaur S, Kalia P, Singh J. Physico-chemical diversity analysis in lime (*C. aurantiifolia* (Christm.) Swingle), lemon (*C. limon* Burm. f.) and hill lemon (*C. pseudolimon* Tan.) species collected from the foothills of Himalaya, India. *Int J Curr Microbiol Appl Sci*. 2018;7:3220-3227. DOI:10.20546/ijcmas.2018.701.385.
- Liu N, Niu L, Li D, Feng J, Feng L, Zhang Z, *et al.* Effect of different small molecule sugars/sugar alcohols as sucrose substitutes in osmotic dehydration on the texture and gel properties of strawberry preserves. *Food*

- Res Int. 2025;221:117421. DOI:10.1016/j.foodres.2025.117421.
20. Mohanta V, Mukherjee I, Chottopadhyay J. Waste product utilization: preparation of candy from orange (*Citrus sinensis*) peel. Int J Agric Appl Sci. 2021;2:114-119. DOI:10.52804/ijaas2021.2217.
 21. Pham HTT, Kityo P, Buvé C, Hendrickx ME, Van Loey AM. Influence of pH and composition on nonenzymatic browning of shelf-stable orange juice during storage. J Agric Food Chem. 2020;68:5402-5411. DOI:10.1021/acs.jafc.9b07630.
 22. Rafiq S, Kaul R, Sofi SA, Bashir N, Nazir F, Nayik GA. Citrus peel as a source of functional ingredient: a review. J Saudi Soc Agric Sci. 2018;17:351-358. DOI:10.1016/j.jssas.2016.07.006.
 23. Ranganna S. Handbook of analysis and quality control for fruit and vegetable products. 2nd ed. Tata McGraw-Hill; 2020.
 24. Rastogi NK, Raghavarao KSMS, Niranjana K, Knorr D. Recent developments in osmotic dehydration: methods to enhance mass transfer. Trends Food Sci Technol. 2002;13:48-59. DOI:10.1016/S0924-2244(02)00032-8.
 25. Rizvi NB, Fatima A, Busquets R, Khan MR, Ashraf S, Khan MS, *et al.* Effect of the media in the Folin-Ciocalteu assay for the analysis of the total phenolic content of olive products. Food Anal Methods. 2023;16:1627-1634. DOI:10.1007/s12161-023-02527-z.
 26. Sharma P, Vishvakarma R, Gautam K, Vimal A, Gaur VK, Farooqui A, *et al.* Valorization of citrus peel waste for the sustainable production of value-added products. Bioresour Technol. 2022;351:127064. DOI:10.1016/j.biortech.2022.127064.
 27. Smith BC. Fundamentals of Fourier transform infrared spectroscopy. 2nd ed. CRC Press; 2011. DOI:10.1201/b10777.
 28. Stuart B. Infrared spectroscopy. In: Analytical techniques in forensic science. 2021. p. 145-160. DOI:10.1002/9781119373421.ch7.
 29. Sushila, Singh S, Prince, Chitrlekha. Effect of packaging materials on biochemical parameters of ber (*Ziziphus mauritiana* Lamk.) cultivars Thai Apple and Gola. Int J Agric Invention. 2025;10:164-173. DOI:10.46492/IJAI/2025.10.1.20.
 30. Tan X, Jiang W, Su J, Yu F. Recent advances in drying technologies for orange products. Foods. 2025;14:3051. DOI:10.3390/foods14173051.
 31. Tandel KR. Sugar substitutes: health controversy over perceived benefits. J Pharmacol Pharmacother. 2011;2:236-243. DOI:10.4103/0976-500X.85936.
 32. Thakur A, Suhag R, Kumar Y, Sharma A. Innovative applications of hill lemon (*Citrus pseudolimon* Tanaka) in sustainable bioprocessing: bioactive extraction, nanoparticle synthesis, and functional food products. J Food Biochem. 2025;2025:5560966. DOI:10.1155/jfbc/5560966.
 33. Thakur N, Kumari S. Preliminary screening of phytochemicals and antimicrobial activity of *Citrus pseudolimon*. Adv Tradit Med. 2022;22:425-435. DOI:10.1007/s13596-021-00561-y.
 34. Varalakshmi G. Application of analysis of variance (ANOVA) in biological science research. J Exp Agric Int. 2025;47:520-527. DOI:10.9734/jeai/2025/v47i93772.
 35. Xiong Z, Lu L, Ling B, Qiao J, Wang Q. Preparation and evaluation of tangerine peel-niacinamide-gelatin soft candy with antiaging potential. ACS Omega. 2025;10:57753-57764. DOI:10.1021/acsomega.5c09583.
 36. Yadav AK, Singh SV. Osmotic dehydration of fruits and vegetables: a review. J Food Sci Technol. 2014;51:1654-1673. DOI:10.1007/s13197-012-0659-2.
 37. Zayse Z, Tadesse MG. Chemical profiling and applications of lemon (*Citrus limon*) and orange (*Citrus sinensis*) fruit peels essential oils for flavoring as a means for municipal waste management. Berhan Int Res J Sci Humanit. 2022;6:1-16.