



Shelf-life of infrared dry-roasted almonds

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ABSTRACT

Infrared heating was recently used to develop a more efficient roasting technology than traditional hot air roasting. Therefore, in this study, we evaluated the shelf-life of almonds roasted with three different approaches, namely infrared (IR), sequential infrared and hot air (SIRHA) and regular hot air (HA). Nine medium roasted almond samples produced by the aforementioned heating methods were processed at three different temperatures (130, 140 and 150 °C), packed in paper bags and then stored at 37 °C for three, six or eight months. Shelf-life of the roasted almonds was determined by measuring the changes in colour, peroxide value, moisture content, water activity, volatile components and sensory quality. No significant difference was observed in moisture content and water activity among the almond samples processed with different roasting methods and stored under the same conditions. GC/MS analysis showed that aldehydes, alcohols, and pyrazines were the main volatile components of almonds. Aliphatic aldehydes such as hexanal, (*E*)-2-octenal, and nonanal were produced as off-odours during storage. Although the overall quality of roasted almonds produced with SIRHA and HA heating was similar during the first three months of storage, their peroxide value and concentration of aliphatic aldehydes differed significantly for different roasting methods and increased significantly in all roasted samples during storage. We postulate that hexanal and nonanal might be better indicators of the shelf life of roasted almonds than the current standard, peroxide value.

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1. Introduction

Roasting is one of the most popular ways to process almonds (The Nut Factory, 2010). However, traditional hot air roasting involves a relatively long processing time (Almond Board of California, 2007; Anon, 2007a; Centrella, 2007; Issacs et al., 2005) and does not meet the minimum 4-log reduction of *Salmonella* Enteritidis phage type 30 (SE PT 30) for pasteurisation of almond products mandated by the Almond Board of California and the U.S. Department of Agriculture (Anon, 2007b). Yang et al. (2010) recently developed two new roasting methods for almonds, infrared (IR) roasting and sequential infrared and hot air (SIRHA) roasting. Compared with traditional hot air (HA) roasting, SIRHA heating can produce roasted almonds with up to 30–70% reductions in processing time and meet pasteurisation requirements for producing medium degree roasted almonds at 130, 140, and 150 °C.

Almonds are a high oil yield seed containing around 50% lipids (Ahrens, Venkatachalam, Mistry, Lapsley, & Sathe, 2005; Harris,

Westcott, & Henick, 1972; Miraliakbari & Shahidi, 2008; Sathe, Seeram, Kshirsagar, Heber, & Lapsley, 2008). Two unsaturated fatty acids, oleic (C18:1) and linoleic acid (C18:2) account for over 90% of the total soluble lipids (Pičurić-Jovanović & Milovanović, 1993; Sathe et al., 2008). In general, foods with a higher content of unsaturated fatty acids are more susceptible to the development of rancidity and have a shorter shelf life. García-Pascual, Mateos, Carbonell, and Salazar (2003) explained that rancidity originates from the reaction of unsaturated fatty acids with oxygen followed by the degradation of fatty acid peroxides to produce off-flavor compounds.

Roasting of whole cashew nuts improved the oxidative stability of the resulting nut oils (Chandrasekara & Shahidi, 2011a). The effect may have been due to the formation of Maillard reaction products (MRP) which are known to exhibit antioxidant effects. Chandrasekara and Shahidi (2011b) studied the effect of roasting on the content of phenolic compounds and antioxidant activities of cashew nuts and testa. High temperature treated (130 °C for 33 min) cashew nuts and testa showed higher phenolic content and antioxidant activity than low temperature treated (70 °C for 6 h) samples. Similarly, roasting enhanced the antioxidant activity

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of cashew phenolic extracts compared to their raw counterparts when evaluated for their potential in inhibiting accelerated oxidation of commercial stripped corn oil at 100 °C (Chandrasekara & Shahidi, 2011c).

Most of the previous studies on roasted almond storage investigated the influence of various factors (i.e., packaging materials, moisture content, water activity, temperature, time, light or irradiation) on several physical, sensory and chemical parameters of the seeds (Abegaz, Kerr, & Koehler, 2004; Buranasompob et al., 2007; García-Pascual et al., 2003; Sattar, Mohammad, Saleem, Jan, & Ahmad, 1990; Wambura, Yang, Williams, Feng, & Rababah, 2007; Zacheo, Cappello, Gallo, Santino, & Cappello, 2000). Moisture and water activity are important criteria for the evaluation and control of food safety and quality. According to the Grocery Manufacturers Association's recent survey (2010), industry moisture specifications of 3.5–5.5% for raw almonds and 1.5–2.5% for roasted almonds, and a water activity in the range of 0.2–0.3 represent the optimal moisture content and yield the maximum shelf life. Colour is regarded as one of the most important quality attributes of roasted nuts (Francis, 1995; Wall & Gentry, 2007; Warmund, Elmore, Adhikari, & McGraw, 2009; Yang et al., 2010; Özdemir & Devres, 2000), as it affects consumer acceptability. Colour is also used in industry to specify the desired degree of roasting.

The oxidation of fats and the rate of rancidity development are highly dependent on the storage temperature. Commonly, the shelf life of nuts is inversely proportional to storage temperature. Thus, high temperatures can be used to accelerate ageing reaction rates. However, Mattei (1969) observed that almond quality was different when storage temperatures exceeded 43 °C compared with accelerated temperature tests at lower temperatures. Due to this observation and the desire to simulate summer temperatures, storage temperatures of 35–38 °C were selected by researchers performing accelerated shelf life tests (Budín & Breene, 1993; Fritsch, Hofland, & Vickers, 1997; García-Pascual et al., 2003; Harris et al., 1972; Wambura et al., 2007).

Peroxide value is frequently used to measure the progress of oxidative rancidity and as an index to evaluate shelf-life (Chun, Lee, & Eitenmiller 2005; Fritsch et al., 1997; Sánchez-Bel, Martínez-Madrid, Egea, & Romojaro, 2005; Wambura et al., 2007). Moreover, roasting and storage produce different changes in nuts (e.g., volatile compounds) as a result of different heating methods (El-Kayati, Fadel, Abdel Mageed, & Farghal, 1998; García-Pascual et al., 2003; Takei, Shimada, Watanabe, & Yamanishi, 1974; Takei & Yamanishi, 1974; Uysal, Sumnu, & Sahin, 2009). Pyrazines have been reported to be some of the most important flavor compounds in roasted nuts (El-Kayati et al., 1998; Kinlin, Muralidhara, Pittet, Sanderson, & Walradt, 1972; Walradt, Pittet, Kinlin, Muralidhara, & Sanderson, 1971), whereas aldehydes are responsible for dominating off-flavors produced during storage. The concentration of these flavor constituents varies with different roasting and storage conditions.

Krishnamurthy, Khurana, Jun, Irudayaraj, and Demirci (2008) stated that the investigation of the quality and sensory changes occurring during IR heat treatment is critical for its commercial success. Several researchers have studied the quality and sensory changes of food materials during IR heating. The results substantiated that IR heating itself does not significantly change the quality attributes of foods such as vitamins, protein, antioxidant activities and sensory quality (Chua & Chou, 2005; Huang, 2004; Khan & Vanderney, 1985; Meeso, Nathakaranakule, Madhyanon, & Soponronnarit, 2004; Tanaka et al., 2007). Kouzeh, van Zuilichem, Roozen, and Pilnik (1982) found that full-fat flour made from IR heat-treated soybeans maintained freshness similar to fresh flour for one year. To the best of our knowledge further studies on the shelf life of products processed by IR roasting have not been reported.

The goal of our study was to test the shelf-life of medium roasted almonds produced at different temperatures with three roasting methods, namely IR, SIRHA and conventional HA, and to provide a science-based approach for processing and storage of roasted almonds.

2. Materials and methods

2.1. Almonds

Raw almonds of the Nonpareil variety with size 27/30 CPO (counts per ounce) were provided by the Almond Board of California (Modesto, CA, USA). Almonds were sorted to remove any damaged kernels and then stored in plastic bags at 4 °C. The initial moisture content of raw almonds was 4.6% (w.b.). The average weight of raw almond was 1.04 ± 0.07 g and their dimensions were 7.8 ± 0.4 , 12.3 ± 0.3 , and 22.2 ± 1.2 mm in thickness, width, and length, respectively.

Raw almonds were roasted to medium degree with three different methods, IR, SIRHA, and HA. The roasting time for IR heating was 11, 6, and 4 min, for SIRHA heating was 21, 11, and 5 min and for HA heating was 34, 18, and 13 min at 130, 140 and 150 °C, respectively. Three replicate samples were processed separately for each roasting condition. The methods of almond roasting were previously described in detail (Yang et al., 2010).

2.2. Temperature-accelerated shelf life test

Nine roasted almond samples processed with different methods were packed individually in paper bags and stored at 37 ± 0.5 °C with 7–8% relative humidity in a Model 70D incubator (Precision Scientific Inc., Winchester, IL, USA). Storage behaviours were determined by measuring changes in colour, peroxide value, moisture content, and water activity each month during six months of storage. The experiment was done in triplicate.

2.2.1. Colour

The colour of raw and roasted samples was measured using a colorimeter (Minolta Chroma meter CR-200, Minolta Corporation, now Konica Minolta Sensing Americas, Inc., Ramsey, NJ, USA). At least thirty randomly selected roasted almond kernels were ground in a blender (Waring Commercial Heavy-Duty Blender 38BL 19 CB10, Waring Laboratory & Science, Torrington, CT, USA) for 5 s. The ground sample (8 g) was placed in a plastic Petri dish (5 cm diameter) for measurement. The total colour difference, ΔE , was calculated using the following equation:

$$\Delta E = \sqrt{(L_f - L_0)^2 + (a_f - a_0)^2 + (b_f - b_0)^2} \quad (1)$$

The subscripts 0 and *f* denote raw and roasted almonds, respectively, at a given time during storage.

2.2.2. Peroxide value

A sample of ground almonds (30 g) was combined with 75 mL of hexane and extracted for 1 min using a Sonifier model S-450 ultrasonic processor (Branson Ultrasonics Corporation, Danbury, CT, USA). The mixture was filtered through a Whatman No. 50 filter paper with vacuum using a Büchner funnel. The solvent was removed using a rotary evaporator (Büchi Rotavapor® R-205, BÜCHI Labortechnik AG, Flawil, Switzerland) at 30 °C. The peroxide value was determined according to Commission Regulation (E C) No. 2568/91 (1991) methods (García-Pascual et al., 2003). The lipid sample (2–5 g) was placed in a flask with 10 mL of chloroform, 15 mL of glacial acetic acid and 1 mL of water solution saturated with potassium iodide. It was left in the dark for 5 min, after which

75 mL of water and 1 mL of starch solution were added. The liberated iodine was titrated with 0.01 M sodium thiosulphate.

2.2.3. Moisture content and water activity

Roasted almond samples (20 ± 1 g) were weighed every month during six months of storage. Samples stored for six months were dried for 24 h at 70 ± 1 °C under 25–30 mmHg of pressure in a vacuum oven (Model No. V01218A, Lindberg/Blue, Ashville, NC, USA) to determine the dry sample mass. The moisture content (MC) was calculated based on the initial and final sample weights. A sample of ground almonds (2 g) was spread over the bottom of a sample cup and placed in an Aqua Lab water activity meter Model CX-2 (Decagon Devices, Inc., Pullman, WA, USA) to measure water activity.

2.3. Composition of volatiles

The volatiles of fresh roasted almonds and roasted almonds stored for three and eight months were isolated using dynamic headspace sampling. The isolated volatiles were analysed by GC and GC/MS.

2.3.1. Isolation of almond volatiles

A sample of ground almonds (30 g) was placed into a 1 L round-bottomed flask with 150 mL of purified water and 54 g NaCl (previously heated to 150 °C to remove volatiles). A Tenax trap (10 g of Tenax in a glass column 14×2.2 cm) was attached via ball joints, and an all-Teflon diaphragm pump (model UN726 FTP, KNF Neuberger, Inc., Trenton, NJ, USA) was connected (via Teflon tubing) after the trap. The pump circulated air at a flow rate of ~ 6 L/min through the system for 2 h while the sample was continuously stirred. The Tenax trap was removed and eluted with 70 mL of freshly distilled diethyl ether (containing 1–2 ppm of antioxidant 330 (1,3,5-trimethyl-2,4,6-tris-[3,5-di-tert-butyl-4-hydroxybenzyl]-benzene; Ethyl Corporation, Richmond, VA, USA). The eluate was concentrated to about 0.6 mL using a Vigreux column (15×1 cm) and a water bath at 40 °C. Final concentration to approximately 200 μ L was achieved using a purified nitrogen stream.

2.3.2. Capillary GC and GC/MS

The GC system consisted of an HP 6890 gas chromatograph (Hewlett–Packard, Avondale, PA, USA) equipped with a split/splitless injector and a flame ionisation detector (FID). A 60 m \times 0.32 mm i.d. DB-1 fused silica capillary column ($d_f = 0.25$ μ m) was employed. The temperature program for the GC oven was 30 °C (4 min isothermal) to 200 °C (final hold = 25 min) at 2 °C/min. The injector and detector temperatures were 180 and 260 °C, respectively. Split injections (1:20) were used. Helium was used as the carrier gas at a linear velocity of 38.3 cm/s (30 °C). The GC/MS system consisted of an Agilent model 6890 gas chromatograph coupled to an Agilent 5973 N (Palo Alto, CA, USA) quadrupole mass spectrometer (capillary direct interface). A 60 m \times 0.25 mm i.d. ($d_f = 0.25$ μ m) DB-1MS bonded phase fused-silica capillary column was used. The injector, interface, quadrupole and ion source temperatures were 180, 200, 130, and 170 °C, respectively. Helium was used as the carrier gas at a headpressure of 22 psi.

The content of each odorant was calculated by comparing the areas of the odorants with that of an internal standard. The following internal standards were used: 3-hexanone for the quantification of the C₄, C₅, and C₆ compounds, 2-octanone for 1-octen-3-ol, and anethole for all of the other compounds.

2.4. Sensory quality evaluation

The sensory quality of almond samples was evaluated for fresh roasted almonds (before storage) and for almonds stored for

3 months. The sensory attributes were evaluated by a panel of 90 untrained panellists. The panellists were asked to rate the samples for flavor, texture, appearance and overall quality on a 9-point hedonic scale anchored at the endpoints from 'non-preferred' to 'preferred'. The almonds processed at 130 °C with HA were used as a reference; each attribute of the reference sample was given five points.

2.5. Statistical methods

SAS version 9.3 (SAS Institute, Cary, NC, USA) was used to fit a split plot in time mixed model. Roasting method, temperature, time and their interactions were the fixed effects. Replicates within roasting method and temperature was the random effect. Tukey's multiple comparison procedure was used to compare method main effect means.

3. Results and discussion

3.1. Colour change

Based on the tests of the fixed effects (Table S1), attention was focused on the method \times temperature interaction ($(Pr > F)^a < 0.0001$; ^a*p*-value associated with F statistic of a given effect and test statistic) and the month main effect ($(Pr > F) < 0.0001$). Separation among the methods was observed for the 140 °C treatment but not for the 130 and 150 °C treatments (See Supplementary Fig. S1). Overall colour change decreased significantly in the last two months of storage (See Supplementary Fig. S2).

3.2. Moisture content and water activity

The moisture content (MC) decreased from 4.6% (raw almonds) to a low MC of 0.7–1.7% immediately after roasting with different methods. The final MC of almonds was consistent with values reported for different roasted nuts (Saklar, Katnas, & Ungan, 2001; Uysal et al., 2009). Similarly, the water activity decreased from 0.44 (raw almonds) to the 0.2–0.32 range after roasting. After roasting, the almonds were packaged in paper bags and stored under the same conditions.

Although not significant, during several months of storage due to the storage room conditions and good permeability of the packaging material the almonds' MC fluctuated in a narrow range (Fig. 1, top), similarly the water activity changed mostly between 0.2–0.3 (Fig. 1, bottom). It is known that the monolayer MC of almonds occurs at an a_w of 0.2–0.3, which represents the range of optimal MC where dehydrated foods have the maximum shelf life. Our results further confirmed that a moisture content of 1.5–2.5% and a water activity of 0.2–0.3 represents the optimal moisture content range for roasted almonds and produces the maximum shelf life.

3.3. Peroxide value

Fig. 2 shows the average peroxide values of nine roasted almond samples produced by different roasting methods at different heating temperatures and stored under the same conditions. For each roasting method, samples heated to higher roasting temperatures had higher peroxide values during 6 months of storage. Peroxide values increased more rapidly in IR and SIRHA roasted almonds. The effect was particularly dramatic with IR roasting at higher temperatures; peroxide values after 3 months of storage were 1.59, 12.10 and 36.07 meq/kg for samples heated at 130, 140 and 150 °C, respectively. Samples produced by IR heating at 130 °C had a peroxide value similar to that of almonds produced with

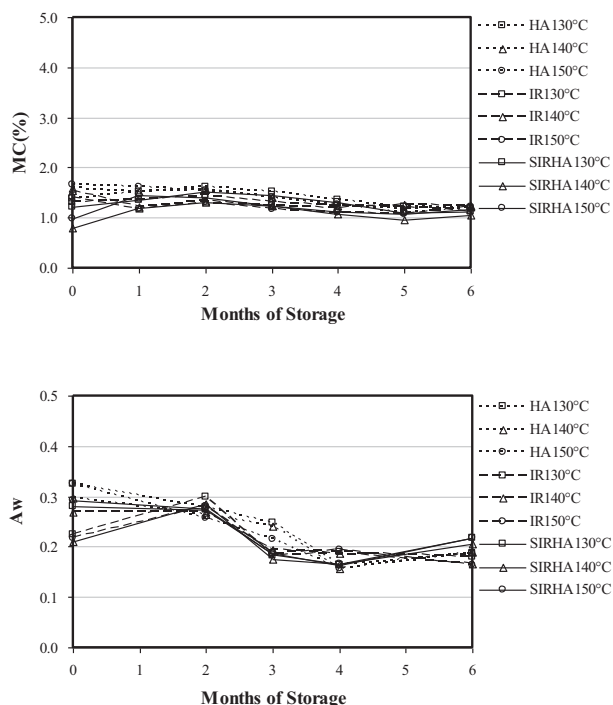


Fig. 1. Changes in moisture content (top) and water activity (bottom) of roasted almonds during storage at 37 °C.

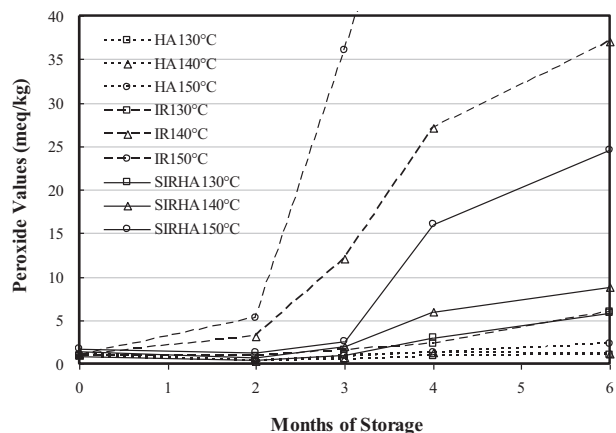


Fig. 2. Changes in peroxide value of roasted almonds during storage at 37 °C.

SIRHA at 130 °C and with HA at all three temperatures. Samples treated with IR at 150 °C showed remarkably higher peroxide values and had higher oxidation rates than other treatments at every storage time. This might be partially attributable to the fact that IR heating can penetrate samples very rapidly, thereby inducing lipids to move out to the skin of the almond at higher temperature and promote rapid oxidation as a consequence of direct oxygen contact. Picse, (2010) reported that the peroxide values of “fresh” almond oils are less than 10 meq/kg, whereas when peroxide values are between 20 and 40 meq/kg, a rancid taste is noticeable. According to industry specifications (Almond Board of California), the peroxide value of “fresh” almond oils must be less than 5.0 meq/kg. Thus, HA and SIRHA roasting methods at all three temperatures and IR at 130 °C, can meet industry specifications for peroxide values after 3 months of storage which is typically required in the food industry. SIRHA and IR roasting at 130 °C can

provide 4–5 months of shelf life at 37 °C storage, while HA roasting has the longest shelf life compared with IR and SIRHA roasting.

3.4. Volatile constituents

To assess the difference in volatile constituents of almonds treated with different roasting methods and at different temperatures, only predominant volatile compounds were quantified: 25 constituents for fresh roasted almonds and 27 constituents for roasted almonds stored for 3 and 8 months. The results are shown in Tables 1–3, respectively.

3.4.1. The volatile compounds in fresh roasted almonds

The concentration of most compounds such as limonene, 2,5-dimethyl-3-ethylpyrazine and 5-pentyl-2(3H)-furanone increased after roasting. Moreover, some new volatile compounds such as methylpyrazine, furfural, 2,5 and 2,6-dimethylpyrazine and 3-octen-2-one were detected due to their formation by thermal processing.

The concentration of aromatic aldehydes, such as phenylacetaldehyde was also higher in roasted almonds than in raw almonds. Additionally, a higher concentration of 2-phenylethanol was detected in roasted almonds than has been reported in both natural and roasted hazelnuts with almond flavour.

Five pyrazines were detected in this study. Pyrazines, which contribute desirable nutty and roasty odours, have been previously reported by Vázquez-Araújo, Verdú, Navarro, Martínez-Sánchez, and Carbonell-Barrachina (2009) in roasted hazelnuts and roasted hazelnut oil. Various researchers (El-Kayati et al., 1998; Kinlin et al., 1972; Walradt et al., 1971) also stated that pyrazines were the most important compounds produced during peanut roasting (Ho, Jin, Lee, & Chang, 1983; Ho, Lee, & Chang, 1982). Moreover, Abegaz et al. (2004) observed significant positive correlations between pyrazine concentrations and ‘roasted peanutty’ flavour. Thus, pyrazines are an important group of compounds that may also provide the roasted aroma in fresh roasted almonds. The data listed in Table 1 show an overall increase in pyrazine content with increasing roasting temperature with the same heating method. The most distinct difference in these three roasting methods was the pyrazine content; IR or SIRHA treatments produced higher concentrations of pyrazines than HA treatment. Aromatic hydrocarbons and pyrazines were the main compounds in fresh roasted almonds in this study. Takei et al. (1974) considered 2,5-dimethyl-4-hydroxy-3(2H)-furanone to be a contributor to the characteristic sweet aroma of roasted almonds. Due to its high water solubility this compound has a very low recovery with the dynamic headspace sampling method employed in our study. Therefore, 2,5-dimethyl-4-hydroxy-3(2H)-furanone was probably present but not detected due to the low sensitivity of our method for this compound. Overall, our chemical analysis provides evidence that the aroma quality of roasted almonds differs due to the heating processes tested in our study.

Aliphatic aldehydes, such as hexanal, heptanal, (*E*)-2-heptenal, (*E*)-2-octenal, nonanal, (*E*)-2-nonanal, 2,4-nonadienal, (*E*)-2-decenal and (*E,E*)-2,4-decadienal, were produced or detected in higher concentrations after almond roasting. Alasalvar, Shahidi, and Cadwallader (2003) reported that concentration of several aliphatic aldehydes increased significantly after roasting Turkish Tombul hazelnuts. Aliphatic alcohols, the majority of which are formed by the decomposition of hydroperoxides of fatty acids or by reduction of aldehydes (Lee, Vázquez-Araújo, Adhikari, Warmund, & Elmore, 2011; Vázquez-Araújo et al., 2009) and ketones, were detected as volatile compounds of fresh roasted almonds. Aliphatic aldehydes, aliphatic alcohols and ketones are likely contributors to off-flavour. Pattee (1984) noticed that alcohols and aldehydes were among the principal volatiles found in off-flavoured peanuts.

Table 1
Volatile constituents of fresh roasted almonds.

No.	RI	Constituent	Concentration (mg/g)								
			HA130	HA140	HA150	IR130	IR140	IR150	SIRHA130	SIRHA140	SIRHA150
1	779	Hexanal	0.32 ± 0.01 ^a	0.09 ± 0.00 ^d	0.07 ± 0.01 ^d	0.25 ± 0.01 ^{bc}	0.10 ± 0.00 ^d	0.27 ± 0.02 ^b	0.33 ± 0.00 ^a	0.22 ± 0.03 ^c	0.09 ± 0.00 ^d
2	794	Methylpyrazine	0.07 ± 0.01 ^f	0.06 ± 0.00 ^f	0.00 ± 0.00 ^h	0.02 ± 0.00 ^g	0.13 ± 0.01 ^d	0.72 ± 0.00 ^a	0.11 ± 0.00 ^e	0.23 ± 0.02 ^c	0.32 ± 0.01 ^b
3	798	Furfural	0.26 ± 0.06 ^{bcd}	0.14 ± 0.01 ^e	0.02 ± 0.01 ^f	0.19 ± 0.00 ^{de}	0.13 ± 0.01 ^e	0.42 ± 0.02 ^a	0.33 ± 0.01 ^b	0.31 ± 0.06 ^{bc}	0.25 ± 0.03 ^{cd}
4	860	Hexanol	0.23 ± 0.03 ^b	0.08 ± 0.01 ^d	0.03 ± 0.01 ^e	0.16 ± 0.01 ^c	0.06 ± 0.00 ^{de}	0.13 ± 0.01 ^c	0.49 ± 0.00 ^a	0.05 ± 0.01 ^{de}	0.02 ± 0.01 ^e
5	866	2-Heptanone	0.01 ± 0.01 ^b	0.00 ± 0.00 ^c	0.00 ± 0.00 ^c	0.01 ± 0.00 ^b	0.00 ± 0.00 ^c	0.01 ± 0.00 ^b	0.02 ± 0.01 ^a	0.01 ± 0.00 ^b	0.00 ± 0.00 ^c
6	880	Heptanal	0.02 ± 0.00 ^c	0.01 ± 0.00 ^d	0.00 ± 0.00 ^e	0.02 ± 0.00 ^c	0.01 ± 0.00 ^d	0.02 ± 0.01 ^c	0.04 ± 0.00 ^a	0.03 ± 0.00 ^b	0.01 ± 0.00 ^d
7	884	2,5 and 2,6-Dimethylpyrazine	0.21 ± 0.01 ^e	0.38 ± 0.05 ^{de}	0.03 ± 0.01 ^f	0.32 ± 0.00 ^{de}	0.47 ± 0.02 ^d	1.82 ± 0.23 ^a	0.77 ± 0.01 ^c	1.05 ± 0.01 ^b	0.99 ± 0.03 ^b
8	924	Benzaldehyde	4.77 ± 1.14 ^a	0.31 ± 0.01 ^b	0.67 ± 0.09 ^b	4.02 ± 0.25 ^a	0.38 ± 0.02 ^b	0.29 ± 0.00 ^b	0.88 ± 0.12 ^b	0.22 ± 0.03 ^b	0.20 ± 0.02 ^b
9	930	(E)-2-Heptenal	0.08 ± 0.00 ^a	0.03 ± 0.00 ^{cd}	0.02 ± 0.00 ^d	0.06 ± 0.03 ^{ab}	0.03 ± 0.00 ^{cd}	0.08 ± 0.01 ^a	0.04 ± 0.01 ^{bcd}	0.05 ± 0.00 ^{bc}	0.04 ± 0.00 ^{bcd}
10	960	Heptanol	0.06 ± 0.00 ^a	0.02 ± 0.01 ^c	0.01 ± 0.00 ^c	0.04 ± 0.00 ^b	0.02 ± 0.00 ^c	0.04 ± 0.01 ^b	0.02 ± 0.00 ^c	0.01 ± 0.00 ^c	0.02 ± 0.00 ^c
11	972	1-Octen-3-ol	0.04 ± 0.01 ^b	0.02 ± 0.00 ^c	0.02 ± 0.00 ^c	0.04 ± 0.00 ^b	0.01 ± 0.00 ^c	0.04 ± 0.01 ^b	0.02 ± 0.00 ^c	0.02 ± 0.01 ^c	0.28 ± 0.01 ^a
12	978	2-Ethyl-5-methylpyrazine	0.06 ± 0.01 ^{ef}	0.12 ± 0.04 ^{de}	0.02 ± 0.00 ^f	0.11 ± 0.01 ^{de}	0.13 ± 0.04 ^{de}	0.70 ± 0.06 ^a	0.15 ± 0.02 ^d	0.41 ± 0.05 ^b	0.33 ± 0.02 ^c
13	1002	Phenylacetaldehyde	1.38 ± 0.03 ^b	1.27 ± 0.00 ^b	0.45 ± 0.03 ^e	0.74 ± 0.10 ^d	0.77 ± 0.03 ^d	1.65 ± 0.01 ^a	0.89 ± 0.08 ^c	0.90 ± 0.03 ^c	0.99 ± 0.07 ^c
14	1016	3-Octen-2-one	0.02 ± 0.01 ^c	0.01 ± 0.01 ^c	0.01 ± 0.00 ^c	0.01 ± 0.00 ^c	0.02 ± 0.00 ^c	0.07 ± 0.01 ^b	0.02 ± 0.00 ^c	0.02 ± 0.00 ^c	0.16 ± 0.03 ^a
15	1018	Limonene	0.20 ± 0.08 ^a	0.18 ± 0.02 ^a	0.09 ± 0.01 ^b	0.15 ± 0.02 ^{ab}	0.09 ± 0.01 ^b	0.18 ± 0.01 ^a	0.18 ± 0.02 ^a	0.18 ± 0.02 ^a	0.14 ± 0.00 ^{ab}
16	1032	(E)-2-Octenal	0.12 ± 0.00 ^b	0.08 ± 0.00 ^c	0.05 ± 0.01 ^c	0.04 ± 0.01 ^c	0.05 ± 0.00 ^c	0.16 ± 0.01 ^a	0.14 ± 0.01 ^{ab}	0.14 ± 0.01 ^{ab}	0.08 ± 0.00 ^c
17	1056	2,5-Dimethyl-3-ethylpyrazine	0.24 ± 0.01 ^{cd}	0.56 ± 0.02 ^c	0.11 ± 0.05 ^d	0.35 ± 0.02 ^{cd}	0.55 ± 0.04 ^c	2.12 ± 0.25 ^a	0.54 ± 0.17 ^c	1.44 ± 0.07 ^b	1.15 ± 0.24 ^b
18	1069	2-Nonanone	0.05 ± 0.01 ^{de}	0.15 ± 0.01 ^c	0.02 ± 0.00 ^e	0.10 ± 0.02 ^{cd}	0.14 ± 0.03 ^c	0.48 ± 0.03 ^a	0.12 ± 0.01 ^c	0.28 ± 0.05 ^b	0.25 ± 0.03 ^b
19	1080	2-Phenylethanol	0.31 ± 0.01 ^a	0.08 ± 0.02 ^c	0.06 ± 0.00 ^c	0.14 ± 0.01 ^b	0.05 ± 0.01 ^c	0.15 ± 0.04 ^b	0.08 ± 0.01 ^c	0.04 ± 0.00 ^c	0.07 ± 0.01 ^c
20	1083	Nonanal	0.53 ± 0.04 ^{cd}	0.33 ± 0.01 ^{ef}	0.21 ± 0.02 ^f	0.01 ± 0.00 ^g	0.26 ± 0.05 ^{ef}	0.71 ± 0.08 ^{ab}	0.57 ± 0.09 ^{bc}	0.78 ± 0.15 ^a	0.39 ± 0.01 ^{de}
21	1134	(E)-2-Nonenal	0.07 ± 0.01 ^d	0.08 ± 0.02 ^d	0.02 ± 0.01 ^e	0.07 ± 0.01 ^d	0.07 ± 0.01 ^d	0.27 ± 0.03 ^a	0.14 ± 0.04 ^c	0.19 ± 0.01 ^b	0.13 ± 0.02 ^c
22	1184	2,4-Nonadienal/decenal	0.04 ± 0.01 ^b	0.02 ± 0.00 ^{cd}	0.01 ± 0.01 ^d	0.03 ± 0.00 ^{bc}	0.02 ± 0.01 ^{cd}	0.04 ± 0.01 ^b	0.04 ± 0.01 ^b	0.07 ± 0.01 ^a	0.03 ± 0.01 ^{bc}
23	1229	(5-Pentyl-2(3H)-furanone) ^g	0.64 ± 0.07 ^a	0.23 ± 0.01 ^b	0.09 ± 0.02 ^{bc}	0.11 ± 0.00 ^{bc}	0.05 ± 0.01 ^c	0.17 ± 0.15 ^{bc}	0.14 ± 0.01 ^{bc}	0.18 ± 0.01 ^{bc}	0.09 ± 0.01 ^{bc}
24	1236	(E)-2-Decenal	0.01 ± 0.00 ^e	0.05 ± 0.01 ^{bc}	0.02 ± 0.00 ^{de}	0.03 ± 0.01 ^{cde}	0.03 ± 0.01 ^{cde}	0.08 ± 0.02 ^a	0.06 ± 0.02 ^{ab}	0.05 ± 0.00 ^{bc}	0.04 ± 0.00 ^{bcd}
25	1285	(E,E)-2,4-Decadienal	0.03 ± 0.00 ^{de}	0.02 ± 0.01 ^{de}	0.01 ± 0.01 ^e	0.15 ± 0.01 ^a	0.03 ± 0.00 ^{de}	0.04 ± 0.00 ^{cd}	0.02 ± 0.00 ^{de}	0.09 ± 0.01 ^b	0.06 ± 0.02 ^c

Values in the same row with different letters (a–f) are significantly different at $p < 0.05$. ^gTentative identification based on mass spectrum.

3.4.2. The change of volatile compounds of roasted almonds during storage

With prolonged storage, the concentration of aliphatic aldehydes, aliphatic alcohols and ketones increased dramatically. These compounds were the main volatile compounds of roasted almonds, especially after 8 months of storage (Table 3). Abegaz et al. (2004) found that the development of rancidity and other off-flavours during storage was important to the flavor of peanut butter due to its high fat content (approximately 50 g/100 g). The oxidation of polyunsaturated fatty acids produce monohydroperoxides that become precursors for volatile aldehydes such as hexanal, octanal, nonanal, and decanal (Min, Lee, & Lee, 1989). Fritsch et al. (1997) indicated that the major deterioration in roasted sunflower kernels was lipid oxidation at low moisture level. Similarly, Buckholz and Daun (1981) and El-Kayati et al. (1998) showed that deterioration in stored roasted peanuts was derived from lipid degradation to form separate volatile components. As with other nuts, higher polyunsaturated fatty acids were oxidised by lipid degradation and produced aliphatic aldehydes, aliphatic alcohols and ketones, which caused off-odours during storage.

Whereas there was a significant increase in the concentration of aliphatic aldehydes in roasted almonds during storage, the concentration of most pyrazines decreased, which is in agreement with previous studies (Abegaz et al., 2004; Braddock, Sims, & O'Keefe, 1995; Reed, Sims, Gorbet, & O'Keefe 2002). Reed, Sims, Gorbet, and O'Keefe (2002) concluded that pyrazines are commonly used as determinants of flavour stability from the observation that peanut flavour is rapidly lost after roasting (termed flavor fade). Bett and Boylston (1992) also found that the concentration of pyrazines and aldehydes decreased and increased, respectively, over time. Contrarily, others have reported that the concentration of alde-

hydes increased while the concentration of pyrazines remained constant during storage; they proposed that the loss of peanut flavour was a result of masking by aldehydes, rather than of a loss of pyrazines per se. However, Bett and Boylston (1992) predicted that lipid radicals and peroxides contribute to the degradation of these heterocyclic compounds. This is contrary to the results of Abegaz et al. (2004) who observed that decreased pyrazine concentrations were measured in systems with the lowest peroxide values. Thus, the actual mechanism for the observed decrease in the concentration of pyrazines is unclear.

3.4.3. The shelf life of roasted almonds

After eight months of storage at 37 °C, the roasted almonds were inedible. Aldehydes are mainly responsible for oxidised and rancid off-flavors of foods. Therefore, the poor quality of the almonds after eight months of storage at warm temperature may be explained by the dramatic increase in concentration of aldehydes such as hexanal, (E)-2-octenal, nonanal and (E)-2-decenal over storage time that we observed in our study (Tables 2 and 3). Heating methods, processing time and temperature, and storage time were significant factors contributing to the high concentration of these aldehydes in roasted almonds.

3.4.4. The indicator of shelf life of roasted almonds

Fritsch et al. (1997) studied the shelf life of roasted sunflower kernels and reported that the predictions from peroxide values were considerably less accurate and not as reliable as hexanal content. Hence, they concluded that hexanal concentration was a better indicator of the shelf life of roasted sunflower kernels than peroxide value. The authors concluded that a hexanal concentration of 6 µg/g was the endpoint of the shelf life of roasted

Table 2
Volatile constituents of roasted almonds after three months of storage at 37 °C.

No.	RI	Constituent	Concentration (µg/g)								
			HA130	HA140	HA150	IR130	IR140	IR150	SIRHA130	SIRHA140	SIRHA150
1	779	Hexanal	0.33 ± 0.09 ^c	0.39 ± 0.10 ^c	0.52 ± 0.10 ^c	0.61 ± 0.10 ^c	3.38 ± 0.88 ^b	4.68 ± 1.14 ^a	0.49 ± 0.08 ^c	0.86 ± 0.10 ^c	0.71 ± 0.10 ^c
2	794	Methylpyrazine	0.07 ± 0.02 ^d	0.06 ± 0.01 ^d	0.08 ± 0.01 ^d	0.06 ± 0.01 ^d	0.20 ± 0.03 ^b	0.26 ± 0.02 ^a	0.10 ± 0.02 ^{cd}	0.14 ± 0.02 ^c	0.31 ± 0.05 ^a
3	798	Furfural	0.11 ± 0.01 ^c	0.10 ± 0.02 ^c	0.12 ± 0.01 ^c	0.08 ± 0.01 ^c	0.19 ± 0.02 ^b	0.22 ± 0.01 ^b	0.24 ± 0.01 ^b	0.22 ± 0.01 ^b	0.37 ± 0.06 ^a
4	860	Hexanol	0.01 ± 0.00 ^e	0.18 ± 0.03 ^c	0.19 ± 0.02 ^c	0.22 ± 0.02 ^{bc}	0.18 ± 0.03 ^c	0.25 ± 0.01 ^{ab}	0.29 ± 0.02 ^a	0.06 ± 0.00 ^d	0.08 ± 0.01 ^d
5	866	2-Heptanone	0.08 ± 0.01 ^b	0.07 ± 0.01 ^b	0.05 ± 0.01 ^b	0.06 ± 0.01 ^b	0.12 ± 0.01 ^a	0.14 ± 0.02 ^a	0.08 ± 0.01 ^b	0.07 ± 0.00 ^b	0.08 ± 0.01 ^b
6	880	Heptanal	0.03 ± 0.01 ^{cd}	0.03 ± 0.00 ^{cd}	0.02 ± 0.01 ^d	0.03 ± 0.00 ^{cd}	0.10 ± 0.01 ^b	0.16 ± 0.01 ^a	0.04 ± 0.01 ^c	0.04 ± 0.01 ^c	0.04 ± 0.01 ^c
7	884	2,5 and 2,6-Dimethylpyrazine	0.32 ± 0.05 ^{fg}	0.41 ± 0.04 ^f	0.54 ± 0.04 ^e	0.24 ± 0.04 ^g	0.85 ± 0.02 ^{bc}	0.95 ± 0.04 ^b	0.76 ± 0.09 ^{cd}	0.66 ± 0.03 ^{de}	1.12 ± 0.10 ^a
8	924	Benzaldehyde	3.58 ± 0.31 ^a	1.47 ± 0.16 ^c	2.70 ± 0.20 ^b	3.00 ± 0.19 ^b	0.98 ± 0.13 ^d	0.6 ± 0.016 ^e	0.35 ± 0.03 ^e	0.47 ± 0.09 ^e	0.45 ± 0.05 ^e
9	930	(E)-2-Heptenal	0.03 ± 0.01 ^d	0.03 ± 0.01 ^d	0.04 ± 0.01 ^d	0.05 ± 0.00 ^{cd}	0.31 ± 0.02 ^b	1.10 ± 0.03 ^a	0.04 ± 0.00 ^d	0.08 ± 0.00 ^c	0.08 ± 0.00 ^c
10	960	Heptanol	0.04 ± 0.01 ^c	0.04 ± 0.01 ^c	0.04 ± 0.00 ^c	0.05 ± 0.01 ^c	0.22 ± 0.01 ^b	0.38 ± 0.01 ^a	0.04 ± 0.01 ^c	0.05 ± 0.01 ^c	0.05 ± 0.00 ^c
11	972	1-Octen-3-ol	0.03 ± 0.00 ^b	0.04 ± 0.01 ^b	0.05 ± 0.01 ^b	0.05 ± 0.01 ^b	0.03 ± 0.00 ^b	0.59 ± 0.09 ^a	0.05 ± 0.01 ^b	0.06 ± 0.01 ^b	0.06 ± 0.01 ^b
12	978	2-Ethyl-5-methylpyrazine	0.09 ± 0.01 ^g	0.13 ± 0.02 ^{fg}	0.22 ± 0.02 ^{def}	0.15 ± 0.03 ^{efg}	0.32 ± 0.05 ^{abc}	0.41 ± 0.07 ^a	0.24 ± 0.02 ^{cde}	0.37 ± 0.05 ^{ab}	0.28 ± 0.03 ^{bcd}
13	982	Octanal	0.05 ± 0.01 ^c	0.05 ± 0.01 ^c	0.05 ± 0.00 ^c	0.07 ± 0.00 ^c	0.19 ± 0.02 ^b	0.26 ± 0.04 ^a	0.05 ± 0.01 ^c	0.07 ± 0.01 ^c	0.07 ± 0.00 ^c
14	1002	Phenylacetaldehyde	0.36 ± 0.03 ^{ab}	0.23 ± 0.06 ^{cd}	0.32 ± 0.04 ^{ab}	0.16 ± 0.01 ^d	0.19 ± 0.06 ^d	0.18 ± 0.02 ^d	0.30 ± 0.03 ^{bc}	0.39 ± 0.02 ^a	0.32 ± 0.01 ^{ab}
15	1016	3-Octen-2-one	0.03 ± 0.01 ^c	0.03 ± 0.00 ^c	0.04 ± 0.01 ^c	0.05 ± 0.01 ^c	0.31 ± 0.06 ^b	0.71 ± 0.07 ^a	0.05 ± 0.00 ^c	0.08 ± 0.00 ^c	0.09 ± 0.00 ^c
16	1018	Limonene	0.34 ± 0.03 ^b	0.22 ± 0.03 ^{bcd}	0.11 ± 0.02 ^d	0.62 ± 0.08 ^a	0.29 ± 0.06 ^{bc}	0.28 ± 0.10 ^{bc}	0.19 ± 0.06 ^{cd}	0.32 ± 0.07 ^{bc}	0.56 ± 0.04 ^a
17	1032	(E)-2-Octenal	0.38 ± 0.03 ^b	0.34 ± 0.07 ^b	0.26 ± 0.07 ^b	0.99 ± 0.05 ^b	4.94 ± 0.57 ^a	5.40 ± 0.88 ^a	0.34 ± 0.01 ^b	0.90 ± 0.11 ^b	0.87 ± 0.12 ^b
18	1056	2,5-Dimethyl-3-ethylpyrazine	0.44 ± 0.07 ^{de}	0.43 ± 0.06 ^{de}	0.42 ± 0.01 ^{de}	0.37 ± 0.02 ^{de}	1.41 ± 0.01 ^b	1.01 ± 0.07 ^c	0.32 ± 0.02 ^e	0.48 ± 0.01 ^d	2.35 ± 0.09 ^a
19	1069	2-Nonanone	0.88 ± 0.09 ^a	0.20 ± 0.02 ^{cd}	0.07 ± 0.03 ^d	0.14 ± 0.09 ^d	0.21 ± 0.04 ^{cd}	0.19 ± 0.03 ^{cd}	0.18 ± 0.01 ^{cd}	0.31 ± 0.03 ^c	0.51 ± 0.11 ^b
20	1080	2-Phenylethanol	0.35 ± 0.03 ^a	0.11 ± 0.08 ^{bc}	0.05 ± 0.05 ^c	0.18 ± 0.09 ^b	0.11 ± 0.01 ^{bc}	0.11 ± 0.01 ^{bc}	0.09 ± 0.01 ^{bc}	0.09 ± 0.02 ^{bc}	0.17 ± 0.01 ^b
21	1083	Nonanal	1.09 ± 0.10 ^{cd}	0.82 ± 0.10 ^d	0.46 ± 0.10 ^e	1.52 ± 0.07 ^b	2.07 ± 0.11 ^a	2.23 ± 0.40 ^a	0.83 ± 0.04 ^d	1.09 ± 0.02 ^{cd}	1.35 ± 0.07 ^{bc}
22	1134	(E)-2-Nonenal	0.15 ± 0.05 ^{cd}	0.12 ± 0.01 ^d	0.09 ± 0.01 ^d	0.21 ± 0.03 ^{bc}	0.44 ± 0.04 ^a	0.41 ± 0.03 ^a	0.15 ± 0.01 ^{cd}	0.23 ± 0.04 ^b	0.27 ± 0.02 ^b
23	1184	2,4-Nonadienal/decenal	0.10 ± 0.03 ^c	0.07 ± 0.01 ^c	0.06 ± 0.02 ^c	0.15 ± 0.03 ^c	0.37 ± 0.09 ^b	0.57 ± 0.05 ^a	0.06 ± 0.00 ^c	0.09 ± 0.00 ^c	0.10 ± 0.01 ^c
24	1205	γ-Octalactone	0.11 ± 0.01 ^b	0.08 ± 0.01 ^{cd}	0.06 ± 0.01 ^{df}	0.09 ± 0.01 ^c	0.13 ± 0.009 ^a	0.08 ± 0.01 ^{cde}	0.08 ± 0.00 ^{cd}	0.07 ± 0.00 ^{cdef}	0.09 ± 0.02 ^c
25	1229	(5-Pentyl-2(3H)-furanone) ^g	0.12 ± 0.01 ^{bc}	0.06 ± 0.02 ^c	0.05 ± 0.01 ^c	0.11 ± 0.01 ^{bc}	0.24 ± 0.08 ^a	0.09 ± 0.01 ^c	0.08 ± 0.01 ^c	0.12 ± 0.01 ^{bc}	0.17 ± 0.03 ^b
26	1236	(E)-2-Decenal	0.05 ± 0.01 ^c	0.05 ± 0.01 ^c	0.04 ± 0.01 ^c	0.10 ± 0.00 ^c	0.60 ± 0.10 ^a	0.50 ± 0.05 ^b	0.04 ± 0.01 ^c	0.08 ± 0.01 ^c	0.13 ± 0.03 ^c
27	1285	(E,E)-2,4-Decadienal	0.05 ± 0.00 ^c	0.05 ± 0.01 ^c	0.04 ± 0.01 ^c	0.07 ± 0.00 ^c	0.26 ± 0.03 ^b	0.34 ± 0.06 ^a	0.04 ± 0.01 ^c	0.05 ± 0.01 ^c	0.06 ± 0.00 ^c

Values in the same row with different letters (^{a–f}) are significantly different at $p < 0.05$. ^gTentative identification based on mass spectrum.

sunflower kernels. Hexanal measurement was also selected by Fritsch and Gale (1977) as a method to evaluate lipid oxidation because it does not require fat extraction of the sample. Compared with peroxide value, we observed that the concentrations of hexanal and nonanal increased steadily during storage (Fig. 3). For the endpoint of shelf life, the concentration of hexanal and nonanal should be less than 2.14 and 5.97 µg/g, respectively. Because the lowest values for hexanal and nonanal after eight months of storage at 37 °C (time at which the almonds were rancid) were 2.14 and 5.97 µg/g, respectively, it is clear that for the endpoint of shelf life, hexanal and nonanal should be present at concentrations less than these. More studies are needed to determine the shelf life of roasted almonds with different treatments, especially in conjunction with trained sensory panels.

3.5. Sensory quality evaluation on almonds roasted to a medium degree

We focused on the method and storage main effects due to the lack of evidence of any significant interactions among the fixed effects (Table S2). Scores for overall quality and flavour were significantly higher for almonds processed by the SIRHA method (mean 4.91, 95% confidence intervals (C.I.) 4.68, 5.15 and mean 4.75, C.I. 4.49, 5.02, respectively) than those processed by the IR method (mean 4.52, C.I. 4.28, 4.75 and mean 4.26, C.I. 3.99, 4.52, respectively) (Table S3). The lower overall quality and flavour scores of the IR method might be due to splitting of the almond skins and development of a slightly bitter taste due to minor burning.

Scores for overall quality and flavour were significantly higher for fresh samples (mean 5.30, C.I. 5.01, 5.38 and mean 5.03, C.I. 4.82, 5.23, respectively) compared with samples stored for three months (mean 4.24, C.I. 4.05, 4.42 and mean 4.00, C.I. 3.80, 4.21,

respectively) (Table S4). Scores for appearance directed inferences to the temperature × storage interaction (Table S2). Sensory scores for appearance were significantly higher for fresh samples than samples stored for three months only for samples roasted at 130 °C (Fig. S3). The storage main effect for texture was close to significance at the 5% level ($p = 0.08$, Table S2). The corresponding means and 95% confidence intervals are included in Table S4, showing that the fresh scores were higher than those of the stored samples. It is evident that flavour significantly degraded after 3 months of storage and that flavour is the most important factor for determining the shelf life of roasted almonds. The order of preference (most to least preferred) was: SIRHA150 (19%) > SIRHA130, SIRHA140 (15%) > HA140 (11%) > HA130 (10%) > IR130, HA150 (9%) > IR140, IR150 (6%). However, since flavour significantly decreased and previous research (Harris et al., 1972) showed that the rancidity of roasted almonds stored for 3 months at 38 °C was unacceptable, we concluded that the samples would not have been suitable for sale. García-Pascual et al. (2003) observed that higher peroxide values correlated with higher rancid flavour in roasted almonds by analysing the results of an untrained sensory panel. They suggested that an expert sensory panel should be used to determine thresholds and more definite relationships. El-Kayati et al. (1998) reported that the high sensory scores of fresh roasted peanut samples heated at 150 °C were due to the presence of high concentrations of pyrazines, which were thought to contribute to flavour and aroma.

4. Conclusions

The storage attributes, moisture content and water activity, did not show significant differences among roasted almonds heated with different methods under the same storage conditions. Perox-

Table 3
Volatile constituents of roasted almonds after eight months of storage at 37 °C.

No. RI	Constituent	Concentration (µg/g)								
		HA130	HA140	HA150	IR130	IR140	IR150	SIRHA130	SIRHA140	SIRHA150
1	779 Hexanal	2.14 ± 0.12 ^e	2.79 ± 0.31 ^{de}	3.31 ± 0.98 ^{de}	5.39 ± 1.04 ^{de}	22.73 ± 3.01 ^b	37.48 ± 5.59 ^a	8.25 ± 2.55 ^d	15.77 ± 1.69 ^c	18.61 ± 1.10 ^{bc}
2	794 Methylpyrazine	0.07 ± 0.00 ^{bc}	0.05 ± 0.01 ^c	0.08 ± 0.01 ^b	0.05 ± 0.01 ^c	0.15 ± 0.02 ^a	0.09 ± 0.01 ^b	0.07 ± 0.02 ^{bc}	0.08 ± 0.01 ^b	0.07 ± 0.00 ^{bc}
3	798 Furfural	0.09 ± 0.01 ^{bcd}	0.06 ± 0.00 ^d	0.10 ± 0.01 ^{bc}	0.09 ± 0.02 ^{bcd}	0.14 ± 0.01 ^a	0.11 ± 0.02 ^{abc}	0.12 ± 0.01 ^{ab}	0.11 ± 0.01 ^{abc}	0.08 ± 0.01 ^{cd}
4	860 Hexanol	1.08 ± 0.02 ^b	0.25 ± 0.08 ^d	0.22 ± 0.03 ^d	1.08 ± 0.07 ^b	1.64 ± 0.22 ^a	1.25 ± 0.32 ^b	0.34 ± 0.05 ^{cd}	0.41 ± 0.04 ^{cd}	0.66 ± 0.08 ^c
5	866 2-Heptanone	0.08 ± 0.01 ^c	0.11 ± 0.03 ^c	0.09 ± 0.02 ^c	0.23 ± 0.02 ^c	1.37 ± 0.30 ^a	1.57 ± 0.20 ^a	0.32 ± 0.06 ^c	0.61 ± 0.06 ^d	0.81 ± 0.07 ^d
6	880 Heptanal	0.14 ± 0.04 ^d	0.20 ± 0.03 ^d	0.16 ± 0.03 ^d	0.26 ± 0.02 ^d	0.98 ± 0.03 ^b	1.65 ± 0.36 ^a	0.34 ± 0.01 ^d	0.68 ± 0.05 ^c	0.77 ± 0.02 ^{bc}
7	884 2,5 and 2,6-Dimethylpyrazine	0.31 ± 0.00 ^c	0.33 ± 0.04 ^{bc}	0.45 ± 0.10 ^{ab}	0.26 ± 0.03 ^c	0.52 ± 0.04 ^a	0.34 ± 0.08 ^{bc}	0.32 ± 0.00 ^{bc}	0.34 ± 0.08 ^{bc}	0.28 ± 0.05 ^c
8	924 Benzaldehyde	1.84 ± 0.50 ^a	0.51 ± 0.16 ^b	0.55 ± 0.24 ^b	2.26 ± 0.12 ^a	2.18 ± 0.08 ^a	0.66 ± 0.09 ^b	0.45 ± 0.01 ^b	0.43 ± 0.12 ^b	0.53 ± 0.11 ^b
9	930 (E)-2-Heptenal	0.10 ± 0.02 ^f	0.13 ± 0.06 ^{ef}	0.15 ± 0.03 ^{ef}	0.37 ± 0.07 ^{ef}	3.13 ± 0.31 ^a	2.51 ± 0.18 ^b	0.58 ± 0.08 ^e	1.19 ± 0.01 ^d	1.98 ± 0.42 ^c
10	960 Heptanol	0.33 ± 0.03 ^d	0.38 ± 0.08 ^d	0.45 ± 0.00 ^d	0.70 ± 0.12 ^{cd}	5.27 ± 1.09 ^a	5.01 ± 0.97 ^a	1.10 ± 0.32 ^{cd}	1.91 ± 0.40 ^{bc}	3.08 ± 0.78 ^b
11	972 1-Octen-3-ol	0.10 ± 0.03 ^d	0.12 ± 0.02 ^d	0.18 ± 0.00 ^d	0.32 ± 0.08 ^d	3.40 ± 1.08 ^a	2.27 ± 0.74 ^b	0.44 ± 0.06 ^d	0.97 ± 0.04 ^{cd}	1.68 ± 0.50 ^{bc}
12	978 2-Ethyl-5-methylpyrazine	0.10 ± 0.02 ^{bc}	0.07 ± 0.00 ^c	0.12 ± 0.02 ^{bc}	0.19 ± 0.03 ^a	0.19 ± 0.02 ^a	0.14 ± 0.02 ^{ab}	0.10 ± 0.03 ^{bc}	0.11 ± 0.01 ^{bc}	0.11 ± 0.02 ^{bc}
13	982 Octanal	0.70 ± 0.17 ^d	0.91 ± 0.24 ^d	0.82 ± 0.17 ^d	0.01 ± 0.00 ^e	3.34 ± 0.12 ^b	4.46 ± 0.68 ^a	1.28 ± 0.17 ^d	2.15 ± 0.37 ^c	2.97 ± 0.18 ^b
14	1002 Phenylacetaldehyde	0.22 ± 0.03 ^{abc}	0.14 ± 0.01 ^{bcd}	0.19 ± 0.06 ^{bcd}	0.25 ± 0.07 ^{ab}	0.33 ± 0.10 ^a	0.1 ± 0.00 ^d	0.17 ± 0.00 ^{bcd}	0.12 ± 0.01 ^{cd}	0.09 ± 0.01 ^d
15	1016 3-Octen-2-one	0.10 ± 0.01 ^e	0.12 ± 0.02 ^e	0.13 ± 0.01 ^e	0.61 ± 0.11 ^{de}	2.52 ± 0.37 ^a	1.97 ± 0.11 ^b	0.39 ± 0.00 ^{de}	0.81 ± 0.14 ^d	1.34 ± 0.50 ^c
16	1018 Limonene	0.36 ± 0.08 ^{cd}	0.21 ± 0.04 ^d	0.17 ± 0.01 ^d	1.02 ± 0.09 ^c	2.50 ± 0.05 ^b	3.33 ± 0.72 ^a	0.33 ± 0.04 ^{cd}	0.91 ± 0.02 ^{cd}	3.01 ± 0.63 ^{ab}
17	1032 (E)-2-Octenal	2.13 ± 0.13 ^e	2.41 ± 0.71 ^e	2.78 ± 0.48 ^e	11.14 ± 2.55 ^{de}	58.34 ± 8.16 ^b	77.03 ± 3.92 ^a	15.47 ± 2.59 ^d	41.2 ± 5.11 ^c	55.16 ± 3.14 ^b
18	1056 2,5-Dimethyl-3-ethylpyrazine	0.73 ± 0.17 ^b	0.52 ± 0.03 ^b	1.01 ± 0.04 ^b	4.20 ± 0.57 ^b	1.36 ± 0.10 ^b	1.62 ± 0.01 ^b	0.98 ± 0.14 ^b	12.25 ± 5.59 ^a	1.36 ± 0.39 ^b
19	1069 2-Nonanone	0.78 ± 0.04 ^c	0.97 ± 0.02 ^c	1.03 ± 0.02 ^c	1.49 ± 0.20 ^{bc}	3.90 ± 0.14 ^a	4.40 ± 1.27 ^a	2.36 ± 0.14 ^b	2.48 ± 0.16 ^b	4.65 ± 0.97 ^a
20	1080 2-Phenylethanol	0.10 ± 0.00 ^e	0.11 ± 0.01 ^e	0.15 ± 0.03 ^{de}	0.27 ± 0.01 ^{cd}	0.57 ± 0.04 ^b	0.60 ± 0.05 ^b	0.33 ± 0.02 ^c	0.29 ± 0.04 ^c	0.83 ± 0.15 ^a
21	1083 Nonanal	5.97 ± 1.68 ^d	6.45 ± 0.02 ^d	6.37 ± 0.02 ^d	10.92 ± 2.45 ^d	16.43 ± 0.02 ^c	25.94 ± 4.02 ^a	11.21 ± 0.91 ^d	20.69 ± 3.10 ^{bc}	24.27 ± 2.76 ^{ab}
22	1134 (E)-2-Nonenal	0.29 ± 0.05 ^d	0.30 ± 0.04 ^d	0.39 ± 0.01 ^{cd}	0.95 ± 0.04 ^{cd}	3.57 ± 0.18 ^a	3.49 ± 0.22 ^a	1.04 ± 0.02 ^c	2.17 ± 0.03 ^b	3.20 ± 0.81 ^a
23	1184 2,4-Nonadienal/decenal	0.72 ± 0.01 ^e	0.83 ± 0.01 ^{de}	0.95 ± 0.10 ^{de}	1.12 ± 0.17 ^{cde}	1.75 ± 0.36 ^{bc}	2.47 ± 0.50 ^a	1.48 ± 0.01 ^{cd}	1.69 ± 0.32 ^{bc}	2.19 ± 0.37 ^{ab}
24	1205 γ-Octalactone	0.16 ± 0.02 ^d	0.18 ± 0.03 ^d	0.19 ± 0.04 ^d	0.39 ± 0.06 ^{cd}	1.08 ± 0.27 ^a	1.04 ± 0.03 ^a	0.43 ± 0.04 ^{cd}	0.60 ± 0.05 ^{bc}	0.89 ± 0.31 ^{ab}
25	1229 (5-Pentyl-2(3H)-furanone) ^g	0.15 ± 0.03 ^d	0.12 ± 0.01 ^d	0.18 ± 0.03 ^{cd}	0.33 ± 0.10 ^{cd}	0.78 ± 0.24 ^a	0.60 ± 0.05 ^{ab}	0.32 ± 0.01 ^{cd}	0.41 ± 0.04 ^{bc}	0.58 ± 0.10 ^{ab}
26	1236 (E)-2-Decenal	0.34 ± 0.08 ^c	0.41 ± 0.03 ^c	0.55 ± 0.04 ^c	1.68 ± 0.25 ^c	7.65 ± 0.59 ^a	6.32 ± 0.72 ^a	2.04 ± 0.12 ^{bc}	3.95 ± 1.01 ^b	6.14 ± 2.16 ^a
27	1285 (E,E)-2,4-Decadienal	0.19 ± 0.05 ^d	0.21 ± 0.00 ^d	0.34 ± 0.03 ^d	0.95 ± 0.05 ^d	4.54 ± 1.00 ^a	3.98 ± 1.08 ^a	1.20 ± 0.08 ^{cd}	2.49 ± 0.53 ^{bc}	3.69 ± 1.02 ^{ab}

Values in the same row with different letters (a–f) are significantly different at $p < 0.05$. ^gTentative identification based on mass spectrum.

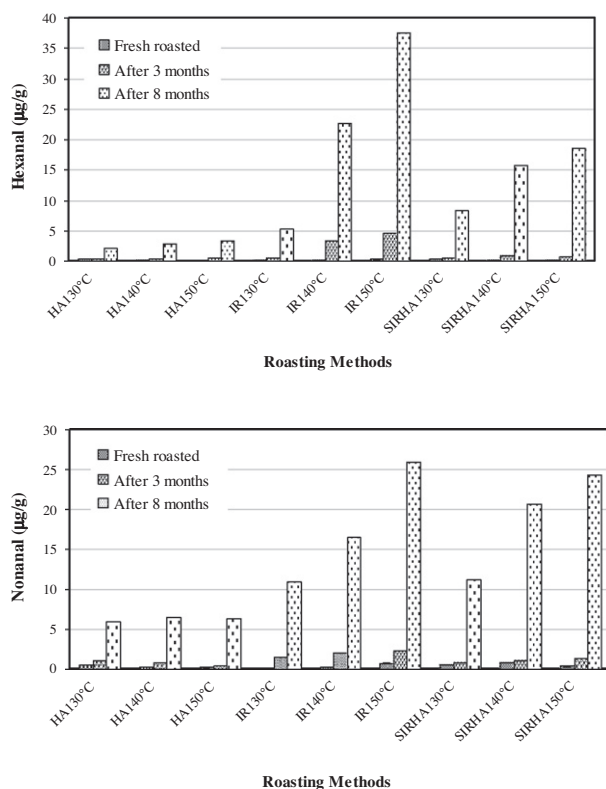


Fig. 3. Changes in hexanal and nonanal concentration of roasted almonds after three and eight months of storage at 37 °C.

ide value and the concentration of aliphatic aldehydes of all roasted almond samples increased significantly during storage. Roasted almonds, packaged in paper bags, were oxidised and rancid after 3 months of storage. The changes might have been induced by the high oil content and polyunsaturated fatty acids which produced volatile aliphatic aldehydes such as hexanal, heptanal, (E)-2-octenal, octanal, and nonanal. Hexanal and nonanal concentrations were better indicators of the shelf life of roasted almonds than peroxide value. The quality of roasted almonds produced with SIRHA and HA heating was similar after the 3-month storage period that is typically required in the food industry. It was concluded that SIRHA roasting is an effective method for producing pasteurised almonds with similar quality as HA and has potential for lowering production costs due to reduced roasting time compared with conventional hot air roasting.

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Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at <http://dx.doi.org/10.1016/j.foodchem.2012.09.142>.

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