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Impact of frying methods on colours, morphological properties, and aroma compounds of arrowhead (*Sagittaria latifolia*) corm chips

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Abstract

Arrowhead is a starchy vegetable with a unique taste and many health promoting effects. To diversify the usage and increase the consumption of arrowhead, the effects of different frying methods on the morphology and aroma compounds of arrowhead corm chips were studied. The analysis of aroma compounds by accelerated solvent extraction coupled with high-vacuum flavour extraction analysis (ASE-HVFEA), gas chromatography-mass spectrometry (GC-MS), and gas chromatography-olfactometry (GC-O) of deep- and air-fried arrowhead corm chips was conducted. The aim was to understand the variability and abundance of aroma compounds between deep- and air-fried arrowhead chips. In addition, the colours and morphological characteristics of the corm chips were also studied. Twenty-three aroma compounds were identified in the differently fried chips. The predominant aroma compounds were the Strecker-aldehydes, in which 2-methylbutanal, (*E*)-2-heptenal, hexanal, and (*E,E*)-2,-4-decadienal were identified as the major aroma constituents of the fried chips. This was followed by the pyrazines. Results of the odour activity values (OAVs) revealed significant ($p < 0.05$) differences in the aroma profiles of the differently fried chips. Deep-fried chips produced more potency for the baked-like, 2-3-diethyl-5-methylpyrazine, potato-like, methional, deep-fried, (*E,E*)-2,4-decadienal, roasty, 2-ethyl-3,5-dimethylpyrazine, malty, and 2-methylbutanal. However, air-fried chips exhibited similar but lower potency for the same compounds. Whilst there was no significant ($p \geq 0.05$) difference in the external appearance of the differently fried chips, deep-frying significantly ($p < 0.05$) altered the cell walls of the deep-fried chips more than the air-fried chips. These results would serve as a guidance for aroma flavour evaluation, improvement, and quality control during oil- and air-frying of chips.

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Introduction

Arrowhead (*Sagittaria latifolia* L. var. *sinensis* Makino), which is also known as swan potato, duck potato, or pond potato, belongs to family Alismataceae (Wani *et al*., 2015). The plant can be identified by its rosettes of long slender arrowhead-shaped leaves that extend on tall stalks. Arrowhead grows rapidly in ponds and rice-fields (Wani *et al.*, 2015). In the United States and Canada, arrowhead starch has been used in the food industry (Kuhn-lein and Turner, 1991). The X-ray diffractogram of its native starch granule showed a C-pattern (Chang, 1998) like those of sweet potato and water chestnut. In addition, the arrowhead corm is popular in the diets of the Chinese because of its unique nutrient and taste. Previous study revealed that dried arrowhead corm contains 54.60% starch and 16.47% protein (Li *et al*., 2016).

Arrowhead corm may be roasted, boiled, or fried (USDA, 2000); they are also used as an ingredient in many Chinese cuisines. Moreover, an important factor driving consumers' preferences for these products is their flavour. Flavour is known to combine the perceptions of aroma, taste, and mouthfeel sensation. Unlike potato, the volatile flavour compounds of arrowhead corm have not been documented. The volatile compounds of potato have been widely reported. While raw potatoes are known to possess little volatile compounds, more than 400 compounds have been reported in boiled potatoes (Blanda *et al*., 2010). Similarly, more than 500 compounds have been identified in French fries (Chang *et al*., 2019). Among these, Maillard reaction

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products as well as lipid oxidation products have been identified.

Arrowhead crispy chips are regular titbits during Chinese New Year in Malaysia. The flavourful chips are produced by deep-frying raw arrowhead corms in corn oil. Frying is a cooking method that produces unique flavours and textures in foods. Post-frying quality of fried products often depends on certain factors such as frying oil, frying method, and pre-frying processing. Recently, efforts are directed at reducing the fat content of deep-fried products. To achieve this, air fryers are now being used (Teruel *et al*., 2015). Other methods which have been used to reduce the fat content of fried products include the use of hot-air and super-heated steam at the discharged end of the fryer to remove non-absorbed surface oil (Miranda and Aguilera, 2006). The objective of the present work was, therefore, to evaluate the impact of deep- and air-frying methods on the volatile profiles of arrowhead corm chips, and determine their effects on the colour and textural quality of the chips.

Materials and methods

Materials

Arrowhead corms were obtained from a local supplier, Little Boss Enterprise, Taman Puncak, Malaysia while pure corn oil was purchased from Daisy Foods, Malaysia.

Chemicals

Authentic chemical compounds with purity ≥ 96% and GC-grade were obtained commercially. Ethyl acetate, 2-methylbutanal, pentanal, benzaldehyde, 2-pentyl furan, phenyl acetaldehyde, α-bulnesene, and tetradecanal were from Merck Chemicals (Darmstadt, Germany). The other compounds such as 2,3-butanediol, hexanal, methional, (*E*)-2-heptenal, (*E*)-2-octenal, maltol, 2-ethyl-3,5-dimethylpyrazine, nonanal, 2,3-dihydro-3,5-dihydroxy-6-methyl-4H-pyra-4-one, 2,3-diethyl-5-methylpyrazine, (*E,E*)-2,4-decadienal, β-caryophyllene, and *cis*-9-hexadecenal were from Aldrich (Steinhein, Germany).

Sample preparation

Arrowhead corms (*n* = 100) were washed, peeled, and sliced thinly (approximately 1.5 mm in cross section) with a Mandolin slicer (QVC-5, Changzhou Shule Kitchen Utensils Co., Ltd., Jiangsu, China). The sliced corms were rinsed for 1 min in distilled water, dried with paper towel, and divided into three equal parts (150 g). One part was deep-fried in corn oil while the second part was air-fried in a Phillips air fryer (HD 9216/81). The third part was used as control.

Frying conditions

Dried corm slices were deep-fried for about 3 min at 180°C in a Kenwood electric fryer (Kenwood, Heusen Tamm, Germany). The corn oil (1.5 L) was firstly preheated for about 10 min before frying. The corm-to-oil mass ratio was about 1:10. Golden coloured chips were drained, divided into two equal batches (75 g), and vacuum-sealed in plastic bags. Air-frying was carried out for 15 min at 180°C in a Phillips air fryer. Air-fried chips were also divided into two equal batches (75 g), and vacuum-sealed in plastic bags.

Moisture and colour measurement

The moisture content of chips (*i.e.*, deep- and air-fried) was determined following the AOAC (1995) method. The colour measurement of chips was conducted with a chromameter (CR-410, Konica Minolta, Sensing, Singapore). The average of five measurements on each sample was recorded as colour coordinate values (L*, a*, and b*) for each sample.

Scanning electron microscopy

Scanning electron microscopy (SEM) of the raw, deep-, and air-fried arrowhead chips was carried out using a SEM (JSM-6400, JEOL Ltd., Tokyo, Japan) according to Shittu *et al*. (2016). The chip was attached to a circular aluminium specimen stub, coated vertically with gold palladium, and mounted on a carbon sample holder. Electromicrographical analysis of the starch granules were conducted at an accelerated potential of 10 KV with the following magnifications of 50, 100, 250, and 500× for each chip sample.

Accelerated solvent extraction coupled with high-vacuum flavour extraction analysis (ASE-HVFEA)

The extraction was conducted as described by Liu *et al*. (2022). An accelerated solvent extraction unit (E-914, Buchi, Switzerland) was employed for the extraction of the flavour aroma compounds from the arrowhead corm chips. The arrowhead corm chips (*i.e.*, deep- and air-fried) were frozen in liquid nitrogen, and pulverised using a commercial blender. A portion (40 g) of the pulverised chip was dispersed in 40 g of quartz sand and anhydrous potassium sulphate, and the mixture was placed inside the extraction cell of the instrument. The cell was filled with 20 mL of dichloromethane and flushed with high-purity nitrogen at 55°C. A pressurised static extraction phase lasting for 5 min was performed at 110 Bar and 100°C (Liu *et al*., 2022). The extraction was carried out three times with fresh flow of dichloromethane (20 mL). To prevent carry-over, the instrument was flushed with nitrogen for 1 min at the end of each cycle of extraction. Finally, the obtained extract was subjected to solvent-assisted flavour extraction (SAFE) distillation at 40°C. After evaporation, the distillate was concentrated to 200 µL (Lasekan and Ng, 2015).

Gas chromatography-mass spectrometry

A QP-2019 Ultra GC-MS (Shimadzu, Japan) with the following capillary columns: SLB-5 ms (30.0 m × 0.25 mm i.d. × 0.25 µm thickness; Scientific Instrument Services, Inc., NJ, USA), DB-FFAP (30.0 m × 0.32 mm i.d. × 0.25 µm film thickness; Scientific Instrument Services, Inc., Ringoes, NJ, USA), and a mass selective detector (Finnigan TRACE DSQ MS, Thermo Electron Corp) were employed. The extracts (2 µL) were applied using the on-column injection procedure at 230°C. The column temperature was from 50 to 250°C at the rate of 3°C/min with holding at 250°C for 15 min. Pressure was set at 37.1 KPa with helium flow rate at 1.8 mL/min. A series of *n*-alkanes, C6 - C30, were used to calculate the retention indices (Lasekan and Ng, 2015).

The mass spectrometer was operated in the electron impact mode. The source temperature was 250°C and the quadruple temperature was 280°C. Electron energy of 70 eV, data collection rate of 1.5 scan/s over a range of 40 - 450 *m/z*, and a multiplier voltage of 1,100 V were employed. The peak area of each compound was related to that of the corresponding external standard to obtain the necessary quantitative data which were expressed as µg/kg.

Gas chromatography-olfactometry

The identification of the key aroma compounds in the arrowhead corm chips was performed as recently described by Lasekan and Dabaj (2020) on the SLB-5 ms (30.0 m × 0.25 mm i.d. × 0.25 µm thickness; Scientific Instrument Services, Inc., NJ, USA). The GC-O conditions were as earlier described. The serial dilutions of the concentrated high-vacuum extracts obtained from the arrowhead corm chips followed Schieberle (1995). Aliquot (0.5 mL) of the concentrated extracts from the (ASE-HVFEA) of the arrowhead corm chips were diluted in a stepwise manner *via* the addition of dichloromethane (Lasekan *et al*., 2021). Flavour dilution (FD) factors of the aroma compounds were determined by GC-O which was performed by three panellists who evaluated all dilutions in triplicate. Finally, only compounds detected by two or more panellists were reported.

Sensory evaluation

Twelve trained evaluators (six females and six males; aged 18 to 24) from Universiti Putra Malaysia were employed to evaluate the sensory attributes of the differently fried arrowhead corm chips. Before the analysis, aroma descriptors were selected using a descriptive test reported by Thurer and Granvogl (2016). The following descriptors with their corresponding compounds were used: deep-fried [(*E,E*)-2,4-decadienal], fatty [(E)-2-heptenal], grassy-tallow [hexanal], cooked potato-like [methional], nutty-fatty [(*E*)-2-octenal], roasty [2-ethyl-3,5-dimethylpyrazine], and chocolate-baked [2,3-diethyl-5-methylpyrazine]. The intensities of the sensory attributes were rated on a linear scale from 0 (not detectable) to 3 (strongly detectable) with a spacing of 0.5 point. The analysis was repeated three times by each evaluator.

Statistical analysis

The statistical analysis of the data was carried out using a statistical package SPSS 15.0 (Statistical Package for the Social Science for Window). Statistical significance was expressed at $p < 0.05$.

Results and discussion

Colour and morphological characteristics of arrowhead corm chips

The colour measurements (L*, a*, b*) of the raw, deep-, and air-fried arrowhead corm chips are shown in Table 1. Colour represents an important quality index of arrowhead corm chips. Previous study on potato chips revealed a significant influence of chemical composition, slice thickness, frying temperature, and time on colour development (Lee and Pangloli, 2013). In the present work, the L* value of the raw arrowhead slices was 79.54, and it decreased significantly ($p < 0.05$) in the fried chips (*i.e.*, deep- and air-fried). The deep-fried chips were darker (lower L*) and more yellowish (higher b*) than the air-fried chips (Figure 1), although the differences were not significant ($p \geq 0.05$). As expected, the moisture content of the deep-fried chips decreased rapidly ($p \leq 0.05$) than the air-fried chips (Table 1). This observation was consistent with the higher heat flux reported by Andres *et al*. (2013) during deep-frying of French fries. Therefore, the high temperature (180°C) during frying as well as the rapid moisture loss might have accelerated caramelisation which led to sugar dehydration and a series of reactions to form caramel/dark-coloured pigments observed in the fried arrowhead corm chips. Colour development only began when enough drying had occurred on the arrowhead corm chips. Colour is visually considered one of the most important parameters in the definition of quality of fried foods, and is the result of the Maillard reaction that depends on the content of the reducing sugars and amino acids or proteins at the surface coupled with the temperature, thickness, and duration of frying. Similar observation was also reported in potato chips (Nourian *et al*., 2003) and cassava chips (Oyedeji *et al*., 2017).

Table 1. Colour intensity and moisture content of arrowhead chips.

	L*	**a***	**b***	**Moisture content (%)**
Air-fried	59.38 ± 0.41[a]	9.53 ± 0.77[a]	26.58 ± 0.68[a]	9.38 ± 0.92[a]
Deep-fried	58.57 ± 0.43[a]	12.68 ± 0.37[b]	30.24 ± 0.53[b]	0.22 ± 0.02[b]
Raw	79.53 ± 0.07[b]	1.26 ± 0.10[c]	27.24 ± 0.05[a]	65.3 ± 0.46[c]

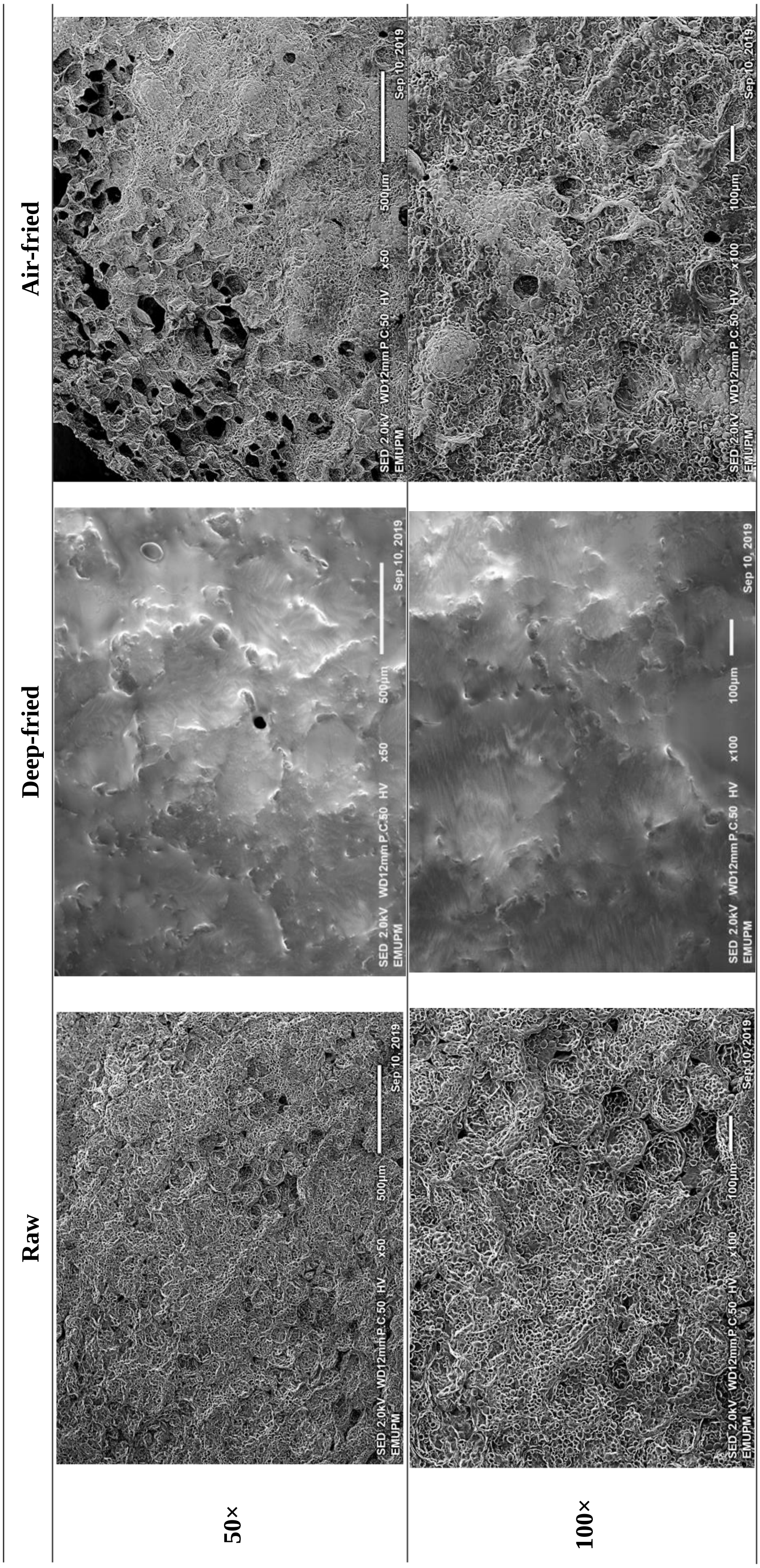
Mean ± SD with different lowercase superscripts in the same column are significantly different ($p < 0.05$).

(A) **(B)**

Figure 1. Deep-fried **(A)** and air-fried **(B)** arrowhead corm chips at 180°C.

Morphological characteristics of arrowhead corm chips

The morphological characteristics of the raw, deep-, and air-fried chips as determined *via* SEM are shown in Figure 2. The shape of the starch granules in the raw samples appeared oval and smooth when viewed at 500× magnification. This was consistent with previous studies (Du *et al*., 2010; Li *et al*., 2016), and the shape of the starch granules fairly resembled those of potato. However, there were distinctive differences between the morphological appearance of the raw sample and the fried chips. The raw sample revealed several well-arranged starch granules, and a closer look at the fried chips showed that deep- and air-frying at 180°C significantly altered the microstructures of the arrowhead chips. For instance,


Raw
Deep-fried
Air-fried
50×
100×

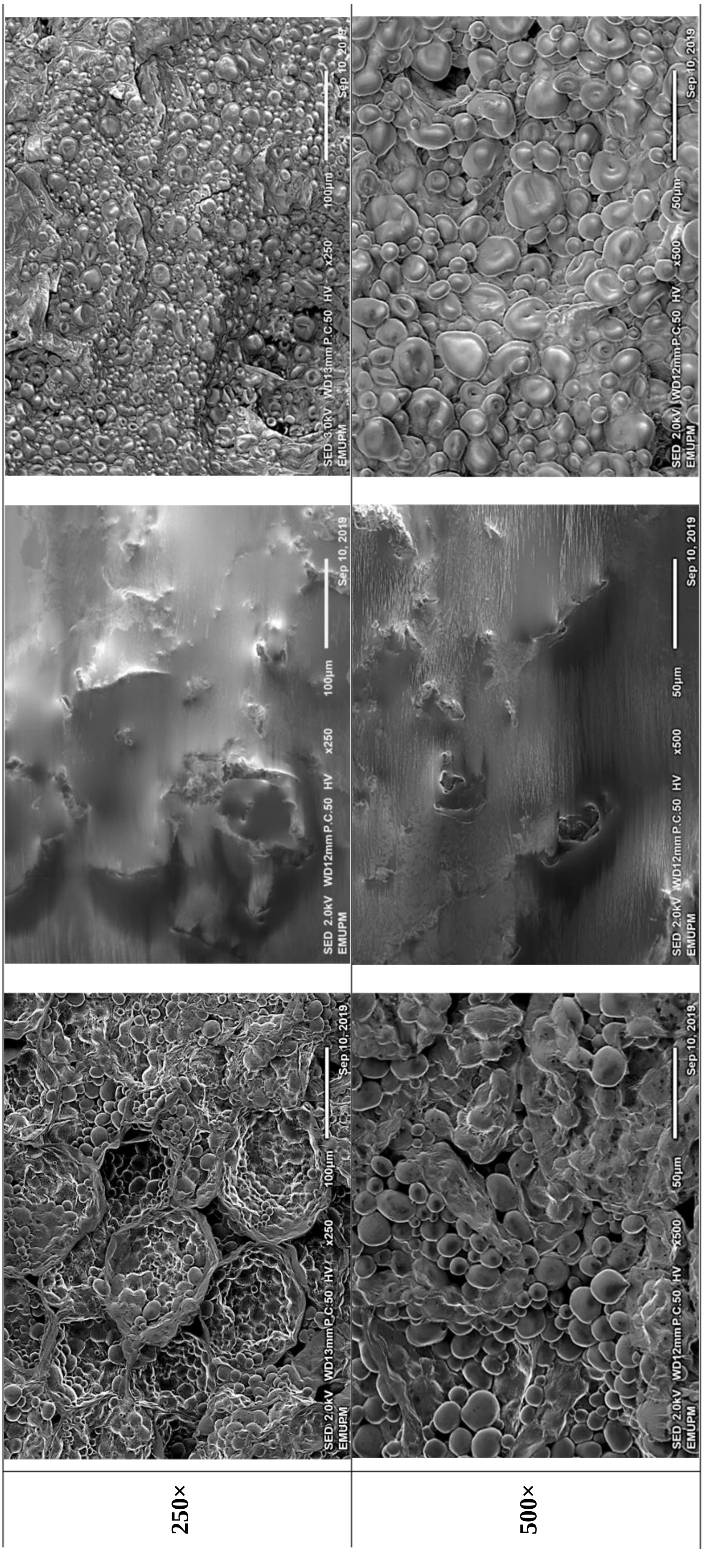


Figure 2. Electron micrographs of raw, deep-, and air-fried arrowhead chips at 180°C.

there was significant deformation of the chip's cell wall accompanied with flooded oil in the deep-fried chips than the air-fried at 500× magnification. In contrast, the air-fried chips retained more intact starch granules as observed by SEM at 500× magnification. Previous studies (Bouchon and Aguilera, 2001; Miranda and Aguilera, 2006) have reported on the significant changes in the microstructural characteristics of deep-fried potato chips. For example, a vivid demonstration of the impact of frying on the microstructural changes occurring in fried potato cells was provided by Bouchon and Aguilera (2001) who applied a video microscopy to *in situ* frying of potato cells. The authors revealed that the water inside the cells (*i.e.*, intercellular water) was rapidly absorbed by starch granules before the dehydration effects set in. This was followed by cell dehydration and shrinkage which commenced soon after gelatinisation of starch *in situ* as the oil was heated to 180°C.

Aroma compounds in fried arrowhead corm chips

A total of 23 aroma compounds were identified in the fried arrowhead corm chips (Table 2): 12 aldehydes, three heterocyclic aromatic organic compounds, three sesquiterpenes, one ketone, one ester, two organic compounds, and one glycol. The flavour of the differently fried arrowhead chips was quite different as revealed in their respective aroma compounds profile and concentrations (Tables 2 and 3). The application of the AEDA revealed an FD factor range of between 2 to 128 for the compounds. An array of aroma nuances including fruity, malty, almond, buttery-like, grassy, tallow, potato-like, fatty, and deep-fried were perceived at the sniffing port. The aroma compound with the highest FD value was the deep-fried (*E,E*)-2,4-decadienal with values of 128 and 32 in the deep- and air-fried chips, respectively (Table 2). Other compounds with significantly high FD were the nutty, fatty (*E*)-2-octenal, 2-ethyl-3,5-dimethylpyrazine with a roasty nuance, phenyl acetaldehyde, (*E*)-2-heptenal, 2-methylbutanal, and the potato-like methional, respectively. These were followed by grassy-like hexanal and chocolate-like 2,3-diethyl-5-methylpyrazine with FD of 8 each, respectively.

A comparative analysis of the composition and concentration of the aroma compounds in the raw, deep-, and air-fried chips revealed that the aroma compounds of the raw arrowhead slices comprised mainly of short chain aldehydes (Table 3) and as hypothesised by Buttery and Ling (1973), these short chain aldehydes were most likely derived from the biosynthetic processes rather than thermal catalysed reactions. The raw arrowhead aroma compounds were made up of pentanal, hexanal, methional, (*E*)-2-heptenal, benzaldehyde, (*E*)-2-octenal, and nonanal, all of which are lipid oxidation products of unsaturated fatty acids.

After deep- and air-frying of the arrowhead corm chips at 180° C, the aroma compounds in the highest concentration were the Strecker-aldehydes namely 2-methylbutanal (malty), hexanal (grassy, tallow), methional (potato-like), (*E*)-heptenal (fatty, grassy), nonanal (fatty, floral), and (*E,E*)-2,4-decadienal (deep-fried). The Strecker-aldehydes which are formed *via* Strecker degradation of amino acids in the Maillard reaction are known to impact significantly on the aroma of thermally heated food products (Bowman and Barringer, 2012; Agarwal *et al.*, 2021). Most of these aldehydes have been identified previously in fry bread (Lasekan and Dabaj, 2020), fried tilapia (*Oreochromis niloticus*) (Liu *et al*., 2022), and French fries (Xu *et al*., 2022), respectively.

Air frying which only sparged hot air around the chips produced significantly ($p < 0.05$) lower concentrations of Strecker-aldehydes in the air-fried chips as compared to the deep-fried chips. Earlier report on air-frying has revealed that the lower heat transfer coefficient of air as compared to oil generally results in slower heat transfer during air frying (Teruel *et al*., 2015). This phenomenon probably caused the significant ($p \leq 0.05$) reduction in the concentrations of the aroma compounds generated in the air-fried chips. Apart from the Strecker-aldehydes, the pyrazines were the next prominent aroma compounds identified in the fried chips. 2-Ethyl-3,5-dimethylpyrazine and 2,3-diethyl-5-methylpyrazine that contributed roasty, chocolate, and baked nuances to the fried chips were detected at higher concentrations in the deep-fried chips than the air-fried chips. These pyrazines were likely generated by the Maillard reaction between glucose and amino acids (Song *et al*., 2015). Other compounds including 2,3-dihydro-3,5-dihydroxy-6-methyl-4H-pyran-4-one, ethyl acetate, 2,3-butanediol, maltol, β-caryophyllene, and α-bulnesene were detected in significant ($p < 0.05$) amounts in the deep-fried chips (Table 3).

Table 2. Identified compounds in deep- and air-fried arrowhead chips.

No.	Compound[a]	RI on SLB-5ms	RI on DB-FFAP	Odour description[b]	FD Deep-fried	FD Air-fried	Identification method
1	Ethyl acetate	600	896	Fruity	2	4	MS/RI/O/ST
2	2-Methylbutanal	646	915	Malty	16	8	MS/RI/O/ST
3	Pentanal	669	992	Almond-like	2	2	MS/RI/O/ST
4	2,3-Butanediol	782	1547	Buttery	4	4	MS/RI/O/ST
5	Hexanal	797	1089	Grassy	8	8	MS/RI/O/ST
6	Methional	903	1466	Potato-like	16	16	MS/RI/O/ST
7	(*E*)-2-Heptenal	959	1353	Fatty, grassy	16	8	MS/RI/O/ST
8	Benzaldehyde	961	1523	Almond-like	4	4	MS/RI/O/ST
9	2-Pentyl furan	991	1252	Caramel	4	2	MS/RI/O/ST
10	Phenyl acetaldehyde	1042	1653	Honey, rosy	16	16	MS/RI/O/ST
11	(*E*)-2-Octenal	1056	1423	Nutty, fatty	64	32	MS/RI/O/ST
12	Maltol	1060	1963	Caramel	4	2	MS/RI/O/ST
13	2-Ethyl-3,5-dimethylpyrazine	1070	1435	Roasty	32	16	MS/RI/O/ST
14	Nonanal	1097	1406	Fatty, floral	4	4	MS/RI/O/ST
15	2,3-Dihydro-3,5-dihydroxy-6-methyl-4H-pyran-4-one	1134	2310	Roasty	4	4	MS/RI/O/ST
16	2,3-Diethyl-5-methylpyrazine	1160	1524	Chocolate	8	8	MS/RI/O/ST
17	(*E*,*E*)-2,4-Decadienal	1311	ND	Deep-fried	128	32	MS/RI/O/ST
18	Longifolene	1403	1608	Woody-like	2	2	MS/RI/O/
19	β-Caryophyllene	1415	1619	Woody, spicy	2	4	MS/RI/O/ST
20	Geranyl acetone	1456	1715	Fruity, rosy	2	2	MS/RI/O/ST
21	α-Bulnesene	1493	1720	Weak spicy	4	2	MS/RI/O/ST
22	Tetradecanal	1618	1937	Waxy, floral	2	2	MS/RI/O/ST
23	*cis*-9-Hexadecenal	1805	ND	Fatty	4	2	MS/RI/O/ST

[a]Compound identified by comparison of its aroma quality and intensity, retention indices on capillaries SLB-5ms and DB-FFAP with their mass spectra in EI compared with data of reference compounds. MS, RI, O, and ST are mass spectra, retention indices, olfactometry, and standard compounds, respectively. [b]Odour quality at the sniffing port. n.d. = not detected.

Table 3. Aroma compounds and concentrations of deep- and air-fried arrowhead chips.

No.	Compound	Odour description	Concentration (μg/kg)		
			Raw	Deep-fried	Air-fried
1	Ethyl acetate	Fruity	1.9 (0.1)[c]	2.3 (0.1)[a]	6.1 (0.1)[b]
2	2-Methylbutanal	Malty	n.d.	193 (5.4)[a]	76 (1.2)[b]
3	Pentanal	Almond	5.2 (0.2)[c]	16 (1.1)[a]	11 (0.4)[b]
4	2,3- Butanediol	Buttery	1.5 (0.1)[c]	8.5 (0.2)[a]	2.4 (0.1)[b]
5	Hexanal	Grassy, acorn	20 (1.4)[c]	64 (1.7)[a]	43 (0.1)[b]
6	Methional	Potato-like	12.6 (0.1)[c]	25.6 (0.4)[a]	22.0 (0.1)[b]
7	(*E*)-2-Heptenal	Fatty, grassy	18 (2.0)[c]	124 (3.0)[a]	65 (2.4)[b]
8	Benzaldehyde	Almond	3.5 (0.1)[c]	18 (0.4)[a]	12 (0.1)[b]
9	2-Pentylfuran	Cocoa, caramel-like	2.0 (0.1)[c]	10.8 (0.2)[a]	5.9 (0.1)[b]
10	Phenyl acetaldehyde	Honey, rose	10.0 (1.0)[c]	20.0 (2.1)[a]	12.0 (1.0)[b]
11	(*E*)-2-Octenal	Nutty, fatty	10 (0.2)[c]	28 (1.2)[a]	16 (0.5)[b]
12	Maltol	Caramel	n.d.	5.6 (0.1)[a]	2.0 (0.1)[b]
13	2-Ethyl-3,5-dimethylpyrazine	Roasty	n.d.	126.0 (4.1)[a]	62 (1.2)[b]
14	Nonanal	Fatty, floral	8.5 (0.1)[c]	27.9 (0.4)[a]	13.5 (0.2)[b]
15	2,3-Dihydro-3,5-dihydroxy-6-methyl-4H-pyran-4-one	Roasty	n.d.	56.0 (2.1)[a]	23.4 (0.2)[b]
16	2,3-Diethyl-5-methyl pyrazine	Chocolate, baked	n.d.	15.6 (0.2)[a]	5.6 (0.1)[b]
17	(*E*,*E*)-2,4-Decadienal	Deep fried	n.d.	791 (5.7)[a]	391 (0.6)[b]
18	Longifolene	Woody-like	12.1 (0.3)[a]	9.6 (1.2)[c]	10.6 (1.0)[b]
19	β-Caryophyllene	Woody, spicy	3.5 (0.1)[c]	11.4 (3.0)[a]	7.8 (1.0)[b]
20	Geranyl acetone	Fruity, rose	1.8 (0.1)[c]	4.4 (0.1)[b]	6.0 (0.2)[a]
21	α-Bulnesene	Weak spicy, woody	n.d.	7.8 (0.1)[a]	5.0 (0.1)[b]
22	Tetradecanal	Waxy, floral	n.d.	4.5 (0.1)[a]	4.5 (0.1)[a]
23	*cis*-9-Hexadecenal	Fatty	n.d.	12.6 (0.1)[a]	6.1 (0.1)[b]

Relative standard deviations are presented in parentheses. Means with different lowercase superscripts in the same row are significantly different($p < 0.05$).

Comparative aroma compounds potency

A detailed analysis of the aroma compound potency between the deep- and air-fried chips revealed clear differences (Table 4). The results of the AEDA on the compounds with FD ≥ 8 showed that deep-fried chips produced more potency for the baked, potato-like, and deep-fried notes as shown by the high OAVs obtained for their corresponding aroma compounds namely 2,3-diethyl-5-methylpyrazine (15.6), methional (14.2), (*E*,*E*)-2,4-decadienal (12), 2-ethyl-3,5-dimethylpyrazine (10.3), and 2-methylbutanal (5.7), respectively. Conversely, the air-fried chips produced lower potency for these compounds. Moreover, some compounds with high concentrations such as hexanal and (*E*)-2-heptanal recorded OAVs below 1, and it was assumed that they did not contribute to the overall aroma of the fried chips.

Table 4. Concentrations and odour activity values of aroma compounds with FD ≥ 8 in arrowhead chips.

No	Compound	Aroma description	Conc. (µg/kg)		Odour threshold in oil	OAVs	
			DF	AF		DF	AF
1	2-Methylbutanal	Malty, burnt	193	76	34[c]	5.7	2.2
2	Hexanal	Grassy, tallow	64	43	120[a]	< 1	< 1
3	Methional	Potato-like	25.6	22.0	1.8[a]	14.2	12.2
4	(*E*)-2- Heptenal	Fatty, grassy	124	65	3750[a]	< 1	< 1
5	Phenyl acetaldehyde	Honey, rose	20	12	22[a]	< 1	< 1
6	(*E*)-2-Octenal	Nutty, fatty	28.0	16.0	7×10^3 [a]	< 1	< 1
7	2-Ethyl-3,5-dimethyl pyrazine	Roasty	123	62	12.2[a]	10.1	5.1
8	2,3-Diethyl-5-methylpyrazine	Chocolate, baked	15.6	5.6	1.0[b]	15.6	5.6
9	(*E*,*E*)-2,4-Decadienal	Deep-fried	791	391	66[c]	12.0	5.9

[a]Rychlik *et al*. (1998); [b]Cerny and Grosch (1993); and [c]Thurer and Granvogl (2016). DF = deep-fried chips; AF = air-fried chips; and OAVs = calculated by dividing the compound concentration by their respective odour threshold in oil.

Sensory analysis of fried arrowhead corm chips

The sensory scores of the two differently fried arrowhead corm chips were plotted by the spider diagram (Figure 3). The intensity of the sensory attributes exhibited distinct differences. By contrast, the deep-fried chips produced stronger deep-fried and fatty attributes probably because of the higher frying temperature (180°C) employed for the deep frying. Similar observation was reported in fried shallot (*Allium cepa* L. var *aggregatum*) (Tian *et al*., 2021). Also, the deep-fried chips exhibited stronger nutty, roasty, and chocolate attributes as compared to the air-fried chips. This observation was in tandem with the pyrazine's concentration in the different chips (Table 3). Previous studies on the aroma profile of potato chips also reported that pyrazines were responsible for the nutty, roasty, and chocolate aroma in potato chips (Mohamed *et al*., 2020; Xu *et al*., 2021) and corn tortilla chips (El-Shayeb *et al*., 2018), respectively. Overall, the sensory evaluation of the deep-fried chips was characterised by deep-fried, fatty, nutty, roasty, chocolate-like, and malty nuances (Figure 3). On the other hand, the air-fried chips were characterised with similar but lower aroma nuances as the deep-fried chips. In terms of crispiness, the deep-fried chips were more preferred by the consumers probably because of its lower moisture content.

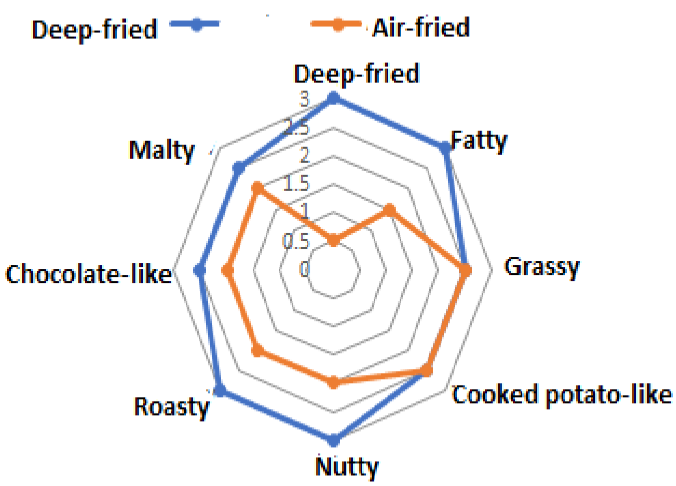


Figure 3. Sensory analysis of deep-fried (blue) and air-fried (orange) arrowhead chips.

Conclusion

Whilst the external appearance of the deep- and air-fried arrowhead chips was not significantly ($p \geq 0.05$) different. Deep-frying significantly altered the cell walls of the deep-fried chips more than the air-fried chips. Air-fried chips retained more intact starch granules than the deep-fried chips. In addition, the characterisation of the aroma compounds in the fried arrowhead chips revealed a total of 18 compounds with the Strecker-aldehydes being the predominant group. This was followed by the pyrazines namely 2-ethyl-3,5-dimethylpyrazine (roasty) and 2,3-diethyl-5-methylpyrazine (chocolate, baked). Results of the OAVs produced significant ($p \leq 0.05$) differences between the aroma profiles of the different chips. While the deep-fried chips produced more potency for the baked-like 2,3-diethyl-5-methylpyrazine, potato-like methional, deep-fried (*E,E*)-2,4-decadienal, roasty-like 2-ethyl-3,5-dimethylpyrazine, and malty-like 2-methylbutanal; the air-fried chips produced similar but lower potency for the same compounds as in the deep-fried chips. The present work provided a guide into aroma compounds' generation during deep- and air-frying of chips.

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