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The impact of multiple pre-treatment combinations and storage on some quality parameters of apple chips fried by vacuum combined infrared radiation

S. Uğurlu[a,✉], E. Bakkalbaşı[b] and İ. Cavidoğlu[b]

[a]Department of Plant and Animal Production, Yüksekova Vocational School, Hakkari University, Hakkari, 30100, Türkiye
[b]Department of Food Engineering, Faculty of Engineering, Van Yüzüncü Yıl University, Zeve Campus, 65080 Van, Türkiye
✉Corresponding author: serdarugurlu@hakkari.edu.tr

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SUMMARY: The effects of citric acid, ethanol, and ultrasound pre-treatments and storage on the quality characteristics of semi-dried and subsequently fried apple chips by using vacuum combined infrared technique were investigated. While increasing ethanol concentration resulted in better color values and lower 5-hydroxymethylfurfural (HMF) content, the fat content in the sample increased with increasing ultrasound amplitude. The most effective pre-treatment for the production of apple chips with lower fat content and higher general acceptability was the combination of 50% ultrasonic amplitude/100% ethanol/%0.75 citric acid. During storage, while peroxide and *p*-anisidine values remained almost constant at 20 °C, these parameters showed an increasing trend at 30 and 40 °C. *P*-anisidine values of samples kept at 30 and 40 °C showed a remarkable increase after the 4th and 2nd months, respectively. The results showed that the 50% ultrasonic/100% ethanol/0.75% citric acid combination, could be successfully applied as a pre-treatment to produce fried apple chips with higher quality and greater oxidative stability.

KEY-WORDS: *Apple chips; Ethanol; Infrared frying; Oxidation; Ultrasound.*

RESUMEN: ***Impacto de múltiples combinaciones de pretratamientos y almacenamiento en algunos parámetros de calidad de chips de manzana fritas al vacío con radiación infrarroja combinada.*** Se investigaron los efectos del ácido cítrico, etanol, pretratamientos ultrasónicos y el almacenamiento sobre las características de calidad de chips de manzana semisecos y posteriormente fritos mediante técnicas de infrarrojos combinados al vacío. Si bien el aumento de la concentración de etanol resultó en mejores valores de color y un menor contenido de 5-hidroximetilfurfural (HMF), el contenido de grasa de la muestra aumentó con el aumento de la amplitud ultrasónica. El pretratamiento más eficaz para la producción de chips de manzana con menor contenido de grasa y mayor aceptabilidad general fue la combinación de 50% de amplitud ultrasónica/100% de etanol/0,75% de ácido cítrico. Durante el almacenamiento, si bien los valores de peróxido y *p*-anisidina se mantuvieron casi constantes a 20 °C, estos parámetros mostraron una tendencia ascendente a 30 y 40 °C. Los valores de *p*-anisidina de las muestras conservadas a 30 y 40 °C mostraron un aumento notable después del cuarto y segundo mes, respectivamente. Los resultados mostraron que la combinación de 50 % de ultrasonidos/100 % de etanol/0,75 % de ácido cítrico, podría aplicarse con éxito como pretratamiento para producir chips de manzana fritos con mayor calidad y estabilidad oxidativa.

PALABRAS CLAVE: *Chips de manzana; Etanol; Fritura por infrarrojos; Oxidación; Ultrasonido.*

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1. INTRODUCTION

Apples are grown in many countries around the world and have been used as an important raw material for many food products (Velić *et al.,* 2004). As a rich source of monosaccharides, minerals, dietary fiber, and various biologically active compounds, such as vitamin C, and certain phenolic compounds which are known to act as natural antioxidants, the apple constitutes an important part of the human diet (Wu *et al.,* 2007). Apples and apple-derived products have been linked to beneficial effects against cancer, cardiovascular, asthma, and Alzheimer diseases due to their antioxidant contents (Hyson, 2011).

There are several apple-derived products such as canned apples, apple juice, dried apples, fried apple chips, etc. As a popular method in food processing, frying increases the flavor of food, speeds up the cooking process, and enhances its shelf-life. Deep fat frying, also known as immersion frying, is the method of cooking and removing moisture from foods by submerging them in hot oil. During frying, chemical and physical structural changes such as starch gelatinization, protein denaturation, taste development, decrease in moisture content, increase the oil content and crust formation occurs on the product (Moreira, 2014). The snack industry has been compelled by consumer demand for healthier foods to create substitute technologies for conventional frying while maintaining their distinctive flavors and textures.

The quality of fried foods is enhanced by innovative technologies including vacuum, microwave, infrared, pulsed electric fields, superheated steam drying, and ultrasound (Oladejo *et al.,* 2018). Vacuum frying has been a particularly noteworthy option among the innovative techniques. Vacuum frying with shorter application time compared to deep fat frying reduces the rate of deterioration reactions in the oil and improves product quality (Crosa *et al.,* 2014). Vacuum frying seems to be the best option to reduce the disadvantages of conventional cooking methods such as oil frying, which leads to the formation of compounds (eg. acrylamide) with harmful effects (Choudhari *et al.,* 2023).

Recently, the superiority of infrared frying regarding the quality of fried products and frying medium has garnered a lot of attention. Infrared frying also slows down the deterioration of oil and enhances the physicochemical characteristics of fried fruits and vegetables (Su *et al.,* 2022). In addition, infrared frying allows efficient heat transfer and low energy cost (Rastogi, 2012). In recent years, vacuum combined infrared radiation has been used as a frying technique with a potential to reduce the fat content and the rate of oxidation in fried apple chips without sacrificing the color quality (Uğurlu *et al.,* 2024).

Some pre-treatment methods such as ethanol, ultrasound and pre-drying have been used for lowering oil levels and increasing the quality of fried foods. Ethanol has the potential to quickly replace water under the influence of ultrasound, thereby significantly improving the food drying process and the quality of the dried food (Feng *et al.,* 2019). Gao *et al.* (2021) noted that pretreating apples with ethanol and ultrasound before frying improved the appearance, increased their total phenolic and flavonoid levels, and decreased oil uptake. Uğurlu *et al.* (2024) found that the pre-drying treatment improved the fried samples' qualitative attributes. The frying time, oil content, browning, and oxidation rate of fried apples were decreased with pre-drying treatment.

The aim of this study was to determine the differences in the quality characteristics of apple chips, semi-dried after some pre-treatments (ethanol, ultrasound, citric acid and their combinations) and then fried using the vacuum combined infrared technique. It was also aimed to determine the effect of storage on the physicochemical properties of apple chips.

2. MATERIALS AND METHODS

2.1. Sample preparation and pre-treatments

A manual fruit slicer was used to cut the fresh apple samples (Starking Delicious from Hakkari province, Türkiye) into 3 mm thick slices after the peel was removed.

Absolute ethanol (99.9%) without (E100) and with ultrasound treatment (E100US), ethanol: distilled water (1:1) without (E50) and with ultrasonic treatment (E50US), and distilled water without (E0) and with ultrasound treatment (E0US) were the solutions in which the samples were submerged. Citric acid (0.75 g/100 ml) was added to different immersion solutions. The ratio of apple slices to immersion solutions, amplitude values, and citric acid were selected after preliminary experiments. Sunflower oil (Yudum Oils, Balıkesir, Türkiye) intended for frying was purchased from a local market in Van, Türkiye. A probe connected to a 20 kHz frequency ultrasonic generator (Bandelin Sonopuls, HD 3200, Germany) running at 200 W power was used to sonicate the samples at specific amplitudes of 0, 50, and 100%. Each pre-treatment had a 1:4 ratio (sample weight/solution volume) and lasted 5 min. A schematic representation of the experimental design is given in Figure 1.

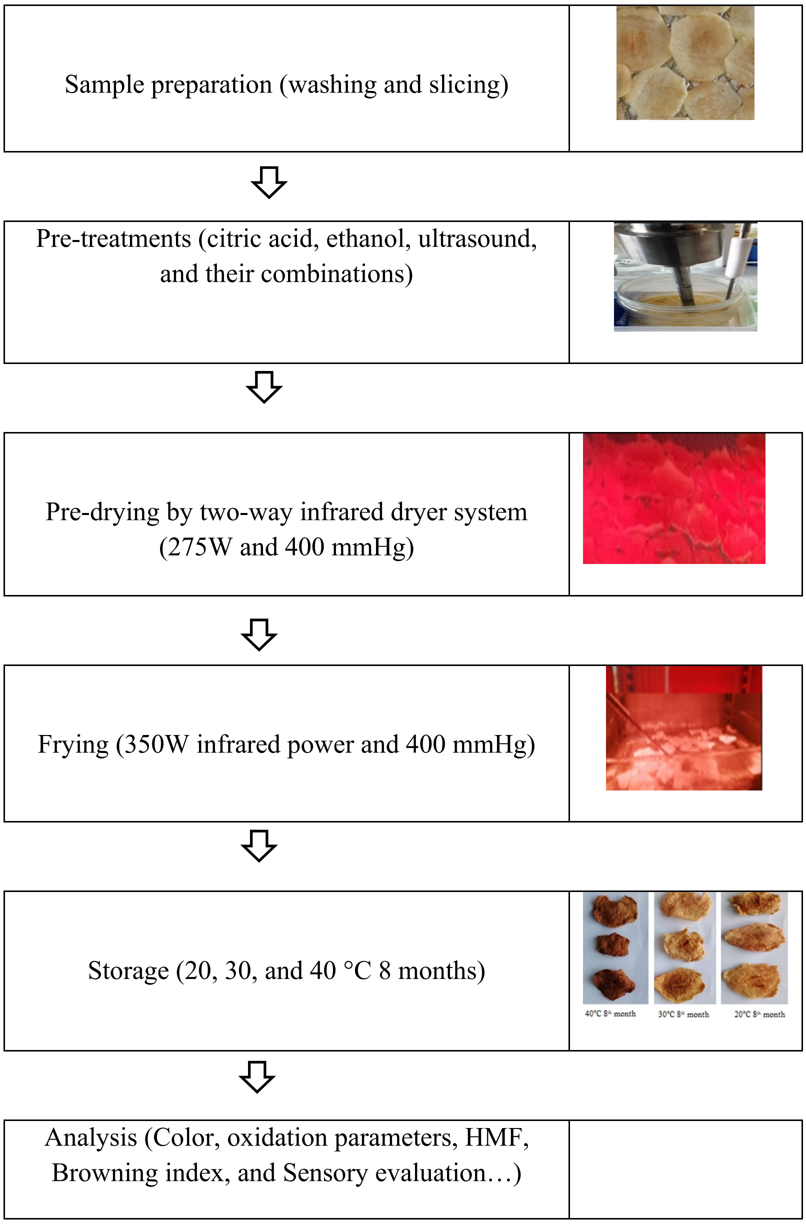

FIGURE 1. Schematic representation of experimental design.

2.2. Pre-drying and frying process

A vacuum pump (DOA-P730-BN, USA) in combination with a new two-way infrared dryer system (Uniterm, Ankara) (VCIR) was used for the pre-drying of apple slices. Four 250 W infrared lights were placed on the oven's floor and ceiling as part of the drying system, and slices were spaced 12 cm apart from the lamps. The duration of the pre-drying process was approximately 38 min. While the initial moisture content of the apple slices was 84.41±0.28% (w.b) (Uğurlu *et al.,* 2023), the apple slices after pre-treatment were dehydrated to 41% moisture content by VCIR dryer at 275 W and 400 mmHg.

For frying, two 250 W infrared lamps placed 12.5 cm above the oil surface were used. The sample/oil ratio was kept at 1:20 (weight/volume). Pre-dried apple slices were fried at 350 W infrared power and 400 mmHg vacuum pressure. The frying process was stopped when the samples reached a moisture content of 1.5-2.5% (w.b). After frying, the chips were centrifuged at 1600 g for 5 min. to remove excess oil. The oven-drying procedure was used to determine the samples' moisture levels (AOAC, 2003).

2.3. Storage

The apple chips with the highest scores in the sensory analysis were used for storage. The 20 g chips were packed in metalized PET (polyethylene terephthalate) packaging and stored in incubators at 20, 30, and 40 °C for 8 months. At the 1st, 2nd, 4th, 6th, and 8th months, five packages from each sample group were used for physical and chemical analyses.

2.4. Color analysis

The L*, a*, and b* values of the apple chips were determined by using a Konica Minolta CR-400 chromometer (Japan). Five slices of the samples were taken and three readings were made on each slice.

2.5. HMF

For HMF extraction, 1 g of de-oiled apple chips was mixed with 15 mL of 80% methanol in a centrifuge tube. The mixture was shaken at 150 rpm for 2 h at room temperature in the dark and centrifuged at 8000 xg for 10 min at 4 °C. The residue and 10 ml of the same solvent were used for a second extraction. The collected supernatants were combined and adjusted with 80% methanol to a volume of 25 mL (Bakkalbaşı *et al.,* 2013).

A HPLC system (Shimadzu, Kyoto, Japan) equipped with a Symmetry C18 column (250×4.6 mm id, particle size 5 µm) was used for HMF analysis. Column temperature was 25 °C and flow rate was 1.0 mL/min under isocratic conditions. The mobile phase was composed of 2% acetic acid in water (A) and 0.5% acetic acid in a water and acetonitrile mixture (1:1, v/v; B). The HMF standard (2295.2, Carl Roth, Germany) was used for the identification and quantification of the HMF (Colaric *et al.,* 2005).

2.6. Browning index value

The browning index (BI) value was calculated using the methodology of Akyıldız and Öcal (2006). A de-oiled sample (1 g) was mixed with 25 mL of distilled water, homogenized for 30 seconds at 10,000 rpm and kept at ambient temperature for 1 h. The homogenate was centrifuged for 20 min. at 800×g. After adding 15 mL of 95% ethanol to 10 mL of the supernatant, the mixture was centrifuged once more at 800×g for 20 min. A spectrophotometer (8453, Agilent, USA) was used to measure the absorbance of the supernatant at 420 nm in order to calculate the BI in terms of absorbance (Abs/g initial DM).

2.7. Oil

The Soxhlet extraction method was used to determine the oil content in fried apple slices (AOAC, 2003). A 10 g sample was extracted with 150 mL n-hexane in a Soxhlet extractor for 6 h. At the end of the extraction, n-hexane was removed in a rotary evaporator under vacuum at 40 ºC. The remaining oil was then dried in an oven at 105 ºC until constant weight.

2.8. Oil extraction and oxidation parameters

Cold extraction was carried out to extract the oil from the fried apple slices. The slices were ground in a coffee grinder and mixed with n-hexane (10 times of the estimated oil content in the sample). The mixture was put in an extraction flask under nitrogen flux and shaken at 180 rpm for 2 h at room temperature in the dark. Following extraction, the mixture was filtered and n-hexane was removed using a rotary vacuum evaporator (R100, Buchi, Switzerland). Cold extracted oil was used for the determination of peroxide value (PV) and p-anisidine value (AV).

The PV and AV of the oil extracted from the samples were determined according to the official methods recommended by AOCS (Cd 8-53 and Cd 18-90, respectively) (AOCS, 2006). The TOTOX value was calculated by the following equation (Shahidi and Wanasundara, 2002).

$$\text{TOTOX value} = 2(\text{PV}) + \text{AV} \tag{1}$$

2.9. Sensory evaluation

In a fully randomized design, sixteen semi-trained panelists evaluated the sensory qualities of the apple chips, which were coded with a three-digit random number. Using a nine-point hedonic scale, ranging from 1 (extremely disliked) to 9 (extremely liked), the panelists evaluated the fried apple chips' appearance, color, odor, crispness, chewiness, flavor, oiliness, and overall acceptability (Soysal *et al.,* 2009).

2.10. Statistical analysis

SPSS 20.0 software was used to perform one-way variance analysis on the experimental data. The groups that were statistically different ($p < 0.05$) were identified using a Duncan multiple comparison test.

3. RESULTS AND DISCUSSION

3.1. Some physical and chemical properties of apple chips

Frying time and some physical and chemical properties of the samples are given in Table 1. The pre-treatments applied to the apple slices did not make a significant impact on the frying time (5 min 50 sec-8 min). The moisture contents in samples varied in a narrow range (2.03-2.36%). However, the ultrasound amplitudes (0, 50, and 100%) and the ethanol concentrations (0 and 50%) were significantly affected the moisture contents ($p < 0.05$).

TABLE 1. Frying time, some physical and chemical properties of samples (n=5)

Samples	Frying times	Moisture Content	L*	a*	b*	Browning index	HMF	Oil (g oil/ 100 g)
Fresh apple*	-	84.41±0.28	74.37±0.82	0.39±0.56	18.00±1.55	0.001±0.00	-	-
E0-0US**	5 min 50 sec	2.34±0.14^{deB2}	60.51±3.71^{abA1}	7.59±1.89^{bcA2}	29.57±2.72^{abA1}	0.070±0.00^{aA12}	208.31±21.62^{abA1}	30.69±0.28^{bA1}
E0-50US	8 min	2.03±0.04^{aA1}	59.17±2.40^{abA1}	7.95±2.32^{cA2}	30.36±1.82^{abA1}	0.080±0.01^{aA1}	372.92±163.19^{bcdA1}	33.26±0.14^{dB3}
E0-100US	7 min	2.32±0.00^{deB1}	58.03±2.87^{aA1}	8.39±1.24^{cA1}	30.80±1.48^{bA1}	0.085±0.03^{aA1}	413.95±88.73^{cdA12}	36.07±0.28^{gC2}
E50-0US	6 min 25 sec	2.36±0.00^{eB2}	61.11±3.28^{abA1}	6.75±2.73^{abcA12}	27.44±4.97^{aA1}	0.074±0.01^{aA2}	375.59±73.18^{bcdA2}	34.46±0.24^{fC2}
E50-50US	6 min 30 sec	2.17±0.01^{bcA2}	59.13±3.90^{abA1}	7.46±1.61^{bcA12}	28.97±1.82^{abA1}	0.081±0.04^{aA1}	418.46±58.25^{cdA1}	33.79±0.13^{eB2}
E50-100US	6 min 45 sec	2.32±0.05^{deB1}	58.11±1.74^{aA1}	7.61±1.13^{bcA1}	30.01±2.94^{abA1}	0.083±0.00^{aA1}	522.74±11.64^{dA2}	31.74±0.05^{cA1}
E100-0US	6 min 45 sec	2.06±0.00^{abA1}	62.08±1.98^{bA1}	5.09±0.99^{aA1}	27.83±1.13^{abA1}	0.043±0.00^{aA1}	178.66±1.49^{aA1}	30.37±0.26^{bB1}
E100-50US	6 min 35 sec	2.17±0.00^{bcB2}	61.46±2.68^{abA1}	5.29±1.23^{abA1}	28.66±1.34^{abA1}	0.061±0.00^{aA1}	218.62±71.74^{abA1}	27.97±0.02^{aA1}
E100-100US	6 min 45 sec	2.22±0.03^{cdB1}	59.67±3.25^{abA1}	6.36±2.53^{abcA1}	29.43±1.91^{abA1}	0.071±0.02^{aA1}	319.80±61.34^{abcA1}	28.34±0.22^{aA1}

Values are given as mean±standard deviation. Lowercase letters show the differences among samples in the same column according to the Duncan multiple comparison test. Uppercase letters show the differences among the ultrasound amplitudes of the samples to which the same ethanol concentration was applied. Numbers show the differences among the ethanol concentrations of the samples to which the same ultrasound amplitude was applied ($p < 0.05$). * and ** were reported previously in our studies (Uğurlu *et al.,* 2023; and Uğurlu *et al.,* 2024). Abbreviations: Ethanol is abbreviated as E, and the number next to E gives the ethanol concentration (%). Ultrasound is abbreviated as US, and the number before US shows the amplitude (%). 0.75% citric acid was added to all samples.

As expected, fried samples showed lower L* values (lightness) than the fresh samples probably due to browning reactions which occurred during processing. While the samples with increasing ethanol concentration showed a lower decrease in L* value, the samples treated with higher ultrasound amplitude gave lower L* values. The L* values generally increased as the ethanol ratios in the samples exposed to the same ultrasonic amplitude increased. As expected, The L* value was negatively related to the BI.

The a* (redness) and b* (yellowness) values of the fried samples were found to be significantly higher than those of the fresh apple. Samples treated with 100% ethanol concentration showed the highest L* and the lowest a* and b* values. The ethanol concentration significantly affected the a* values of samples treated with 0 and 50% ultrasound amplitude ($p < 0.05$). It was also observed that the samples exposed to higher frying time (7 and 8 min) showed lower L* and higher a* and b* values than the other treatments. Gao *et al.* (2021) noted that the color and appearance of deep-fried apple slices were generally improved by the combined ultrasonic and ethanol pre-treatment.

The BI and HMF contents in the apple chips samples ranged between 0.043 and 0.085 Abs/g initial DM and 178.66 and 522.74 mg/kg DM, respectively. The frying process significantly increased the BI and HMF of the samples ($p < 0.05$). The BI slightly increased with increasing ultrasound amplitude ($p > 0.05$). The BI of the ethanol-treated samples showed irregular variations. Ultrasound amplitude significantly increased the HMF contents in the samples. Interestingly, samples with 100% ethanol and increasing ultrasound amplitude showed lower BI and HMF than their counterparts with lower ethanol ratios (E0 and E50) and the same ultrasound amplitude. The 100% ethanol treatment probably caused the extraction of compounds that contributed to browning and HMF formation. The most remarkable result was found in the E100-0US treated sample, with the lowest HMF (178.66 mg/kg DM) and BI values (0.043 Abs/g initial DM). The HMF contents in the samples pretreated with E100-0US samples were higher than those reported by Topuz *et al.* (2023) for pear sample dried with vacuum-combined infrared radiation at 300W infrared power and 250 mmHg vacuum pressure for 120 min (132.94 mg/kg DM). Different production techniques and pre-treatments may lead to these differences. Frying is a more rigid technique compared to drying. Deng *et al.* (2018) reported that the BI values in red peppers dried at different temperatures (60-80 °C) by infrared radiation-assisted hot air-drying ranged from 0.32 to 0.80 Abs/g DM.

3.2. Oil content and oxidation parameters

The oil contents in the fried apple chips varied between 27.97 and 36.34 g oil/ 100 g (Table 1). It was found that when ultrasound was applied alone, the oil content in the samples was increased with increasing ultrasound amplitude ($p < 0.05$). The deformation of the structure due to ultrasound treatment led to rapid evaporation of water and consequently the displacement of water with oil, resulting in an increase in oil content. As the ethanol concentration and the ultrasound amplitude increased, a decrease in the oil content of the samples was detected. The morphological observation showed that the ultrasound+ethanol pre-treatment produced a denser and smoother surface as well as more micron-sized pores on the crust of fried apple slices, which would be the primary cause of the decrease in oil uptake (Gao *et al.,* 2021). Gao *et al.* (2021) noted that the oil uptake was achieved at the lowest value and reduced by 34.5 and 28.2% in the fried apple samples which were pre-treated with 95% ethanol and US+ethanol, respectively, compared to the untreated samples (60.5 g/100 g db). Uğurlu *et al.* (2024) reported that the apple chip samples fried under VCIR showed lower oil contents than their deep-fried counterparts.

The peroxide, p-anisidine, and TOTOX values for the frying oils were higher than those for fresh oil ($p < 0.05$) The PV, AV, and TOTOX values for fresh oil were found to be 5.62 meq O_2/kg oil, 4.44, and 15.69, respectively (Uğurlu *et al.,* 2024) and those extracted from fried samples varied between 13.95 and 20.71 meq O_2/kg oil, 9.29-16.75, and 41.99-57.06, respectively (data not in tabular form).

3.3. Sensory evaluation

The results of the sensory analysis of the experimental apple chips samples are given in Table 2. It was found that the appearance and color scores increased with increasing ultrasound amplitude in fried apple chips without (0%) and with 100% ethanol pre-treatment. Ultrasound amplitude significantly affected the color, crispness, and chewiness of the samples prepared without ethanol treatment as well as the appearance, color, and general acceptance of the sample prepared with 50% ethanol, and the appearance and color of the sample prepared with 100% ethanol ($p < 0.05$). Ethanol concentration significantly affected the color, odor, crispness, chewiness, and taste of non-ultrasound treated samples along with the appearance, color, crispness, chewiness, taste and general acceptance of 50% ultrasound treated sample, and the appearance, color, crispness, chewiness, taste, and general acceptance of 100% ultrasound treated samples ($p < 0.05$). The apple chips pretreated with 50% amplitude had generally high scores for all ethanol concentrations. The highest odor, crispness, chewiness, taste, oiliness, and general acceptance scores were obtained for the E100-50US sample. Zhang *et al.* (2021) studied the effect of ultrasound pre-treatment on potato slices fried at 180 °C. It was reported that the potato chips pretreated with ultrasound had the lowest fat content and the highest general acceptance score. The higher overall liking score of ultrasound pretreated potato chips may be due to the reduction in fat content (Zhang *et al.,* 2021). Similarly, in our study, the E100-50US sample with the lowest fat content received the highest appreciation scores and was the most preferable sample.

TABLE 2. Sensory characteristics of samples (n=5).

Sample	Appearance	Color	Odor	Crispness	Chewiness	Taste	Oiliness	General Acceptance
E0-0US	5.75 ± 1.91^{bA1}	5.16 ± 2.12^{aA1}	6.75 ± 0.86^{abA1}	5.75 ± 1.81^{abA1}	5.25 ± 1.76^{aA1}	6.58 ± 1.50^{abA12}	6.41 ± 1.62^{abA1}	6.16 ± 1.40^{abA1}
E0-50US	6.33 ± 1.61^{bcA1}	6.41 ± 1.50^{bAB1}	6.75 ± 1.21^{abA1}	7.33 ± 0.98^{cdeB12}	7.41 ± 0.90^{deB12}	7.00 ± 1.47^{abA12}	6.58 ± 1.78^{abA1}	7.08 ± 0.99^{bcdA1}
E0-100US	7.00 ± 0.85^{cdA2}	7.33 ± 0.88^{bcB2}	6.75 ± 0.75^{abA1}	6.16 ± 1.58^{abcAB1}	6.00 ± 1.53^{abA1}	6.50 ± 1.24^{abA12}	6.16 ± 1.40^{aA1}	6.25 ± 1.28^{abA1}
E50-0US	6.66 ± 1.23^{bcdB1}	6.75 ± 1.28^{bB2}	6.75 ± 0.86^{abA1}	5.66 ± 1.77^{abA1}	5.91 ± 1.83^{abA12}	6.08 ± 1.44^{aA1}	6.25 ± 1.48^{aA1}	6.16 ± 1.26^{abAB1}
E50-50US	7.00 ± 0.85^{cdB12}	6.91 ± 0.99^{bB12}	6.91 ± 0.90^{abA1}	6.75 ± 1.21^{bcdA1}	6.58 ± 1.24^{bcdA1}	6.41 ± 1.31^{abA1}	6.58 ± 1.50^{abA1}	6.83 ± 0.83^{bcB1}
E50-100US	4.66 ± 1.66^{aA1}	4.58 ± 1.62^{aA1}	6.50 ± 1.16^{aA1}	5.50 ± 1.50^{aA1}	6.16 ± 1.02^{abcA1}	6.16 ± 0.83^{aA1}	6.08 ± 0.79^{aA1}	5.75 ± 0.75^{aA1}
E100-0US	6.66 ± 1.07^{bcdA1}	6.66 ± 1.30^{bA2}	7.50 ± 0.67^{bA2}	7.58 ± 1.31^{deA2}	6.91 ± 1.50^{bcdeA2}	7.33 ± 1.15^{bA2}	7.33 ± 1.15^{abA1}	7.25 ± 1.05^{cdA1}
E100-50US	7.66 ± 1.07^{deB2}	7.58 ± 1.16^{bcAB2}	7.33 ± 0.88^{abA1}	8.08 ± 0.99^{eA2}	8.00 ± 1.12^{eA2}	7.50 ± 0.79^{bA2}	7.50 ± 1.08^{bA1}	8.00 ± 0.73^{dA2}
E100-100US	8.33 ± 0.65^{eB3}	8.33 ± 0.77^{cB3}	7.08 ± 0.79^{abA1}	7.75 ± 0.86^{deA2}	7.33 ± 1.07^{cdeA2}	7.16 ± 0.71^{abA2}	6.83 ± 0.71^{abA1}	7.58 ± 0.79^{cdA2}

Values are given as mean±standard deviation. Lowercase letters show the differences among samples in the same column according to the Duncan multiple comparison test. Uppercase letters show the differences among the ultrasound amplitudes of the samples to which the same ethanol concentration was applied. Numbers show the differences among the ethanol concentrations of the samples to which the same ultrasound amplitude was applied ($p < 0.05$). Abbreviations: Ethanol is abbreviated as E, and the number next to E gives the ethanol concentration (%). Ultrasound is abbreviated as US, and the number before US shows the amplitude (%). 0.75% citric acid was added to all samples.

3.4. The effect of storage conditions on some quality parameters of apple chips

The E100-50US sample, which had the highest general acceptance, was selected to assess the impact of storage time and temperature on the quality of apple chips. The samples were stored at 20, 30, and 40 °C for eight months. The initial moisture content in the E100-50US sample used for storage was 2.17% and the moisture content in the samples stored at 20, 30, and 40 °C for 8 months increased to 3.91, 3.39, and 2.33%, respectively (Figure 2). The moisture content in the stored apple chips at 20 °C increased continuously during the storage period and the moisture contents in the samples stored at 30 and 40 °C increased until the 4th month and then started to decrease. The storage temperature and time significantly affected the moisture contents in the samples during storage ($p < 0.05$). These changes are related to moisture permeability of the packaging material and relative humidity inside the incubator. Higher temperatures lead to lower relative humidity in the storage atmosphere. This may cause a decrease in the moisture content in apple chips stored at high temperatures after 4 months. L* and b* values for the samples decreased during the 8 months of storage. However, a steady increase in a*, BI, and HMF was observed during the storage of apple chips (Figures 3 and 4).

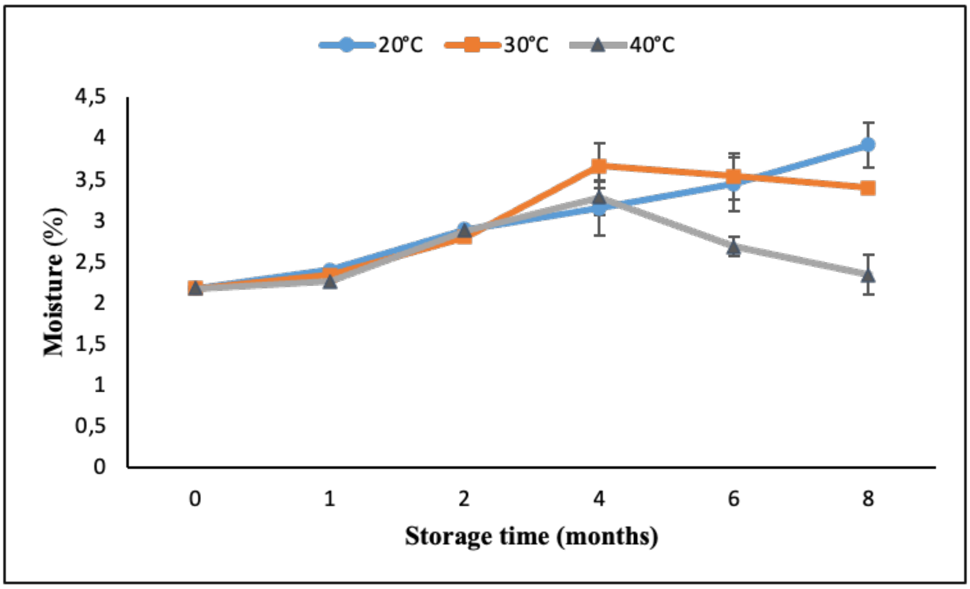

FIGURE 2. Moisture contents in the samples stored at different temperatures (n=5).

Similar findings for L*, a*, and b* were reported by Piyalungka *et al.* (2019) in vacuum fried pumpkin during 35 days of storage. Liu *et al.* (2017) reported that the decrease in L values of vacuum-fried Pleurotus eryngii might be due to non-enzymatic browning, including Maillard reaction and lipid oxidation. Samples stored at the highest temperature (40 °C) showed the most significant differences in terms of color values (L*, a*, and b*), HMF, and BI when compared to their counterparts kept at 20 and 30 °C. The HMF content, a*, and BI values of samples stored at 20 and 30 °C were significantly lower compared to those stored at 40 °C ($p < 0.05$). While L* and a* values were significantly changed at all temperatures ($p < 0.05$), there were significant changes in b*, HMF, and BI values only in samples stored at 30 and 40 °C ($p < 0.05$). The HMF content in the initial sample was high, and it gradually increased with increasing storage temperature and time. A similar situation was reported by Liu *et al.* (2017). However, BI values sharply increased at 40 °C after 2 months of storage. In this case, 2 months of storage at a high temperature may be sufficient for the formation of melanoidin pigments.

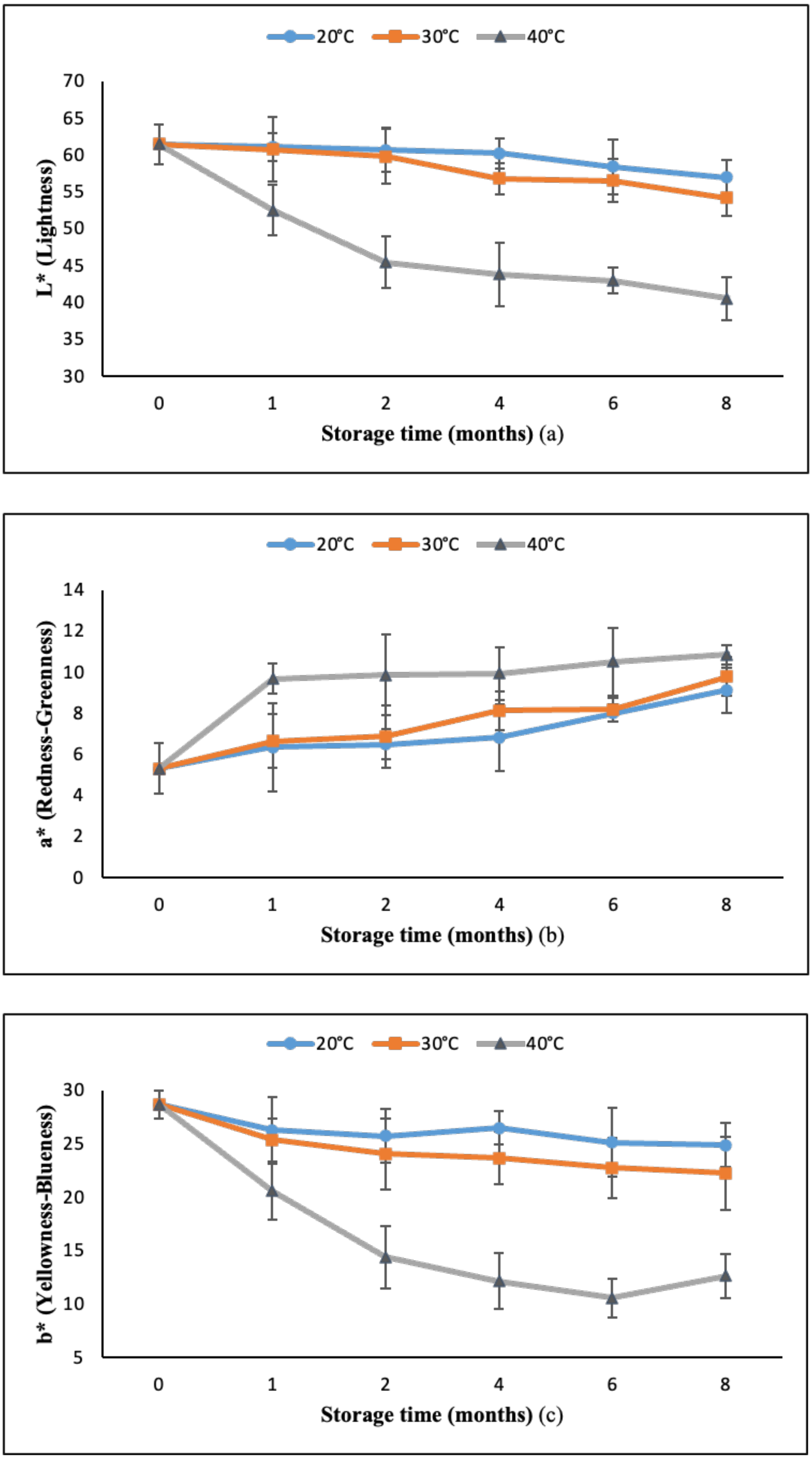

FIGURE 3. Color values (a, b, and c) of samples stored at different temperatures (n=5).

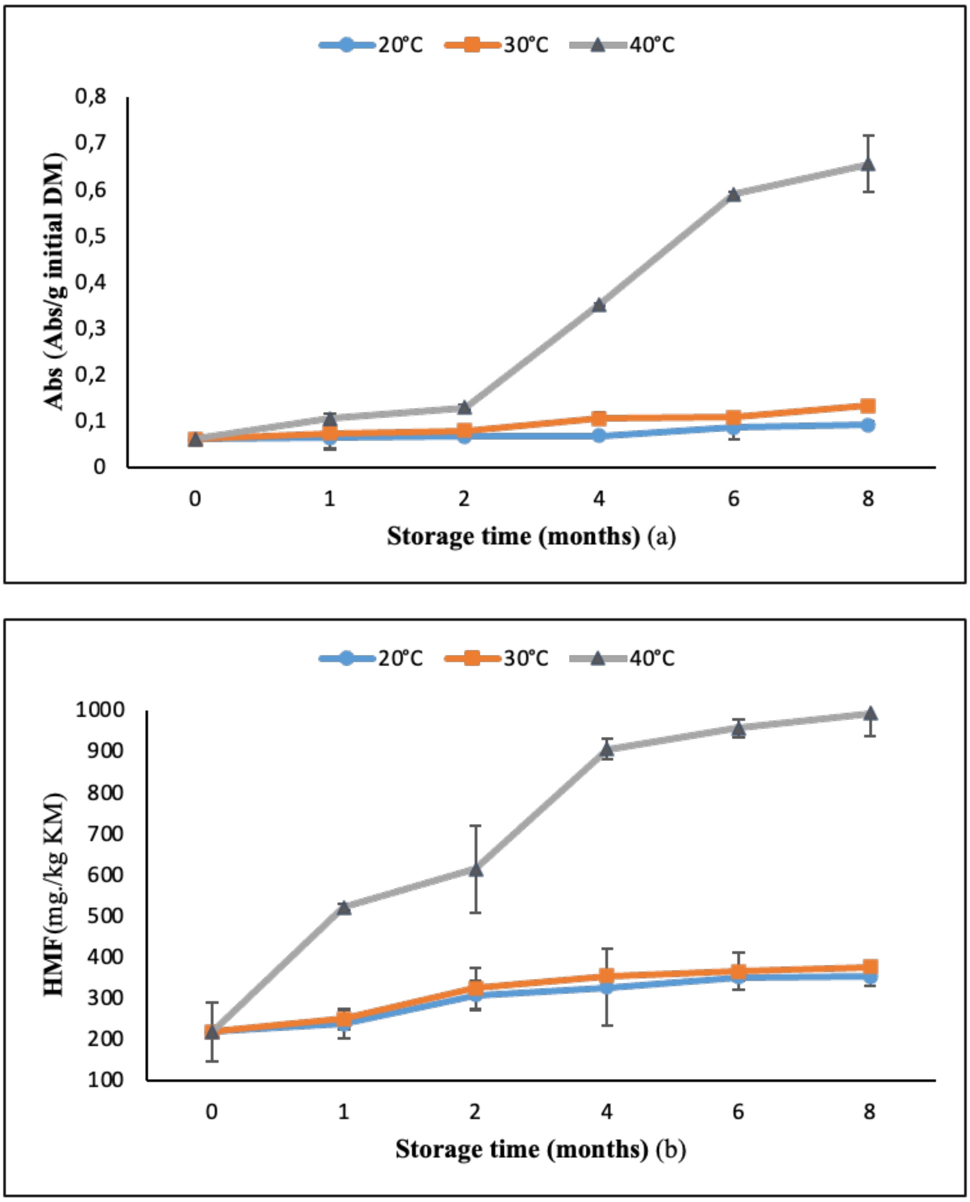

FIGURE 4. Browning index (a) and HMF content (b) of samples stored at different temperatures (n=5).

Oxidation consists of a series of chain reactions, resulting in quality loss, including the formation of primary and secondary oxidation products and undesirable rancid taste and flavor in oils. The most frequently used parameters to assess the oxidation rate of fats and oils are peroxide and anisidine values. PV represents the concentration of hydroperoxides as the primary oxidation products. AV shows the ratio of secondary oxidation products including aldehydes, principally 2-alkenals and 2,4-alkadienals. TOTOX value (2xPV+AV) is a parameter that integrates information on the current and past history of oil (Shahidi and Wanasundara, 2002). The PV, AV, and TOTOX values of the samples during storage at 20, 30, and 40 °C for 8 months are given in Figure 5. Increasing the storage temperature and time considerably affected the PV and AV of the samples stored at 30 and 40 °C. PV showed an increasing trend from the beginning up to the end of the storage period in samples stored at 30 °C. The PVs of samples stored at 40 °C increased during the 4th month, followed by a decreasing trend up to the end of the storage. This result indicated that a significant amount of peroxides in stored apple chips kept at 40 °C was converted to secondary oxidation products after 4 months. While the AVs of samples kept at 20 °C remained almost constant during 8-months' storage, those kept at 30 and 40 °C showed a remarkable increase after the 4^{th} and 2^{nd} months, respectively. The simultaneously evaluation of PVs and AVs showed that when the concentration of hydroperoxides reached approximately 65 meq O_2/ kg oil, the formation of secondary oxidation products represented by AV was accelerated at high temperatures (30 and 40 °C). Especially, after the 4^{th} month of storage at 40 °C, the conversion of peroxides to secondary oxidation products was higher than peroxide formation. Peroxides are unstable substances that readily break down at high temperatures into more stable substances such as aldehydes and ketones. Javidipour *et al.* (2017) noted that during microwave heating a considerable number of peroxides converted to hexanal in hazelnut, olive, soybean, and sunflower oils. As expected, the TOTOX values for the samples showed combined effects of PV and AV. Oils show different reactions under different conditions. Generally, increasing temperature increases the concentration of primary and secondary oxidation products, particularly at high temperatures. In some oil samples under different storage conditions, the generation of secondary oxidation products begins almost simultaneously with the generation of hydroperoxides, and in other samples, the degradation of hydroperoxides begins when the concentration of these compounds is appreciable (Guillen and Cabo, 2002). The results showed that storage at 20 °C limited the formation of oxidation products in fried apple chips.

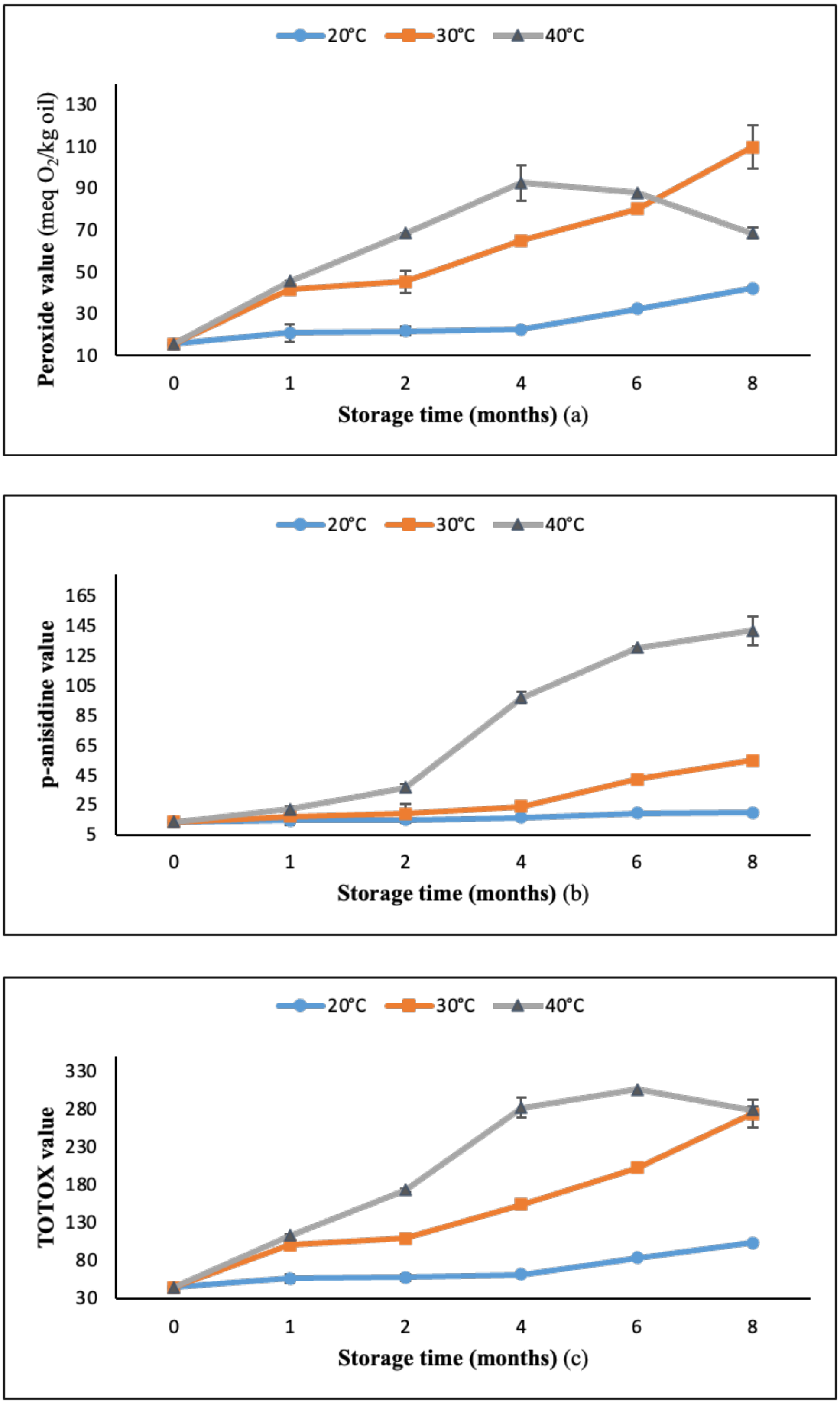

FIGURE 5. Oxidation parameters of samples stored at different temperatures (a, b, and c) (n=5).

4. CONCLUSIONS

This study investigated the effects of some pre-treatments and their combinations on the quality parameters of apple chips fried by VCIR. Small differences were observed among frying times in samples treated with different levels of ethanol, ultrasound and their combinations. L* values decreased in fried samples compared to fresh samples. High ethanol concentration led to higher L* and lower a* values compared to the other apple chips samples. The combination of 50% ultrasound amplitude and 100% ethanol concentration, as a pre-treatment, was the best method for the preparation of fried apple chips in terms of sensory evaluation and low-fat content. The oil uptake of E100-50US decreased by 22.45% compared to E0-100US. The color values, HMF, and oxidation parameters of apple chips were more stable at a low storage temperature (20 °C). At higher storage temperatures (30 and 40 °C), the formation of secondary oxidation products was accelerated after the 4^{th} and 2^{nd} months, respectively. Oxidative stability was maintained for 4 months at 20 °C storage. In addition, the HMF content considerably increased in samples kept at 40 °C. Further studies including the investigation of the alternative fruit or vegetable matrices, kinetic modeling of heat/mass transmission, the possibilities for scaling up VCIR systems and packaging treatments are necessary to produce high quality products with long-term shelf stability.

RESEARCH DATA POLICY

DATA AVAILABILITY

The authors do not have permission to share data.

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DECLARATION OF COMPETING INTEREST

The authors of this article declare that they have no financial, professional or personal conflicts of interest that could have inappropriately influenced this work.

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AUTHORSHIP CONTRIBUTION STATEMENT

SU: Conceptualization, Formal analysis, Investigation, Methodology, Writing – original draft, EB: Conceptualization, Formal analysis, Funding acquisition, Investigation, Methodology, Project administration, Writing – review & editing, IC: Writing – review & editing.

REFERENCES

Akyıldız A, Öcal ND. 2006. Effects of dehydration temperatures on colour and polyphenoloxidase activity of Amasya and Golden Delicious apple cultivars. *J. Sci. Food Agric.* **86**, 2363–2368. https://doi.org/10.1002/jsfa.2624

AOAC. 2003. *Official Methods of Analysis*, Association of Official Analytical Chemists, Washington, DC.

AOCS. 2006. Sampling and analysis of commercial fats and oils. American Oil Chemists' Society, Champaign, Illinois, USA.

Bakkalbaşı E, Yılmaz ÖM, Yemiş O, Artık N. 2013. Changes in the phenolic content and free radical-scavenging activity of vacuum packed walnut kernels during storage. *Food Sci. Technol. Res.* **19** (1), 105–112. https://doi.org/10.3136/fstr.19.105

Choudhari A, Rayar P, Shimpi S, Pawar N, Ambetkar S. 2023. Design and development of vacuum frying machine for the production of high-quality fried products. In: Vasudevan H, Kottur VKN, Raina AA. (Eds.) *Proceedings of International Conference on Intelligent Manufacturing and Automation. Lecture Notes in Mechanical Engineering*. Springer, Singapore. https://doi.org/10.1007/978-981-19-7971-2_50

Colaric M, Veberic R, Solar A, Hudina M, Stampar F. 2005. Phenolic acids, syringaldehyde, and juglone in fruits of different cultivars of *Juglans regia* L. *J. Agric. Food Chem.* **53**, 6390–6396. https://doi.org/10.1021/jf050721n

Crosa MJ, Skerl V, Cadenazzi M, Olazábal L, Silva R, Suburú G, Torres M. 2014. Changes produced in oils during vacuum and traditional frying of potato chips. *Food Chem.* **146**, 603–607. http://dx.doi.org/10.1016/j.foodchem.2013.08.132

Deng LZ, Yang XH, Mujumdar AS, Zhao JH, Wang D, Zhang Q, Wang J, Gao ZJ, Xiao HW. 2018. Red pepper (*Capsicum annuum* L.) drying: Effects of different drying methods on drying kinetics, physicochemical properties, antioxidant capacity, and microstructure. *Dry. Technol.* **36** (8), 893–907. https://doi.org/10.1080/07373937.2017.1361439

Feng Y, Zhou C, Yagoub AEA, Sun Y, Owusu-Ansah P, Yu X, Wang X, Xu X, Zhang J, Ren Z. 2019. Improvement of the catalytic infrared drying process and quality characteristics of the dried garlic slices by ultrasound-assisted alcohol pretreatment. *LWT - Food Sci. Technol.* **116**, 108577. https://doi.org/10.1016/j.lwt.2019.108577

Gao J, Su Y, Zhu C, Li J, Zheng T, Chitrakar B. 2021. Reduction of oil uptake in deep-fried apple slices by the combined ultrasonic and ethanol pre-treatment. *LWT - Food Sci. Technol.* **152**, 112274. https://doi.org/10.1016/j.lwt.2021.112274

Guillen MN, Cabo N. 2002. Fourier Transform Infrared Spectra Data Versus Peroxide and Anisidine Values to Determine Stability of Edible Oils. *Food Chem.* **77**, 503–510.

Hyson DA. 2011. A comprehensive review of apples and apple components and their relationship to human health. *Adv. Nutr.* **2**, 408–420. https://doi.org/10.3945/an.111.000513

Javidipour I, Erinç H, Baştürk A, Tekin A. 2017. Oxidative changes in hazelnut, olive, soybean, and sunflower oils during microwave heating, *Int. J. Food Prop.* **20** (7), 1582–1592. http://dx.doi.org/10.1080/10942912.2016.1214963

Liu Y, Zheng W, Ibrahim SA, Yang H, Huang W. 2017. Chemical properties of vacuum-fried *Pleurotus eryngii* during storage and characterization of brown pigment. *Int. J. Food Prop.* **20**, S2349–S2358. https://doi.org/10.1080/10942912.2017.1369993

Moreira RG. 2014. Vacuum frying versus conventional frying - An overview. *Eur. J. Lipid Sci. Technol.* **116**, 723–734. https://doi.org/10. 1002/ejlt.201300272

Oladejo AO, Ma H, Qu W, Zhou C, Wu B, Uzoejinwa BB, Onwude DI, Yang X. 2018. Application of pretreatment methods on agricultural products prior to frying: a review. *J. Sci. Food Agric.* **98** (2), 456–466. https://doi.org/10.1002/jsfa.8502

Piyalungka P, Sadiq MB, Assavarachan R, Nguyen LT. 2019. Effects of osmotic pretreatment and frying conditions on quality and storage stability of vacuum-fried pumpkin chips. *Int. J. Food Sci. Technol.* **54**, 2963–2972. https://doi.org/10.1111/ijfs.14209

Rastogi NK. 2012. Recent Trends and Developments in Infrared Heating in Food Processing. *Crit. Rev. Food Sci. Nutr.* **52**, 737-760. https://doi.org/10.1080/10408398.2010.508138

Shahidi F, Wanasundara, UN. 2002. Methods for measuring oxidative rancidity in fats and oils. *In Food Lipids-Chemistry, Nutrition, and Biotechnology*, 2nd Ed, (C.C. Akoh and D.B. Min, eds.) Marcel Dekker, Inc., New York, NY. pp. 465– 487.

Soysal Y. Ayhan Z. Eştürk O. Arıkan MF. 2009. Intermittent microwave–convective drying of red pepper: Drying kinetics, physical (colour and texture) and sensory quality. *Biosystems Eng.* **103**, 455–463. https://doi.org/10.1016/j.biosystemseng.2009.05.010

Su Y, Gao J, Chen Y, Chitrakar B, Li J, Zheng T. 2022. Evaluation of the infrared frying on the physicochemical properties of fried apple slices and the deterioration of oil. *Food Chem.* **379**, 132110. https://doi.org/10.1016/j.foodchem.2022.132110

Topuz FC, Uğurlu S, Bakkalbaşı E. 2023. Comparison of a Novel Vacuum-Combined Infrared and Hot-Air Convection Methods for Drying of Deveci (Pyrus Communis L.) Pear Slices. *Latin Am. Appl. Res.* **53** (4), 317-325. https://doi.org/10.52292/j.laar.2023.1200

Uğurlu S, Aldemir A, Bakkalbaşı E. 2023. Investigating the effects of a novel combined infrared-vacuum dryer on the drying kinetics and quality parameters of apple chips. *Iran. J. Chem. Eng.* **42**, 4225–4237. https://doi.org/10.30492/IJCCE.2023.1975814.5743

Uğurlu S, Yücel T, Cavidoğlu İ, Bakkalbaşı E. 2024. The impact of pre-drying and different infrared powers on some quality parameters of apple chips fried by vacuum-combined infrared radiation. *Grasas Aceites,* **75** (2), 2052. https://doi.org/10.3989/gya.1077231.2052

Velić D, Planinić M, Tomas, S, Bilić, M. 2004. Influence of airflow velocity on kinetics of convection apple drying. *J. Food Eng.* **64**, 97–102. https://doi.org/10.1016/j.jfoodeng.2003.09.016

Wu J, Gao H, Zhao L, Liao X, Chen F, Wang Z, Hu X. 2007. Chemical compositional characterization of some apple cultivars. *Food Chem.* **103**, 88–93. https://doi.org/10.1016/j.foodchem.2006.07.030

Zhang J, Xie T, Fan L. 2021. Improving the quality and reducing oil absorption of fried potato chips by ultrasound pretreatment. *LWT - Food Sci. Technol.* **148**, 111763. https://doi.org/10.1016/j.lwt.2021.111763