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Chemical, mechanical and sensory monitoring of hot air- and infrared-roasted hazelnuts (*Corylus avellana* L.) during nine months of storage

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ABSTRACT

Roasted hazelnuts can be consumed as whole nuts, or as an ingredient in the confectionary and bakery industries and are highly appreciated for their typical taste, aroma and crunchy texture. In this work, two hazelnut types (TGT, Ordu) from two harvests were roasted using two different systems (hot air, infrared) at different time/temperature combinations, and the evolution of oxidative stability, the total phenolic content (TPC), the antioxidant capacity, the mechanical and acoustic properties and the sensory perception were determined during storage. The results showed that the oxidative stability was increased by roasting hazelnuts at 120 °C for 40 min with hot air system. Similar overall trends were not found for the TPC, the antioxidant capacity and the mechanical-acoustic properties. However, for the maintenance of high antioxidant activity, a storage time of 6 months at 4 °C is recommended. The two roasting systems gave hazelnuts with significant sensory differences only at high roasting temperature.

1. Introduction

Hazelnuts are typically consumed as whole nuts (raw or roasted) or as ingredient for confectionary and bakery industries as they are highly appreciated for their typical taste, aroma and crunchy texture. An industrial roasting process is applied to remove the hazelnut skin, to reduce the moisture and to develop the unique sensory features (Demir & Cronin, 2005; Özdemir et al., 2001). Additionally, roasting is often used to extend the nut's shelf life due to the inactivation of the oxidative enzyme system (lipoxygenic enzymes) and the formation of reaction products, which exhibit antioxidant activity (Krings & Berger, 2001; Perren & Escher, 2007).

Although favourable for many aspects, roasting can also lead to a number of physical and chemical changes, such as microstructural and lipid modifications, which might increase the sensitivity of the product to oxidation and, hence, reduce its shelf life (Alamprese, Ratti, & Rossi, 2009). Due to these modifications, the assessment of hazelnut characteristics after roasting has been the subject of different studies (Brown, Rothwell, & Davidson, 2001; Demir & Cronin, 2005; Uysal, Sumnu, & Sahin, 2009) aimed at both determining the most suitable machines and parameters for roasting as well as at obtaining high quality indexes in terms of colour, texture, moisture, oxidative stability (in terms of peroxide value and free fatty acids) and sensory characteristics.

Industrially, the most commonly reported roasting time–temperature combinations are in the range of 100–180 °C for 5–60 min (Demir & Cronin, 2005). Moreover, roasting can be achieved by using different methods, such as commercial electrical ovens, hot air dryers or even by exploiting other techniques, such as infrared heating and the dielectric processes of radiofrequency and microwave (Ciarmiello et al., 2013). Infrared heating has been reported to have many advantages over conventional heating, such as reduced heating time, uniform heating, reduced quality losses, compactness of equipment and significant energy savings (Rastogi, 2012). Infrared roasters have been developed to roast cracked cereal grain, whereas infrared combined with microwave techniques have been used to roast hazelnuts, producing results in terms of colour, texture, moisture content and fatty acid composition similar to the results obtained by a commercial electrical oven (Brown et al., 2001; Uysal et al., 2009).

The effect of roasting has been studied extensively on metabolites, such as volatile compounds, amino acids, vitamin B, the lipidic fraction (unsaturated fatty acids and tocopherols) and phenolic compounds (Alasalvar, Shahidi, & Cadwallader, 2003; Amaral, Casal, Seabra, & Oliveira, 2006; Kirbaşlar & Erkmen, 2003; Pelvan, Alasalvar, & Uzman, 2012; Schlörmann et al., 2015;

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Schmitzer, Slatnar, Veberic, Stampar, & Solar, 2011; Özdemir et al., 2001). Roasting has been shown to not substantially affect the content of mono- and polyunsaturated fatty acids, tocotrienols, and phenolic compounds, whereas roasting caused a decrease in the content of tocopherols. All of these compounds have been indicated as health-related compounds, and although controversial, data with respect to their fate during roasting is of great interest.

The preservation of the overall characteristics of the roasted hazelnuts during storage should be a major concern for the industry and market. In fact, from an industrial point of view, it could be desirable to have ready-to-use roasted hazelnuts that are well preserved for as long as possible. Unfortunately, very little information is currently available in the literature about the shelf life of roasted hazelnuts.

Therefore, the aim of this work was to contribute to knowledge about the chemical (fatty acids, peroxide value, oleic to linoleic ratio, iodine value, total phenolic content and antioxidant capacity), mechanical (rupture force, rupture slope and rupture energy), acoustic (maximum acoustic emission peak, acoustic peak number and average peak emission) and sensory changes in two different hazelnut cultivars that were both hot air (HA) roasted, as a "traditional method," and infrared (IR) roasted, as an "innovative method," using two combinations of time and temperature common used by processors, for two consecutive years. In each year, parameters were monitored at three points over 9 months of storage.

2. Materials and methods

2.1. Chemicals

Supelco 37 component FAME mix 10 mg/mL, nonadecanoic acid methyl ester (C19:0), 2,2-diphenyl-1-picrylhydrazyl (DPPH), potassium persulfate, sodium carbonate, Trolox (6-hydroxy-2,5,7,8-tetramethylchroman-2-carboxylic acid), 2,2′-Azino-bis-(3-ethylbenzothiazolin-6-sulfonic acid) diammonium salt (ABTS), Folin-Ciocalteu reagent, ethanol, methanol, *n*-hexane and acetone were purchased from Sigma-Aldrich (Milan, Italy); potassium hydroxide, formic acid and gallic acid were purchased from Fluka Chemicals (Milan, Italy). Acetone, methanol, *n*-hexane were of analytical or higher grade. Aqueous solutions were prepared using ultra-pure water produced with a Milli-Q System (Millipore, Milan, Italy).

2.2. Hazelnuts

One Italian cultivar, Tonda Gentile Trilobata (TGT), and one Turkish blend consisting of three major cultivars, Tombul, Palaz and Kalinkara from the Ordu region (here called Ordu), were used in this study. Raw hazelnuts from the 2010 and 2011 harvests (calibre within 12–13 mm) were supplied by La Gentile S.r.L. (Cortemilia, CN, Italy). The initial moisture content of the raw hazelnuts was 3.26% and 3.86% for TGT and Ordu, respectively, harvested in 2010, and 3.13% and 3.76% for TGT and Ordu, respectively, harvested in 2011. The moisture content was determined using a Eurotherm EUR thermo-balance (Gibertini, Milano, Italy) at 105 °C. Hazelnuts were roasted using the HA and IR roasting methods at the Brovind – GBV company Srl (Cortemilia, CN, Italy). HA roasting was performed with three forced air circulation sections (drying, roasting and cooling to obtain a product using an optimal thermal process) using electronic control of planned and recorded process parameters, whereas IR roasting was carried out with a patented system using a vibrating helical track and a ventilation system to obtain a uniform roasting level. Hazelnuts were roasted at 120 °C for 40 min (light roast) and 170 °C for 20 min (dark roast) with both systems separately. Three sample replicates for each roasting condition were processed. After roasting, hazelnut samples were let cooling before being placed in non-permeable polypropylene/aluminium/polyethylene bags under vacuum and stored at 4 °C for 9 months. The sampling times were 0, 6 and 9 months. At time 0, raw hazelnut samples obtained by hand peeling after soaking in warm water were also analysed to determine the effect of roasting on the kernel without skin.

2.3. Extraction of hazelnut oil

The hazelnut oil was extracted using a cold-pressing method using CDR's nut oils extraction system (CDR s.r.l., Florence, Italy). Approximately 50 g of the hazelnut kernels were compressed, and the recovered oil was clarified by centrifugation at 4800 rpm for 5 min. The oil was stored at −18 °C in an amber vial until analyses. Each sample was prepared in triplicate.

2.4. Fatty acid composition

Fatty acid methyl esters (FAMEs) were determined by gas-chromatography according to the method described by Ficarra, Lo Fiego, Minelli, and Antonelli (2010), with slight modification. Briefly, 50 mg of oil was mixed thoroughly with 1 ml of hexane and 300 µl of 2 M KOH in methanol (w/v) in a dark tube. The tube was shaken vigorously for 1 min, and then, C19:0 (200 mg/L) was added as an internal standard. The extract was then transferred into a dark glass vial and immediately analysed by GC. Profiling of the FAMEs was determined using a GC-2010 Shimadzu gas chromatograph (Shimadzu, Milan, Italy) equipped with a flame ionization detector, split-splitless injector, an AOC-20i autosampler and a capillary column SP-2560 (100 m × 0.25 mm id × 0.20 µm, Supelco, Milan, Italy). The following temperature program was used: the initial oven temperature was 165 °C increasing to 200 °C at 3 °C/min, and then, the temperature was held at 200 °C for 45 min. The injector temperature and the detector were 250 °C. Each fatty acid methyl ester was identified and quantified by comparing retention times with Supelco 37 components FAME mix 10 mg/mL. The fatty acid concentration was expressed as mg fatty acid/g of oil calculated according to the AOAC 963.22 method (AOAC, 2000). All analyses were performed in triplicate.

The obtained fatty acid composition was used to calculate the sum of the saturated (Σ SFA), monounsaturated and polyunsaturated (Σ MUFA, Σ PUFA) fatty acids as well as the ratio (Σ MUFA + Σ PUFA)/(Σ SFA).

2.5. Oxidation parameters

To evaluate the oxidative stability, the peroxide value (PV), which is expressed as meqO_2/kg oil, the ratio of oleic to linoleic (O/L), and the iodine value (IV) were determined.

The PV was performed using the *FoodLab* method (CDR s.r.l., Florence, Italy) on the hazelnut oil (Kamvissis, Barbounis, Megoulas, & Koupparis, 2008). The IV was determined according to the percentages of fatty acids using the following formula: (palmitoleic acid * 1.901) + (oleic acid * 0.899) + (linoleic acid * 1.814) + (linolenic acid * 2.737) (Hashempour, Ghazvini, Bakhshi, & Sanam, 2010). All analyses were performed in triplicate.

2.6. Extraction of antioxidant compounds

Hazelnuts were frozen using liquid nitrogen and ground finely using an A 11 basic analytical mill (IKA®-Werke GmbH & Co. KG, Staufen, Germany). Ground kernels (approximately 2 g) were then extracted according to El Monfalouti et al. (2012) with some modifications. Briefly, samples were mixed with a fresh mixture of acetone/water/formic acid (70:29.5:0.5, v/v/v), and the combined

extracts obtained after the two-step extraction procedure were defatted by washing with hexane (10 mL × 3 times, 3 min each). Then, acetone was evaporated under nitrogen by using a digital pulse mixer with an evaporator (Glas-Col, Terre Haute, Indiana, USA), and the aqueous extracts obtained were filtered (0.45 μm) and used for further analyses. All extractions were performed in triplicate.

2.6.1. Determination of total phenolic content (TPC)

The amount of total phenolics was determined spectrophotometrically by means of the modified Folin–Ciocalteu method (Singleton, Orthofer, & Lamuela-Raventós, 1999; Singleton & Rossi, 1965). Briefly, 2.5 mL of 10-fold diluted Folin–Ciocalteu reagent, 2 mL of 7.5% aqueous sodium carbonate solution, and 0.5 mL of phenolic extract were mixed well. After 15 min of heating at 45 °C (Pinelo, Rubilar, Sineiro, & Núñez, 2004), the absorbance was measured at 765 nm with a UV–Visible spectrophotometer (UV-1700 PharmaSpec, Shimadzu, Milan, Italy). A mixture of solvent and reagents was used as a blank. The phenolic content was expressed as mg of gallic acid equivalents (GAE) per g of sample by means of a calibration curve. All analyses were performed in triplicate.

2.6.2. Determination of antioxidant activity

2.6.2.1. Trolox equivalent antioxidant capacity (TEAC). The Trolox equivalent antioxidant capacity (TEAC) of the hazelnut extract was estimated according to the original analytical procedure described by Re et al. (1999), with slight modifications. The ABTS radical cation ($ABTS^{\cdot+}$) was produced by reacting 7 mmol of the ABTS stock solution with 2.45 mmol of potassium persulphate (final concentration). The mixture was allowed to stand in the dark at room temperature for 12–16 h before use. The radical was stable in this form for no more than two days when protected from light and stored at room temperature. Just prior to analysis, the $ABTS^{\cdot+}$ stock solution was diluted with ethanol to an absorbance of 0.70 (± 0.02) at 734 nm and allowed to equilibrate at 30 °C. Sample solutions (or standard) (30 μL) were mixed with the $ABTS^{\cdot+}$ solution (3 mL). Absorbance readings were taken at 30 °C exactly 6 min after the initial mixing. An appropriate solvent blank was obtained by mixing ultrapure water (30 μL) with the $ABTS^{\cdot+}$ solution (3 mL). The $ABTS^{\cdot+}$ scavenging effect (% Inhibition) was calculated using the following equation:

$$\%\ \text{Inhibition} = [(A_{734\text{blank}} - A_{734\text{sample}})/A_{734\text{blank}}] \times 100$$

where $A_{734\text{blank}}$ and $A_{734\text{sample}}$ are the absorbances of the $ABTS^{\cdot+}$ solution at 734 nm before and after the sample addition. The results were expressed as micromoles of Trolox equivalents (TE) per gram of sample by means of a dose–response curve for Trolox (0–350 μmol). All analyses were performed in triplicate.

2.6.2.2. DPPH radical scavenging capacity. The radical scavenging activity (RSA) of the hazelnut phenolic extract was measured using the discoloration of a purple-coloured methanol solution of the 2,2-diphenyl-1-picrylhydrazyl (DPPH) radical (von Gadow, Joubert, & Hansmann, 1997). Briefly, 75 μL of the sample extract was added to 3 mL of a 6.1×10^{-5} mol l^{-1} $DPPH^{\cdot}$ methanol solution and was incubated for 1 h at room temperature in the dark. The absorbance was measured at 515 nm against a methanol solution of $DPPH^{\cdot}$ as a blank. The inhibition percentage (IP) of the $DPPH^{\cdot}$ by the hazelnut extract was calculated according to the following formula:

$$\text{IP} = [(A_{0\text{min}} - A_{60\text{min}})/A_{0\text{min}}] \times 100$$

where $A_{0\text{min}}$ is the absorbance of the blank at t = 0 min and $A_{60\text{min}}$ is the absorbance of the samples at 60 min. The results were expressed as micromoles of Trolox equivalent (TE) per gram of sample. All analyses were performed in triplicate.

2.7. Instrumental mechanical and acoustic properties

For the evaluation of the mechanical and acoustic properties, a TA.XTplus universal testing machine (Stable Micro Systems, Godalming, UK) was used with the following operating conditions: 50-kg load cell, P/75 flat probe, HDP/90 platform from the same manufacturer, acquisition at 200 points per second, and a compression test speed of 1 mm/s until 50% of sample deformation (Ghirardello et al., 2013). The hazelnuts were compressed along the compression axis, which corresponded to the longitudinal axis through the hilum containing the major dimension (Güner, Dursun, & Dursun, 2003), and 20 hazelnuts were analysed for each sample. From the resulting force-distance curve, three mechanical parameters were calculated in accordance with Saklar, Ungan, and Katnas (1999): rupture force (F1, N), rupture slope (E1, N/mm), and rupture energy (W1, mJ), which corresponded to the first fracture point force, the slope with respect to the initial point, and the total area beneath the curve, respectively.

The instrumental acoustic properties evaluated during the compression test were acquired using an acoustic envelope detector (AED) (SMS, Stable Micro Systems, Surrey, UK) equipped with a 12.7-mm diameter Brüel & Kjær 4188-A-021 microphone (Nærum, DK). The microphone was positioned at an angle of 30° and 40 mm from the sample (due to the shape of the probe) and was connected to the TA.XTplus equipment. No instrumental gain or filters were applied. The acoustic emissions were acquired for the entire compression measuring the following parameters: maximum acoustic emission peak [dB], acoustic peak number and average peak emission [dB] (Torchio et al., 2012) using a peak threshold value of 10 dB.

2.8. Sensory analysis

A sensory evaluation was performed using a duo-trio test (ISO 10399, 2004) with $\alpha = 0.05$, $p_d = 30\%$ and $\beta = 0.2$ on a group of 70 panellists (42 female, 28 male, 25–35 years old). Hazelnut samples coded with different three-digit numbers were furnished in white plastic cups containing 6–7 kernels. Water was provided for palate cleaning. The testing was carried out in a sensory laboratory that was designed in accordance with ISO 8589 (1988). The tests were performed after roasting and during storage at 6 and 9 months comparing for each hazelnut and roasting system, the two roasting conditions.

2.9. Statistical analysis

An analyses of variance was performed using SPSS software (version 18.0 for Windows, SPSS Inc., Chicago, Illinois). Significant differences ($P < 0.05$) among the means were determined using the Duncan's test at a fixed level of $\alpha = 0.05$.

3. Results and discussion

3.1. Fatty acids

The FAMEs analysis of the TGT and Ordu hazelnuts identified a total of fourteen fatty acids, among which oleic acid (C18:1ω9) was predominant, followed by linoleic acid (C18:2ω6), palmitic acid (C16:0), stearic acid (C18:0), palmitoleic acid (C16:1) and α-linolenic acid (C18:3ω3) (Supplementary Tables 7 and 8). Table 1 shows the sum of the fatty acids detected in the raw and roasted TGT and Ordu hazelnuts during the first year of study. In general,

the sum (∑) of MUFAs was predominat in both varieties, but TGT had a lower amount of ∑PUFAs and had a greater amount of ∑SFAs than the Ordu.

With the aim of studying the oxidation stability of the roasted hazelnuts, the fatty acids mentioned above were considered when calculating the oxidative parameters presented in Tables 1 and 2. The oleic to linoleic acid (O/L) ratio was considered to be an important criterion to evaluate the kernel quality, as a greater value indicates better oxidative stability (Alasalvar, Pelvan, & Topal, 2010; Vujević, Petrović, Vahčić, Milinović, & Čmelik, 2014). During the first year of study (Table 1), significant differences were observed in the O/L ratio for the TGT and Ordu roasted at the two different conditions: 170 °C for 20 min and 120 °C for 40 min. In particular, IR roasting appeared to have a more positive effect than HA, resulting in greater oxidative stability in the TGT hazelnuts. The same behaviour was observed in the Ordu, but only for the initial point at 170 °C – 20 min. Instead, when the 120 °C – 40 min treatment was applied, similar O/L ratio values were observed (except at month 6). The rapid decrease of the values observed during storage highlighted the decreased stability for both the TGT and Ordu

Table 1
Sums of fatty acids and oxidative stability of raw and roasted hazelnuts from TGT and ORDU cultivars as function of roasting system (IR = infrared rays, HA = hot air), roasting conditions and storage time, harvest 2010.

Parameter	Roasting system	Storage (months)	TGT				ORDU			
			Raw	170 °C – 20 min	120 °C – 40 min	Sign.[a]	Raw	170 °C – 20 min	120 °C - 40 min	Sign.[a]
∑SFAs (mg/g)	IR	0	9.75 ± 0.00	9.73 ± 0.03c	9.04 ± 0.02a	***	7.16 ± 0.03	7.37 ± 0.02a	8.15 ± 0.01b	***
		6		9.41 ± 0.06b	9.19 ± 0.02b	**		7.40 ± 0.01b	7.62 ± 0.01a	***
		9		9.32 ± 0,00a	9.23 ± 0.01b	***		7.61 ± 0.00c	7.62 ± 0.04a	ns
	HA	0	9.75 ± 0.00	9.23 ± 0.13b	9.18 ± 0.00a	ns	7.16 ± 0.03	7.82 ± 0.02	7.57 ± 0.34c	ns
		6		9.09 ± 0.01ab	9.24 ± 0.00b	***		7.44 ± 0.02	7.77 ± 0.01a	***
		9		8.94 ± 0.02a	9.29 ± 0.03c	***		7.62 ± 0.00	7.64 ± 0.06b	ns
	Sign.[b]			**, **, ***	***, *, *			***, **, ns	*, ***, ns	
∑MUFAs (mg/g)	IR	0	83.70 ± 0.00	84.68 ± 0.02c	85.21 ± 0.01c	***	85.71 ± 0.02	85.47 ± 0.03c	84.59 ± 0.01a	***
		6		84.46 ± 0.08b	84.32 ± 0.03a	*		84.91 ± 0.01b	85.13 ± 0.01b	***
		9		84.03 ± 0.04a	84.68 ± 0.04b	***		84.67 ± 0.01a	84.45 ± 0.12c	*
	HA	0	83.70 ± 0.00	84.24 ± 0.05a	84.21 ± 0.01b	ns	85.71 ± 0.02	84.68 ± 0.03	84.33 ± 0.89a	ns
		6		84.47 ± 0.01b	84.61 ± 0.01c	***		85.40 ± 0.02	84.90 ± 0.01c	***
		9		84.48 ± 0.02b	83.66 ± 0.07a	***		85.11 ± 0.00	84.66 ± 0.10b	**
	Sign.[b]			***, ns, ***	***, ***, ***			***, ***, ***	ns, ***, ns	
∑PUFAs (mg/g)	IR	0	6.53 ± 0.00	5.59 ± 0.01a	5.76 ± 0.01a	***	7.13 ± 0.01	7.16 ± 0.02a	7.25 ± 0.01a	**
		6		6.13 ± 0.14b	6.48 ± 0.00c	*		7.70 ± 0.01b	7.25 ± 0.01a	***
		9		6.65 ± 0.04c	6.09 ± 0.03b	***		7.72 ± 0.01c	7.93 ± 0.08b	*
	HA	0	6.53 ± 0.00	6.53 ± 0.17	6.61 ± 0.01b	ns	7.13 ± 0.01	7.50 ± 0.01	8.11 ± 1.24c	ns
		6		6.44 ± 0.01	6.15 ± 0.01a	***		7.15 ± 0.00	7.33 ± 0.01a	***
		9		6.55 ± 0.03	7.01 ± 0.04c	***		7.27 ± 0.00	7.70 ± 0.16b	*
	Sign.[b]			**, *, *	***, ***, ***			***, ***, ***	ns, ***, ns	
∑(MUFAs + PUFAs)/SFAs	IR	0	9.26 ± 0.00	9.28 ± 0.03a	10.06 ± 0.02b	***	12.97 ± 0.05	12.57 ± 0.02c	11.26 ± 0.01a	***
		6		9.62 ± 0.07b	9.88 ± 0.03a	**		12.52 ± 0.01b	12.12 ± 0.01b	***
		9		9.73 ± 0.00c	9.84 ± 0.01a	***		12.14 ± 0.01a	12.13 ± 0.04b	ns
	HA	0	9.26 ± 0.00	9.84 ± 0.16a	9.89 ± 0.01c	ns	12.97 ± 0.05	11.79 ± 0.03	12.24 ± 0.58	ns
		6		10.00 ± 0.01ab	9.82 ± 0.00b	***		12.43 ± 0.03	11.87 ± 0.01	***
		9		10.18 ± 0.02b	9.76 ± 0.04a	***		12.12 ± 0.00	12.09 ± 0.10	ns
	Sign.[b]			**, **, ***	***, *, *			***, **, **	*, ***, ns	
O/L	IR	0	12.91 ± 0.01	15.23 ± 0.01c	14.97 ± 0.01c	***	12.13 ± 0.01	12.07 ± 0.03c	11.76 ± 0.01b	***
		6		13.93 ± 0.34b	13.13 ± 0.01a	*		11.13 ± 0.01b	11.86 ± 0.01b	***
		9		12.77 ± 0.08a	14.06 ± 0.07b	***		11.07 ± 0.01a	10.77 ± 0.11a	**
	HA	0	12.91 ± 0.01	13.03 ± 0.34	12.88 ± 0.01b	ns	12.13 ± 0.01	11.40 ± 0.01	10.68 ± 1.94a	ns
		6		13.25 ± 0.01	13.89 ± 0.01c	***		12.08 ± 0.01	11.71 ± 0.01c	***
		9		13.03 ± 0.06	12.03 ± 0.07a	***		11.83 ± 0.01	11.11 ± 0.24b	**
	Sign.[b]			***, **, *	***, ***, ***			***, ***, ***	ns, ***, ns	
IV	IR	0	86.94 ± 0.00	86.16 ± 0.04a	86.85 ± 0.02a	***	89.84 ± 0.70	89.68 ± 0.02a	89.12 ± 0.01a	***
		6		87.04 ± 0.20b	87.57 ± 0.03c	*		90.23 ± 0.01b	89.63 ± 0.00c	***
		9		87.71 ± 0.04c	87.25 ± 0.03b	***		90.10 ± 0.01c	90.28 ± 0.15b	***
	HA	0	86.94 ± 0.00	87.40 ± 0.28a	87.53 ± 0.01b	ns	89.84 ± 0.70	89.60 ± 0.02	90.38 ± 1.43b	ns
		6		87.61 ± 0.01ab	87.22 ± 0.01a	***		89.68 ± 0.02	89.56 ± 0.01a	***
		9		87.89 ± 0.03b	88.01 ± 0.01c	**		89.68 ± 0.01	90.05 ± 0.19b	*
	Sign.[b]			**, **, **	***, ***, ***			**, ***, ***	ns, ***, ns	
PV (meqO_2/kg)	IR	0	0.01 ± *0.00*	1.31 ± 0.01c	0.64 ± 0.00b	***	0.70 ± *0.01*	4.69 ± 0.01c	4.07 ± 0.02c	***
		6		0.37 ± 0.04a	0.42 ± 0.00a	ns		0.21 ± 0.01a	0.20 ± 0.01a	***
		9		2.95 ± 0.01b	2.15 ± 0.08c	***		1.32 ± 0.00b	0.16 ± 0.00b	***
	HA	0	0.01 ± 0.00	2.54 ± 0.01c	nq	***	0.70 ± 0.01	9.98 ± 0.08	0.06 ± 0.01b	***
		6		0.51 ± 0.08a	nq	***		1.42 ± 0.15	0.01 ± 0.01a	***
		9		1.64 ± 0.09b	nq	***		1.74 ± 0.12	0.28 ± 0.03c	***
	Sign.[b]			***, ns, ***	***, ***, ***			***, ***, **	***, ns, **	

Values are expressed as mean ± standard deviation ($n = 9$). Different letters in columns, for each different roasting system, mean significantly different values among storage points. Where letters in columns were not reported, no statistical differences were observed.
Sign[a]: *, **, *** and "ns" mean significance at $p < 0.05$, 0.01, 0.001 and "not significant", respectively, between roasting time-temperature conditions.
Sign[b]: *, **, *** and "ns" mean significance at $p < 0.05$, 0.01, 0.001 and "not significant", respectively, between roasting systems for each point separately.
nq: not quantifiable.

Table 2
Sums of fatty acids and oxidative stability of raw and roasted hazelnuts from TGT and ORDU cultivars as function of roasting system (IR = infrared rays, HA = hot air), roasting conditions and storage time, harvest 2011.

Parameter	Roasting system	Storage (months)	TGT				ORDU			
			Raw	170 °C – 20 min	120 °C – 40 min	*Sign.*[a]	*Raw*	170 °C – 20 min	120 °C – 40 min	*Sign.*[a]
∑SFAs (mg/g)	IR	0	8.31 ± 0.00	7.68 ± 0.63	8.41 ± 0.00b	ns	8.50 ± 0.71	7.76 ± 0.01a	8.13 ± 0.21	ns
		6		8.41 ± 0.02	8.25 ± 0.00a	**		7.85 ± 0.05ab	7.99 ± 0.01	ns
		9		8.36 ± 0,00	8.43 ± 0.01b	*		7.96 ± 0.04c	7.76 ± 0.01	*
	HA	0	8.31 ± 0.00	8.14 ± 0.00a	8.34 ± 0.01b	**	8.50 ± 0.71	7.83 ± 0.01a	8.50 ± 0.70	ns
		6		8.62 ± 0.00c	8.26 ± 0.02a	**		7.87 ± 0.01a	7.87 ± 0.01	ns
		9		8.31 ± 0.00b	8.66 ± 0.01c	***		8.03 ± 0.01b	8.20 ± 0.00	**
	Sign.[b]			ns, **, ***	**, ns, **			*, ns, ns	ns, **, **	
∑MUFAs (mg/g)	IR	0	85.31 ± 0.00	86.68 ± 1.10	85.43 ± 0.01	ns	85.28 ± 0.01	84.90 ± 0.01	85.38 ± 0.38	ns
		6		85.15 ± 0.05	85.08 ± 0.01	ns		85.25 ± 0.06	85.33 ± 0.05	ns
		9		85.13 ± 0.44	85.33 ± 0.30	ns		85.43 ± 0.48	85.55 ± 0.36	ns
	HA	0	85.31 ± 0.00	85.25 ± 0.01b	85.02 ± 0.01	**	85.28 ± 0.01	87.51 ± 0.01c	85.28 ± 0.01a	***
		6		84.34 ± 0.01a	85.34 ± 0.01	***		84.72 ± 0.01a	85.25 ± 0.04a	**
		9		84.91 ± 0.34ab	85.00 ± 0.33	ns		85.73 ± 0.33b	86.36 ± 0.31b	ns
	Sign.[b]			ns, **, ns	***, **, ns			***, **, ns	ns, ns, ns	
∑PUFAs (mg/g)	IR	0	6.38 ± 0.01	5.65 ± 0.47	6.17 ± 0.01	ns	6.73 ± 0.01	7.34 ± 0.00	6.49 ± 0.17	*
		6		6.45 ± 0.03	6.68 ± 0.01	**		6.91 ± 0.01	6.68 ± 0.03	**
		9		6.51 ± 0.44	6.25 ± 0.29	ns		6.61 ± 0.44	6.70 ± 0.37	ns
	HA	0	6.38 ± 0.01	6.61 ± 0.01	6.65 ± 0.00	ns	6.73 ± 0.01	6.65 ± 0.01a	6.73 ± 0.01b	*
		6		7.05 ± 0.01	6.41 ± 0.01	***		7.42 ± 0.01b	6.88 ± 0.06b	**
		9		6.79 ± 0.33	6.35 ± 0.31	ns		6.24 ± 0.31a	5.44 ± 0.31a	ns
	Sign.[b]			ns, **, ns	***, **, ns			***, ***, ns	ns, *, ns	
∑(MUFAs + PUFAs)/SFAs	IR	0	11.03 ± 0.00	12.07 ± 1.07	10.89 ± 0.00a	ns	10.87 ± 0.90	11.89 ± 0.01c	11.31 ± 0.31a	ns
		6		10.90 ± 0.04	11.12 ± 0.01b	*		11.75 ± 0.08ab	11.51 ± 0.02ab	ns
		9		10.96 ± 0.00	10.87 ± 0.02a	*		11.57 ± 0.06a	11.90 ± 0.02b	*
	HA	0	11.03 ± 0.00	11.29 ± 0.00c	11.00 ± 0.01b	**	10.87 ± 0.90	12.02 ± 0.03c	10.87 ± 0.91	ns
		6		10.60 ± 0.00a	11.11 ± 0.03c	**		11.71 ± 0.01b	11.71 ± 0.02	ns
		9		11.04 ± 0.00b	10.56 ± 0.01a	***		11.46 ± 0.02a	11.20 ± 0.01	**
	Sign.[b]			ns, **, ***	**, ns, **			*, ns, ns	ns, *, **	
O/L	IR	0	13.54 ± 0.01	15.60 ± 1.50	14.03 ± 0.01	ns	12.78 ± 0.03	11.66 ± 0.00	13.30 ± 0.42	*
		6		13.37 ± 0.06	12.86 ± 0.02	**		12.46 ± 0.01	12.90 ± 0.07	*
		9		13.27 ± 0.98	13.86 ± 0.70	ns		13.10 ± 0.91	12.93 ± 0.77	ns
	HA	0	13.54 ± 0.01	13.05 ± 0.02	12.93 ± 0.00	*	12.78 ± 0.03	13.01 ± 0.02b	12.78 ± 0.03a	*
		6		12.09 ± 0.01	13.48 ± 0.02	***		11.52 ± 0.03a	12.48 ± 0.11a	**
		9		12.68 ± 0.70	13.58 ± 0.76	ns		13.93 ± 0.76b	16.12 ± 1.03b	ns
	Sign.[b]			ns, **, ns	***, **, ns			***, **, ns	ns, *, ns	
IV	IR	0	88.27 ± 0.00	88.15 ± 0.13	87.98 ± 0.01a	ns	88.78 ± 0.04	89.56 ± 0.00b	88.45 ± 0.03	***
		6		88.23 ± 0.01	88.57 ± 0.01b	**		89.08 ± 0.04ab	88.74 ± 0.02	**
		9		88.30 ± 0.45	88.03 ± 0.28a	ns		88.66 ± 0.35a	88.97 ± 0.40	ns
	HA	0	88.27 ± 0.00	88.64 ± 0.01	88.49 ± 0.01	**	88.78 ± 0.04	88.86 ± 0.01b	88.78 ± 0.04b	ns
		6		88.60 ± 0.00	88.35 ± 0.02	**		89.55 ± 0.02c	89.04 ± 0.08b	*
		9		88.61 ± 0.35	87.93 ± 0.33	ns		88.29 ± 0.30a	87.41 ± 0.31a	ns
	Sign.[b]			*, ***, ns	***, **, ns			***, **, ns	*, *, ns	
PV (meqO_2/kg)	IR	0	0.03 ± 0.02	1.27 ± 0.04a	0.75 ± 0.01c	**	0.97 ± 0.08	4.73 ± 0.00b	0.06 ± 0.02a	***
		6		1.55 ± 0.01a	0.21 ± 0.02a	***		4.66 ± 0.17b	0.20 ± 0.00a	**
		9		9.92 ± 0.25b	0.37 ± 0.05b	***		3.08 ± 0.03a	1.66 ± 0.17b	**
	HA	0	0.03 ± 0.02	1.33 ± 0.04a	1.33 ± 0.04c	ns	0.97 ± 0.08	0.43 ± 0.06a	0.06 ± 0.00b	*
		6		1.93 ± 0.18b	0.15 ± 0.00b	**		1.63 ± 0.11c	0.08 ± 0.02b	**
		9		1.69 ± 0.22ab	0.01 ± 0.00a	**		1.37 ± 0.04b	0.01 ± 0.00a	***
	Sign.[b]			ns, ns, **	**, ns, *			***, **, ***	ns, *, **	

Values are expressed as mean ± standard deviation ($n = 9$). Different letters in columns, for each different roasting system, mean significantly different values among storage points. Where letters in columns were not reported, no statistical differences were observed.
Sign[a]: *, **, *** and "ns" mean significance at $p < 0.05$, 0.01, 0.001 and "not significant", respectively, between roasting time–temperature conditions.
Sign[b]: *, **, *** and "ns" mean significance at $p < 0.05$, 0.01, 0.001 and "not significant", respectively, between roasting systems for each point separately.

roasted at 170 °C for 20 min by IR. Overall, during storage a more pronounced decrease in the values were observed in both hazelnuts roasted at 170 °C – 20 min.

The iodine value is a measure of the degree of unsaturation of a lipid. A greater iodine value indicates that the oil is more reactive, less stable, and more susceptible to oxidation and rancidification. Between the two varieties, a general increase in IV can be observed during storage, which appeared to be more pronounced in the IR compared with the HA system.

The peroxide value is a common lipid oxidation index. The greatest PV values were detected when the 170 °C for 20 min roasting conditions were used for both the TGT and Ordu. Between varieties and during all storage times, the lowest results were detected in the TGT hazelnuts.

These results were in agreement with others (Amaral, Casal, Alves, Seabra, & Oliveira, 2006; Schlörmann et al., 2015), confirming that lower roasting temperatures increase the stability of the hazelnuts without any particular changes in the lipid profile composition. The greatest PV value was found for the Ordu roasted at 170 °C for 20 min by HA at the initial point; then, the PV values decreased. This result is likely due to the fluctuation of PV during processing or storage (Özdemir et al., 2001). In general, hazelnuts roasted using the HA system at 120 °C for 40 min were more stable in terms of O/L, IV as well as PV after 6 months of storage where

the three indexes seem to be not strongly affected. As showed by data, under the influence of unfavourable conditions as high temperatures (170 °C – 20 min) combined with extreme exposure to light as IR, increases of PV and IV values and corresponding decreases of O/L values were observed. In particular, PV and IV indexes highlight as the primary oxidation as well as the number of degree of unsaturation of the lipids change proportionally due to the presence of much higher contents of oleic acid. The latter is affected at high temperatures hence lowering its relative levels and, as a consequence, increasing saturated and polyunsaturated fatty acids percentages (Amaral et al., 2006). Therefore, the degradation rate of oleic acid led to an increase of O/L value as reported in Table 1, with similar trends for both hazelnut varieties roasted using IR system. Regarding HA roasting system, the data obtained showed that the values of the three indexes remained unvaried, less than for PV value, which significantly decreased when TGT as well as Ordu were roasted at 170 °C for 20 min. This PV value decreasing highlights the low incidence of the treatment on the primary oxidation of lipids in terms of hydroperoxide production.

In the second year of study (Table 2), slight changes in the FA composition were observed. At the beginning, the TGT was characterized by an increase in MUFAs balanced by a decrease in SFAs, and the PUFAs were almost unchanged. In the Ordu, the MUFA content was stable, whereas the SFA and PUFA content increased and decreased, respectively.

These differences in the FA composition were likely due to the difference in the harvest season and growing conditions, as previously reported by other authors (Alasalvar, Amaral, Satir, & Shahidi, 2009; Beyhan, Elmastas, Genc, & Aksit, 2011; Vujević et al., 2014). Despite the slight variations, better oxidative stability in both varieties was confirmed by roasting at 120 °C for 40 min for both the HA and IR conditions. In particular, the O/L ratio for both varieties significantly increased, reaching the greatest values in the TGT roasted using HA at 120 °C for 40 min. No differences were observed for the IV values in both the TGT and Ordu, whereas PV significantly increased more in the TGT roasted using IR at 170 °C for 20 min compared with the Ordu subjected to the same conditions. As observed in first year, data obtained for the three indexes confirmed the prevalent influence of the IR system compared to HA on the oxidative stability of the hazelnuts.

3.2. TPC and antioxidant capacity

There are very few works in the literature reporting data on the TPC and antioxidant capacity of roasted hazelnuts, whereas there are no works at all, to our knowledge, that reported this type of data over an extended storage period. A comparison with data already present in the literature is not always possible due to the different experimental conditions used. Therefore, here, a comparison with related literature trends rather than with numerical values was attempted.

The results of the TPC, TEAC and RSA of the TGT and Ordu, which were harvested 2010, are shown in Table 3. The TPC content of the roasted TGT ranged from 0.48 to 0.69 mg GAE g^{-1}, depending on the roasting conditions and systems applied. Moreover, the TPC slightly increased during roasting. These results were similar to those obtained by Schmitzer et al. (2011) who studied the effect of roasting on various parameters, such as the TPC and antioxidant capacity among others. The similarity of our results to the previous study is likely due to the use of a raw hazelnut without a pellicle. Indeed, when a raw hazelnut with a pellicle is used as reference, there is a dramatic decrease in the TPC content after roasting, due to the loss of the skin (Pelvan et al., 2012). Both roasting conditions and storage time had a significant effect on the TPC content of the TGT. The effects of the roasting conditions could be seen at the 9th month of storage for the TGT roasted using IR, with a greater TPC content for the 120 °C – 40 min treatment, and at months 0 and 9 for the TGT roasted using HA, with a greater TPC content for the 170 °C – 20 min treatment. A significant increase in TPC was observed during storage in the TGT roasted with IR at 120 °C for 40 min and in the TGT roasted with HA at 170 °C for 20 min. Instead, the TPC content of the hazelnuts roasted at

Table 3
Total phenolic content (TPC) and antioxidant capacity (TEAC and RSA) of raw and roasted hazelnuts from TGT and ORDU cultivars as function of roasting system (IR = infrared rays, HA = hot air), roasting conditions and storage time, harvest 2010.

Parameter	Roasting system	Storage (months)	TGT				ORDU			
			Raw	170 °C – 20 min	120 °C – 40 min	*Sign.*[a]	*Raw*	170 °C – 20 min	120 °C – 40 min	*Sign.*[a]
TPC (mg GAE/g)	IR	0	0.42 ± 0.01	0.48 ± 0.02	0.49 ± 0.02a	ns	0,51 ± 0,01	0.57 ± 0.01a	0.61 ± 0.00a	**
		6		0.50 ± 0.01	0.53 ± 0.00ab	ns		0.63 ± 0.04a	0.90 ± 0.04c	**
		9		0.51 ± 0.00	0.54 ± 0.01b	**		0.94 ± 0.06b	0.71 ± 0.02b	**
	HA	0	0.42 ± 0.01	0.61 ± 0.02a	0.47 ± 0.01	***	0,51 ± 0,01	0.91 ± 0.01ab	0.64 ± ± 0.02	***
		6		0.64 ± 0.01ab	0.69 ± 0.23	ns		1.09 ± 0.16b	0.82 ± 0.27	ns
		9		0.67 ± 0.01b	0.56 ± 0.03	**		0.72 ± 0.01a	0.99 ± 0.10	*
	Sign.[b]			***, ***, ***	ns, ns, ns			***, **, **	ns, ns, **	
TEAC (μmol TE/g)	IR	0	1.99 ± 0.07	2.20 ± 0.07	2.09 ± 0.09a	ns	1,76 ± 0,05	1.64 ± 0.01a	1.99 ± 0.13a	**
		6		2.10 ± 0.10	2.10 ± 0.05a	ns		2.32 ± 0.24b	4.13 ± 0.29c	**
		9		2.04 ± 0.01	2.25 ± 0.08b	*		4.58 ± 0.37c	2.50 ± 0.15b	**
	HA	0	1.99 ± 0.07	3.01 ± 0.11	2.13 ± 0.06	***	1,76 ± 0,05	4.16 ± 0.10ab	2.19 ± 0.08	***
		6		2.83 ± 0.06	3.09 ± 1.36	ns		5.71 ± 1.54b	3.78 ± 1.76	ns
		9		2.82 ± 0.11	2.40 ± 0.10	**		2.50 ± 0.06a	4.40 ± 0.68	**
	Sign.[b]			***, ***, ***	ns, ns, ns			***, *, ***	ns, ns, **	
RSA (μmol TE/g)	IR	0	0.64 ± 0.05	0.79 ± 0.08a	0.76 ± 0.05a	ns	0,60 ± 0,02	0.55 ± 0.01a	0.63 ± 0.02a	**
		6		1.02 ± 0.07b	0.84 ± 0.03a	*		1.17 ± 0.17b	2.26 ± 0.27c	**
		9		0.88 ± 0.04ab	0.97 ± 0.02b	*		2.63 ± 0.27c	1.09 ± 0.06b	**
	HA	0	0.64 ± 0.05	1.22 ± 0.06	0.78 ± 0.03	***	0,60 ± 0,02	1.99 ± 0.04ab	0.70 ± 0.05a	***
		6		1.24 ± 0.03	1.42 ± 0.79	ns		3.01 ± 0.84b	1.99 ± 1.14ab	ns
		9		1.21 ± 0.02	1.12 ± 0.04	**		1.03 ± 0.01a	2.41 ± 0.51b	*
	Sign.[b]			**, **, ***	ns, ns, **			***, *, ***	ns, ns, *	

Values are expressed as mean ± standard deviation ($n = 9$). Different letters in columns, for each different roasting system, mean significantly different values among storage points. Where letters in columns were not reported, no statistical differences were observed.
Sign[a]: *, **, *** and "ns" mean significance at $p < 0.05$, 0.01, 0.001 and "not significant", respectively, between roasting time–temperature conditions.
Sign[b]: *, **, *** and "ns" mean significance at $p < 0.05$, 0.01, 0.001 and "not significant", respectively, between roasting systems for each point separately.

170 °C for 20 min using IR and at 120 °C for 40 min using HA did not vary during storage. The comparison between the two roasting systems showed that the TPC contents of the TGT roasted using HA were greater than the TPC contents of the TGT roasted using IR at each time of storage for the 170 °C – 20 min treatment, probably because IR caused a higher heating in the hazelnut than HA and, then, a higher degradation of phenolic compounds.

With respect to antioxidant capacity, the TEAC values of the roasted TGT ranged from 2.09 to 3.09 μmol TE g^{-1}, whereas the RSA ranged from 0.76 to 1.42 μmol TE g^{-1}. As for the TPC, roasting gave rise to a slight increase in the TEAC and RSA values compared with the raw TGT. These results were still in agreement with the results from Schmitzer et al. (2011), who also determined the antioxidant capacity of TGT by means of the DPPH radical scavenging method. The effects of roasting conditions, storage time and roasting system on the TEAC were almost the same as the effects described above for the TPC. Indeed, the unique difference was that storage time had no effect on the TEAC values of the TGT roasted using HA at 170 °C for 20 min. The RSA pattern was quite similar to that of the TEAC and TPC with the main differences being that storage time had an additional and significant effect on RSA of TGT roasted by IR at 170 °C – 20 min, and the roasting system had a significant effect on RSA value of TGT roasted at 120 °C for 40 min at the 9th month. The observed relationship between TPC and TEAC/RSA values was not surprising, because all these assays are similar and act by the same mechanism. It is well known that Folin-Ciocalteu, ABTS and DPPH assays, based on similar electron-transfer redox reactions, are able to assess not only the phenolic compounds but also the antiradical or antioxidant capacity of non-phenolic compounds, such as the Maillard reaction products, including melanoidins formed during roasting (Pérez-Martínez, Caemmerer, Paz De Peña, Cid, & Kroh, 2010). Similar to TGT, in most cases, the TPC, TEAC and RSA values of the roasted Ordu were similar or greater than the corresponding values for the raw sample. Again, similar to TGT, a significant effect of roasting system could be seen on the Ordu roasted at 170 °C for 20 min, but in this case, not all of the greatest values were associated with the HA roasting system. Unlike the TGT, in most cases, the roasting conditions significantly affected the Ordu parameters and the storage time had a more marked effect. However, it was not possible to find a regular pattern because the greatest values were randomly distributed between the two roasting conditions. Even the trend due to the storage time was not regular: the highest values were distributed between months 6 and 9. Ordu TPC, TEAC and RSA were in the ranges 0.57–1.09 mg GAE g^{-1}, 1.64–5.71 μmol TE g^{-1} and 0.55–3.01 μmol TE g^{-1}, respectively. The TPC values were similar to those found by Pelvan et al. (2012) in a study of different Turkish varieties of roasted hazelnuts.

The results of the TPC, TEAC and RSA for the TGT and Ordu that were harvested in 2011 are shown in Table 4.

An overall view of the data from the harvest in 2011 shows behaviour and trends that are different from the hazelnuts harvested in 2010. Indeed, as opposed to the hazelnuts harvested in 2010, the TPC content and antioxidant capacity of the roasted TGT were affected by storage time and, in most cases, by the roasting conditions and the roasting system. Basically, roasting using IR at 170 °C for 20 min resulted in greater TPC compared with HA at 120 °C for 40 min. Furthermore, in most cases the greatest TPC, TEAC and RSA values were achieved at month 6 and were followed by a decrease. The TPC content and TEAC and RSA values were in the range 0.28–0.91 mg GAE g^{-1}, 0.71–5.03 μmol TE g^{-1} and 0.76–3.73 μmol TE g^{-1}, respectively. As in 2010, roasting resulted in an increase in these parameter values compared with raw hazelnuts

With respect to Ordu, it was confirmed that in 2011 there was an effect of storage time on all of the studied parameters. Moreover, there was a more regular trend than in 2010, with the greatest values always found at month 6. Instead, the effect of roasting system and roasting conditions were less significant in 2010. However, when significantly different, most of the greatest parameters values were obtained when using the IR roasting system and roasting conditions at 120 °C for 40 min. The TPC, TEAC

Table 4
Total phenolic content (TPC) and antioxidant capacity (TEAC and RSA) of raw and roasted hazelnuts from TGT and ORDU cultivars as function of roasting system (IR = infrared rays, HA = hot air), roasting conditions and storage time, harvest 2011.

Parameter	Roasting system	Storage (months)	TGT				ORDU			
			Raw	170 °C – 20 min	120 °C – 40 min	*Sign.*[a]	*Raw*	170 °C – 20 min	120 °C – 40 min	*Sign.*[a]
TPC (mg GAE/g)	IR	0	0.27 ± 0.01	0.62 ± 0.02a	0.51 ± 0.02a	**	0.39 ± 0.05	0.60 ± 0.05a	0.52 ± 0.02a	ns
		6		0.83 ± 0.03b	0.91 ± 0.10b	ns		1.58 ± 0.15b	1.96 ± 0.22b	ns
		9		0.89 ± 0.03b	0.47 ± 0.02a	***		0.57 ± 0.01a	0.55 ± 0.04a	ns
	HA	0	0.27 ± 0.01	0.35 ± 0.02a	0.28 ± 0.04a	ns	0.39 ± 0.05	0.51 ± 0.01a	0.48 ± 0.02a	ns
		6		0.77 ± 0.05c	0.59 ± 0.07c	*		1.31 ± 0.05b	2.18 ± 0.00b	***
		9		0.57 ± 0.02b	0.47 ± 0.00b	**		0.56 ± 0.01a	0.45 ± 0.03a	**
	Sign.[b]			***, ns, ***	***, *, ns			ns, *, ns	ns, ns, *	
TEAC (μmol TE/g)	IR	0	0.59 ± 0.09	2.12 ± 0.05a	1.67 ± 0.03a	***	1.08 ± 0.25	1.75 ± 0.03a	1.69 ± 0.17a	ns
		6		3.16 ± 0.14b	5.03 ± 0.82b	*		8.49 ± 0.85b	10.63 ± 0.51b	*
		9		3.55 ± 0.17c	1.52 ± 0.00a	***		1.90 ± 0.03a	1.76 ± 0.14a	ns
	HA	0	0.59 ± 0.09	0.96 ± 0.07a	0.71 ± 0.13a	*	1.08 ± 0.25	1.44 ± 0.06a	1.13 ± 0.10a	*
		6		3.73 ± 0.45c	2.60 ± 0.48c	*		7.22 ± 0.18b	11.20 ± 0.00b	***
		9		2.02 ± 0.10b	1.47 ± 0.04b	**		1.93 ± 0.08a	1.52 ± 0.18a	*
	Sign.[b]			***, ns, ***	***, *, ns			***, ns, ns	**, ns, ns	
RSA (μmol TE/g)	IR	0	0.68 ± 0.08	1.50 ± 0.05a	1.20 ± 0.03a	**	0.67 ± 0.08	1.22 ± 0.10a	1.04 ± 0.19a	ns
		6		2.12 ± 0.09b	3.56 ± 0.44b	**		5.29 ± 0.30b	6.02 ± 0.26b	*
		9		2.02 ± 0.12b	0.79 ± 0.03a	***		1.02 ± 0.02a	0.91 ± 0.02a	**
	HA	0	0.68 ± 0.08	0.89 ± 0.03a	0.76 ± 0.08a	*	0.67 ± 0.08	0.85 ± 0.04a	0.77 ± 0.03a	ns
		6		2.55 ± 0.23b	1.65 ± 0.54b	ns		4.57 ± 0.12b	6.81 ± 0.07b	***
		9		1.11 ± 0.01a	0.84 ± 0.03a	***		1.04 ± 0.03a	0.77 ± 0.10a	**
	Sign.[b]			***, *, ***	***, **, ns			**, *, ns	ns, **, ns	

Values are expressed as mean ± standard deviation ($n = 9$). Different letters in columns, for each different roasting system, mean significantly different values among storage points. Where letters in columns were not reported, no statistical differences were observed.
Sign [a]: *, **, *** and "ns" mean significance at $p < 0.05$, 0.01, 0.001 and "not significant", respectively, between roasting time-temperature conditions.
Sign[b]: *, **, *** and "ns" mean significance at $p < 0.05$, 0.01, 0.001 and "not significant", respectively, between roasting systems for each point separately.

and RSA values were in the range 0.45–2.18 mg GAE g^{-1}, 1.13–11.20 μmol TE g^{-1} and 0.77–6.81 μmol TE g^{-1}, respectively.

In both years, the parameter values measured for Ordu were basically greater than the parameters measured for TGT. The increase in the parameters values (TPC, TEAC and RSA), which occurred after roasting, was not surprising; indeed, other authors have observed the same behaviour in other nuts and have linked the increase in extractable phenolic compounds after roasting to the formation of Maillard products (Ioannou & Ghoul, 2012). Thermal processing may cause complex physical and chemical reactions on phenolics, including leaching of water soluble phenolics, freeing phenolics from bond forms, degradation of polyphenols, breakdown and transformation of phenolics, such as formation of complex products from phenolics and proteins, and formation of Maillard reaction products having antioxidative activity (Xu & Chang, 2008).

3.3. Instrumental mechanical and acoustic properties

The results of the assessment of the first year's mechanical and acoustic properties are shown in Table 5. To our knowledge, the assessment of the joint mechanical-acoustic properties on roasted hazelnut kernels during storage is presented here for the first time. Several parameters were selected to evaluate the ease of breaking a hazelnut during compression and to evaluate a possible crunchiness indicator for the roasted product. A decrease in the rupture force (F1) was found with the roasting process, and in particular, the use of the IR or the HA roasting systems reduced F1. With respect to the raw hazelnut measurements, the HA treatment was more effective in the reduction of the force necessary to break the nut.

In relation to the applied time-temperature roasting conditions, a rupture force reduction was found using the IR system when

Table 5
Mechanical properties of raw and roasted hazelnuts from TGT and ORDU cultivars as function of roasting system (IR = infrared rays, HA = hot air), roasting conditions and storage time, harvest 2010.

Parameter	Roasting system	Storage (months)	TGT				ORDU			
			Raw	170 °C – 20 min	120 °C – 40 min	*Sign.*[a]	*Raw*	170 °C – 20 min	120 °C – 40 min	*Sign.*[a]
F1 (N)	IR	0	93.2 ± 16.7	83.4 ± 18.7	57.7 ± 19.5	***	96.4 ± 20.4	78.7 ± 19.2b	63.3 ± 25.7	*
		6		80.3 ± 16.7	59.9 ± 17.9	***		73.7 ± 12.9b	45.7 ± 18.7	***
		9		80.5 ± 26.0	61.3 ± 18.2	**		62.0 ± 19.8a	51.8 ± 29.9	ns
	HA	0	93.2 ± 16.7	40.1 ± 14.8	47.9 ± 16.5	ns	96.4 ± 20.4	35.0 ± 17.1	41.7 ± 15.6	ns
		6		38.8 ± 12.4	44.7 ± 17.4	ns		37.7 ± 13.8	40.4 ± 16.3	ns
		9		44.0 ± 17.4	57.7 ± 21.4	*		43.9 ± 21.0	48.9 ± 17.7	ns
	Sign.[b]			***, ***, ***	ns, **, ns			***, ***, **	**, ns, ns	
W1 (mJ)	IR	0	113.9 ± 53.0	82.4 ± 42.7	37.7 ± 24.1	***	117.6 ± 45.9	78.2 ± 39.2b	42.4 ± 23.8	**
		6		83.3 ± 34.4	38.8 ± 21.0	***		67.4 ± 26.2ab	24.4 ± 13.1	***
		9		72.6 ± 45.7	45.9 ± 31.8	*		48.4 ± 26.1a	33.0 ± 34.4	ns
	HA	0	113.9 ± 53.0	23.1 ± 18.6	29.1 ± 22.1	ns	117.6 ± 45.9	17.2 ± 14.7	19.9 ± 13.5	ns
		6		20.9 ± 13.5	27.8 ± 18.6	ns		20.7 ± 16.4	21.5 ± 15.1	ns
		9		29.8 ± 22.8	43.7 ± 31.1	ns		27.5 ± 24.4	32.5 ± 22.6	ns
	Sign.[b]			***, ***, ***	ns, ns, ns			***, ***, *	***, ns, ns	
E1 (N/mm)	IR	0	40.9 ± 7.0	44.0 ± 7.2ab	44.1 ± 10.3	ns	39.6 ± 8.1	41.6 ± 11.6	45.5 ± 15.6	ns
		6		39.3 ± 8.0a	46.7 ± 7.4	**		39.1 ± 5.6	44.2 ± 19.8	ns
		9		49.0 ± 11.8b	42.7 ± 7.5	*		40.8 ± 7.4	44.3 ± 12.5	ns
	HA	0	40.9 ± 7.0	35.3 ± 8.9	40.9 ± 12.4	ns	39.6 ± 8.1	36.2 ± 15.9	43.2 ± 11.2	ns
		6		37.2 ± 7.8	39.6 ± 8.2	ns		36.3 ± 8.3	40.2 ± 7.6	ns
		9		34.6 ± 5.3	41.5 ± 8.4	**		36.9 ± 8.8	38.8 ± 7.3	ns
	Sign.[b]			**, ns, ***	ns, **, ns			ns, ns, ns	ns, ns, ns	
Maximum acoustic peak (dB)	IR	0	99.9 ± 6.4	101.3 ± 5.7	97.5 ± 8.2	ns	95.7 ± 7.7	101.9 ± 6.1	100.0 ± 6.5	ns
		6		101.3 ± 8.5	100.2 ± 4.7	ns		102.0 ± 5.2	100.0 ± 4.3	ns
		9		103.8 ± 4.6	100.7 ± 5.7	*		104.5 ± 4.4	100.1 ± 6.1	*
	HA	0	99.9 ± 6.4	93.3 ± 5.5a	93.8 ± 7.1a	ns	95.7 ± 7.7	92.7 ± 5.4a	95.4 ± 4.8a	ns
		6		99.1 ± 5.0b	99.5 ± 5.4b	ns		100.3 ± 4.3b	97.0 ± 6.9a	ns
		9		99.7 ± 6.1b	101.0 ± 5.3b	ns		97.9 ± 7.1b	101.8 ± 5.4b	ns
	Sign.[b]			***, ns, **	ns, ns, ns			***, ns, **	*, ns, ns	
Number of acoustic peaks	IR	0	26.0 ± 10.5	32.0 ± 20.2a	52.5 ± 18.9a	**	48.3 ± 17.3	80.6 ± 42.2a	85.2 ± 37.2a	ns
		6		102.5 ± 34.0b	139.9 ± 70.0b	*		104.0 ± 32.7a	165.9 ± 49.1b	***
		9		164.5 ± 51.4c	184.7 ± 61.2c	ns		156.6 ± 68.4b	202.2 ± 50.0c	*
	HA	0	26.0 ± 10.5	61.8 ± 22.7a	58.8 ± 22.0a	ns	48.3 ± 17.3	117.8 ± 35.6a	85.6 ± 45.7a	*
		6		91.4 ± 22.1b	63.5 ± 31.8a	**		96.2 ± 27.4a	198.8 ± 37.3b	***
		9		215.6 ± 58.8c	269.6 ± 56.2b	**		162.3 ± 57.7b	225.3 ± 52.6b	***
	Sign.[b]			***, ns, **	ns, ***, ***			**, ns, ns	ns, *, ns	
Average acoustic peaks emission (dB)	IR	0	59.9 ± 6.6	59.9 ± 6.2a	55.3 ± 4.9a	*	59.4 ± 5.0	61.6 ± 4.7ab	60.5 ± 4.3a	ns
		6		60.3 ± 5.4a	62.1 ± 6.4b	ns		60.8 ± 5.5a	62.1 ± 3.8a	ns
		9		65.7 ± 4.0b	63.2 ± 3.0b	*		64.4 ± 3.9b	66.6 ± 3.7b	ns
	HA	0	59.9 ± 6.6	56.2 ± 5.1a	53.8 ± 3.9a	ns	59.4 ± 5.0	61.5 ± 3.1a	65.5 ± 3.1b	***
		6		61.1 ± 6.0b	56.2 ± 5.0a	**		60.0 ± 5.3a	63.1 ± 3.1a	*
		9		68.0 ± 3.7c	67.7 ± 2.3b	ns		68.8 ± 2.9b	66.6 ± 2.8b	*
	Sign.[b]			*, ns, *	ns, **, ***			ns, ns, ***	***, ns, ns	

Values are expressed as mean ± standard deviation ($n = 9$). Different letters in columns, for each different roasting system, mean significantly different values among storage points. Where letters in columns were not reported, no statistical differences were observed.
Sign [a]: *, **, *** and "ns" mean significance at $p < 0.05$, 0.01, 0.001 and "not significant", respectively, between roasting time–temperature conditions.
Sign[b]: *, **, *** and "ns" mean significance at $p < 0.05$, 0.01, 0.001 and "not significant", respectively, between roasting systems for each point separately.

Table 6
Mechanical properties of raw and roasted hazelnuts from TGT and ORDU cultivars as function of roasting system (IR = infrared rays, HA = hot air), roasting conditions and storage time, harvest 2011.

Parameter	Roasting system	Storage (months)	TGT				ORDU			
			Raw	170 °C – 20 min	120 °C – 40 min	*Sign.*[a]	*Raw*	170 °C – 20 min	120 °C – 40 min	*Sign.*[a]
F1 (N)	IR	0	83.3 ± 21.8	48.8 ± 19.1	40.7 ± 16.2	ns	84.3 ± 22.0	42.7 ± 14.5	30.3 ± 12.4	**
		6		57.5 ± 21.9	40.7 ± 19.3	*		41.6 ± 13.9	27.7 ± 8.7	***
		9		57.0 ± 26.8	44.7 ± 22.6	ns		51.0 ± 13.6	37.6 ± 18.5	*
	HA	0	83.3 ± 21.8	40.8 ± 10.5a	41.5 ± 19.2	ns	84.3 ± 22.0	40.8 ± 16.1	37.7 ± 10.7	ns
		6		49.6 ± 17.4ab	38.6 ± 13.5	*		41.6 ± 11.6	37.4 ± 11.5	ns
		9		54.9 ± 14.8b	38.5 ± 15.8	**		47.5 ± 11.2	44.2 ± 19.1	ns
	Sign.[b]			ns, ns, ns	ns, ns, ns			ns, ns, ns	ns, **, ns	
W1 (mJ)	IR	0	67.4 ± 32.2	31.7 ± 24.2	28.8 ± 17.7	ns	94.9 ± 42.7	26.2 ± 18.3	16.4 ± 14.2ab	ns
		6		39.3 ± 30.3	27.1 ± 20.4	ns		25.9 ± 21.0	12.3 ± 5.8a	**
		9		36.7 ± 26.5	37.7 ± 29.6	ns		34.1 ± 17.2	26.9 ± 24.3b	ns
	HA	0	67.4 ± 32.2	21.7 ± 11.2a	25.1 ± 23.9	ns	94.9 ± 42.7	23.6 ± 20.0	19.5 ± 10.3	ns
		6		29.6 ± 20.4ab	22.6 ± 18.7	ns		24.3 ± 11.0	21.5 ± 12.7	ns
		9		39.0 ± 23.3b	23.6 ± 18.2	*		26.7 ± 11.1	31.6 ± 28.0	ns
	Sign.[b]			ns, ns, ns	ns, ns, ns			ns, ns, ns	ns, **, ns	
E1 (N/mm)	IR	0	50.1 ± 6.6	40.2 ± 9.7	29.8 ± 9.5	**	37.8 ± 3.6	38.3 ± 8.9	29.5 ± 6.9	**
		6		45.7 ± 12.3	31.5 ± 9.5	***		34.9 ± 8.3	31.4 ± 12.2	ns
		9		47.9 ± 18.5	26.6 ± 8.1	***		38.0 ± 6.8	27.4 ± 7.3	***
	HA	0	50.1 ± 6.6	37.4 ± 6.5	35.5 ± 6.6	ns	37.8 ± 3.6	37.0 ± 8.1a	36.4 ± 7.4	ns
		6		41.3 ± 7.2	35.9 ± 7.0	*		34.8 ± 4.9a	34.0 ± 8.7	ns
		9		39.4 ± 5.9	31.9 ± 6.6	***		41.6 ± 8.2b	32.4 ± 6.3	***
	Sign.[b]			ns, ns, ns	*, ns, *			ns, ns, ns	**, ns, *	
Maximum acoustic peak (dB)	IR	0	100.6 ± 7.2	97.9 ± 5.6b	96.2 ± 7.8	ns	95.8 ± 6.3	89.9 ± 5.4a	84.9 ± 7.9a	*
		6		89.6 ± 9.2a	91.5 ± 4.7	ns		91.5 ± 6.8a	89.5 ± 5.8b	ns
		9		96.5 ± 5.4b	93.4 ± 7.0	ns		99.7 ± 3.9b	91.5 ± 7.8b	***
	HA	0	100.6 ± 7.2	99.2 ± 5.6b	94.9 ± 6.2b	*	95.8 ± 6.3	95.7 ± 5.5a	96.9 ± 5.9b	ns
		6		89.4 ± 8.1a	86.6 ± 7.9a	ns		93.3 ± 5.2a	89.9 ± 4.3a	*
		9		99.0 ± 7.0b	95.3 ± 6.4b	ns		99.1 ± 3.9b	96.3 ± 5.8b	ns
	Sign.[b]			ns, ns, ns	ns, *, ns			**, ns, ns	***, ns, *	
Number of acoustic peaks	IR	0	122.3 ± 32.0	285.6 ± 46.5b	232.4 ± 28.8b	***	214.3 ± 37.4	190.2 ± 41.6a	203.2 ± 54.8a	ns
		6		195.7 ± 66.6a	255.7 ± 46.9c	**		250.2 ± 74.5b	282.1 ± 52.2b	ns
		9		181.0 ± 24.4a	171.4 ± 23.5a	ns		198.6 ± 24.3a	178.6 ± 41.6a	ns
	HA	0	122.3 ± 32.0	231.6 ± 33.3	200.0 ± 28.9b	**	214.3 ± 37.4	270.5 ± 71.9b	260.3 ± 50.8	ns
		6		215.0 ± 63.3	265.8 ± 35.5c	**		217.6 ± 71.2a	252.3 ± 63.3	ns
		9		204.2 ± 33.7	173.4 ± 29.2a	**		197.1 ± 32.5a	223.3 ± 28.0	**
	Sign.[b]			***, ns, *	**, ns, ns			***, ns, ns	**, ns, ***	
Average acoustic peaks emission (dB)	IR	0	64.5 ± 2.9	63.9 ± 1.3	64.5 ± 3.0b	ns	67.9 ± 2.8	64.9 ± 3.4	61.8 ± 3.8a	**
		6		63.8 ± 1.9	64.3 ± 3.1b	ns		64.5 ± 2.5	65.0 ± 3.5b	ns
		9		64.0 ± 1.6	62.3 ± 1.6a	**		66.0 ± 2.0	61.4 ± 2.0a	***
	HA	0	64.5 ± 2.9	63.4 ± 2.4	62.4 ± 3.4	ns	67.9 ± 2.8	65.1 ± 3.5ab	66.4 ± 2.0c	ns
		6		64.1 ± 2.9	62.4 ± 2.7	ns		64.1 ± 3.0a	63.3 ± 2.6a	ns
		9		63.3 ± 2.2	63.1 ± 2.4	ns		66.5 ± 2.9b	64.9 ± 2.4b	ns
	Sign.[b]			ns, ns, ns	*, *, ns			ns, ns, ns	***, ns, ***	

Values are expressed as mean ± standard deviation ($n = 9$). Different letters in columns, for each different roasting system, mean significantly different values among storage points. Where letters in columns were not reported, no statistical differences were observed.
Sign [a]: *, **, *** and "ns" mean significance at $p < 0.05$, 0.01, 0.001 and "not significant", respectively, between roasting time–temperature conditions.
Sign[b]: *, **, *** and "ns" mean significance at $p < 0.05$, 0.01, 0.001 and "not significant", respectively, between roasting systems for each point separately.

increasing the treatment time to 40 min despite the lower temperature. This was not found in the HA treatment where the longer treatments resulted in greater F1 values; however, these differences were not significantly different from the 170 °C – 20 min treatment. In particular, the predominance of roasting temperature effect over the roasting time was also found by Demir and Cronin (2005) when using conventional fan ovens.

The reduction in F1 when using the HA system also caused a reduction in the maximum acoustic peak intensity, which decreased to a lower value than those found for the IR trials with significant differences at the initial point. This could be related to the crunchiness sensory perception; however, selective studies on the correlation between sensory and mechanical-acoustic properties on hazelnuts were not carried out in the present work. Limited only to the relationship with mechanical properties, Saklar et al. (1999) found a negative correlation between the sensory crunchiness and crispness and the force parameters specifically the rupture force. In addition, the same authors, by using the response surface methodology, showed that more intense roasting conditions caused a reduction in the force parameters and an increase in sensory crispness and crunchiness parameters. Based on the data included in the present work, this cannot be confirmed, neither for IR or HA roasting systems, but some hypotheses about the crunchiness based on the loss of rupture force could indicate the HA roasting system potentially results in crunchier products.

When observing the results of the second year (Table 6), all of the aforementioned differences were reduced either by treatment or roasting system. A steep decrease of the F1 parameter values between raw and roasted samples was already found, but no or few significant differences were found in the force measurements between the roasting systems or conditions. The lower rupture force found in the raw second harvest samples with respect to those at the first harvest, in both cultivars, might have had a role

in this behaviour. In particular, the IR roasting system samples also resulted in an important F1 reduction from raw to roasted. Greater F1 values were found in the 170 °C – 20 min roasting condition.

Moreover, these differences may have characterized the acoustic measurements values found before and after roasting. The number of acoustic peaks detected was quite high in the raw hazelnuts from the second harvest as well the average peak emission.

The overall results from the two-year data set did not show common trends for the mechanical and acoustic properties between the two harvest years. The different raw samples seemed to change the evaluated properties trends; indeed, the different composition of the raw hazelnuts between the two harvests may have caused a different response to the roasting process and thus different products.

In general, the HA roasting system appears to be less sensitive to starting product variations. Unfortunately, to our knowledge, the literature data covering two consecutive harvests in raw and roasted hazelnuts composition is scarce and limited to physical properties (Koksal, Gunes, & Belge, 2012). Single compositional effects or characteristics might have had an influence on the mechanical properties, such as a different water activity effect as previously found on hazelnuts and other nut samples (Borges & Peleg, 1997).

The storage of raw hazelnuts (TGT cultivar) was found to have significant effects on the mechanical properties of the hazelnuts: after 8–12 months, an increase in the rupture force was observed, whereas a decrease in the rupture energy was observe, except for hazelnuts stored in-shell, at ambient temperature (Ghirardello et al., 2013). In the present study, roasted hazelnuts from the first harvest after 9 months of storage showed some trends. A significant decrease in the rupture force and energy was found in the Ordu samples, but only when using IR roasting at the high temperature. In the second harvest, an increase of the F1 and W1 parameters was found in almost all of the samples, but the differences were, for the most part, not significant likely due to the common high variability in these measurements as found by others (Ghirardello et al., 2013).

3.4. Sensory analysis

For all of the sampling times, years and hazelnut cultivars, the obtained results from the duo-trio test highlighted a significant difference ($\alpha < 0.05$) between the IR and HA roasting method when roasted at 170 °C for 20 min. Instead, no significant differences between roasting methods were found when the low temperature (120 °C for 40 min) was used. The two roasting processes, independent of the hazelnut cultivars, resulted in products with significant sensory differences only when the roasting temperature was high, and this difference persisted during storage.

4. Conclusions

In conclusion, this study showed that roasting with hot air system at low temperature gave rise to products with a better oxidative stability over six months of storage at 4 °C. Hot air system also seemed to be better for obtaining hazelnuts with lower rupture force which probably correlates with crunchier products. Significant sensory differences between hazelnuts roasted with HA and IR systems were found only when roasting was performed at high temperatures (170 °C – 20 min). Even if it was not possible to draw similar overall conclusion for the TPC and antioxidant capacity, the storage time of six months at 4 °C could be suggested for the maintenance of a high antioxidant capacity of the hazelnuts.

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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.2016.08.103.

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