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ORIGINAL PAPER

A comparison of phenolic compounds, antioxidant activity, and α-glucosidase inhibitory activities of apple chips dried and fried by vacuum combined infrared radiation

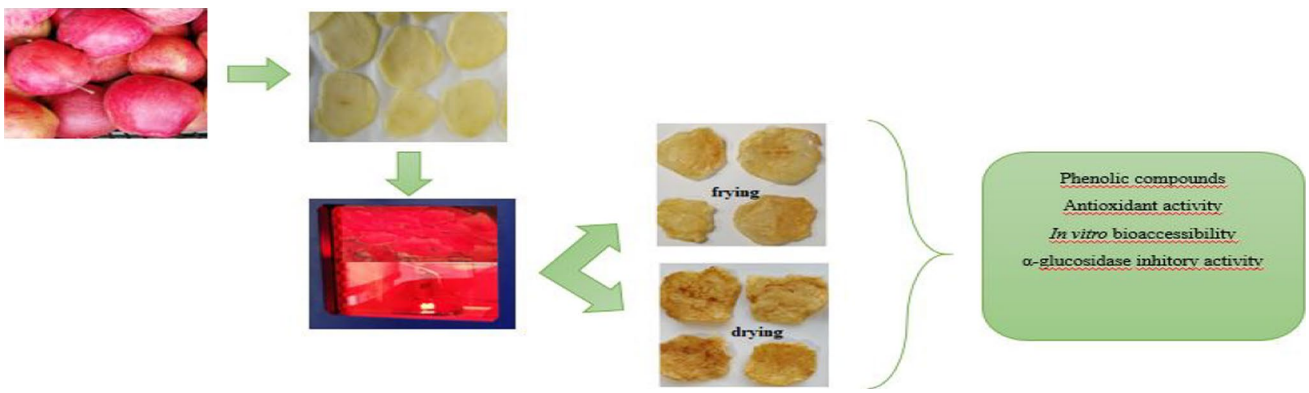
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Abstract

In this study, the effects of different drying (180–325 W and 100–400 mmHg) and frying (250–350 W and 400 mmHg) parameters on phenolic compounds, bioaccessibilities, antioxidant activities, and α-glucosidase inhibitory activities of apple chips dried and fried by vacuum-combined infrared radiation were investigated. Catechin (12.15–34.48 mg/kgDM), epicatechin (34.33–137.07 mg/kgDM), procyanidin B1 (14.07–30.05 mg/kgDM), procyanidin B2 (48.10–95.76 mg/kgDM), procyanidin C1 (14.95–42.97 mg/kgDM), chlorogenic acid (262.70–397.97 mg/kgDM), and rutin (0–5.94 mg/kgDM) were identified in apple chips. The phenolic content of apple chips increased with increasing infrared power during the drying and frying process. The phenolic contents of fried apple chips were generally higher than dried apple chips. However, the bioaccessibility rates of total flavan-3-ols in dried apple chips were higher than those of fried apple chips. It was determined that the initial total phenolic, flavonoid, and flavan-3-ol contents and antioxidant activity levels of the samples decreased after in-vitro gastrointestinal digestion. It was determined that all drying and frying samples showed higher α-glucosidase inhibitory activities (15.52–28.77 mg/mL) compared to acarbose (30.87 mg/mL). The apple chips dried and fried by infrared radiation had higher phenolic content, antioxidant activity, bioaccessibility, and α-glucosidase inhibitory activity than their counterparts (convectional drying and deep-fat frying, respectively). Vacuum-combined infrared drying and frying is a promising method to preserve the phenolic content, antioxidant, and antidiabetic activities of apple chips, especially at high temperature applications. Further research is needed on new designs for the production of fruit chips using infrared radiation and their effects on bioactive components.

Graphical abstract



Keywords Apple chips · Antioxidant activity · Bioaccessibility · Phenolics · Vacuum-combined infrared drying and frying · α-Glucosidase

Extended author information available on the last page of the article

Introduction

Apples are rich source of phenolics, vitamin C, sugars, organic acids, and minerals [1]. Apple phenolics are naturally occurring compounds that act as efficient antioxidants by preserving the cell against damaging impacts of free radicals and by inhibiting the oxidation of low density lipoproteins [2]. Epidemiological studies have linked the consumption of apples with decreased risk of cardiovascular diseases, some cancers, asthma, and diabetes. Apples are consumed either fresh or various processed products like juice, jam, marmalade, and chips [3]. Consumer interest in apple chips as a healthy snack has increased over the last decade. Therefore, high-quality new and attractive apple chips are desired to be developed to expand product availability and diversify the market [4]. Apple chips are produced by drying and frying processes [4, 5].

Drying is a good alternative for processing fresh fruits and providing out of season fruits [6]. The most common drying method has been convective drying utilizing hot air. However, this method has drawbacks including long processing time, high temperatures requiring excessive energy consumption, high production costs, and a decline in thermo-sensitive nutritional components [7]. Innovative techniques for reducing drying time, saving energy consumption, and providing excellent quality in final products are continually investigated [8]. One of the innovative techniques is to provide heat with infrared radiation. The application of infrared heating to food has received special attention recently [9]. There is smaller energy loss in infrared drying and the electromagnetic wave energy is absorbed directly by the dried food. Therefore, infrared radiation has important advantages over conventional drying. These benefits include higher drying rates resulting in significant energy savings, and uniform temperature distribution giving a better quality product [10].

Deep-fat frying, one of the oldest methods of food preparation, involves immersing food pieces in hot oil. This high temperature leads to the evaporation of water and the water evaporating from the food is replaced by the surrounding oil [11]. Nevertheless, deep-fat frying involves cooking at elevated temperatures under normal pressure, resulting in surface darkening and various undesirable reactions occurring due to the high heat [12]. In recent years, the superiority of infrared frying in the quality attributes of fried products and frying medium has attracted much attention [13]. Apple samples were fried by infrared and conventional frying and results showed that the infrared frying slowed down the rate of oil deterioration [13]. In another study, the acrylamide content of *Musa paradisiaca* samples fried with infrared frying was found to be lower compared to deep-fried samples [14]. The use of drying as a pretreatment method before frying has been widely reported in food processing [15, 16]. Cruz et al. [17] reported that the pre-drying process had a positive impact on the attributes of fried potato chips, including color, texture, low-fat content, and good acceptance scores. Dry air dehydration of the apple sample before vacuum frying can also result in a reduction in oil content [18]. Particularly, the vacuum infrared dehydration process before vacuum frying could obtain higher quality products and less oil content [15].

Foods are in nature sensitive to heat so it is desirable to process these products at low temperature to maintain their quality. Under vacuum, water evaporates at a lower temperature, so drying or frying can be carried out at low temperature, resulting high quality products [19, 20]. Therefore, several drying and frying techniques were tried to combine with vacuum application by several researchers [21, 22]. Infrared radiation can be successfully combined with vacuum application. Vacuum-combined infrared radiation provide high quality product and short process time [21, 23]. To our knowledge,there is no study about using vacuum-combined infrared radiation to fry process. In addition, no study has assessed the impact of vacuum-combined infrared radiation (VCIR) on the bioaccessibility of polyphenols and α-glucosidase inhibitory activity of dried and fried apple chips.

The objective of this study was to investigate the use of VCIR in frying and drying processes for the production of apple chips and to determine its effects on phenolic compounds, antioxidant and α-glucosidase inhibitory activities of apple chips, and *in-vitro* bioaccessibility of phenolic compounds.

Materials and methods

Sample preparation

Fresh apples (Starking Delicious) were purchased from the Hakkari province in Turkey. Before drying/frying the apple samples were cleaned, peeled and sliced to a thickness of 3 mm. The material was immersed in the % 0.75 citric acid solutions for 5 min in order to prevent enzymatic browning reactions. Surface water of the samples was wiped with soft absorbent paper.

Chemicals and reagents

Standards of rutin (≥ 94%), catechin (≥ 98%), epicatechin (≥ 90%), chlorogenic acid (≥ 95%), 2,2-diphenyl-1-picrylhydrazyl (DPPH), 2,2′-azino-bis (3-ethylbenzothiazoline-6-sulfonic acid) (ABTS), potassium persulfate,

6-hydroxy-2,5,7,8-tetramethylchromane-2-carboxylic acid (Trolox), alpha-glucosidase from *Saccharomyces cerevisiae*, pancreatin (from porcine pancreas) and bile extract (porcine) were purchased from Sigma-Aldrich Co. (St. Louis, MO, USA). Acetonitrile (high-performance liquid chromatography [HPLC] grade) and methanol were purchased from Carlo ERBA (Carlo ERBA reagents SAS, France). Procyanidin B1 (80%) and procyanidin B2 (90%) were purchased from abcr (Karlsruhe, Germany). Procyanidin C1 (98.30%) was purchased from Chem Scene (USA). Acarbose (98%) was purchased from BLD Pharm (Shanghai, China). p-nitrophenyl-α-D-glucopyranoside (99%) purchased from Boston Usa Chemistry (USA).

Drying experiments

Vacuum (DOA-P730-BN, USA) combined infrared (Uniterm, Ankara) –dryer was used to dry the apple slices. Dryer system has four 250 W infrared lamps placed on the both ceiling and the floor inside the oven. Distance between the slices and lamps was kept at 12 cm. Slices were dried at 3 different infrared powers (180, 275, and 325 W) and 2 different vacuum pressures (100 and 400 mmHg). For control, convectional drying was also done at 75 ºC in a convection oven (OSCC 61, Öztiryakiler, Turkey). Drying was carried out at the 3nd fan speed in the convectional dryer with 5 different fan speeds (1: lowest, 5: highest). The drying process continued until 4.5–5% (w.b) moisture content of dry apple slices was reached. Drying trials were done in 5 repetitions. The initial moisture content of apple slices was 84.41 ± 0.28% (w.b) and they were dried until they reached a range of 4.5–5% (w.b). Moisture content of sample was determined by the oven-drying method [24].

Frying process

Vacuum (DOA-P730-BN, USA) combined infrared (Uniterm, Ankara) radiation was used to fry the apple slices. Frying is done in oven that has two 250 W infrared lamps placed on the ceiling. Distance between the oil surface and lamps was kept at 12.5 cm. Pre-dried (PD) and non pre-dried apple slices were used for frying. The apple slices were pre-dried up to 41% moisture content by the VCIR drying at 275 W and 400 mmHg. PD and non-pre-dried (NPD) samples were fried at 3 different infrared powers (250, 300, and 350 W) and constant vacuum pressure (400 mmHg). The deep-fat frying (165 °C) experiments were carried out in an atmospheric fryer (Philips Cucina, HD 6155, China). The frying process was stopped when the moisture content reached 1.5–2.5% (w.b). After frying, the chips were centrifuged in the vessel at 1600 g for 5 min to remove excess oil. The sample/oil ratio was kept at 1:20 (w/v). All experiments were performed in five replicates.

Preparation of methanolic extracts

Methanolic extracts of fresh, dried, and fried apple samples were prepared according to Bakkalbaşı et al. [25], with some modifications. 5 g fresh apple and 1 g ground drying or deoiled frying chips were put into a centrifuge tube in the presence of 15 mL methanol:water (80:20) and shaken for 2 h in the dark at room temperature. The mixture was centrifuged at 8000 × g for 10 min at 10 °C. Then, supernatant and residue were separated and extraction was performed again with residue and 10 mL of the same solvent. The supernatants were combined and reached a final volume of 25 mL with the solvent. Methanolic extracts were stored at − 24 °C until further analyses.

Total phenolic content (TPC)

The TPC of samples was performed according to Singleton and Rossi [26] with slight modifications. 0.4 mL of methanolic extract, 2 mL of 1/10 water-diluted Folin-Ciocalteu reagent, and 1.6 mL of 7.5% sodium carbonate solution were mixed. The mixture was kept in the dark at room temperature for 60 min. The absorbance was measured at 765 nm. The TPC is expressed as gallic acid equivalent (mg GAE/kg DM).

Total flavonoid content (TFC)

The TFC was measured according to Zhishen et al. [27] with a slight modification. The extract (1 mL) added to 10 mL volumetric flasks containing 5 mL water. At the onset of the experiment, 0.3 mL of 5% $NaNO_2$ was added to the flask. 0.3 mL of 10% $AlCl_3$ was added 5 min later. After 6 min, 2 mL of 1 M NaOH was added to the mixture. Immediately, the final volume of the solution was adjusted to 10 mL with water. The absorbance at 510 nm was measured by a spectrophotometer. The results were expressed as mg catechin equivalents (CE) per kg drying matter.

Total flavan-3-ol content (TF-3ol)

TF-3ol in the extract was determined by the vanillin assay method described by Sun et al. [28]. The following A_s, A_b, A_c, and A_o reaction mixtures were prepared into separate tubes and incubated for 20 min at 30 °C. The absorbance of each reaction mixture was measured at 500 nm with a spectrophotometer (8453, Agilent, USA).

A_s = 1 mL of extract, 2.5 mL of 1% vanillin (in methanol) and 2.5 mL of 25% H_2SO_4.

A_b = 1 mL of methanol, 2.5 mL of 1% vanillin (in methanol) and 2.5 mL of 25% H_2SO_4.

A_c = 1 mL of extract, 2.5 mL of methanol and 2.5 mL of 25% H_2SO_4.

A_o = 1 mL of methanol, 2.5 mL of methanol and 2.5 mL of 25% H_2SO_4.

A value was calculated for each standard and sample solution as follows:

$$A = (As - Ab) - \left(Ac - A_o\right) \quad (1)$$

Results were expressed as milligrams of equivalent catechin per kg of dried matter (mg CE/ kg DM).

DPPH assay

DPPH assay was performed according to Pyo et al. [29] with a slight modification. Extract (0.1 mL) was added to 3.9 mL of DPPH solution (0.025 g/L in methanol). The mixture was left for 60 min in the dark at room temperature. The absorbance at 515 nm was measured by a spectrophotometer. The results were expressed as Trolox equivalent antioxidant capacity (mmol Trolox eq./g DM).

ABTS assay

ABTS assay was measured using the method of Re et al. [30]. Briefly, $ABTS^{+\cdot}$ Radical cation was generated by creating a reaction between 7 mM ABTS and 2.45 mM potassium persulfate via incubation for 12–16 h under a dark room temperature condition. The $ABTS^{+\cdot}$ Solution was diluted with ethanol to obtain an absorbance of 0.700 ± 0.05 at 734 nm. After $ABTS^{+\cdot}$ Solution (1980 µL) was mixed with 20 µL of the extract. The mixture was incubated at room temperature for 6 min in dark and the absorbance of the mixture was measured at 734 nm. The results were expressed as Trolox equivalent antioxidant capacity (mmolTrolox eq./g DM).

HPLC determination of phenolic compounds

Phenolic compounds were analyzed by HPLC system (Shimadzu, Kyoto, Japan) that consists of an LC-20 AD pump, a SIL-20 A HT auto-sampler, a CTO-10AS VP column oven, and a SPD-M20A diode array detector. The method was made according to Colaric et al. [31] with minor modifications. HPLC system Separation of components was carried out using a Symmetry C18 (250 × 4.6 mm id, particle size 5 µm) column (Waters, USA) at 25 °C. The method utilized a binary mobile phase consisting of 2% acetic acid in water (A) and 0.5% acetic acid in water:acetonitrile (1:1, v/v) (B). Gradient program was as follows: 0 min 90% A; 30 min 80% A; 60 min 65% A. The flow rate was 1.0 mL/min. Detection was made at 280 and 320 nm for phenolic acids, 280 nm for flavan-3-ols, and 360 nm for flavonols. Phenolic compounds appearing in chromatograms were identified according to retention times and spectral data by comparison with standards.

Bioaccessibility of apple chips

In vitro gastrointestinal digestion method was used to evaluate the bioaccessibility of phenolics in fresh apple and apple chips as previously described [32]. In brief, 30 mL of distilled water and 1.5 mL of pepsin (20 g/L in 0.1 mol/L HCl) were mixed with 1.5 g of samples. The mixture was adjusted to pH 2 with 6 mol/L of HCl. For gastric digestion, the mixture was incubated in a shaking water bath at 37 °C for 1 h. The gastric digestion was stopped by adding 1 mol/L $NaHCO_3$ into each mixture to adjust the pH to 7.2. Bile/pancreatin solution (7.5 mL) (2 g/L of pancreatin and 12 g/L of bile salt in 0.1 mol/L $NaHCO_3$) and NaCl/KCl (7.5 mL) (120 mmol/L NaCl and 5 mmol/L KCl) was added to the mixture. The mixture was incubated for another 2.5 h under the same conditions. At the end of incubation period, the mixture was centrifuged at 8000 g for 10 min and the supernatant was stored at -24 degrees until analysis time.

Determination of α-glucosidase inhibitory activity of apple chips

The α-glucosidase inhibitory activity was determined as described by Zhang et al. [33] method with slight modifications. Briefly, 50 µL α-glucosidase (1 U/mL) in phosphate buffer (0.1 M, pH 6.8) was mixed with 100 µL of various concentrations of the extract and preincubated at 37 °C for 10 min. Then, 100 µL 5 mM 4-nitrophenyl α-D-glucopyranoside was added as a substrate and incubated for 15 min at 37 °C, and the incubation was stopped by adding 750 µL of Na_2CO_3 (0.1 M). The absorbance was measured at 405 nm. The α-glucosidase inhibitory activity was calculated as percentage inhibition with the following formula (2). The α-glucosidase inhibitory activity of the extract was expressed as IC_{50}, which was calculated graphically. Acarbose was used as a positive control.

$$\% \text{ Inhibition} = ((\text{Acontrol} - \text{Asample})/(\text{Acontrol})) \times 100 \quad (2)$$

Statistical analysis

All the samples analyses were performed at least three times. Values are given as mean ± standard deviation. The data obtained were analyzed using SPSS 20.0 software for variance analyses. Duncan multiple comparison test was applied to identify significantly different groups ($p < 0.05$).

Results and discussion

Effects of drying on the phenolic composition of apple chips

Apple phenolics range from low molecular weight phenolics to large and complex tannins and derived polyphenols. In this study, seven individual phenolic compounds (chlorogenic acid, rutin, catechin, epicatechin, procyanidin B1, B2, and C1) were determined in the fresh apple and apple chips (Table 1). The most predominant phenolic compound in a sample was chlorogenic acid. Li et al. [34] reported that chlorogenic acid and/or epicatechin were found as the predominant phenolic compounds in different apple varieties. In our study, the chlorogenic acid, epicatechin, and procyanidin B2 content of all apple chips were approximately 2 and threefold higher than fresh apple. It may be due to the release of free phenolics from bound form by the breakdown of cellular constituents and cell walls during thermal processes. Chlorogenic acid, catechin, epicatechin, procyanidin B1, B2, and C1 contents of both dried and fried apple chips raised with increasing IP. However, the contents of rutin in dried and fried chip was decreased with increasing infrared power. Apple chips fried at 350W and deep-fat frying samples were not detected. Similar results were reported in dried figs by Kelebek et al. [35]. The catechin and rutin contents of all samples dried by VCIR were found to be higher than the control sample. Infrared radiation can destroy fruit cell walls and thus facilitate the liberation of phenolic compounds [36]. In the fried process, the sample fried NPD had higher chlorogenic acid, epicatechin, procyanidin C1, and rutin values compared to the sample fried PD. This may be due to the fact that PD samples were exposed to more heat. For catechin in NPD samples and epicatechin and procyanidin C1 in PD samples, the differences between the infrared powers were found to be statistically significant ($p < 0.05$). When drying and frying treatments were compared, it was determined that drying application resulted higher levels of phenolic compounds, especially at high infrared powers. It can be said that high frying temperatures were not as effective as drying in preserving these compounds and could potentially cause their degradation. For catechin, epicatechin, procyanidin B1, procyanidin B2, and rutin, the difference between drying and frying applications was found to be significant ($p < 0.05$).

Total phenolic, flavonoid, and flavan-3-ol content and their bioaccessibility rates

The TPC, TFC, and TF3-ol content of samples before and after digestion and their bioaccessibility results were given in Table 2. The TPC, TFC, and TF3-ol content of the sample dried and fried by VCIR were higher than those of the fresh sample. In addition, the TPC, TFC, and TF3-ol contents of apple chips increased with increasing infrared power during

Table 1 Phenolic contents of apple chips (mg/kg DM)

Sample	Catechin	Epicatechin	Procyanidin B1	Procyanidin B2	Procyanidin C1	Chlorogenic Acid	Rutin
Fresh	18.26 ± 0.08	47.80 ± 14.90	23.05 ± 3.26	47.66 ± 4.23	19.31 ± 1.47	116.76 ± 5.04	23.65 ± 0.00
180W-100	18.95 ± 5.63^{aA}	70.23 ± 1.88^{aA}	17.48 ± 1.47^{aA}	63.56 ± 1.57^{aA}	17.60 ± 0.48^{aA}	284.25 ± 41.46^{aA}	5.89 ± 0.20^{bA}
275W-100	28.83 ± 0.04^{bcA}	105.45 ± 30.98^{bcAB}	23.49 ± 0.28^{abA}	86.98 ± 2.26^{bcB}	21.04 ± 5.33^{abA}	317.30 ± 36.75^{aA}	5.14 ± 0.56^{abA}
325W-100	29.48 ± 4.45^{bcA}	137.07 ± 1.41^{cB}	28.88 ± 6.44^{bA}	90.17 ± 2.43^{cAB}	41.04 ± 23.44^{bA}	318.76 ± 24.61^{aA}	4.73 ± 0.20^{abA}
180W-400	15.00 ± 2.30^{aA}	82.95 ± 0.04^{abA}	19.92 ± 0.00^{abA}	71.02 ± 0.02^{abA}	22.57 ± 0.02^{abA}	262.70 ± 83.68^{aA}	5.94 ± 0.00^{bA}
275W-400	27.22 ± 0.00^{bB}	123.07 ± 0.00^{cB}	24.54 ± 3.87^{abA}	89.73 ± 0.00^{cA}	23.22 ± 0.21^{abA}	291.32 ± 50.94^{aA}	5.41 ± 0.36^{abA}
325W-400	34.48 ± 0.07^{cC}	131.40 ± 0.67^{cC}	29.73 ± 8.14^{bA}	95.76 ± 14.31^{cA}	42.97 ± 1.41^{bB}	315.02 ± 12.70^{aA}	4.95 ± 1.22^{abA}
Convectional drying	12.15 ± 0.00^{a}	118.83 ± 17.14^{c}	20.61 ± 3.04^{ab}	71.09 ± 10.49^{ab}	23.02 ± 0.00^{ab}	317.01 ± 77.16^{a}	4.13 ± 0.31^{a}
NPD-250W	18.09 ± 1.41^{aA}	87.78 ± 9.55^{bcA}	15.96 ± 3.71^{aA}	61.05 ± 7.66^{abA}	16.54 ± 3.95^{aA}	331.45 ± 12.78^{aA}	4.10 ± 0.35^{aA}
NPD-300W	18.79 ± 2.91^{aAB}	112.65 ± 27.04^{cdA}	16.63 ± 0.42^{aA}	61.42 ± 10.05^{abA}	26.54 ± 16.14^{aA}	391.62 ± 140.54^{aA}	4.50 ± 0.04^{aA}
NPD-350W	25.80 ± 2.45^{bB}	124.01 ± 2.66^{dA}	21.07 ± 0.09^{abA}	66.37 ± 6.59^{abcA}	29.81 ± 16.35^{aA}	397.97 ± 41.71^{aA}	n.d
PD-250W	19.29 ± 0.28^{aA}	79.07 ± 9.40^{bA}	22.10 ± 3.73^{abcA}	70.01 ± 12.80^{bcA}	14.95 ± 0.13^{aA}	288.62 ± 1.44^{aA}	3.93 ± 0.05^{aA}
PD-300W	19.82 ± 0.71^{abA}	81.34 ± 0.00^{bA}	27.00 ± 7.16^{bcA}	80.56 ± 4.21^{cA}	23.51 ± 0.09^{aB}	335.14 ± 65.79^{aA}	4.00 ± 0.16^{aA}
PD-350W	22.41 ± 4.36^{abA}	120.70 ± 6.98^{dB}	30.05 ± 0.91^{cA}	83.96 ± 1.86^{cA}	23.61 ± 0.10^{aB}	335.51 ± 29.16^{aA}	n.d.
Deep-fat frying	21.33 ± 2.97^{ab}	34.33 ± 3.20^{a}	14.07 ± 0.75^{a}	48.10 ± 0.21^{a}	15.28 ± 0.51^{a}	305.98 ± 1.41^{a}	n.d.

Data were expressed as mean ± standard deviation. n.d.: not detected. For both drying and frying, different lower case letters indicate the significant difference among samples within the same column ($p < 0.05$). Different capital letters indicate the significant difference between infrared powers within the same vacuum pressure for drying and the same pretreatment for frying (NPD: Non-pre-dried, PD: Pre-dried)

Table 2 Total phenolic, total flavonoid and total flavan-3-ol contents of apple chips and bioaccessibility after in vitro digestion

Sample	TPC (mgGAE/kg DM)	GID TPC (mgGAE/kg DM)	Bioaccessibility (%)	TFC (mgCE/kg DM)	GID TFC (mgCE/kg DM)	Bioaccessibility (%)	TF3-ol (mgCE/kg DM)	GID TF3-ol (mgCE/kg DM)	Bioaccessibility (%)
Fresh	1940.86 ± 221.99	1697.37 ± 103.06	87.45 ± 5.31	778.75 ± 40.78	581.27 ± 82.91	74.64 ± 10.64	881.94 ± 227.58	699.85 ± 0.00	79.35 ± 0.00
180W-100	4184.53 ± 470.61^{aA}	2885.42 ± 0.00^{abA}	68.95 ± 0.00^{aA}	1640.59 ± 0.00^{abA}	1176.69 ± 19.59^{cdA}	71.72 ± 1.19^{eC}	1021.70 ± 0.00^{aA}	597.42 ± 25.39^{bcB}	58.47 ± 2.48^{cB}
275W-100	5501.73 ± 42.05^{bB}	3473.77 ± 292.74^{abB}	63.13 ± 5.32^{aA}	1810.61 ± 69.66^{abcA}	1196.25 ± 33.71^{cdAB}	66.06 ± 1.86^{cdB}	1357.10 ± 1.41^{bcB}	520.61 ± 23.43^{bA}	38.36 ± 1.72^{bA}
325W-100	5939.06 ± 0.00^{bB}	4093.66 ± 241.18^{bC}	68.92 ± 4.06^{aA}	2130.22 ± 100.38^{bcB}	1259.66 ± 0.00^{deB}	59.13 ± 0.00^{bA}	1414.06 ± 5.65^{cC}	500.39 ± 0.04^{bA}	35.38 ± 0.00^{bA}
180W-400	3614.65 ± 0.00^{aA}	2740.15 ± 0.01^{abA}	75.80 ± 0.01^{aA}	1555.88 ± 0.00^{aA}	1077.41 ± 0.00^{bA}	69.24 ± 0.00^{deB}	1141.14 ± 4.24^{abA}	677.03 ± 1.41^{cA}	59.32 ± 0.42^{cB}
275W-400	5637.67 ± 873.76^{bB}	3335.65 ± 890.78^{abA}	59.16 ± 15.80^{aA}	$1822.31 \pm 301.75^{abcAB}$	1135.41 ± 18.05^{bcA}	62.30 ± 0.99^{bcA}	$1252.87 \pm 230.65^{abcA}$	506.89 ± 93.07^{bA}	40.45 ± 7.42^{bA}
325W-400	6038.71 ± 419.41^{bB}	3877.25 ± 1190.08^{bA}	64.20 ± 19.70^{aA}	2192.59 ± 433.30^{cB}	1289.28 ± 58.73^{eB}	58.80 ± 2.67^{bA}	1308.84 ± 9.83^{bcA}	499.34 ± 63.79^{bA}	38.15 ± 4.87^{bA}
Convectional drying	3544.25 ± 301.02^{a}	2245.35 ± 16.46^{a}	63.35 ± 0.46^{a}	1946.87 ± 148.85^{abc}	816.55 ± 64.30^{a}	41.94 ± 3.30^{a}	1260.06 ± 107.04^{abc}	316.27 ± 0.88^{a}	25.10 ± 0.07^{a}
NPD-250W	5651.19 ± 415.17^{aA}	3896.79 ± 241.25^{abA}	68.95 ± 4.26^{aA}	2004.82 ± 98.76^{abA}	1210.58 ± 2.82^{bcA}	60.38 ± 0.14^{aA}	1152.55 ± 354.83^{bA}	281.23 ± 99.31^{abA}	24.40 ± 8.61^{aA}
NPD-300W	5828.79 ± 75.50^{aA}	4114.30 ± 586.59^{abA}	70.58 ± 10.06^{aA}	$2289.68 \pm 203.19^{bcAB}$	1464.40 ± 14.14^{cdB}	63.95 ± 0.61^{aB}	1304.06 ± 0.82^{bA}	336.76 ± 81.95^{bA}	25.82 ± 6.28^{aA}
NPD-350W	6346.72 ± 83.22^{aA}	4565.98 ± 18.17^{bA}	71.94 ± 0.28^{aA}	2432.59 ± 120.30^{cB}	1560.88 ± 4.24^{dC}	64.16 ± 0.17^{aB}	1347.60 ± 53.36^{bA}	390.39 ± 83.18^{bA}	28.96 ± 6.17^{aA}
PD-250W	5458.83 ± 846.13^{aA}	3643.92 ± 183.65^{abA}	66.75 ± 3.36^{aA}	1963.80 ± 153.20^{abA}	1148.36 ± 196.50^{abA}	58.47 ± 10.00^{aA}	968.31 ± 1.41^{abA}	231.54 ± 118.21^{abA}	23.91 ± 12.20^{aA}
PD-300W	5641.60 ± 614.59^{aA}	3969.41 ± 150.43^{abA}	70.35 ± 2.66^{aA}	2030.16 ± 1.41^{abA}	1267.08 ± 113.56^{bcA}	62.41 ± 5.59^{aA}	1266.30 ± 107.79^{bB}	319.69 ± 32.49^{abA}	25.24 ± 2.56^{aA}
PD-350W	5826.48 ± 248.07^{aA}	4133.76 ± 367.81^{abA}	70.94 ± 6.31^{aA}	2138.30 ± 87.46^{bcA}	1350.27 ± 1.61^{bcdA}	63.14 ± 0.07^{aA}	1331.88 ± 0.14^{bB}	364.97 ± 4.85^{bA}	27.40 ± 0.36^{aA}
Deep-fat frying	5442.36 ± 255.32^{a}	3379.11 ± 756.56^{a}	62.08 ± 13.90^{a}	1700.24 ± 369.66^{a}	935.30 ± 39.89^{a}	55.00 ± 2.34^{a}	699.64 ± 171.10^{a}	166.20 ± 6.13^{a}	23.75 ± 0.87^{a}

Data were expressed as mean ± standard deviation. For both drying and frying, different lower case letters indicate the significant difference among samples within the same column ($p < 0.05$). Different capital letters indicate the significant difference between infrared powers within the same vacuum pressure for drying and the same pretreatment for frying (NPD: Non-pre-dried, PD: Pre-dried)

both drying and frying. For TPC, similar behavior in infrared drying of rose petals samples was reported by Selvi et al. [37]. The higher temperature/high infrared power might have affected the retention of phenolic compounds from the cells due to deterioration of cell integrity, and consequently release of more phenolic compounds, as well as resulted in efficient enzyme inactivation [37]. Flavonoid compounds are part of phenolic compounds, factors affecting flavonoids will also affect total phenolic compounds [38]. In the drying process, for TPC and TFC, the differences among infrared powers at both vacuum pressures were significant ($p < 0.05$). However, for TF3-ol, the differences among infrared powers at only 100 mmHg vacuum pressure in drying were significant ($p < 0.05$). For TFC and TF3-ol, the difference between the vacuum pressures of the samples dried at 180W IP was found to be statistically significant ($p < 0.05$). Drying application at 180 W had a long dying time when compared to 275 and 325 W IPs. It can be expressed that the effect of vacuum could be observed during long drying times in our study conditions.

In the frying process, the TPC, TFC, and TF3-ol contents of the PD apple chips are lower than those of NPD apple chips. The less phenolic content in PD samples might be due to long exposure of sample to heat during pretreatment [16]. While TPCs, TFCs, and TF3-ol contents of PD apple chips were lower than those of NPD apple chips, the differences between TPCs, TFCs, and TF3-ol contents of PD and NPD apple chips fried by VCIR were not significant ($p > 0.05$). While the TF3-ol contents of samples dried and fried by VCIR were similar, the samples fried by VCIR had higher TPC and TFC than the samples dried by IR ($p < 0.05$). The sample dried with convectional oven had the lowest TPC when compared to their counterparts. The all samples fried by VCIR had higher TPC, TFC, and TF3-ol than deep-fat fried sample. The results indicated that the VCIR was an important technique to the preservation of the phenolics in especially high temperature processes.

TPC, TFC, and TF3-ol content of dried and fried apple chips decreased after in vitro digestion (GID) (Table 2). Except for TF3-ol contents of dried apple, dried and fried samples at high infrared power had high TPC, TFC, and TF3-ol content after digestion. While the bioaccessibility rate of TPC, TFC, and TF3-ol content in the drying process was decreased with increasing infrared power, in the frying process was increased. It can be suggested that free phenolic compounds formed by high temperatures in frying may be more resistant to the enzymes and acid environment in the digestive system. In frying processes, NPD samples had higher bioaccessibility rates of TPC, TFC, and TF3-ol compared to PD samples. The all samples dried and fried by infrared radiation had higher GID-TPC, GID-TFC, and GID-TF3-ol content and higher bioaccessibility rates for the TPC, TFC, and TF3-ol when compared to their counterparts (convectional drying and deep-fat frying, respectively).

In the drying process, for bioaccessibility rates of the TPC, the difference between the vacuum pressures at only 180W infrared power was found to be statistically significant ($p < 0.05$). The long process time at 180W may have made differences between vacuum pressures visible. For the bioaccessibility rates of TFC and TF3-ol, the differences among infrared powers at the same vacuum pressure during drying were significant ($p < 0.05$). Previous studies have suggested that the various microstructures formed during the drying process can have an impact on the release of phenolics, thereby changing their bioaccessibility [39, 40]. In the frying process, for bioaccessibility rates of TFC in only NPD samples, the differences among infrared powers were found statistically significant ($p < 0.05$). The bioaccessibility rates of TF3-ol in dried apple chips showed higher values than those of fried apple chips ($p < 0.05$), probably due to the higher temperature applied during the frying process. Wojdyło et al. [41] reported that catechin and procyanidin B1 phenolics in dried apple samples degrade faster compared to other compounds.

Antioxidant activity and bioaccessibility in sample

The antioxidant activity values and their bioaccessibility rates in the fresh, dried, and fried samples are shown in Table 3. The antioxidant activity of fresh apple was initially measured as 9.38 and 22.04 mmol Trolox eq/g DM by DPPH and ABTS assays, respectively. The antioxidant activities of the dried and fried samples were higher than that of the fresh sample. Similar results were reported by Vega-Gálvez et al. [42], for the DPPH values of apple dried with hot air dryer. The antioxidant activity showed a similar trend with the TPC and increased with increasing infrared power. Phenolic chemicals are responsible for significant portions of the antioxidant activity in fruits and vegetables [43]. The 325W 400 mmHg among drying samples and NPD-350W among frying samples displayed the highest DPPH and ABTS values. Similarly, Zhou et al. [44] reported that dried garlic samples showed higher antioxidant activity with increasing infrared power. In the frying process, NPD samples had higher DPPH values than PD sample, due to the longer thermal treatment. In addition, deep fat-fried sample showed lower DPPH and ABTS values than sample fried by infrared radiation, probably due to the higher temperature. For DPPH values, the differences between the vacuum pressures in the drying process and the initial moisture contents in the frying process were found to be statistically significant ($p < 0.05$).

The antioxidant activities of samples after in-vitro digestion were decreased compared to antioxidant activity values of sample. The antioxidant activity of chips after digestion

Table 3 Antioxidant activities and their bioaccessibility rate after in-vitro digestion

Sample	(mmol Trolox eq./g DM)		Bioaccessibility (%)	(mmol Trolox eq./g DM)		Bioaccessibility (%)
	DPPH	GID DPPH		ABTS	GID ABTS	
Fresh	9.38 ± 0.88	8.78 ± 0.21	93.68 ± 2.29	22.04 ± 5.72	20.97 ± 0.13	95.14 ± 0.61
180W-100	10.34 ± 0.02^{aA}	8.34 ± 0.41^{aA}	80.65 ± 3.99^{aA}	24.06 ± 8.43^{aA}	19.84 ± 1.56^{abA}	82.44 ± 6.52^{aA}
275W-100	12.85 ± 1.00^{bB}	10.25 ± 0.00^{aB}	79.77 ± 0.02^{aA}	27.38 ± 7.52^{aA}	21.94 ± 1.70^{abA}	80.12 ± 6.22^{aA}
325W-100	12.89 ± 0.00^{bB}	9.95 ± 0.41^{aB}	77.20 ± 3.21^{aA}	29.98 ± 4.16^{aA}	22.79 ± 6.95^{bA}	76.02 ± 23.20^{aA}
180W-400	10.51 ± 0.01^{aA}	8.34 ± 0.39^{aA}	79.43 ± 3.73^{aA}	22.23 ± 0.00^{aA}	18.12 ± 1.47^{abA}	81.48 ± 6.63^{aB}
275W-400	12.07 ± 1.13^{abAB}	8.37 ± 2.94^{aA}	69.37 ± 24.39^{aA}	22.46 ± 0.70^{aA}	18.13 ± 0.18^{abA}	80.70 ± 0.81^{aAB}
325W-400	13.45 ± 0.68^{cB}	9.40 ± 0.00^{aA}	69.87 ± 0.00^{aA}	33.20 ± 1.08^{aB}	23.74 ± 0.54^{bB}	71.52 ± 1.65^{aA}
Convectional drying	12.39 ± 0.09^{b}	9.88 ± 0.02^{a}	79.75 ± 0.17^{a}	24.22 ± 2.32^{aA}	14.05 ± 1.08^{a}	58.03 ± 4.46^{a}
NPD-250W	11.77 ± 0.59^{bA}	9.14 ± 0.24^{bcA}	77.70 ± 2.06^{aA}	22.02 ± 4.09^{aA}	15.66 ± 1.85^{abA}	71.11 ± 8.43^{aA}
NPD-300W	13.30 ± 1.11^{cB}	10.55 ± 0.56^{cdAB}	79.33 ± 4.25^{aA}	23.64 ± 1.69^{aA}	17.08 ± 2.82^{abcAB}	72.23 ± 11.96^{aA}
NPD-350W	13.68 ± 0.47^{cB}	11.00 ± 0.70^{dB}	80.39 ± 5.16^{aA}	27.31 ± 2.18^{aA}	21.73 ± 0.15^{cB}	79.56 ± 0.58^{aA}
PD-250W	10.28 ± 0.19^{abA}	7.80 ± 1.34^{abA}	75.95 ± 13.11^{aA}	21.41 ± 6.72^{aA}	14.54 ± 1.11^{abA}	67.93 ± 5.20^{aA}
PD-300W	10.67 ± 0.35^{abA}	8.24 ± 0.45^{abA}	77.22 ± 4.23^{aA}	23.61 ± 0.74^{aA}	16.93 ± 3.62^{abcA}	71.72 ± 15.35^{aA}
PD-350W	11.07 ± 0.71^{abA}	8.81 ± 0.12^{bA}	79.61 ± 1.14^{aA}	25.83 ± 3.04^{aA}	19.80 ± 3.40^{bcA}	76.67 ± 13.18^{aA}
Deep-fat frying	9.99 ± 1.41^{a}	6.97 ± 0.62^{a}	69.81 ± 6.25^{a}	21.36 ± 0.35^{a}	13.73 ± 1.91^{a}	64.27 ± 8.95^{a}

Data were expressed as mean ± standard deviation. For both drying and frying, different lower case letters indicate the significant difference among

samples within the same column ($p < 0.05$). Different capital letters indicate the significant difference between infrared powers within the same vacuum

pressure for drying and the same pretreatment for frying (NPD: Non-pre-dried, PD: Pre-dried)

rised with increasing infrared power. While the bioaccessibility rates of dried apple chips decreased with increasing infrared power, the bioaccessibility rates of fried apple chips increased. Fresh sample had the highest bioaccessibility rate of antioxidant activities. There is no difference between samples dried by VCIR and convectional oven ($p > 0.05$). The bioaccessibility rates of samples fried by infrared radiation was higher than that of deep fat fried sample. However, this difference was statistically insignificant ($p > 0.05$). The results was similar trend to bioaccessibility rates of TPC, TFC, and TF3-ol. It is due to the reflection of the bioaccessibility rate of phenolic content on the bioaccessibility of antioxidant activity.

Inhibitory effects on α-glucosidase activities

The inhibition of α-glucosidase, a crucial enzyme responsible for breaking down nonabsorbable oligosaccharides into absorbable monosaccharides in the small intestine, can delay the digestion process of both oligosaccharides and disaccharides. As a result, glucose absorption is reduced, leading to a decrease in postprandial hyperglycemia [45]. Antioxidants have been shown to prevent the destruction of β-cells by inhibiting the peroxidation chain reaction and thus may protect against the development of diabetes [46]. The inhibitory effects of extracts from apple chips on α-glucosidase activity are shown in Fig. 1. The IC_{50} value of the fresh sample for α-glucosidase inhibition activity was 27.29 mg/mL. Especially α-glucosidase inhibitory activity of dried apple chips was higher than that of the fresh apple and fried apple. The 325W-400 sample showed the highest α-glucosidase inhibition performance and had significantly higher α-glucosidase inhibitor activity than sample dried with convectional dryer. Similar situation among freeze, vacuum, solar, convective, and infrared dried samples was reported by Vega-Gálvez et al. [47]. The highest inhibition of α-glucosidase was found in samples dried by infrared drying. This can be attributed to the best retention of TPC and some individual phenolic acids in infrared drying samples [47]. The α-glucosidase inhibitory activity of apple chips increased with increasing infrared radiation during the drying and frying process ($p < 0.05$). The difference among NPD and PD samples in the frying process was found to be significant ($p < 0.05$). The deep fat fried sample had lower α-glucosidase inhibitory activity than all samples fried by infrared radiation ($p < 0.05$). The α-glucosidase inhibition activity of the fresh, dried, and fried samples was higher than acarbose as a positive control group. Similar situation was observed in the study by de Oliveira Raphaelli et al. [48], where apple phenolic extracts showed better inhibitory activity against α-glucosidase than acarbose. The high chlorogenic acid,

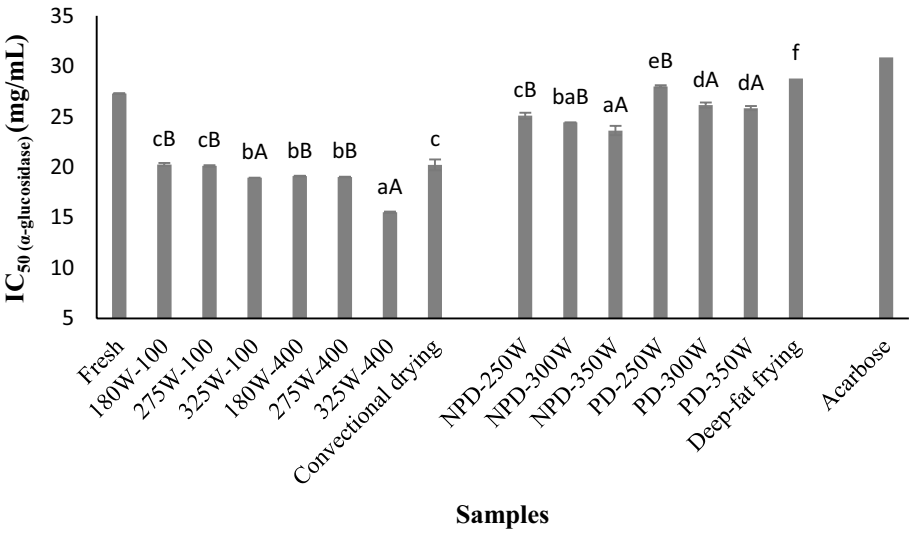


Fig. 1 α-glucosidase inhibitory activities of apple chips. Data were expressed as mean ± standard deviation. For both drying and frying, different lowercase letters indicate significant difference between samples ($p < 0.05$). Different capital letters indicate the significant difference between infrared powers within the same vacuum pressure for drying and the same pretreatment for frying (NPD: Non-pre-dried, PD: Pre-dried)

procyanidin B2, and epicatechin contents of samples may contribute to the highest α-glucosidase inhibitory activity. Ma et al. [49] reported that the inhibition of α-glucosidase increased with increasing molecular weight of flavan-3-ol and pentamers had the strongest inhibitor activity. As a result, fresh, fried, or especially dried apple can be a suitable food source and used as an antidiabetic agent due to its high phenolic content.

Conclusion

In this study, the effects of VCIR drying and frying applications on phenolic compounds, antioxidant activity, their in-vitro bioaccessibility, and α-glucosidase inhibitory activity of apple chips were investigated. The high infrared radiation applications showed higher bioactive compounds, antioxidant activity, and α-glucosidase inhibitory activity in apple chips. While the bioaccessibility rates of dried apple chips decreased with increasing infrared power, the bioaccessibility rates of fried apple chips increased. Infrared radiation application both drying and frying had high phenolic content, antioxidant activity, bioaccessibility, and α-glucosidase inhibitory activity when compared to counterparts (convectional drying and deep-fat frying, respectively). As a result, the applications of infrared radiation as an innovative technology can improve the bioactive compounds of apple chips and their positive effects on health. In vivo studies are also needed to determine the potential bioaccessibility and α-glycosidase inhibitory activity of apple chips produced by VCIR.

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Data Availability Data will be made available on request.

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