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Ultrasonication-assisted polyol-osmosed persimmon candies: effect of ultrasonication and drying techniques on product quality†

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Persimmon is a widely cultivated fruit known for its sweet and rich flavour and nutrition. However, this climacteric seasonal fruit is underutilized and scarcely processed. Persimmon has good potential for conversion into dehydrated fruit candies. To override the high calorific value associated with sugar-osmosed fruit candies, xylitol and erythritol were used as osmotic agents. The long processing duration for osmotic dehydration (OD) was aimed to be shortened through ultrasonication (US) for enhancing the mass transfer rate and product quality. The moisture ratio, weight loss, solid gain with osmotic agents, sucrose, erythritol and xylitol at 30–60% concentrations and 50–70 °C were modelled using non-linear models. The logistic model was found to be most appropriate to describe the kinetics of the OD process. Rates of OD varied in the following order: xylitol > erythritol > sucrose. US significantly affected the rate of polyol-osmosed dehydration and greatly improved textural and sensory qualities. To offer convenience attribute to the fruit, the osmosed fruits were converted into dry candies using a tray dryer and infra-red dryer and compared for nutritional, textural and sensory attributes. SEM images and lower bite force confirmed that US-OD followed by IR drying yielded much better quality of candies than conventional methods for all sweeteners. The highest carotenoid retention, L^* values, and ascorbic acid retention were recorded for persimmon candies osmosed in 60% erythritol. This study provides valuable insights into the application of ultrasonication and polyols for the effective utilization of nutritious persimmon and caters to the needs of faster processing times, higher nutrient retention and low calorific load in fruit candies.

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Sustainability spotlight

This research work on the development of low-calorie candies from persimmon aligns to two SDG goals: **Goal 3 Ensure healthy lives and promoting well-being for all at all ages**: and specifically relates to reduction of mortality from non-communicable diseases (NCDs). Calorie management in the age of sedentary lifestyle is a major challenge globally. Diabetes and healthy weight management account for more than 70% of world population concerns, with NCDs accounting for 63% of total deaths. In this respect, development of fruit candies with low calorific load and their comparison to conventional sugar-osmosed candies aim to provide fruit snacks with lesser concerns of calorific load. **Goal 12 Responsible production and consumption**: Persimmon is emerging as a popular crop in temperate regions. However, it is a climacteric fruit that rapidly undergoes softening (few hours) soon after ripening initiates. This results in a glut situation in the market and high postharvest losses. Currently, these are hardly processed for any value-added product. Low-cost and simple processing techniques to process the ripe fruit on farm will prevent wastage of fruits and their preservation for use in off-season as a healthy snack. This activity will bolster farmers' incomes and provide incentives for traditional osmosedehydration activity since conventional sugar-osmosed fruits are losing customers in the health-conscious society. The products thus prepared shall meet the requirements of modern-day consumers.

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Introduction

Persimmon (*Diospyros kaki*) is a highly nutritious fruit rich in vitamins; minerals such as potassium, sodium, iron, and calcium; and antioxidants.¹ Its production area is increasing rapidly in India owing to the development of attractive, non-astringent varieties, low plant maintenance and increasing popularity amongst consumers. However, its seasonality, highly climacteric nature and rapid perishability mandate the development of low-cost, on-farm technologies to process it into



shelf-stable forms. It is worth noting that despite their acknowledged health benefits and abundance of bioactive components, persimmons remain underutilized. Moreover, sufficient studies on their potential applications are lacking.²

Dehydration is the most convenient, economic and widely used method to preserve fruits on farm while reducing their volume and weight, thereby reducing the cost of packaging, storage and transport. There is a growing consumer preference for dehydrated fruit as a healthy and convenient snack option with an extended shelf life.³ Osmotic dehydration (OD) using sucrose, fructose, and common salt is the most common practice for fruit and vegetable dehydration. OD is a form of non-thermal dehydration method that involves counter-current transfer of mass from a hypertonic solution into the fruit tissue, while moisture is extracted from the interior of the fruit into the hypertonic solution, thereby causing moisture reduction and solute gain by fruits. The conventional process however suffers from drawbacks of a highly time-consuming process and production of high-calorie or salt-rich, syrupy products. Considering the requirement of today's industry and consumer preferences, technological innovations such as an improved rate of mass transfer, higher retention of nutrients, lesser shrinkage, better mouthfeel in the OD process using more efficient methods such as ultrasound, promoting longer shelf life and waste utilization of persimmon are imminent. As dried persimmon is popular in Japan and Korea, the development of low-calorie polyol-based persimmon candies will create more ventures.

Persimmons are traditionally sundried in Japan and Korea, retaining valuable dietary fibers, minerals, and antioxidants, despite some loss of bioactive compounds. Drying enhances their flavor, color, and nutritional value by concentrating sugars and phytochemicals, while also extending the shelf life. Dried persimmons are lightweight, efficient for storage and shipping, and helpful to reduce food waste during surplus seasons. Traditional drying methods such as solar and air drying are cost-effective and eco-friendly but can be time-consuming and susceptible to contamination. Weather-dependent and prone to inconsistent results, they may also lead to nutrient loss. Modern techniques such as tray drying and infrared drying offer improved efficiency and quality control. Tray drying provides consistent results but can lead to fruit shrinkage and uneven drying. Infrared drying addresses these issues by offering faster, uniform heating that preserves color and nutrients while minimizing the drying time. Although initial costs are higher, it typically results in lower energy consumption and a more appealing texture for consumers.

Ultrasonication (US) has been employed by several researchers^{4–7} to reduce the processing time for mass transfer. Being residue-free, effective and environmentally friendly, various forms of US are used for pre-treatment, extraction and dispersion in food processing. Ultrasound-assisted osmotic dehydration (USOD) has a highly positive influence on the dehydration parameters for reducing the drying time, minimizing costs and improving quality. Bozkir *et al.*⁸ highlighted that USOD increased water reduction and sugar gain in persimmon samples, reducing the overall drying time by 46%.

The reduction of drying time for pineapples, increased water diffusivity and sucrose incorporation have been reported through use of ultrasound.⁹

The problem of high calorific value in osmodehydrated fruits may be resolved by use of sugar-alcohols or polyols (xylitol, erythritol, maltitol, sorbitol, *etc.*) as osmotic agents, which have good dehydration capacity. Polyols have a lower caloric value (0.2 to 2.7 kcal g⁻¹) than sucrose (4 kcal g⁻¹). Erythritol (E968) and xylitol (E967) both are GRAS food additives and are routinely used in a number of food products such as toothpaste and chewing gums. Erythritol provides 0.2 kcal g⁻¹ compared to sucrose that provides 4 kcal g⁻¹, while xylitol provides 2.4 kcal g⁻¹. Both of these have no after taste, rather erythritol enhances mouthfeel and effectively masks unwanted aftertastes, such as astringency. Its use is allowed up to 45% by weight in fruit leathers, candies, and fruit novelty snacks. Erythritol creates a notable cooling effect when dissolved, attributed to its high negative heat of solution. These characteristics make erythritol a valuable ingredient in food and beverage applications.¹⁰ As these polyols are not as humectant (like sorbitol) or expensive (maltitol), instead of more expensive sweeteners, less viscous erythritol (1.3 cP) and xylitol (2.3 cP) are used, which are preferred for value addition of persimmon at the farmgate level. Moreover, the consumption of products containing sugar alcohols does not induce an increase in blood glucose or insulin secretion, and thus, such products are recommended for diabetes¹¹ or weight management. Mäkinen¹² has recommended a safe daily dose of 20 to 70 g xylitol per day, while Wölnerhanssen *et al.*¹³ have recommended that the largest safe dose for a single bolus lies around 0.6–0.8 g kg⁻¹ bw. Jacqz-Aigrain *et al.*¹⁴ reported good tolerance for rapid ingestion of up to 15 g (corresponding to 0.73 g kg⁻¹ bw) of erythritol by 184 children aged four-six years. Lowe and Anthony¹⁵ have suggested recommendation of 71 to 143 mg kg⁻¹ BW per day of xylitol to reach plaque-reducing therapeutic levels of xylitol after conducting clinical trials on dogs. EFSA Panel on Food Additives and Flavourings¹⁶ have recommended an acceptable daily intake (ADI) of 0.5g kg⁻¹ body weight for erythritol considering protection for the immediate laxative effect as well as potential chronic effects, secondary to diarrhoea.

Cichowska-Bogusz *et al.*⁴ reported that sugar alcohols enabled shorter drying times for apples, and ultrasound during osmotic dehydration did not significantly affect sensory attributes. Though this domain is less explored, the area seems promising and has wide industrial acceptance since global market for candied and osmodehydrated fruits was valued at USD 42,159.0 million in 2022, with projections of growth at a CAGR of 4.03% through 2028, reaching 53 436 million USD. Consumption trends suggest a rising trajectory, with anticipated annual growth rates of 1.5% in volume and 3.5% in value from 2022 to 2030. India secured the third position in this market segment, contributing 57 000 tons with a 7.1% share.^{17,18}

In the above context, this study aimed to determine the effect of temperature, osmotic agent (sucrose, erythritol, and xylitol), concentration and ultrasonication on the mass transfer kinetics during the osmodehydration of persimmon fruit 'Fuyu'. Further the effect of tray drying and infrared drying on the quality of



candy has been analyzed. This is the first report that deals with ultrasonication-assisted osmodehydration of persimmon with polyol solutions and their conversion to fruit candies.

Materials and methods

The red fleshed variety 'Fuyu' persimmon fruits were procured from Azadpur mandi, Delhi. Sucrose, erythritol (Herboveda, India), and xylitol (Herboveda, India) with >99% purity were obtained from the local market. Reagents and chemicals including ethanol, dichlorophenol indophenol dye, petroleum ether, lead acetate, potassium acetate, Fehling's solution, methylene blue, potassium oxalate, phenolphthalein, NaOH, sodium bicarbonate, sodium carbonate, metaphosphoric acid, ascorbic acid, Folin-Ciocalteu reagent, copper chloride, neocuproine, ammonium acetate buffer, sodium anhydrous, glucose, phenol, HCl, H_2SO_4 , acetone, glutaraldehyde, sodium phosphate buffer, and phenol red were sourced from SRL, Mumbai, and Merck, India.

Ultrasonication treatment

Ultrasonication treatments were administered using a probe sonicator assembly (PRO650, Labman Scientific Instruments, India) at a power rate of 10%. The probe-type sonicator was used at 10 watts equivalent to 0.6 kHz in the pulse mode (2 s Off and 2 s On). The time duration of 90 minutes was standardized based on preliminary trials and used for modelling and quality parameters.

Preparation of fruits

Persimmon fruits were peeled, and cubes of $0.7 \times 0.7 \times 0.7 \text{ cm}^3$ size were prepared using a molded cutter. These cubes were weighed and immersed in an osmotic solution with a sample-to-solution ratio of 1/10 (w/v).

Osmotic dehydration process

The cubes were treated with different concentrations of sucrose, xylitol, and erythritol solutions ranging from 30% to 60%. Citric acid at 0.7% concentration was added to enhance the taste. Osmotic solutions were maintained at temperatures of 50, 60, and 70 °C using a water bath. Samples were withdrawn at time intervals of 0, 10, 20, 30, 40, 50, 60, 90, and 120 min for analysis. For USOD treatments, similar conditions were provided to persimmon cubes, with the application of ultrasound at 10% power rate. This power intensity was standardized to ensure effective treatment without compromising the structural integrity of the fruit tissue.

Preparation of osmodehydrated persimmon candies

Peeled persimmon fruits were sliced into 0.7 cm thick slices. Osmotic dehydration was conducted for 90 min in sucrose (60%), erythritol (40%, 50%, and 60%), and xylitol (40%, 50%, and 60%) solutions containing 0.7% citric acid at 60 °C (Fig. 1). The osmotically dehydrated persimmon slices were further dried in a tray dryer (60 °C for 4 to 5 h) and an infrared dryer

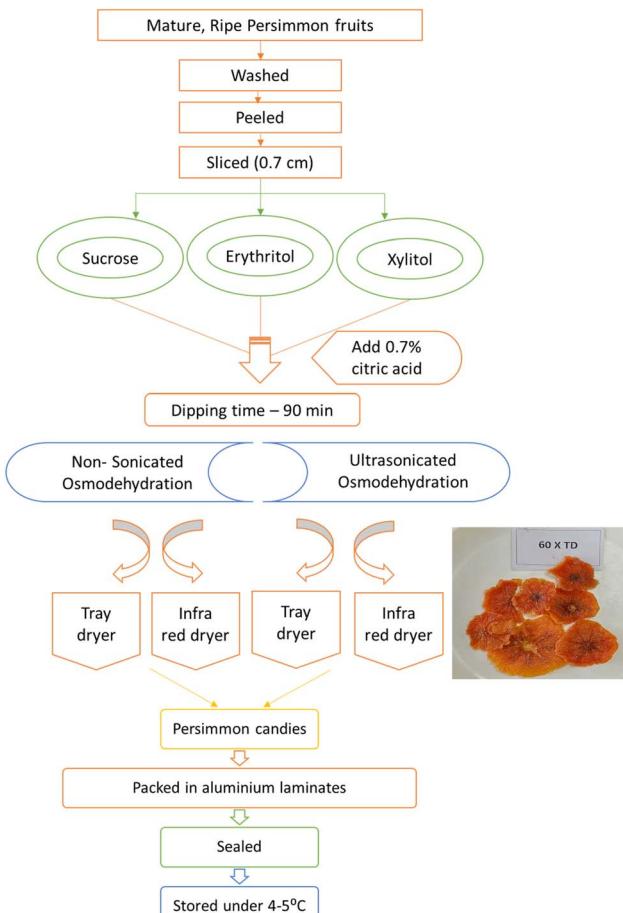


Fig. 1 Flowchart of preparation of ultrasonicated osmodehydrated persimmon candies.

(25–30 °C for 120 to 140 min) until a constant moisture level was attained. The persimmon candies were then sealed in aluminum laminates until analysis within 15 days.

Quality evaluation studies

Physico-chemical parameters including fruit firmness, moisture content, titratable acidity, total soluble solids (TSS), ascorbic acid, total carbohydrates, total sugars, reducing sugars, carotenoids, total phenolic content, antioxidant activity, and tannin content of fresh persimmon were evaluated. The candies obtained from the above-mentioned experiments were analyzed for moisture content, ascorbic acid, total carbohydrates, carotenoids, total phenolic content, antioxidant activity, and bite force. All processes and the quality measurements were conducted in triplicates.

The moisture content of the cubes was determined in a hot air oven maintained at 60 °C for 8 h until attainment of constant weight. The moisture ratio was determined as follows:

$$\text{Moisture ratio (MR)} = \frac{M_t}{M_o} \quad (1)$$

The firmness of persimmon fruits (N) was measured using a texture analyzer (TAXT2, Stable Micro Systems, UK) with a 2 mm



cylindrical SS probe. The test speed was 0.5 mm s⁻¹, respectively, until a distance of 10 mm. The bite force for the candied persimmon discs was measured using a texture analyzer with a knife blade attachment probe, and expressed in Newton (N).

Total soluble solids (TSS) was measured with a hand refractometer (Atago, Tokyo). The reducing sugars were estimated by titrating the sample filtrate against Fehling's solution and using methylene blue as an indicator. Similar to reducing sugars, total sugars were determined by acid hydrolysis, neutralization, and titration against Fehling's solution. Ascorbic acid was measured by titrating the sample against a dichloroindophenol solution and expressed in mg/100 g.¹⁹ The total phenolic content was determined using the Folin-Ciocalteu reagent, the absorbance was measured at 750 nm and expressed in milligram of Gallic Acid Equivalents (GAE) per 100 g. The antioxidant activity was expressed in μ mol Trolox equivalents per gram. Total carbohydrates were estimated by the phenol-sulfuric acid method, and the absorbance was measured at 490 nm against a blank. The titratable acidity was determined by titrating the sample with 0.1 N NaOH using a phenolphthalein indicator. Total Carotenoids were measured using acetone and petroleum ether extraction, with absorbance measurement at 452 nm. Scanning Electron Microscopy (SEM): samples were fixed, dehydrated, and observed at 500–10000 \times magnification using an SEM machine (VEGA3, TESCAN).

The browning index of candies was measured by extracting 1 g of sample in 100 mL ethanol (67%) and determining absorbance at 420 nm. The colour values were measured using the rapid tables software and expressed as L^* (lightness), a^* (redness), and b^* (yellowness).

$$\Delta E^* = \sqrt{(L_2^* - L_1^*)^2 + (a_2^* - a_1^*)^2 + (b_2^* - b_1^*)^2} \quad (2)$$

$$C^* = \sqrt{a^{*2} + b^{*2}} \quad (3)$$

Sensory evaluation

The persimmon candies were evaluated using a 9-point hedonic scale by a panel of 20 members comprising 10 females and 10 males aged between 21 and 26 years. The panel was apprised and informed about the samples prior to the evaluation.

Data analysis

At each time interval during osmodehydration (OD) up to 120 min, three cubes were taken out and the surface of the OD cubes was cleaned gently with the help of blotting paper. The samples were weighed using a digital balance (± 0.01 g). Water loss (WL) and solid gain (SG) were determined according to eqn (4) and (5).⁷

$$\text{Solid gain (SG)} = \frac{S_t - S_0}{A_0} \times 100 \quad (4)$$

$$\text{Water loss (WL)} = \frac{W_0 - W_t}{A_0} \times 100 = \frac{W_0 - (A_t - S_t)}{A_0} \times 100 \quad (5)$$

where A_0 is the fresh persimmon cube weight before treatments; A_t is the final persimmon cube weight after treatments; W_0 is the fresh persimmon cube moisture content before treatments; W_t is the final persimmon cube moisture content after treatments; S_0 is the fresh persimmon cube dry solid matter content before treatments; and S_t is the final persimmon cube dry matter content after treatments.

Kinetic modelling. Non-linear regression analysis was done using Statistica software (Statsoft, version 9, Tibco GmbH) to determine the best fit of models to explain the variation in moisture ratio with time duration during osmotic dehydration of persimmon cubes. The experimental data were fit into three models, namely Henderson Pabis, Simplified Fick and Logistic models. The models were applied to fit the data on moisture ratio during OD of persimmon cubes under various experimental conditions.

The goodness of fit of models was based on the degree of fit as determined using variance explained, coefficient of determination (R^2), root mean square error (RMSE), mean absolute error (MAE), mean absolute percentage error (MAPE) and mean squared error (MSE) based on comparison of observed and predicted MR as per models. The higher value of coefficient of determination (R^2) and the lower root mean square error (RMSE) indicate the accuracy of the fit.²⁰

The Arrhenius equation introduces an exponential factor that demonstrates how a reduction in activation energy leads to a significant exponential increase in the rate constant of a reaction. As the rate of a reaction is directly linked to its rate constant, this exponential growth also applies to the reaction rate itself.

The Arrhenius equation is as follows:

$$K = A \times \exp^{-E_a/RT} \quad (6)$$

where A is the pre-exponential factor; E_a is the activation energy (J mol⁻¹); R is the universal gas constant (8.314 J mol⁻¹ °C); and T is the temperature (K).

The experimental data for osmodehydration and candying of persimmon were organized using a full factorial design at a significance level of $p = 0.05$. Statistical analysis was performed using the SAS (Statistical Analysis System) software. Each treatment was replicated to ensure the reliability and accuracy of the results.

Results and discussion

Composition of persimmon fruit var. Fuyu

The persimmon fruits of Fuyu variety were bright orange-reddish in colour and weighed between 200 and 300 g. These attractive fruits were firm fleshed (158–203 N) and had shelf-life of 6 weeks in refrigerated storage and approximately 7 days under ambient conditions. Once the fruit entered the climacteric phase, it underwent rapid softening, leading to the development of unmarketable fruits with a jelly-like texture within just a day.

The moisture content of the fruits was 82.62%. Mature fresh persimmon fruits were rich in sugars (16.17%) with a reducing



Table 1 Physico-chemical compositions of fresh persimmon fruits^a

Attribute	Value
Moisture content (%)	82.62 ^a ± 1.42
Titratable acidity (%)	0.34 ^a ± 0.07
TSS (°Brix)	21.3 ^a ± 0.17
Ascorbic acid (mg/100 g)	14.95 ^a ± 0.01
Reducing sugars (%)	6.93 ^a ± 0.64
Total carbohydrates (%)	18.51 ^b ± 0.03
Total sugars (%)	16.17 ^a ± 0.16
Carotenoids (µg per g)	17.85 ^a ± 0.03
Total phenols (mg GAE/100 g)	163.09 ^a ± 55.88
Antioxidant activity (µmol TEAC per g)	9.07 ^a ± 0.32

^a Different superscripts indicate difference in the level of significance ($p < 0.05$).

sugar content of 6.9% and total soluble solids of 21.3 °Brix. The water activity samples were observed as 0.56. The TSS varied considerably with maturity with values ranging from 12 to 23 °B². Our findings are close to those of Smrke²¹ who reported persimmon (Fuyu cv) to have a carbohydrate content of 14.30%, primarily in the form of glucose (7.50 g per 100 g) and fructose (6.40 g per 100 g) and a calorific value of persimmon between 102.90 and 274.40 kcal. The fruits had low acidity (0.34%), which gave a sweet bland taste on consumption. Persimmon was found rich in total phenolics (163.09 ± 55.88 mg/100 g) and antioxidants (907.00 ± 0.32 µmol TEAC/100 g). Persimmon fruits were found to have 8.3 µg g⁻¹ total carotenoids (Table 1), while the tannin content was below the measurable range. β-Carotene has been reported to be most abundant in ripe persimmons, especially in the peel of the Hana-Fuyu variety (8.75 mg kg⁻¹ (ref. 22)). González *et al.*²³ reported Rojo Brillante variety of persimmon to contain β-carotene and other carotenoids, including β-cryptoxanthin, violaxanthin, zeaxanthin, and lutein. Ascorbic acid in the mature Fuyu persimmons was found to be 14.34 mg/100 g in concurrence to Preethika *et al.*² who has reported persimmon fruits to contain vitamin C from 7.5 to 29.6 mg/100 g. Persimmons are known to possess high antioxidant capacity over other fruits due to their rich content of phenolic compounds, carotenoids, and water-soluble vitamins such as vitamin C. The fruits were found to have a total phenolic content of 163.09 mg GAE/100 g. Giordani *et al.*²⁴ have reported a similar amount of vitamin C, total phenolic compounds, and flavonoids in Fuyu peel as 139.91, 169.36, and 60.79 mg%, respectively. They identified the polyphenols to be catechin, epigallocatechin, *p*-coumaric acid, epicatechin, and proanthocyanidin. The astringency of persimmons varies among different cultivars based on their tannin content. The higher the tannin content, the more astringent the fruit is. The astringency of persimmons is also influenced by their ripeness. Young fruits are rich in proanthocyanidins, which contribute to their astringent taste. However, certain cultivars like 'Fuyu' have low or undetectable tannin content, making them non-astringent when ripe. The tannin concentration was reported by Altuntas *et al.*²⁵ in Fuyu as 9–27%. In the studied ripened 'Fuyu' variety of persimmon fruits, tannin content was not detectable.

Osmodehydration with polyols

The impact of ultrasound during osmotic dehydration on water loss (WL) and solid gain (SG) varied depending on the type of osmoactive substance used (erythritol, sorbitol, and sucrose), with the most significant effects observed in sucrose. However, the highest dehydration, along with a simultaneous increase in SG, was observed when using sugar alcohols. In our study, USOD resulted in a reduction in OD duration only for samples treated with sugar alcohols. Our findings are in variation with Salehi *et al.*⁷ who reported that for the USOD, the apple slices gained 12.5% of sucrose after 60 min and in NSOD, the apple slices gained 9.1% of sucrose in the 60 min.

Osmotic dehydration conducted in low-molecular-weight polyols presents an advantageous blend of processes that facilitate a higher osmotic driving force in osmo-dehydrated products without the presence of simple sugars, all while conserving energy—a boon for sustainable technologies. The preference for low-molecular-mass saccharides such as sorbitol, fructose, and glucose lies in their swift penetration due to high velocity.²⁶ Cichowska *et al.*²⁷ found that OD in a 40% solution concentration of erythritol and xylitol surpassed the effectiveness of the dehydration process in a sucrose solution, attributed to the lower molecular weights of erythritol (122.12 g mol⁻¹) and xylitol (152.15 g mol⁻¹). Huang *et al.*²⁸ also proposed that sugar alcohols with lower molecular weights, such as xylitol, can intensify the osmotic pressure and enhance the mass transfer.

The superiority of xylitol and erythritol solutions in generating larger osmotic effects, compared to sucrose, stems from the significantly higher molecular weight of sucrose and the ensuing lower osmotic pressure.²⁷ Substances with higher molecular weights exhibit lower osmotic pressures, resulting in diminished kinetic parameters and reduced penetration into the material.²⁹ The strategic use of xylitol as an osmotic substance during dehydration of apples notably lowered the water activity in dried apple samples.⁴

Water loss. At 40% sweeteners concentration at 60 °C, the highest value of WL (48%) was recorded for persimmon cubes immersed in xylitol towards the end of OD process, followed by erythritol (45%) and sucrose (40%). A steady increase in WL with time was recorded for erythritol and xylitol, but in sucrose the rate of WL increased only after 25 min of dipping. At 60% concentration significantly higher WL was recorded for persimmon cubes OD in erythritol (52%) and xylitol (51%) followed by sucrose (47%).

Solid gain. With increased duration of immersion, a steady increase in solid gain was observed in erythritol solution. In xylitol and sucrose solutions however, the rate of SG plateaued after 60 and 90 min respectively. At a 40% sweetener concentration, the highest SG was recorded for xylitol (12.3 to 12.9%) followed by erythritol (11.3 to 11.9%) and sucrose (10.7 to 11.6%). With the increase in the concentration of sweeteners, the SG increased as anticipated. The uptake of solids was higher at 60% sweetener concentration. Erythritol- and xylitol-dipped persimmon cubes recorded an SG of 14.3 to 14.7% compared to 14.1% in sucrose solutions. Kroehnke⁵ has also reported the



first 30 minutes as the most effective osmotic dehydration period for kiwifruit slices dipped in erythritol.

Effect of ultrasonication on osmodehydration process

The application of ultrasound during the process of OD greatly helped in maximizing the rate of water loss and solid gain. Ultrasonication had significant effects on the rate and extent of mass transfer during OD in all sweeteners. Fig. S1–S3† depict the decline in moisture ratio during the osmodehydration of persimmon cubes in non-sonicated (NSOD) and (b) ultrasonication-assisted OD processes (USOD). A steeper decline is visible in most USOD samples, especially in the case of xylitol and erythritol. As the concentration of sweeteners increased, the MR value decreased. As the concentration of sucrose increased from 30 to 60%, the MR values decreased from 1 to 0.83 following 120 min of OD. Moreover, the effect of increased sucrose concentration on lowering the MR became more evident at higher temperatures. Similarly, for xylitol and erythritol, the MR values decreased from 1–0.76 to 1–0.79, respectively, as the concentration enhanced from 30 to 60%. As the temperature increased, the slope of curves increased. As anticipated, the lower MR (0.7073–0.77) was recorded at 70 °C with USOD at higher concentrations of xylitol (50–60%) followed by sucrose and erythritol. Moisture removal was directly proportional to temperature during USOD in sucrose solutions, with a faster mass transfer (moisture removal) and reduction in drying time. Xylitol and erythritol showed the effects of increased temperature during USOD mainly during the first 30–60 min.

With ultrasonication, lower MR values could be obtained. A clear distinction between the final MR of persimmon cubes processed with USOD (for 120 min at 60 °C) was observed for 60% sucrose (0.78), followed by 60% xylitol (0.81) and 60% erythritol (0.84). For persimmon cubes to attain an MR of 0.4, higher time was recorded in erythritol dipped cubes (90 min) compared to sucrose (61 min) and xylitol (57.5 min) at 60 °C. Comparatively lower ranges of MR from 0.74 to 0.79 were recorded for USOD of persimmon cubes immersed in xylitol solutions at all concentrations (30–60%) over erythritol and sucrose. The lowest MR was recorded for sonicated persimmon cubes immersed in 50% xylitol solutions at 70 °C (0.7073). Significantly lower MR was recorded for USOD treatments of persimmon cubes. Sucrose USOD cubes showed a lower MR than erythritol cubes, in general.

Similarly, in erythritol solutions, the rate of decrease in MR increased with the use of ultrasonication at all concentrations. Lower MR values were realized in erythritol solutions of same concentration upon application of US at all temperatures. This effect of US in decreasing MR effectively can be clearly seen from Fig. S1–S3† and 2. The final MR of persimmon cubes was also lesser in USOD treatment for all the three sweeteners.

Mathematical modeling of the moisture ratio

The experimental moisture data obtained during OD was fit to non-linear models. Though the Henderson-Pabis and simplified Fick model showed a reasonable degree of fit, the best prediction of our experimental data was by a logistic model. The use of logarithmic transformation and complex models such as

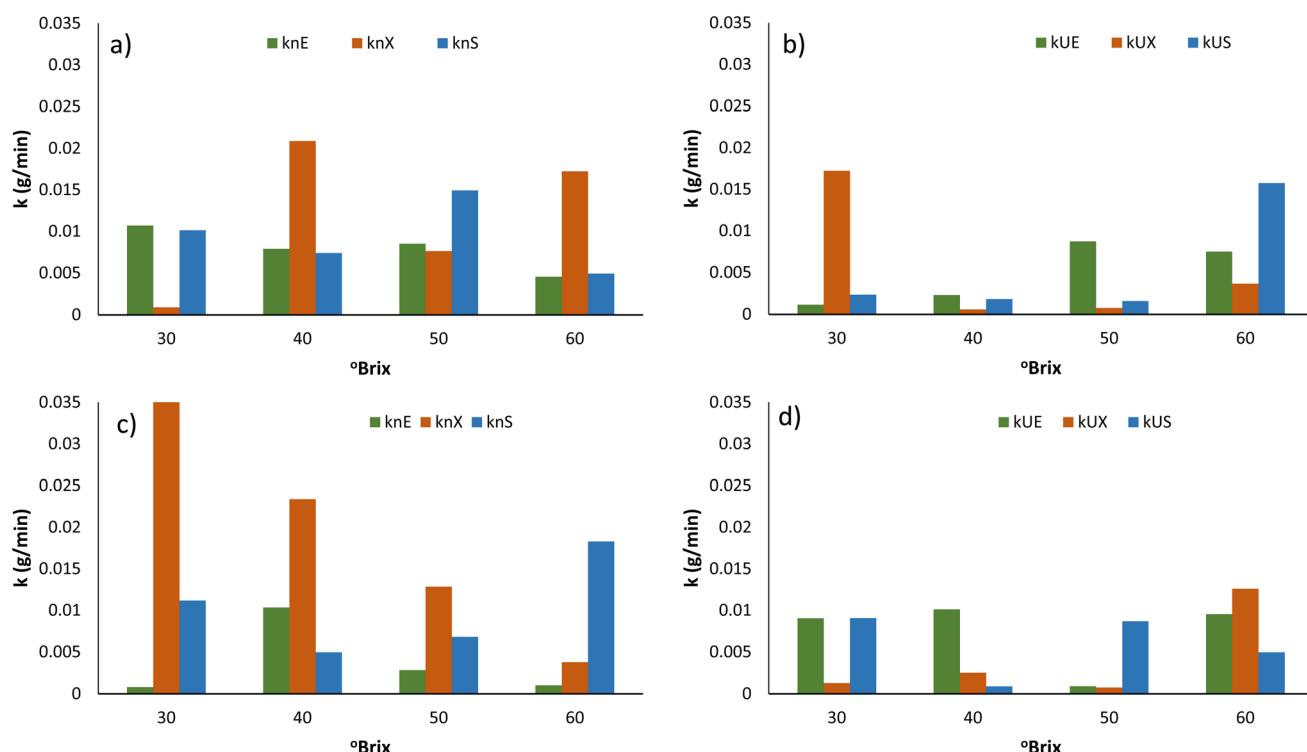


Fig. 2 Effect of the concentration of sweeteners and temperature (50 °C, a and b; 60 °C, c and d) on the rate of moisture loss during non-sonication- (a and c) and sonication- (b and d) assisted osmodehydration (S: sucrose; E: erythritol; X: xylitol, n: non-sonicated, u: sonicated).



Henderson-Pabis has however been discouraged by researchers.³⁰ A logistic model with the highest R^2 and the lowest RMSE, MAE, MAPE and MSE values exhibited the highest goodness of fit. The logistic model is among the most popular models used by researchers to explain the sigmoidal pattern of data. Logistic regression's dependent variable obeys the 'Bernoulli distribution' and the estimation is based on 'maximum likelihood method'. The logistic regression does not evaluate the coefficient of determination (R^2), as observed in linear regression. Instead, the model's fitness is assessed through a concordance, which can be seen clearly in the model fit curves. In logistic-type regression, the logit transformation shows the impact of independent variables on the variation of the dependent variable's natural logarithm of the odds.

The parameters of logistic models are B, A and k , indicating the intercepts and drying rate constant. The rate parameter, k , holds most significance to compare the effect of temperature, ultrasonication and sweetener on the OD process. In general, the k values were higher for the USOD process than for the OD process for all three sweeteners. In particular, for xylitol and sucrose at 60 °C, the USOD k values were higher over the NSOD process by 22.24% and 57.26%, and at 70 °C, the rates of USOD treatments were higher by 247% and 37.89%, respectively.

As expected, the k values were higher for xylitol (overall average 0.0372 min⁻¹) followed by sucrose (0.0225 min⁻¹) and erythritol (0.0149 min⁻¹). With the increase in the concentration of sucrose, increased k values were obtained for both USOD and NSOD. A 0.8-fold increase was recorded for the averaged k values for increase in sucrose from 50 to 70%. For USOD samples, the increase in the concentration of xylitol from 50 to 60% leads to an increase in the k value by 0.68-fold, while in NSOD, 0.92-fold. In NSOD treatment with erythritol, as the concentration was increased from 50 to 60%, a 5.88-fold increase in k (rate of mass transfer) was observed (Fig. 2). At 70 °C, xylitol showed a 2.47-fold increase in the k value for the non-sonicated sample compared to the ultrasonicated sample. Similarly, at 60 °C, erythritol exhibited a 1.975-fold increase in the k value for the NSOD sample over the ultrasonicated sample. Overall, the k values increased 0.625 folds as the concentrations of sweeteners increased from 30% to 60%. As expected, USOD treatment showed 1.36 folds increase in k values over the same concentration range.

The quantifiable effect was also evident from the rate parameters of the mathematical model (Logistic) used to predict the variation of moisture ratio with time for each sweetener: concentration and temperature combination. Overall, the k values were 0.48 folds for USOD in sucrose, 1.025 folds for erythritol and 0.47 folds for xylitol compared to the NSOD process. In particular for 60% xylitol at 70 °C, the k values of USOD were 11.84 times higher than that of the NSOD process. For sucrose, the k value was 25% higher under same conditions. For erythritol, the k USOD was 1.8 times that of NSOD. The USOD process was found to be more effective for accelerating the OD process for sucrose and erythritol than xylitol. However, USOD in xylitol at 70 °C was found beneficial for enhancing the rate of OD at 30–50%. These findings are in agreement with those of Fadil *et al.*⁶ and Salehi *et al.*⁷ who have reported

increased mass transfer during OD and reduction in the drying time of kiwifruit and apple.

Under USOD, the highest k values among all sweeteners were observed for 30% xylitol solutions maintained at 60 °C. Xu *et al.*³¹ reported that strawberry slices subjected to ultrasonic treatment with different frequency modes exhibited significantly higher WL and SG values ($p < 0.05$). They attributed this to the "sponge effect" generated by ultrasonic treatment, which led to the formation of micro pores in the strawberry tissue and facilitated the discharge of water. They concluded that ultrasonic pretreatment, particularly with dual-frequency ultrasound, could enhance the water removal during the osmotic dehydration of strawberry slices, offering potential benefits for improving the dehydration process and preserving the quality of the fruit. Li *et al.*³² reported that Sanhua plum treated with ultrasound-assisted osmotic dehydration showed reduced drying time, improved drying rate, and increased effective water diffusivity.

Briki *et al.*³³ applied a modified logistic model for modelling the drying kinetics of pomegranate arils in an infrared and tray dryer. Chin *et al.*³⁴ have shown that for convective drying of kiwi slices at different temperatures, the best fit was obtained using simplified Fick's second law of diffusion.

The coefficient of determination (R^2) was in the range between 0.998 and 0.999, RMSE from 0.0052 to 0.0255 and χ^2 ranged from 9.275×10^{-5} to 6.72×10^{-4} . The correlation coefficient R^2 was found to be 0.67 between the predicted and experimental values of effective diffusion coefficient. The effective diffusion coefficient was empirically correlated with the concentration and temperature using the Arrhenius-type equation. The Arrhenius model was applied to determine the temperature dependence of k for MR for each sweetener for USOD treatment data. The activation energy was found to be 0.021 J mol⁻¹ (xylitol); 0.304 J mol⁻¹ (erythritol) and 0.358 J mol⁻¹ (sucrose). Lower activation energy facilitates a quicker transition to the reaction's transition state, resulting in a more rapid progression than the reactions with a higher activation energy. The Arrhenius model has been applied by several researchers^{35,36} for OD of fruits such as guava, apricots, aonla and apples in sucrose. This is however the first report on polyols under ultrasonicated conditions.

Effect of ultrasonication on the quality characteristics of candied persimmon

Appearance. The significant effects of ultrasonication on the L^* (brightness/lightness) of candied persimmon slices were observed. The NSOD persimmon candy showed a higher L^* (65.07) than USOD (60.71) with the least significant difference value of 1.82. Higher L^* values indicate the lightness of colour, indicative of less browning. Ultrasonication retained higher colour in candied persimmon slices. No significant difference was observed in a^* (reddish hue), b^* (yellowish hue) and chroma. There was a significant effect of ultrasonication on the total colour difference (ΔE) of candied persimmon slices, with higher values observed for NSOD (8.26) than USOD candies (7.15). Our findings are in accordance with previous studies^{37,38}



which reported better or unchanged color of USOD samples in comparison to OD, as noted for bananas, kiwifruits and pomegranate arils.

Though the difference was non-significant, higher values of browning index were recorded for NSOD candies (0.3948) than those for USOD (0.3857). Rahaman *et al.*³⁹ reported a significant decrease in lightness, *a**, *b** and chroma parameters of USOD plum, which were explained by increased Maillard reactions. The higher *L** and NEB may be attributed to the release of bound sugars contributing to browning reactions during dehydration.

The shrinkage of persimmon slices was much lower in USOD samples (2.72%) than the 8.9% in NSOD candies, thus making the USOD persimmon candy more attractive in appearance. Similar findings have been reported by Prithani and Dash⁴⁰ for US-assisted OD kiwifruit.

Composition of persimmon candies. There was a significant effect of ultrasonication on the moisture content of candied persimmon slices. The moisture content of NSOD persimmon candies ranged widely from 12 to 18% and while that of USOD ranged from 9.55 to 24.22%. The moisture content of infrared (IR) dried NSOD was higher by 2.03% over USIRD candies. In the case of tray-dried (TD) candies also, a higher moisture was retained by NSOD over USOD candies. A higher carbohydrate content was noted for NSOD candies (18.59%) over USOD candies (15.79). This decrease could be due to the loss of sugars on the disruption of fruit tissues during US. A higher carotenoid content was determined for NSOD candies (0.70 mg/100 g) than that of USOD candies (0.58 mg/100 g; Table 2). The loss of carotenoids during US could also be a result of tissue damage and leaching during US. Kroehnke *et al.*⁵ also observed a decrease in carotenoids as well as total phenolics in UOD carrots compared to OD ones, while a better retention of these compounds was achieved when hybrid US-assisted conventional drying was applied.

Ultrasonication caused a reduction in the total phenolic content of persimmon candies. NSOD candies contained higher

phenolics (118.95 mg/100 g) than USOD candies (80.83 mg/100 g). However, the antioxidant activity was not affected by US treatment. Non-significant but higher antioxidant values were estimated for the NSOD samples (27.739 µmol TEAC per g) over USOD candies (23.307 µmol TEAC per gram).

Chandra *et al.*⁴¹ also reported that the sample pre-treated with 33 kHz ultrasound and osmodehydrated with 35 °Brix sucrose resulted in a lower moisture content (<12% w.b.) and water activity (<0.41), higher phenolic content (88.5 mg GAE mL⁻¹), higher β-carotene content (184.54 mg g⁻¹) and antioxidant capacity (48.3%), and preserved color after drying. They recommended the pre-treatment of papaya slices with ultrasound and osmotic dehydration before drying. Li *et al.*³⁴ also reported that Sanhua plum with low ultrasound intensity treatment exhibited a higher antioxidant capacity and total phenolic retention.

Overall, the ascorbic acid content in NSOD candies was higher (126.20 mg/100 g) than USOD candies (110.95 mg/100 g; Table 2). The highest ascorbic acid retention of 49.62% was found for the 60% erythritol USOD candied persimmon slices and dried in an IR dryer (60E USIRD), and the remarkable ascorbic acid retention suggests that erythritol may play a protective role. Erythritol is known for its low hygroscopicity and ability to stabilize the moisture content during drying, which can help maintain the integrity of heat-sensitive compounds such as ascorbic acid. This contrasts with traditional sugar drying methods, where higher sugar concentrations can create a more hostile environment for nutrient retention; followed by 60% sucrose USIRD (43.24%) and 50% xylitol USIRD (39.94%), ultasonication while effective for certain textural improvements may lead to nutrient loss due to the intense energy and pressure changes that can destabilize certain vitamins.

Ultrasonication had significant effects on lowering the bite force of candied persimmon slices. The normal bite force for chocolate candies ranges from 191 to 275 N. The lowest bite force was recorded for 50× USIRD (109 N) and the highest for

Table 2 Nutrient retention in non-sonication and sonication-assisted osmodehydrated persimmon slices using different sweeteners and dried to candies using tray and infrared drying^a

Sweeteners	Concentration	NSOD			Antioxidant activity (µmol TEAC per g)	USOD			Antioxidant activity (µmol TEAC per g)
		Drying technique	Carotenoids (µg per g)	Ascorbic acid (mg/100 g db)		Carotenoids (µg per g)	Ascorbic acid (mg/100 g db)		
Sucrose	60%	Tray	0.35 ± 0.04 ^a	178.40 ± 0.07 ^d	2.96 ± 0.12 ^c	0.23 ± 0.01 ^a	120.37 ± 0.27 ^f	3.35 ± 0.03 ^b	3.35 ± 0.03 ^b
		Infrared	1.78 ± 0.02 ^f	73.40 ± 0.40 ^b	2.36 ± 0.06 ^c	0.37 ± 0.07 ^b	24.29 ± 0.29 ^a	1.31 ± 0.03 ^d	
Erythritol	50%	Tray	0.77 ± 0.03 ^e	200.19 ± 0.47 ^e	1.31 ± 0.08 ^b	0.37 ± 0.09 ^b	78.47 ± 0.60 ^d	2.78 ± 0.10 ^f	2.78 ± 0.10 ^f
		Infrared	0.75 ± 0.01 ^e	36.86 ± 0.14 ^a	1.21 ± 0.06 ^b	0.21 ± 0.08 ^a	60.42 ± 0.44 ^c	4.25 ± 0.48 ^f	
	60%	Tray	0.70 ± 0.04 ^d	66.94 ± 0.93 ^b	5.35 ± 0.10 ^e	0.90 ± 0.03 ^c	105.88 ± 0.21 ^e	7.58 ± 0.09 ^a	
		Infrared	0.64 ± 0.01 ^c	60.69 ± 0.35 ^b	1.26 ± 0.02 ^b	0.32 ± 0.03 ^b	36.78 ± 0.22 ^a	0.26 ± 0.03 ^c	
Xylitol	50%	Tray	1.21 ± 0.04 ^f	179.25 ± 0.43 ^d	0.22 ± 0.04 ^a	0.48 ± 0.01 ^c	101.08 ± 0.54 ^e	0.57 ± 0.06 ^f	0.57 ± 0.06 ^f
		Infrared	0.54 ± 0.04 ^b	40.10 ± 0.12 ^a	0.20 ± 0.01 ^a	0.37 ± 0.02 ^b	49.07 ± 0.80 ^b	1.45 ± 0.01 ^f	
	60%	Tray	0.60 ± 0.02 ^c	99.34 ± 0.57 ^c	8.83 ± 0.17 ^f	0.57 ± 0.03 ^d	128.34 ± 0.46 ^f	0.16 ± 0.03 ^a	
		Infrared	0.52 ± 0.04 ^b	86.84 ± 0.15 ^c	3.15 ± 0.04 ^d	0.83 ± 0.05 ^e	73.00 ± 0.06 ^d	0.47 ± 0.03 ^f	

^a Different letters across individual columns show significant differences (*p* < 0.05) in the mean values of triplicates.



Table 3 Bite force and overall acceptability for non-sonication and sonication-assisted osmodehydrated persimmon slices using different sweeteners and dried to candies using tray and infrared drying^a

Sweeteners	Concentration	Drying technique	Non-ultrasonicated		Sonicated	
			Bite force (N)	Overall acceptability	Bite force (N)	Overall acceptability
Sucrose	60%	Tray	478.43 ± 7.82 ^d	7.91 ± 0.08 ^d	117.15 ± 3.55 ^a	8.00 ± 0.04 ^b
		Infrared	262.72 ± 8.87 ^b	7.89 ± 0.09 ^c	226.87 ± 9.42 ^b	8.00 ± 0.05 ^b
Erythritol	50%	Tray	293.1 ± 3.34 ^b	7.97 ± 0.04 ^d	213.52 ± 3.15 ^b	8.26 ± 0.06 ^d
	60%	Tray	323.77 ± 9.28 ^c	7.84 ± 0.01 ^c	244.01 ± 5.16 ^b	8.35 ± 0.07 ^e
Xylitol	50%	Tray	349.98 ± 6.05 ^c	7.84 ± 0.07 ^c	208.71 ± 1.99 ^b	8.15 ± 0.09 ^c
	60%	Infrared	293.5 ± 4.29 ^b	7.66 ± 0.08 ^b	208.59 ± 8.58 ^b	8.34 ± 0.04 ^e
Xylitol	50%	Tray	447.35 ± 2.47 ^c	7.93 ± 0.07 ^d	334.01 ± 15.84 ^c	8.05 ± 0.04 ^f
	60%	Infrared	315 ± 1.69 ^a	8.41 ± 0.04 ^e	109.64 ± 3.64 ^a	8.69 ± 0.05 ^f
Xylitol	60%	Tray	435.41 ± 6.68 ^b	7.34 ± 0.02 ^a	242.53 ± 10.69 ^c	7.75 ± 0.08 ^a
		Infrared	437.84 ± 6.76 ^d	7.16 ± 0.04 ^a	213.36 ± 3.28 ^b	7.89 ± 0.09 ^a

^a Different letters across individual columns show significant differences ($p < 0.05$) in the mean values of triplicates.

60S TD (478.43 N; Table 3). The 60S TD sample indicates that traditional drying methods without ultrasonication can lead to denser and tougher textures. This aligns with the findings of Li *et al.*³⁴ which showed that ultrasound treatment effectively softens fruit by altering its physical properties, thereby enhancing consumer acceptance. In the 50× USIRD samples, ultrasound treatment not only improved the texture but also resulted in a more appealing product with a desirable mouth-feel. Chandra *et al.*⁴³ also reported more desirable texture (hardness) of the USOD papaya from an industrial standpoint,

which was further validated using SEM micrographs that showed a more porous structure.

Regarding the bite force, the substantial reduction observed in the ultrasonicated samples can be explained by the effect of ultrasonication on the cellular structure of the persimmons. Ultrasonication generates high-frequency sound waves that create cavitation bubbles in the liquid surrounding the fruit. When these bubbles collapse, they produce micro-jets that can disrupt the cell walls of the fruit. This breakdown in structure can lead to a softer texture, making the candies easier to chew.

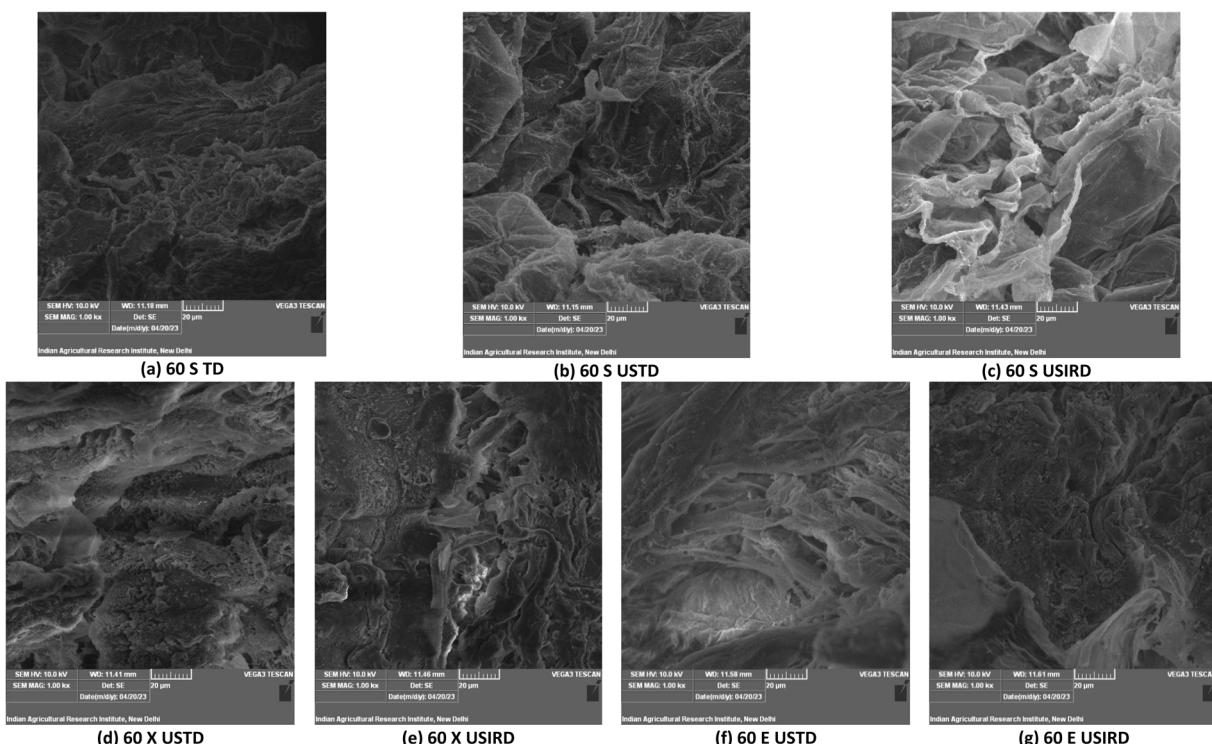


Fig. 3 SEM images for selected candied persimmon slices prepared with different sweeteners (a) 60% sucrose NSOD tray dried; (b) 60% sucrose USOD tray dried; (c) 60% sucrose USOD infra red dried; (d) 60% xylitol USOD tray dried; (e) 60% xylitol USOD infra red dried; (f) 60% erythritol USOD tray dried; and (g) 60% erythritol USOD infra red dried.



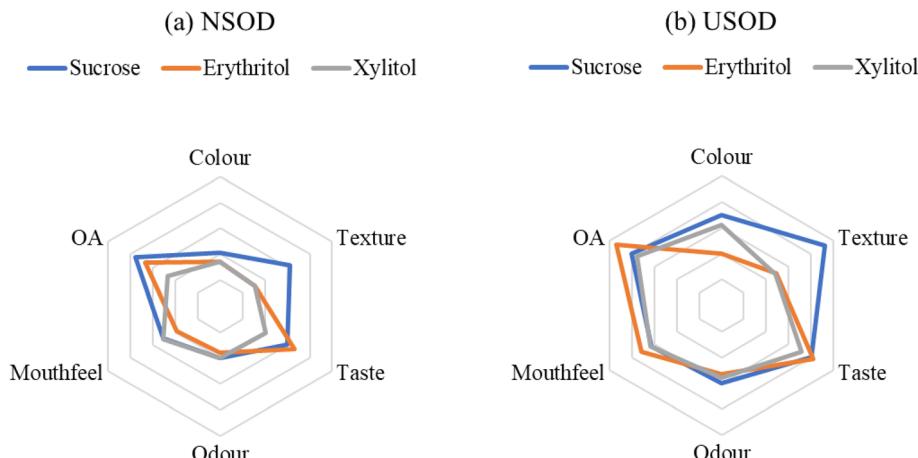


Fig. 4 Sensory scores for candied persimmon slices prepared with (a) NSOD and (b) USOD.

Overall, the importance of selecting appropriate drying and treatment methods to optimize both nutritional content and textural characteristics in fruit processing ultimately enhances the quality and marketability of the final product.

Microstructural analysis. Fig. 3 presents the detailed SEM images (1000 \times magnification) of OD persimmon candies subjected to ultrasonication. The tray-dried persimmon candies exhibited a denser composition. Notably, ultrasonicated persimmon candies subjected to infrared drying display a distinctive ribbon-like arrangement at 60XIRD, indicating a loose and less compact structure. This structural variation contributes to a diminished bite force, resulting in a desirable mouthfeel (Table 3). Among the samples tested, the ultrasonicated infrared dried persimmon candies displayed the most favorable attributes, particularly those treated with sucrose, which exhibited a well-defined network structure with minimal disruption compared to those treated with xylitol and erythritol.

Sensory evaluation. USOD candies scored higher in terms of appearance, texture, taste, smell, mouthfeel and overall acceptability over NSOD candies on 9-point hedonic scale (Fig. 4). The Hedonic scores for the appearance of candied persimmon slices were higher for USOD treatment (7.14) over the NSOD samples (6.73). Similarly, odour (7.15), mouthfeel (7.28), texture (7.03) and taste (7.28) of the USOD candied persimmon slices were significantly higher. The corresponding scores for NSOD candies were 6.79; 6.84; 6.71 and 6.85, respectively.

The better sensory experience of USOD could be due to the lesser force required for mastication and better release of flavour due to disrupted tissue structure caused by ultrasonication. Higher total solid retention in USOD candies might also enhance the flavour and taste appeal of consumers. Sensory evaluation results clearly indicated significantly higher overall acceptability for USOD candies (7.35) over NSOD (6.98; Table 3). Thus, ultrasonication played an important role in enhancing the mouthfeel and appearance, ultimately resulting in very good overall acceptability. The highest overall acceptability scores were those of erythritol followed by xylitol and sucrose.

Conclusion

Our study on the composition of the Fuyu persimmon variety revealed its rich nutritional profile, with high moisture content (82.62%), sugars (16.17%), total soluble solids (21.3 °Brix), and notable levels of carotenoids and phenolics. The effect of ultrasonication on osmodehydration showed significant improvements in water loss, solid gain, and drying kinetics across different sweeteners, particularly xylitol and erythritol. Ultrasonication-assisted osmodehydration (USOD) enhanced the quality of candied persimmons, resulting in better color retention, texture, and overall sensory acceptability compared to non-sonicated samples. The logistic model provided the best fit for predicting moisture ratio changes during drying. Overall, ultrasonication proved to be a beneficial pre-treatment for improving the efficiency and quality of persimmon osmodehydration. The study conclusively demonstrated that ultrasonication, when combined with specific sweeteners and infrared dehydration technique, had a substantial impact on the physical, chemical, and sensory attributes of persimmon candies. The findings suggest that ultrasonication holds great potential for the valorization of persimmons, opening avenues for further research in optimizing process parameters and exploring its applicability in other fruits and food products. Based on the study, further research avenues could include investigating the scalability of ultrasonication-assisted osmodehydration for industrial applications. Additionally, exploring the economic feasibility and environmental impact of this novel technique would be valuable for commercial adoption.

Abbreviations

OD	Osmodehydration
US	Ultrasonication
MR	Moisture ratio
NSOD	Non-sonicated osmodehydration
USOD	Ultrasonication-assisted osmodehydration



Data availability

The data shall be made available upon reasonable request.

Conflicts of interest

The authors report no conflict of interest.

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