

Review

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Review

Conventional and Innovative Drying/Roasting Technologies: Effect on Bioactive and Sensorial Profiles in Nuts and Nut-Based Products

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Abstract: Nuts are widely recognized for their exceptional nutritional value, being rich in bioactive compounds such as polyphenols, mono- and polyunsaturated fatty acids, dietary fiber, and essential minerals. Roasting, a common processing technique, enhances the sensory attributes of nuts, including flavor, aroma, and texture, while influencing their nutritional and chemical profiles. This review focuses on the effects of roasting technologies specifically on pistachios, hazelnuts, and almonds. The Maillard reaction, triggered during roasting, is pivotal in developing the characteristic flavors of roasted nuts but can also lead to the production of acrylamide under certain conditions. Understanding the balance between enhancing sensory quality and retaining nutritional properties is essential for optimizing roasting conditions. Innovative technologies offer sustainable, efficient alternatives to traditional methods. By emphasizing these three major nut varieties, this review provides valuable insights into the changes occurring before and after roasting, highlighting strategies to balance sensory quality and nutritional preservation. Further research is essential to refine these techniques, enabling the production of high-quality nuts that deliver superior health benefits while meeting consumer expectations.

Keywords: Nuts; Roasting; Polyphenols; VOCs; Maillard

1. Introduction

The inclusion of nuts in the diet has significantly increased due to their unique nutritional value, flavour, nutraceutical properties, and abundance of healthy bioactive compounds, including high-quality proteins, dietary fiber, minerals, tocopherols, phytosterols, and phenolic compounds. Moreover, nuts are a good source of many nutrients, such as Monounsaturated, polyunsaturated fatty acids, and micronutrients like vitamins E and K, magnesium, copper, potassium, and selenium [1].

In general, the most commonly consumed tree nuts worldwide include almonds (*Prunus amygdalus* Batsch), Brazil nuts (*Bertholletia excelsa* Humb. & Bonpl.), cashews (*Anacardium occidentale* Linnaeus), hazelnuts (*Corylus avellana* Linnaeus), macadamias (*Macadamia integrifolia* F. Muell), pecans (*Carya illinoensis* Wangenh), pine nuts, pistachios (*Pistacia vera* Linnaeus), and walnuts (*Juglans regia* Linnaeus) [2]. Nuts are consumed as snacks, desserts, or part of meals. Some epidemiological studies have associated nut consumption with a diminished incidence of coronary heart disease and consistently demonstrate that nut intake lowers cholesterol, promotes healthy diets, reduces oxidative stress, inflammation, and improves vascular reactivity. Indeed, it is clear that regular nut consumption has a beneficial effect on many cardiovascular risk factors and may even aid in weight loss [3].

It's well reported that nuts are rich sources of phytochemical compounds. Among these, flavonoids, characterized by a chalcone structure, are a major class. Flavan-3-ols are the most

abundant flavonoids in nuts, followed by flavonols and anthocyanins [4]. Chlorophylls and carotenoids are pigments that contribute to the color of nuts, including pistachios. Monitoring these pigments can help control the roasting process. The green color of pistachios is primarily due to the presence of chlorophyll. However, during roasting, this vibrant green color can fade, transitioning to brown or dark shades. This loss of color can negatively impact consumer perception and ultimately influence product selection [5]

Proanthocyanidins, oligomers of flavan-3-ols such as catechin, epicatechin, and epigallocatechin, are another important class of polyphenols. Stilbenes, characterized by two phenyl groups connected by an ethene bond, are another class of polyphenols with high value in nuts. Resveratrol is the primary example of stilbenes. Another class are represented by phytosterols that are plant-based steroids. In nuts, carotenoids compounds, a class of polyisoprenes, are generally present in low concentrations in nuts, with α -carotene, β -carotene, lutein, and zeaxanthin typically amount in $\mu\text{g}/100\text{g}$ quantities. However, pistachios are an exception, containing higher concentrations of β -carotene and lutein, often measured in $\text{mg}/100\text{g}$ [4].

In general, the nutritional values of nuts can vary depending on the cultivar and harvest year. For this reason, in 2015, Locatelli, and colleagues investigated the possibility of differentiating between Italian and Chilean *Tonda Gentile Trilobata* hazelnuts based on their post-roasting chemometric profiles. This was achieved by the possibility to identifying and comparing specific chemicals markers that could distinguish between the two varieties such as fatty acids profile, presence of polyphenol, antioxidant activity and protein fingerprint [6].

As documented by Gökmen et al. (2017), the outer layer of nuts, particularly the brown skin, is a significant reservoir of phenolic compounds, both in free and bound forms. The predominant phenolic acids identified include caffeic, chlorogenic, coumaric, ferulic, gallic, hydroxybenzoic, protocatechuic, and vanillic acids. Furthermore, nut skins are rich in flavonoids, such as quercetin, catechin, and epicatechin [7].

The presence of PUFAs, MUFAs, phytochemical compounds, and dietary fiber in nuts can positively influence glucose homeostasis in healthy, pre-diabetic, diabetic, and obese individuals. Additionally, the high content of prebiotic compounds in nuts can help prevent metabolic syndrome and weight gain. The antioxidant properties, phytochemical compounds, and high levels of PUFAs in nuts also contribute to positive effects on lipid homeostasis, obesity, hypercholesterolemia, and blood pressure. These factors can also improve endothelial function and help prevent cardiovascular disease. The high levels of tocopherols and phenolic compounds, with their potent antioxidant and anti-inflammatory properties, can moderate and control oxidative processes [8]. These factors combined make nuts a health-promoting food.

Typically, nuts can be eaten whole (fresh or roasted), used in spreads like peanut butter or almond paste, or incorporated into commercial products [3].

Roasting is a thermal processing technique that involves the application of dry heat to raw nuts, leading to significant changes in their physical and chemical properties. These changes include improved digestibility, enhanced palatability, and increased bioavailability of nutrients. Additionally, roasting can enhance the sensory attributes of nuts, such as color, aroma, and flavor, as well as their antioxidant properties [9].

In general, roasting involves an intense temperature treatment, where food is heated at temperatures between $150\text{ }^{\circ}\text{C}$ and $300\text{ }^{\circ}\text{C}$ in an oven. The roasting process comprises three distinct phases: drying, roasting and colour/flavour generation. The first phase is characterized by a temperature increase to around $160\text{ }^{\circ}\text{C}$, inducing water vaporization and moisture loss. Subsequently, the roasting phase begins at $190\text{ }^{\circ}\text{C}$, triggering chemical changes such as hydrolysis, oxidation, reduction, and other pyrolytic reactions, leading to the formation of aroma, flavour, and colour components [9].

To optimize roasting conditions, ensure uniform heating, and prevent product degradation, high-efficiency roasting technologies have been developed. Common equipment includes heat conduction, hot air, rotary drum, and continuous roasters [10].

This review aims to comprehensively examine the impact of traditional and innovative roasting technologies on the nutritional composition, bioactive compound profile, aroma, and flavor attributes of hazelnuts, almonds, and pistachios.

2. Nutrition Profile in Hazelnuts, Almonds and Pistachio

2.1. Hazelnuts

Worldwide, numerous hazelnut varieties exist due to differences in growth environments, and each geographical region imparts specific nutritional and taste characteristics. European hazelnut (*Corylus avellana* L.) has the most cultivars. Among them, Italian cultivars such as *Tonda di Giffoni* and *Tonda Gentile delle Langhe* have been awarded the European Protected Geographical Indication (PGI) label [11].

In general, nuts are rich sources of proteins and essential and non-essential amino acids, as indicated by the USDA National Nutrient Database for Standard Reference. Specifically, hazelnuts typically contain between 14 and 15 grams of protein per 100 grams of product, with glutamic acid (3.7%), arginine (2.2%), aspartic acid (1.7%), and leucine (1.1%) as main amino acids [12].

Although the amino acid profile can vary significantly depending on the variety and location of cultivation, these compounds can influence several attributes, including taste, aroma, and colour [13]. Köksal et al. (2006) reported that hazelnuts cultivated in Turkey contain 2.322 g/100g of arginine, 1.271 g/100g of leucine, and 1.475 g/100g of glutamic acid as non-essential amino acids [12].

Hazelnuts are characterized by a high fat content, exceeding 60-70%. The lipid profile of hazelnuts is dominated by monounsaturated fatty acids (MUFAs), with oleic acid as the primary component, accounting for approximately 80% of the total fatty acid content. Polyunsaturated fatty acids (PUFAs), primarily linoleic acid, constitute the second major lipid fraction (13%). Palmitic, stearic, and palmitoleic acids are also present in significant amounts. The ratio of unsaturated to saturated fatty acids is approximately 13:1, while the ratio of polyunsaturated to saturated fatty acids is 1.23:2.87 [12].

Carbohydrates constitute approximately 26% of the total composition, comprising dietary fiber and sugars. Sugars, accounting for 17% of the total carbohydrate content, include disaccharides such as sucrose, stachyose, and raffinose; monosaccharides such as glucose and fructose; and polyols such as myo-inositol. Sucrose is the predominant sugar, comprising over 74% of the total sugar content. The quantity, quality, and composition of sugars directly and indirectly contribute to the sensory profile of hazelnuts, influencing sweetness and serving as fundamental precursors for the Maillard reaction during the roasting process [14].

The levels of niacin, vitamin B1, vitamin B2, vitamin B6, folic acid, and ascorbic acid in hazelnuts are 1.45 mg/100g, 0.276 mg/100g, 0.052 mg/100g, 0.501 mg/100g, 43 µg/100g, and 2.45 mg/100g, respectively. The authors reported that the “Kan” hazelnut variety has the highest levels of folic acid and vitamin B6. Regarding fat-soluble vitamins, the concentrations of retinol, α -, γ -, and δ -tocopherol were found to be 3.25 mg/100g, 24.7 mg/100g, 1.36 µg/100g, and 1.78 mg/100g, respectively [12].

2.2. Almond

Nowadays, the USA is the leading producer of almonds, accounting for nearly 66% of worldwide production, primarily concentrated in California, followed by Spain (Sanahuja et al., 2021).

The lipids in almonds primarily consist of storage lipids, present as intracellular oil droplets in the cotyledon tissues of the kernels. These lipids are predominantly composed of mono- and polyunsaturated fatty acids. Generally, the lipid content in almonds ranges from 44% to 61%, influenced by factors such as local genotype selection, growing region, climatic conditions, and environmental interactions. Numerous studies report that monounsaturated fatty acids predominate, accounting for 62-80% of the oil content, with over 90% composed of oleic acid and linoleic acid. The remaining less than 10% is composed of saturated fatty acids [15]. Sanahuja et al. (2021) reported that unsaturated fatty acids comprise oleic acid (58.1-71.3%), linoleic acid (15.7-29.9%), palmitoleic acid

(0.20-0.62%), and vaccenic acid (0.77-2.17%). In contrast, saturated fatty acids are represented by palmitic acid (5-9.75%), stearic acid (1.0-2.4%), and arachidonic acid (0.07-0.1%) [16].

Polyphenols are concentrated at the lipid-water interface. They are responsible for almond quality, nutritional properties, and increased shelf life. Gas chromatography-mass spectrometry (GC-MS) analysis has identified 0.312 g of polyphenols per 100 g of almonds. These polyphenols include phenolic acids, lignans, isoflavones, stilbenes, and a rich variety of proanthocyanidin polymers, tannins, ellagitannins, gallotannins, and ellagic acid. Different classes of flavonoids have been reported, ranging from 0.02% to 0.4%, including flavanols, anthocyanidins, flavanones, and flavan-3-ols. Minor amounts of galocatechin gallate, epicatechin gallate, and epicatechin glycoside are also present. Flavonols are the most abundant flavonoid class in almonds, ranging from 0.87% to 1.35%, with quercetin being the predominant flavonol (Barreca et al., 2020). The protein content of almonds varies from 14% to 35.1% (w/w) depending on the cultivar. The two major protein fractions are albumins (21%) and globulins (74%). Almond kernels can be considered a high-quality protein source because their amino acid composition is extremely similar to the standard protein profile recommended by the FAO and WHO. Essential amino acids constitute approximately 30% of the total amino acid composition; specifically, almond kernels contain 3.14% threonine, 4% valine, 3.86% isoleucine, 7.47% leucine, and 3.47% lysine [17]. Considering 100 grams of protein, Barreca and colleagues reported that the amino acid composition includes 0.601% threonine, 0.855% valine, 0.751% isoleucine, 1.473% leucine, and 0.568% lysine [18].

Ultimately, almond kernels contain approximately 5.5% carbohydrates and 11.8% dietary fiber, including hemicellulose, cellulose, and lignin [19].

2.2. Pistachio

The pistachio (*Pistacia vera* L.) is an ancient nut, native to the Middle East, and is one of the oldest flowering nut trees eaten since the prehistoric era [20].

Pistachios, like all nuts, are high in fat content (45.3%), primarily composed of mono- and polyunsaturated fatty acids, accounting for 23.3% and 14.4%, respectively. Saturated fatty acids constitute a smaller portion, at 5.9% [21]. Among fatty acids, oleic acid is the primary monounsaturated fatty acid, followed by linoleic acid, together constituting more than 60% of the total fatty acids [22].

Pistachios are also a valuable source of vegetable protein (21%) (Mateos et al., 2022), with approximately 2% of-arginine (Bulló et al., 2015). The total carbohydrate content is low, while the dietary fiber content is high, primarily insoluble fiber (10%) compared to soluble fiber (1%). Pistachios are also rich in minerals such as magnesium, calcium, potassium (1 g/100g), and phosphorus [22].

Numerous studies have reported that pistachios are the only nut with a significant xanthophyll carotenoid content, such as lutein, which is present at 329 µg/100g [20]. They are also rich in vitamins, including ascorbic acid (5.60 mg/100g) and tocopherol (2.17 g/100g) [22]. Moreover, pistachios are a rich source of phenolic compounds, including anthocyanins, flavonoids, proanthocyanidins, flavonols, isoflavones, flavones, stilbenes, phenolic acids, and hydrolysable tannins. These phytochemical compounds are more concentrated in the skins than in the seeds. For example, the skin contains 5.865 mg/g of cyanidin-3-O-galactoside, 1.453 mg/g of gallic acid, and 0.377 mg/g of catechin. In contrast, pistachio kernels contain 0.0981 mg/g of quercetin-3-O-rutinoside, 0.0691 mg/g of genistein, and 0.047 mg/g of genistein-7-O-glucoside. The green colour of pistachio nuts is attributed to lutein and zeaxanthin, the two major xanthophyll carotenoids [23].

3. Roasting Process

The roasting of nuts is a thermal process that aims to improve the sensory attributes of nuts through a series of physical and chemical reactions, including the Maillard reaction. This process can lead to alterations in various compounds, such as fatty acids, peptides, and vitamins. Significant changes that occur during nut roasting include starch gelatinization and protein denaturation [24]. Moreover, the roasting process can extend the shelf life of nuts by inactivating the oxidative enzyme system and reducing the water activity [25].

However, thermal processing can trigger the formation of thermal pollutants, such as acrylamide, and the degradation of certain phytochemical compounds [26]. During the roasting process, Maillard reactions are responsible for the formation of substances that impart desirable roasted aromas and flavours, such as pyrazines, furans, and pyrroles. These reactions occur between the carbonyl groups of reducing sugars and the amino groups of proteins. Additionally, the loss of moisture during roasting contributes to the development of a crunchy mouthfeel, characterized by hardness, fracture force, and firmness [27].

Macroscopically, roasting triggers the evaporation of water and low-boiling-point organic compounds, leading to the formation of large amounts of gas. This increased internal pressure causes structural changes, such as cell wall breakdown, microporosity formation, increased volume, and reduced density. Several studies on cocoa bean roasting have demonstrated that drying and roasting processes disrupt parenchymal cells [28].

3.1. Hot Air Oven

The common method for roasting almonds involves using hot air roasting at temperatures ranging from 129.5 °C to 154.5 °C for 30 to 10 minutes, respectively, to achieve a light to medium roast [29]. During the roasting process, heat is transferred to the food through two primary mechanisms: convection, involving the transfer of heat by the movement of hot air, and radiation, involving the transfer of heat through electromagnetic waves emitted by the oven walls [30]. Ogundipe et al. (2024) reported different temperature ranges: low temperature (120-140 °C), moderate temperature (140-160 °C), and high temperature (160-180 °C) [26]. For example, hazelnuts can be roasted at 140 °C for 17 minutes or at 170 °C for 10 minutes [31], while almonds are roasted for 5 to 60 minutes at temperatures between 100 °C and 180 °C [32].

Shakerardekani et al. (2011) evaluated the impact of different roasting methods on pistachio kernels, varying temperatures from 90 to 190 °C and times from 5 to 65 minutes. They assessed various parameters, including color, hardness, taste, and moisture content, to optimize pistachio paste production. The study revealed a decrease in kernel hardness from 91 N for pistachios roasted at 70 °C for 35 minutes to 26 N for those roasted at 190 °C for 65 minutes. Concurrently, an increase in brown pigments was observed, consistent with caramelization reactions, as temperature and time increased. Similarly, the moisture content of the kernels decreased with increasing roasting time and temperature. Based on these findings, the researchers concluded that roasting at 134 °C for 35 minutes in a conventional oven, represents the optimal temperature and time settings for pistachio paste production [33].

Hot air roasting, hot pan roasting, and classic industrial oven roasting are basic methods for roasting nuts. These methods are time-consuming, energy-intensive, and have low production efficiency. Additionally, classical hot air roasting systems can over-roast the outer surfaces of nuts while leaving the centres under-roasted [24].

To ensure uniform heating and heat distribution in food samples, new technologies have been developed. One such technology is the hot air circulation oven, which circulates hot air at different velocities ranging from 1 to 3 m/s. In this study, cashew nuts were roasted for 20 minutes at three different temperatures: 110, 130, and 150 °C, using a hot air circulation oven. The roasted nuts were then analyzed and tasted by a sensory panel. The results indicated that this innovative roasting process can significantly impact the quality and flavor of cashew nuts. Optimal results were obtained at 110 and 130 °C, comparable to those achieved with traditional oven roasting at 180 °C for 30 minutes. E-nose and GC-MS analyses confirmed that this innovative technology can trigger the formation of traditional flavor and aroma compounds at lower temperatures compared to traditional roasting processes [34].

In recent years, innovative technologies such as infrared heating, dielectric radio frequency, and microwave processing have emerged as promising methods to optimize the roasting process. In particular, infrared roasting offers several advantages, including reduced processing time, uniform heat distribution, minimal quality loss, compact equipment footprint, and significant energy savings [25,26].

3.2. Infrared Roasting

Technically, infrared radiation (IR) is a form of energy within the electromagnetic spectrum, with wavelengths ranging from approximately 0.75 to 1000 μm , falling between microwaves and visible light. The infrared spectrum is divided into three bands: near-infrared (0.75 to 2 μm), mid-infrared (2 to 4 μm), and far-infrared (4 to 1000 μm). IR roasts food in a different way: the IR energy interacts with the food, penetrates it, and transfers thermal energy in the form of electromagnetic waves, uniformly heating the food mass. An important advantage of using IR technologies for roasting nuts is the ability to better control parameters and select different IR emitters [24].

Bagheri et al. (2019) investigated the impact of infrared roasting on peanut kernels. They varied the IR power between 250 and 450 W and the roasting time between 10 and 30 minutes. Subsequently, they assessed various physical parameters such as moisture content, color, texture, taste, and sensory evaluation. The authors reported a decrease in moisture content with increasing IR power and roasting time. A similar linear relationship was observed for color, with an increase in brown pigments as time and power increased. Conversely, longer roasting times and higher power levels adversely affected the texture of peanuts. This is likely due to the degradation of biomolecules during the roasting process. Infrared roasting presents an effective alternative to conventional roasting methods, offering higher efficiency and reduced pollutant emissions [35].

In hazelnuts, infrared (IR) heating offers the advantage of internal heating, minimizing aroma loss compared to conventional methods. This study investigated two roasting conditions (conventional hot air and infrared) using both low-temperature, long-time and high-temperature, short-time approaches. For conventional hot air roasting, 135 °C for 45 minutes was used for low-intensity roasting, while 195 °C for 27 minutes was used for high-intensity roasting. For infrared roasting, the conditions were 135 °C for 40 minutes and 195 °C for 20 minutes, respectively. After roasting, paste and oil were produced to assess the impact of different roasting methods on the final products. The antioxidant profile, electronic nose (E-nose) fingerprint, acidity, peroxide value, and fatty acid composition were analysed. Results indicated that low-intensity infrared roasting was less destructive to antioxidant activity, likely due to the preservation of polyphenols. E-nose analysis revealed that infrared-roasted hazelnuts were perceived as having more intense flavours, likely due to reduced aroma loss [36].

3.3. Radio Frequency Roasting

Radio frequency (RF) heating utilizes electromagnetic fields with frequencies ranging from 13 to 40 MHz to volumetrically heat food products. This heating process leverages the dielectric and thermal properties of food materials. When exposed to an alternating electric field, the molecules within the food undergo thermal and electrical reactions, generating heat. Specifically, ions migrate towards opposite poles (protons to the anode, electrons to the cathode), and dipole molecules, such as water, rotate rapidly in response to the oscillating magnetic field. The friction generated by these molecular motions results in heat generation throughout the food material [37].

RF heating penetrates deeper into food products compared to microwave heating due to its longer wavelength. This enables more uniform heat distribution and the processing of larger food items. Moreover, the direct interaction between electromagnetic energy and food can significantly reduce processing time, eliminate harmful bacteria, and enhance sensory and nutritional qualities. For these reasons, RF heating is employed in various food processing applications, including meat cooking, bread baking, and vegetable dehydration. Additionally, RF technology can be used to inactivate microorganisms and enzymes, extending the shelf life of food products [38].

In contrast to microwave ovens, RF ovens utilize longer wavelengths. RF technology can be integrated with conventional ovens to create hybrid systems, such as hot air-assisted RF ovens. In this study, a 12 kW, 24 MHz RF oven was combined with a hot air system to roast cashew nuts at 120 °C and 130 °C for 30 minutes, with an electrode gap of 8 cm. For comparison, conventional hot air roasting was performed at 140 °C for 33 minutes. The resulting products were evaluated for flavour, taste, and composition. GC-MS analysis of aroma and flavour profiles revealed no significant differences between the two roasting methods. Both techniques produced similar levels of pyrazines

and aldehydes. However, RF roasting resulted in lower furan content and higher ketone and terpene concentrations compared to conventional hot air roasting [39].

Another application of radio frequency roasting has been investigated for coffee beans. A 27 MHz, 6 kW radio frequency system was employed in conjunction with a 48 °C hot air system and continuous agitation to ensure homogenic heating. This method was applied to disinfect coffee beans post-harvest without compromising product quality [40].

3.4. Microwave Roasting

Another alternative method to traditional roasting is microwave energy. This method is currently used for various food heating processes because microwaves can penetrate food, accelerating the heating process and resulting in improved roasting quality and taste [41].

The fundamental physical principle governing these technologies is a simple relationship between microwave wavelength and frequency (oscillations of the electric field per second). Another crucial factor is the capacity of materials to absorb microwave energy, a property known as dielectric heating. The ability of molecules to align with an electric field is influenced by their dipole moment and mobility. Molecules possessing a permanent dipole moment can orient themselves, either fully or partially, with an external electric field through rotational motion. In gaseous or liquid phases, molecules can rotate in synchrony with field frequencies up to 10^6 Hz. However, they cannot indefinitely follow rapid field reversals, resulting in phase shifts and dielectric losses. This phenomenon depends on both the dielectric coefficient (permittivity) and the size (mass) of the molecules. As field energy is transferred to the medium, electrical energy is converted into kinetic or thermal energy. A common model for this process is molecular friction. Numerous polar substances exhibit dielectric losses within the microwave frequency range [42].

Upon penetration of food by microwaves, the electromagnetic field triggers water molecules and other molecules to vibrate, oscillate, and rub against each other, generating heat. This process generates water vapor, which is forced out of the food, leading to a high degree of selective drying [43].

Milczarek et al. (2014) applied an innovative microwave oven to roast almonds. Their oven was equipped with a stirring paddle, enabling continuous mixing of the almonds during the roasting process. The oven had a nominal power of 1300 W. The roasting conditions applied in this study were as follows: light roasting: 50% power for 105 seconds, followed by 60% power for 45 seconds, mimicking light roasting in a hot air oven system, medium roasting: 70% power for 148 seconds and dark roasting: 60% power for 54 seconds, followed by 70% power for 126 seconds. These methods corresponded to power outputs of 231 W, 608 W, and 773 W, respectively. After microwave roasting, the authors conducted various sensory analyses. The results indicated that microwave roasting produced almonds with similar flavor and crunchiness to those roasted in a hot air oven. To achieve comparable results, the following power inputs were required: light roasting: 0.8 W/g for 150 seconds. medium roasting: 0.9 W/g for 148 seconds and for dark roasting: 0.91 W/g for 180 seconds [44].

Alicia et al. (2014) studied the differences in roasting results for peanuts using various conditions. Traditional oven roasting was conducted at temperatures of 135, 163, 177, and 204 °C for 5 to 20 minutes, while microwave roasting was performed for 1 to 3 minutes. After roasting, the researchers evaluated color, flavor, and moisture content. They reported no significant differences in color and flavor between peanuts roasted using microwave or traditional oven methods [45].

However, it was observed that microwave energy was inadequate to trigger Maillard reaction, which is necessary for the formation of desirable volatile flavour compounds such as aldehydes [46].

4. Role of Maillard Reaction on Production of Volatile Organic Compounds

The Maillard reaction (MR) is a complex, non-enzymatic browning reaction that occurs between the amino groups of amino acids, peptides, or proteins and the carbonyl groups of reducing sugars, such as glucose, fructose, and lactose, or other carbonyl-containing compounds, including lipid degradation products. This reaction is induced when the food matrix reaches high temperatures. Also, the reaction products, the final flavour and taste profiles, are influenced by multiple factors,

including water activity, pH, lipid degradation products, and the specific types of amines and carbohydrates involved [47].

The MR is typically divided into three stages.

The first stage involves a condensation reaction between an amino group and a reducing sugar [48]. The nucleophilic addition reaction occurs between these two chemical compounds, resulting in the formation of a Schiff base [49]. The formation of Schiff bases can also occur at room temperature [50]. Schiff bases can be aldosylamine if derived from an aldose sugar or ketosylamine if derived from a ketose [51]. Subsequently, if the reducing sugar is an aldose, an N-glycosylamine is formed, which subsequently rearranges into an Amadori compound. However, if the amino group reacts with a ketose sugar, Heyns rearrangement products are formed [48]. However, after undergoing several reactions, including isomerization, dehydration, hydrolysis, elimination, and condensation, the first stage ultimately yields 5-hydroxymethylfurfural (HMF) [50].

The intermediate stage starts when the food matrix are heated [51], then, starts from Amadori or Heyns products, leading to sugar fragmentation and the release of the amino group [48]. This reaction can lead to various reactions, including fragmentation, cyclization, and Strecker degradation, resulting in the formation of aldehydes, ketones, dicarbonyls, and heterocyclic compounds. Amadori and Heyns products are the first stable products of the MR, and their subsequent degradation products determine the development of flavour, aroma, colour, and taste in food products [49]. In this stage, lipids play a fundamental role in the release of aroma molecules. It is well-known that the type and quality of lipids can generate aroma through the production of organic volatile compounds. These compounds are released during the breakdown of fatty acid macromolecules. For example, aldehydes generated from lipid oxidation can interact with MR products at various stages of the roasting process, leading to the formation of pyrazines, thiophenes, pyridines, oxazoles, and thiazoles. Another example of aroma formation involves the Strecker degradation of amino acids, phenolic compounds and lipid oxidation, which can lead to the production of aldehydes. These aldehydes can then react with MR products to form intermediates that subsequently break down, releasing flavor compounds [52]. During baking process of malt, in the intermediate phase of the MR, are generated various volatile organic compounds such as maltol, phenylacetaldehyde, 2-furan methanol, HMF, and acetic acid. If the temperature exceeds over 200 °C, pyrazines and other nitrogen-containing heterocyclic compounds are released [50]. For example, pyrazines are among the most important volatile organic compounds that contribute to the aroma of products. They are monocyclic aromatic rings containing two nitrogen atoms in the para position. These compounds are formed from nitrogen atoms originating in amino acids and carbon atoms derived primarily from fructose rather than glucose [53]. It is well reported that pyrazines are key aroma compounds in roasted almonds, furthermore, Agila et al. (2012) reported high concentrations of dimethylpyrazine, trimethylpyrazine, and 2-methylpyrazine in roasted almonds [54].

The third stage involves several reactions, such as dehydration, fragmentation, cyclization, and polymerization. The amino group commonly involved in the first stage of the MR is the ϵ -amino group of lysine in peptides or single amino acids. Protein cross-linking occurs, and brown pigments become covalently attached to the protein (Van Boekel, 2006). The brown pigments are formed through the polymerization of cross-linked melanoidins, also known as “advanced glycation end products” (AGEs). These compounds also contribute to the sensory quality of food [49,50].

Furthermore, during the Maillard reaction, reducing sugars can react with free amino acids present in the food matrix. After a series of reactions, including Schiff base formation through the nucleophilic attack between short-chain sugars and the α -amine of asparagine, and Amadori rearrangement, the final product can be acrylamide [55].

In almond samples, acrylamide formation is significantly higher between 145 °C and 180 °C than at 200 °C. Acrylamide formation can occur as early as 165 °C after only five minutes, with a linear increase observed between 7.5 and 15 minutes. Light roasting leads to moderate acrylamide levels of approximately 300 $\mu\text{g/kg}$, while strong roasting at 165 °C can result in levels near 1500 $\mu\text{g/kg}$. The authors observed that the presence of free asparagine in almonds is a key factor in acrylamide

formation. Additionally, almond cultivars and geographical origin influence the levels of free asparagine and, consequently, acrylamide formation [56].

5. Aroma Profile on Nuts Product After and Before Roasting Condition

As reported previously, fatty acids, carbohydrates, and free amino acids are the primary precursors of aroma compounds in nuts. Fatty acids, in particular, can undergo oxidation to form aldehydes and alcohols. Hexanal, a product of linoleic acid oxidation, is one of the most abundant aldehydes. Other important aldehydes, such as nonanal, are derived from oleic acid degradation. Additionally, linoleic and oleic acids can undergo decarboxylation to form α -keto acids, which subsequently yield aldehydes like 3-methylbutanal and 2-methylbutanal, as well as various alcohols. Aromatic amino acids, such as phenylalanine, can undergo decarboxylation to form 2-phenylethanol and phenylacetaldehyde, contributing to floral aromas. Terpenoids, including limonene and linalool, contribute to the characteristic fresh fruit aroma of nuts [57].

Notably, lipids are responsible in generation of flavor to enhance the taste of the roasted products. In general, the lipids oxidation is attributed to the deterioration of food matrix due to the generation of off-flavors. However, during roasting condition, the oxidation of lipids can trigger the development of pleasant aromas. Lipid oxidation can proceed through multiple pathways, including autoxidation, photooxidation, thermal oxidation, and non-enzymatic oxidation. The major compound resulting from lipids oxidation are aldehydes characterizing to low odor threshold and higher concentration. In raw food matrix, in presence of oxygen, the major reaction is the auto oxidation, that occurs in three different stages: initiation; propagation; and termination. In the initial stage, the triplet oxygen is activated to light, temperature, metal ion (Fe^{2+} and Cu^{2+}) in singlet oxygen and produces reactive oxygen species (ROS), able to interact whit unsaturated fatty acids. After the initial stage, the ROS starts to oxidate several fatty acids and extend their degradation process, this phase is called propagation. Subsequently, the formation of primary oxidation products, such as lipid hydroperoxides, dienes, and trienes, occurs. These primary products can undergo further degradation to yield secondary oxidation products, including aldehydes, ketones, alcohols, hydrocarbons, epoxides, and organic acids. One example of oxidase processing start from linoleic acids that produce 9- and 13-hydroperoxides and various volatile compounds such as 2,4-decadienal, 2-octenal and hexanal [52]. Several studies reported that linoleic (18:2) and oleic acids (18:1) account for approximately 97% of the total fatty acids in Iranian bitter almond oil, and in general in other nuts family. These fatty acids are likely precursors to hexanal and (E)-2-hexenal, which contribute to the green note aroma, through the action of lipoxygenase and hydroperoxide lyase enzymes [58]. The reaction between Maillard reaction intermediates and lipid oxidation products, particularly aldehydes, can lead to the formation of a diverse range of aroma compounds, including pyrazines, thiophenes, pyridines, oxazoles, and thiazoles with various alkyl side chains. However, these interactions often result in compounds with higher odor thresholds, leading to a weaker overall aroma intensity [52]. Comparison of the major aromatic molecules present in raw and roasted hazelnuts, almonds, and pistachios is presented below (Table 1).

Table 1. main detectable volatile organic compounds in raw and roasted nuts.

NUTS	Main VOCs	Reference
Raw hazelnuts	• Hexanal (1,790 to 2,780 $\mu\text{g/g}$)	[14,59,60]
	• 2-Pentanone (1,603 $\mu\text{g/g}$)	
	• 2-Pentanol (1,509 $\mu\text{g/g}$)	
	• (E)-3-Penten-one (8,32 $\mu\text{g/g}$)	
	• 3-Methyl-1-butanol (0,482 $\mu\text{g/g}$)	
	• 1-Pentanol (0,344 $\mu\text{g/g}$)	
	• 2,3,5-Trimethylfuran (0,259 $\mu\text{g/g}$)	
	• Nonanal (0,203 $\mu\text{g/g}$)	
	• Acetic acid (0,310 $\mu\text{g/g}$)	

	• Linalool (0,280 µg/g) • Octanal (0,163 µg/g) • 5-Methyl-4-heptanone (0,059 µg/g) • 3-Methylbutanal (0,034 µg/g)	
Roasted hazelnuts	• 2-Methylpropanal (2,517 to 4,8 µg/g) • 3-Methylbutanal (0,027 to 6,6 µg/g) • Hexanal (1,540 µg/g) • 2-Pentanone (2,7 µg/g) • α-Pinene (0,598 µg/g) • 1-Cyclopentyl ethenone (1,5 µg/g) • 1-Pentanol (0,68 µg/g) • 2-Pentylfuran (0,120 µg/g) • (E)-2-Penten-2-one (2,2 µg/g) • 3-Methyl-1-butanol (4,9 µg/g) • 2,3,5-Trimethylfuran (1,5 µg/g) • Methylpyrazine (1,18 µg/g) • 4-Hydroxy-2,5-dimethyl-3(2H)-furanone (1,7 µg/g) • (E,E)-2,4-Decadienal (1,6 µg/g) • Octanal (1,4 µg/g) • (Z)-2-Nonenal (1,2 µg/kg) • Acetic acid (0,9 µg/g)	[14,59–61]
Raw almond	• Benzyl alcohol (6.74 µg/g) • 1-Octanol (0.9 µg/g) • Phenylethyl alcohol • Hexanal (0,4 - 0.69 µg/g) • Nonanal, 3-methyl-1-butanol (18.43 µg/g) • Vanillin (0.83 µg/g) • Acetic acid (0.137 µg/g) • Butanal (9 ng/g) • 2,3-Butanedione (8 ng/g) • 3-Methylbutanal (32 ng/g) • 1-(Methylthio)-2-propanol (12 ng/g)	[62,63]
Roasted almond	• Hexanal (1.1 to 6.39 µg/g) • Phenylacetaldehyde (0.571 µg/g) • 3-Methylbutanal (0.319 µg/g) • HDMF (1.180 µg/g) • Benzaldehyde (240 µg/g) • Limonene (3.39 µg/g) • Benzyl alcohol (1.09 µg/g) • 1-Pentanol (4.59 µg/g) • 3-Methyl-1-butanol (13.79 µg/g) • Butanal (40 ng/g) • 2,3-Butanedione (226 ng/g) • 3-Methylbutanal (4.27 µg/g) • Furfural (460 ng/g) • 1-(Methylthio)-2-propanol (325 ng/g) • 2-Methylpyrazine (26 ng/g) • 2,6-Dimethylpyrazine (4 ng/g) • Trimethylpyrazine (6 ng/g) • 2,5-Dimethylpyrazine (11 ng/g to 66 ng/g)	[62–64]

Raw pistachios	•	α -Pinene (1.68 to 333 $\mu\text{g/g}$)	[65–67]
	•	Nonanal (0.63 $\mu\text{g/g}$)	
	•	1-Methylpyrrole (48 $\mu\text{g/g}$)	
	•	Acetic acid (3.3 $\mu\text{g/g}$)	
	•	Hexanal (9.1 $\mu\text{g/g}$)	
	•	Hexanol (1 $\mu\text{g/g}$)	
	•	β -Pinene (6.5 $\mu\text{g/g}$)	
	•	Limonene (1 $\mu\text{g/g}$)	
Roasted pistachios	•	Benzyl acetate (1.8 $\mu\text{g/g}$)	[68–70]
	•	α -Pinene (2.4 to 3 $\mu\text{g/g}$)	
	•	Limonene (3.5 to 4.96 $\mu\text{g/g}$)	
	•	Nonanal (0.86 $\mu\text{g/g}$)	

5.1. Hazelnuts

A total of 39 compounds contributing to the characteristic aroma of raw Turkish hazelnuts were identified. These compounds were categorized as ketones, aldehydes, alcohols, aromatic hydrocarbons, and furans. The most abundant compounds were hexanal (2780 $\mu\text{g/Kg}$), 2-pentanone (1603 $\mu\text{g/Kg}$), 2-pentanol (1509 $\mu\text{g/Kg}$), (E)-3-penten-one (832 $\mu\text{g/Kg}$), 3-methyl-1-butanol (482 $\mu\text{g/Kg}$), 1-pentanol (344 $\mu\text{g/Kg}$), and 2,3,5-trimethylfuran (259 $\mu\text{g/Kg}$) [59]. Furthermore, Squara et al. (2022) reported associations between specific molecules and aroma qualities in various hazelnut varieties. For instance, hexanal was linked to green aromas, while 3-methylbutanal and 2-methylbutanal were associated with malty notes. Caramel aromas were connected to 2-acetyl-1,4,5,6-tetrahydropyridine and 2-acetyl-3,4,5,6-tetrahydropyridine, and 3-methyl-4-heptanone was linked to fruity notes [14]. Burdack-Freitag et al. (2012) identified several odor-active compounds in raw Italian hazelnuts, including hexanal (1790 $\mu\text{g/Kg}$), acetic acid (310 $\mu\text{g/Kg}$), linalool (280 $\mu\text{g/Kg}$), octanal (163 $\mu\text{g/Kg}$), 5-methyl-4-heptanone (59 $\mu\text{g/Kg}$), and 3-methylbutanal (34 $\mu\text{g/Kg}$), along with other trace of VOCs [60].

After the roasting process, the hazelnut volatile profile undergoes significant changes. Some existing molecules are enhanced through various reactions. Additionally, non-enzymatic reactions can lead to the formation of new molecules, contributing to the characteristic aroma of roasted products, often described as coffee-like or popcorn-like. [14]. Alasalvar et al. (2023) reported the presence or the increases of several volatile compounds in roasted hazelnuts that were not detected in raw samples. These compounds included 2-methylpropanal (4875 $\mu\text{g/kg}$), 3-methylbutanal (27,445 $\mu\text{g/kg}$), 2-pentanone (2772 $\mu\text{g/kg}$), α -pinene (598 $\mu\text{g/kg}$), and 1-cyclopentyl ethenone (1562 $\mu\text{g/kg}$), as well as numerous other minor compounds. While, other compounds, are found in minor quantity such as hexanal (2517 $\mu\text{g/kg}$), 2-methylbutanal, 2-ethyl-5-methylfuran and xylene [59]. 5-methyl-2-hepten-4-one are identified as major ketone that contributes to typical roasty aroma of hazelnuts [61].

Burdack-Freitag et al. (2012) conducted a comprehensive analysis of the volatile organic compound (VOC) profile of roasted hazelnut paste. The study identified several key VOCs, including 3-methylbutanal, 4-hydroxy-2,5-dimethyl-3(2H)-furanone, (E,E)-2,4-decadienal, hexanal, octanal, (Z)-2-nonenal, and acetic acid. Furthermore, the authors proposed that the initial amino acid composition of raw nuts can significantly impact the formation of aroma compounds during the roasting process [60].

One of the most important classes of compounds released during the roasting process is pyrazines. Exclusively detected in roasted hazelnuts, pyrazines can reach concentrations of 4608 $\mu\text{g/kg}$. The most abundant pyrazines include 2,5-dimethylpyrazine, methylpyrazine, and 2-ethyl-5-methylpyrazine. As previously reported, pyrazines contribute to the roasty and sweet flavour profile. Similar to pyrazines, furans are also detected at high levels exclusively in roasted hazelnuts. The most common furans include 2-ethyl-5-methylfuran and 2,3,5-trimethylfuran. Unfortunately, these two compounds are odourless. Other compounds found only in roasted hazelnuts are pyrroles, which contribute to a burnt aroma. Pyrazines, furans, and pyrroles are exclusively found in roasted hazelnuts because they are formed during the Maillard reaction [59].

5.2. Almond

In raw almonds are been detected different family of compounds such as alcohols, aldehydes, benzaldehyde, organic acid, terpenes, sulphur compounds and some pyrazines [64]. The cultivar of almonds can significantly influence the quantity and quality of volatile compounds. For instance, the *Ferragnès* cultivar exhibits a total VOCs content of 19.9 µg/g, while the *Bonita* cultivar has a VOC content of approximately 110 µg/g. Furthermore, the predominant compounds in *Ferragnès* are alcohols, whereas aldehydes are more prevalent in *Bonita*. However, certain compounds, such as benzyl alcohol (6.74 µg/g), 1-octanol (0.9 µg/g), phenylethyl alcohol, hexanal (0.69 µg/g), nonanal, 3-methyl-1-butanol (18.43 µg/g), and benzaldehyde, are commonly found across all cultivars [71]. Another study conducted by Cadwallader et al. (2017) on raw almonds identified vanillin (0.83 µg/g), acetic acid (0.137 µg/g), and trace amounts of 2-acetyl-1-pyrroline [62].

Similar to hazelnuts, the roasting process significantly alters the profile of compounds responsible for the aroma and flavour of almonds. Cadwallader, after roasting almonds at 165 °C for 15 minutes, identified several molecules absent in raw almonds. For example, the Maillard reaction and other non-enzymatic reactions can trigger the synthesis or enhancement of compounds such as hexanal (1.650 µg/g), phenylacetaldehyde (0.571 µg/g), 3-methylbutanal (0.319 µg/g), and HDMF (1.180 µg/g) [62]. Other study reported the VOCs found in roasted almonds, that include hexanal (6.39 µg/g), benzaldehyde (240 µg/g), limonene (3.39 µg/g), benzyl alcohol (1.09 µg/g), 1-pentanol (4.59 µg/g), and 3-methyl-1-butanol (13.79 µg/g) [71]. Furthermore, Francklin et al. (2019) identified 2-pentylfuran, 5-methylfurfural, furfural, 2,3-butanedione, 2,3,5-trimethylpyrazine, 2,6-dimethyl-3-ethylpyrazine, 2-ethylpyrazine, 1H-pyrrole, 2-acetylpyrrole, methional, and other compounds [64].

Xiao et al. (2014) reported that lipid decomposition during almond roasting at 138 °C, ranging from light roasting (28 minutes) to dark roasting (38 minutes), increased the emission of several volatile compounds. These compounds were detected using HS-SPME GC/MS analysis. The authors observed significant increases in various compounds in roasted almonds compared to raw almonds. For example, butanal levels increased from 19 ng/g in raw almonds to 40 ng/g in dark-roasted almonds. Other notable increases included 2,3-butanedione (from 8 to 226 ng/g), 3-methylbutanal (from 32 to 4268 ng/g), furfural (from 0 to 460 ng/g), hexanal (from 422 to 1140 ng/g), and 1-(methylthio)-2-propanol (from 12 to 325 ng/g). Furthermore, the study highlighted a significant rise in pyrazine compounds during roasting. The authors identified seven classes of pyrazines, including 2-methylpyrazine (increased to 26 ng/g), 2,6-dimethylpyrazine (from 0 to 4 ng/g), trimethylpyrazine (from 0 to 6 ng/g), and 2,5-dimethylpyrazine (from 11 to 66 ng/g) [63].

5.3. Pistachios

A total of 39 compounds were identified in raw pistachios, encompassing a diverse range of chemical classes, including carbonyl compounds, terpenes, alcohols, phenols, furanic compounds, pyrazines, pyrroles, lactones, acids, and phenolic and benzene derivatives. These compounds were detected in varying concentrations in both raw and roasted pistachios. While five pyrazines, including methylpyrazine, trimethylpyrazine, and 2-ethyl-5-methylpyrazine, were found in raw pistachios, 16 pyrazines were detected in roasted pistachios [65]. Other compounds identified in raw pistachios are α -pinene (in concentrations of 1.68 µg/g), limonene (1.17 µg/g) and nonanal (0.63 µg/g) [32]. Noguera-Artiga et al. (2019) reported that α -pinene (333 µg/g) and 1-methylpyrrole (48 µg/g) were the most detectable compounds. Other compounds detected include acetic acid (3.3 µg/g), hexanal (9.1 µg/g), hexanol (1 µg/g), β -pinene (6.5 µg/g), limonene (1 µg/g), benzyl acetate (1.8 µg/g), and other trace compounds [66].

Sonmedzdag et al. (2018) conducted a comprehensive analysis of the volatile compound profile of pistachio oil extracted via solvent-assisted flavor evaporation. The study identified 43 classes of compounds, including terpenes, acids, aldehydes, alcohols, esters, phenols, pyrazines, pyrroles, and others. The most abundant compounds were found to be α -pinene, myrcene, hexanal, hexanol, β -pinene, limonene, and acetic acid [67].

The roasting process significantly enhances the intensity of aroma compounds compared to raw pistachios. Hojjat et al. (2012) studied Iranian pistachios and found that α -pinene (3.06 µg/g),

limonene (4.96 µg/g), and nonanal (0.86 µg/g) were the most abundant compounds [32]. Additionally, Rodriguez et al. (2015) identified hexanal, pentanal, benzaldehyde, and (E)-2-pentenal, which are derived from the Strecker degradation, along with other compounds such as short-chain acids and lactones [65]. Hojjat et al. (2015) found that limonene (3.49 µg/g) was the most abundant compound after microwave roasting. α -Pinene (2.38 µg/g) was the second most abundant, followed by nonanal, camphene, phenylacetaldehyde, and others in lower concentrations [68]. Gogus et al. (2011) reported a positive correlation between roasting time and the number of volatile organic compounds (VOCs) in pistachios at a constant temperature of 200°C. The number of VOCs increased from 32 at 0 minutes to a peak of 106 at 20 minutes, followed by a slight decrease to 104 at 25 minutes. Pyrazine levels exhibited a significant increase after 15 minutes of roasting, reaching a maximum of 3.7% at 20 minutes. 5-Methylfurfural levels steadily increased throughout the roasting process, reaching 5% at the end. However, furanones constituted a relatively small proportion of the total VOCs, accounting for only 15%. Regarding terpene compounds, limonene decreased from 9% to 5%, β -pinene decreased from 5% to 2%, and α -pinene decreased from 10% to 4%. In contrast, xylene and furfural increased from 0% to 1.7% and 1.8%, respectively, while pyrrole increased from 0% to 1.8% [69].

6. Effects of Roasting on Polyphenol Content

Polyphenols possess various beneficial properties for human metabolism. These properties are attributed to their antioxidant, anti-inflammatory, neuroprotective, and anticancer effects. Chemically, polyphenols contain one or more aromatic rings bearing one or more hydroxyl groups. They are synthesized through the secondary metabolism of plants. Generally, polyphenols are unstable during food processing methods. This instability arises from their reactivity with other molecules and their susceptibility to epimerization and oxidation when exposed to alkaline conditions, heat, and oxygen [72].

During the cocoa drying process, elevated temperatures negatively impact the polyphenol profile, reducing their content due to oxidative and heat damage. Another factor influencing polyphenol degradation is moisture, as water can dissolve these compounds and subsequently drag them to the surface [73].

Analogous for the cocoa, the profile of bioactive compounds in coffee bean depends on roasting parameters, that range from 160 to 240 °C for 8 to 24 minutes. The content of polyphenols on coffee beans decreases through the roasting process, this is attributed to degradation of chlorogenic, malic and citric acid that influence the antioxidant activity. Moreover, other two things that can trigger the presence and the degradation of polyphenol are the cultivation method and the storage period. The organic harvesting can lead 0.7% of total polyphenol to the conventional method; while the storage period can deteriorate until 83% for organic coffee and 82% for conventional coffee after one years of storage [74].

Nevertheless, in contrast to previous studies, the thermal process of roasting evaporates intracellular water, initiating a series of chemical and physical reactions within the cell structure. These reactions, including the degradation of lignocellulose and proteins, result in increased availability of polyphenolic compounds in nuts. This ultimately enhances their antioxidant activity and facilitates their extraction from the matrix [75].

Alternatively, Bagheri et al. (2016) investigated the impact of different roasting conditions, including conventional, infrared, and hybrid methods, on peanut kernels. Their study revealed an increase in phenolic compounds after roasting. This increase was attributed to the Maillard reaction, which can synthesize compounds with phenolic structures, such as furans and pyrroles. These compounds may contribute to enhanced antioxidant activity and increased total phenolic content [76].

6.1. Hazelnuts

The polyphenol content in hazelnuts is primarily influenced by variety, harvest conditions and geographical origin. Pelvan et al. (2012) studied seven different Turkish hazelnut varieties and reported that total polyphenols can amount between 178 and 727 mg GAE/100 g. After roasting

process, achieved at 140 °C for 30 min, the same authors observed a decrease in phenolics, ranging from 50 to 195 mg GAE/100 g. Furthermore, the scientists measured the loss of antioxidant capacity before and after the roasting process, finding a decrease ranging from 25.3% to 71.7% depending on the cultivar. Similarly, the percentage of tannins decreased significantly, with losses reaching approximately 75.2% [77]. The decrease in phenolic compounds after roasting can be attributed to the removal of the perisperm, the brown skin that envelops the seed. This leads to a decrease in antioxidant activity. As we well know that the perisperm is a significant source of polyphenols, containing levels over 40 times higher than the kernels [78]. Lucchetti et al. (2018) reported that removing the skin can decrease the amounts of phenolics by 59-79% compared to hazelnuts with skin. Furthermore, the TPC ranged from 1,516 mg/g in raw hazelnuts with skin to 0,315 mg/ whit out, from 1,702 mg/g in roasted hazelnuts with skin to 0,691 mg/g in roasted nuts without skin. [79]. Conversely, some authors have reported an increase in soluble phenolics and a decrease in condensed phenolic acids after the roasting process; resulting with higher phenolic compounds compared to raw hazelnuts [80]. In summary, it is difficult to directly compare phenolic content between raw and roasted hazelnuts. For this instance, Marzocchi et al. (2017) revealed that hazelnuts roasted at low temperatures (130 °C for 40 minutes) exhibited lower phenolic compounds levels compared to those roasted at higher temperatures (160 °C for 30 minutes), with an approximate difference of 49%. This difference can be attributed to the potential of high temperatures to disrupt the food matrix, releasing bound polyphenols and making them more readily extractable and quantifiable [61].

6.2. Almond

Lin et al. (2016) investigated the effects of three different roasting conditions (150 °C, 180 °C, and 200 °C for 5, 10, and 20 minutes, respectively) on almonds. They compared the phenolic compounds of these roasted almonds to raw almonds, which contained 7.5 mg GAE/g. Contrary to expectations, an increase in phenolics was observed in all three temperature groups after 20 minutes of roasting. Specifically, the concentration increased to 6.6 mg GAE/g at 150 °C, 13.9 mg GAE/g at 180 °C, and 19.21 mg GAE/g at 200 °C [81]. As mentioned previously, Oliveira et al. (2020) reported an increase in polyphenol levels in almonds after the roasting process compared to raw almonds. This observation is attributed to the increased extractability of polyphenols. Moreover, the variation in polyphenols after roasting can also be influenced by the cultivar. For instance, the *Molar* cultivar experienced a 58% decrease of the antioxidant compounds after roasting, while the *Refêgo* cultivar showed a 72% decrease. These findings contradict the general trend of increased polyphenols observed in roasted almonds [82].

Similar to hazelnuts, the majority of polyphenols in almonds are concentrated in the skin, in general between 70 and 100% of total phenolics [82]. The phenolic concentration of raw almond skin is approximately 27.6 mg GAE/g, while that of roasted almond skin decreases to 18.5 mg GAE/g. In general, unblanched almonds after roasting process contain approximately 0.5 mg/g of polyphenols [83].

6.3. Pistachios

According to hazelnuts and almonds, the roasting process triggers the release of polyphenols which would have been otherwise bound and unmeasurable. To this instance, the total phenolic content generally amounts 25 mg/100g, while on single roasted almond is around 32.4 mg/100g. Furthermore, the third roasting process increase the content to 42.4 mg/100g [65].

Moreover, Yuan et al. (2022) quantified both bound and free polyphenols and flavonoids in raw and roasted pistachios. They reported that bound polyphenols in raw pistachios were 85.1 mg GAE/100g, while in roasted pistachios, it was 73.1 mg GAE/100g. Free phenolics, on the other hand, were higher in raw pistachios (394.8 mg GAE/100g) compared to roasted pistachios (374.4 mg GAE/100g). Regarding flavonoids, bound flavonoids were more abundant in raw pistachios (62.5 mg CE/100g) than in roasted pistachios (42.7 mg CE/100g). Free flavonoids were also higher in raw pistachios (115.8 mg CE/100g) compared to roasted pistachios (101.4 mg CE/100g). Gentisic acid was the most abundant phenolic acid detected in both raw and roasted pistachios. In raw pistachios,

gentisic acid was followed by gallic acid and protocatechuic acid in terms of abundance. Similarly, in roasted pistachios, gentisic acid remained the dominant phenolic acid, followed by gallic acid and protocatechuic acid. The authors of this study have demonstrated that the roasting process can lead to positive alterations in the phytochemical composition of almonds, thereby facilitating the increased bioavailability of health-promoting compounds [84].

7. Effects of Roasting on Lipids Content

The roasting process can exert a significant influence on the quality and fatty acid profile of hazelnuts. Elevated temperatures can accelerate lipid oxidation, leading to the degradation of essential nutrients such as tocopherols and the formation of undesirable compounds, including trans fatty acids and saturated fatty acids. Amaral et al. (2006) reported that prolonged exposure to high temperatures, such as 185 °C for 15 minutes, can result in a decrease in oleic acid and an increase in saturated fatty acids. Conversely, at lower temperatures, such as 165°C for 15 minutes, the fatty acid profile remains relatively stable, and the formation of trans fatty acids is minimal [85].

Lin et al. (2016) examined the influence of various roasting conditions (150, 180, and 200 °C for 5, 10, and 20 minutes) on the fatty acid profile of almonds. The most pronounced changes were observed in almonds roasted at 200°C for 20 minutes. Specifically, significant decreases were observed in palmitic acid (16:0), linoleic acid (18:2), and oleic acid (18:1). Consequently, the total saturated and unsaturated fatty acid content decreased [81].

Schlörmann et al. (2015) investigated the effects of five different roasting conditions (ranging from 139 °C for 18 minutes to 180 °C for 21 minutes) on the fatty acid profile of five nut varieties. The study revealed no significant alterations in the fatty acid composition between raw and roasted nuts, and no detectable increase in trans fatty acids was observed [86].

Cui et al. (2022) studied lipid oxidation in hazelnut oil. At the beginning of the experiment, the initial levels of PUFAs, MUFAs, and SFAs were 136 mg/g, 881 mg/g, and 78 mg/g, respectively. After 40 days of oxidation at 60 °C, the levels of PUFAs decreased to 65 mg/g, MUFAs decreased to 727 mg/g, and SFAs increased to 72 mg/g. Furthermore, the authors observed that lipid oxidation was slow during the first 15 days, followed by a period of accelerated oxidation. This initial delay is attributed to the protective role of antioxidants, which gradually become depleted, leading to increased lipid oxidation [87].

7. Conclusion

Nuts, due to their remarkable nutritional profile and bioactive compounds, play a vital role in promoting health and well-being. Their richness in polyphenols, healthy fatty acids, dietary fiber, and minerals makes them a highly valued food source. Roasting, as a critical processing technique, not only enhances the sensory attributes of nuts, such as flavor and texture, but also influences their nutritional and bioactive composition. The application of conventional and emerging roasting technologies has demonstrated varied impacts on the preservation and transformation of these compounds.

Innovative techniques such as infrared, microwave, and radiofrequency roasting provide promising alternatives, ensuring improved efficiency, uniform heating, and minimal loss of bioactive compounds. Additionally, the Maillard reaction during roasting contributes significantly to the development of distinctive flavors and aromas, further enhancing the appeal of roasted nuts.

Future research should focus on optimizing roasting conditions to strike a balance between flavor enhancement and nutritional preservation. By integrating advanced technologies, it is possible to produce high-quality roasted nuts that retain their health-promoting properties while meeting consumer preferences. This comprehensive understanding of the interplay between roasting techniques and nut composition underscores their potential as functional foods in modern diets.

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References

1. Gonçalves, B.; Pinto, T.; Aires, A.; Morais, M.C.; Bacelar, E.; Anjos, R.; Ferreira-Cardoso, J.; Oliveira, I.; Vilela, A.; Cosme, F. Composition of Nuts and Their Potential Health Benefits—An Overview. *Foods* **2023**, *12*, 942, doi:10.3390/foods12050942.
2. Alasalvar, C.; Salas-Salvado, J.; Ros, E.; Sabate, J. *Health Benefits of Nuts and Dried Fruits*; CRC Press, 2020; ISBN 978-1-351-70052-8.
3. Ros, E. Health Benefits of Nut Consumption. *Nutrients* **2010**, *2*, 652–682, doi:10.3390/nu2070652.
4. Bolling, B.W.; Chen, C.-Y.O.; McKay, D.L.; Blumberg, J.B. Tree Nut Phytochemicals: Composition, Antioxidant Capacity, Bioactivity, Impact Factors. A Systematic Review of Almonds, Brazils, Cashews, Hazelnuts, Macadamias, Pecans, Pine Nuts, Pistachios and Walnuts. *Nutrition Research Reviews* **2011**, *24*, 244–275, doi:10.1017/S095442241100014X.
5. Dini, A.; Khanamani Falahati-Pour, S.; Behmaram, K.; Sedaghat, N. The Kinetics of Colour Degradation, Chlorophylls and Xanthophylls Loss in Pistachio Nuts during Roasting Process. *Food Quality and Safety* **2019**, *3*, 251–263, doi:10.1093/fqsafe/fyz020.
6. Locatelli, M.; Coisson, J.D.; Travaglia, F.; Bordiga, M.; Arlorio, M. Impact of Roasting on Identification of Hazelnut (*Corylus Avellana* L.) Origin: A Chemometric Approach. *J. Agric. Food Chem.* **2015**, *63*, 7294–7303, doi:10.1021/acs.jafc.5b03201.
7. Taş, N.G.; Gökmen, V. Phenolic Compounds in Natural and Roasted Nuts and Their Skins: A Brief Review. *Current Opinion in Food Science* **2017**, *14*, 103–109, doi:10.1016/j.cofs.2017.03.001.
8. Gervasi, T.; Barreca, D.; Laganà, G.; Mandalari, G. Health Benefits Related to Tree Nut Consumption and Their Bioactive Compounds. *International Journal of Molecular Sciences* **2021**, *22*, 5960, doi:10.3390/ijms22115960.
9. Sruthi, N.U.; Premjit, Y.; Pandiselvam, R.; Kothakota, A.; Ramesh, S.V. An Overview of Conventional and Emerging Techniques of Roasting: Effect on Food Bioactive Signatures. *Food Chemistry* **2021**, *348*, 129088, doi:10.1016/j.foodchem.2021.129088.
10. Rojas, M.; Hommes, A.; Heeres, H.J.; Chejne, F. Physicochemical Phenomena in the Roasting of Cocoa (*Theobroma Cacao* L.). *Food Eng Rev* **2022**, *14*, 509–533, doi:10.1007/s12393-021-09301-z.
11. Bottone, A.; Cerulli, A.; D’Urso, G.; Masullo, M.; Montoro, P.; Napolitano, A.; Piacente, S. Plant Specialized Metabolites in Hazelnut (*Corylus Avellana*) Kernel and Byproducts: An Update on Chemistry, Biological Activity, and Analytical Aspects. *Planta Med* **2019**, *85*, 840–855, doi:10.1055/a-0947-5725.
12. Köksal, A.İ.; Artik, N.; Şimşek, A.; Güneş, N. Nutrient Composition of Hazelnut (*Corylus Avellana* L.) Varieties Cultivated in Turkey. *Food Chemistry* **2006**, *99*, 509–515, doi:10.1016/j.foodchem.2005.08.013.
13. Oliveira, I.; Sousa, A.; Morais, J.S.; Ferreira, I.C.F.R.; Bento, A.; Estevinho, L.; Pereira, J.A. Chemical Composition, and Antioxidant and Antimicrobial Activities of Three Hazelnut (*Corylus Avellana* L.) Cultivars. *Food and Chemical Toxicology* **2008**, *46*, 1801–1807, doi:10.1016/j.fct.2008.01.026.
14. Squara, S.; Stilo, F.; Cialie Rosso, M.; Liberto, E.; Spigolon, N.; Genova, G.; Castello, G.; Bicchi, C.; Cordero, C. *Corylus Avellana* L. Aroma Blueprint: Potent Odorants Signatures in the Volatilome of High Quality Hazelnuts. *Front. Plant Sci.* **2022**, *13*, doi:10.3389/fpls.2022.840028.
15. Yada, S.; Lapsley, K.; Huang, G. A Review of Composition Studies of Cultivated Almonds: Macronutrients and Micronutrients. *Journal of Food Composition and Analysis* **2011**, *24*, 469–480, doi:10.1016/j.jfca.2011.01.007.
16. Beltrán Sanahuja, A.; Maestre Pérez, S.E.; Grané Teruel, N.; Valdés García, A.; Prats Moya, M.S. Variability of Chemical Profile in Almonds (*Prunus Dulcis*) of Different Cultivars and Origins. *Foods* **2021**, *10*, 153, doi:10.3390/foods10010153.
17. Shi, T.; Cao, J.; Cao, J.; Zhu, F.; Cao, F.; Su, E. Almond (*Amygdalus Communis* L.) Kernel Protein: A Review on the Extraction, Functional Properties and Nutritional Value. *Food Research International* **2023**, *167*, 112721, doi:10.1016/j.foodres.2023.112721.

18. Barreca, D.; Nabavi, S.M.; Sureda, A.; Rasekhian, M.; Raciti, R.; Silva, A.S.; Annunziata, G.; Arnone, A.; Tenore, G.C.; Süntar, İ.; et al. Almonds (*Prunus Dulcis* Mill. D. A. Webb): A Source of Nutrients and Health-Promoting Compounds. *Nutrients* **2020**, *12*, 672, doi:10.3390/nu12030672.
19. Özcan, M.M. A Review on Some Properties of Almond: Impact of Processing, Fatty Acids, Polyphenols, Nutrients, Bioactive Properties, and Health Aspects. *J Food Sci Technol* **2023**, *60*, 1493–1504, doi:10.1007/s13197-022-05398-0.
20. Dreher, M.L. Pistachio Nuts: Composition and Potential Health Benefits. *Nutrition Reviews* **2012**, *70*, 234–240, doi:10.1111/j.1753-4887.2011.00467.x.
21. Mandalari, G.; Barreca, D.; Gervasi, T.; Roussell, M.A.; Klein, B.; Feeney, M.J.; Carughi, A. Pistachio Nuts (*Pistacia Vera* L.): Production, Nutrients, Bioactives and Novel Health Effects. *Plants* **2022**, *11*, 18, doi:10.3390/plants11010018.
22. Mateos, R.; Salvador, M.D.; Fregapane, G.; Goya, L. Why Should Pistachio Be a Regular Food in Our Diet? *Nutrients* **2022**, *14*, 3207, doi:10.3390/nu14153207.
23. Bulló, M.; Juanola-Falgarona, M.; Hernández-Alonso, P.; Salas-Salvadó, J. Nutrition Attributes and Health Effects of Pistachio Nuts. *British Journal of Nutrition* **2015**, *113*, S79–S93, doi:10.1017/S0007114514003250.
24. Bagheri, H. Application of Infrared Heating for Roasting Nuts. *Journal of Food Quality* **2020**, *2020*, 8813047, doi:10.1155/2020/8813047.
25. Belviso, S.; Dal Bello, B.; Giacosa, S.; Bertolino, M.; Ghirardello, D.; Giordano, M.; Rolle, L.; Gerbi, V.; Zeppa, G. Chemical, Mechanical and Sensory Monitoring of Hot Air- and Infrared-Roasted Hazelnuts (*Corylus Avellana* L.) during Nine Months of Storage. *Food Chemistry* **2017**, *217*, 398–408, doi:10.1016/j.foodchem.2016.08.103.
26. Ogundipe, S.O.; Usack, J.G.; Pegg, R.B.; Suh, J.H. Thermal and Non-Thermal Processing on the Physical and Chemical Properties of Tree Nuts: A Review. *Food Bioprocess Technol* **2024**, *17*, 1727–1751, doi:10.1007/s11947-023-03314-8.
27. Chen, C.; Pan, Z.; Chen, C.; Pan, Z. Processing of Tree Nuts. In *Postharvest Technology - Recent Advances, New Perspectives and Applications*; IntechOpen, 2022 ISBN 978-1-83969-924-5.
28. Peña-Correa, R.F.; Ataç Mogol, B.; Fogliano, V. The Impact of Roasting on Cocoa Quality Parameters. *Critical Reviews in Food Science and Nutrition* **2024**, *64*, 4348–4361, doi:10.1080/10408398.2022.2141191.
29. Yang, J.; Bingol, G.; Pan, Z.; Brandl, M.T.; McHugh, T.H.; Wang, H. Infrared Heating for Dry-Roasting and Pasteurization of Almonds. *Journal of Food Engineering* **2010**, *101*, 273–280, doi:10.1016/j.jfoodeng.2010.07.007.
30. Demir, A.D.; Cronin, K. Modelling the Kinetics of Textural Changes in Hazelnuts during Roasting. *Simulation Modelling Practice and Theory* **2005**, *13*, 97–107, doi:10.1016/j.simpat.2003.11.007.
31. Lamberti, C.; Nebbia, S.; Antoniazzi, S.; Cirrincione, S.; Marengo, E.; Manfredi, M.; Smorgon, D.; Monti, G.; Faccio, A.; Giuffrida, M.G.; et al. Effect of Hot Air and Infrared Roasting on Hazelnut Allergenicity. *Food Chemistry* **2021**, *342*, 128174, doi:10.1016/j.foodchem.2020.128174.
32. Hojjati, M.; Lipan, L.; Carbonell-Barrachina, Á.A. Effect of Roasting on Physicochemical Properties of Wild Almonds (*Amygdalus Scoparia*). *J Am Oil Chem Soc* **2016**, *93*, 1211–1220, doi:10.1007/s11746-016-2868-8.
33. Shakerardekani, A.; Karim, R.; Ghazali, H.M.; Chin, N.L. Effect of Roasting Conditions on Hardness, Moisture Content and Colour of Pistachio Kernels 2011.
34. Chen, H.; He, S.; Pei, H.; Gao, K.; Gao, L.; Cao, X.; Sun, H.; Song, J. Effect of Hot Air Circulation Roasting Temperature on the Sensory Property and Odor Characteristics of Cashew Nut (L.). *Journal of Food Process Engineering* **2024**, *47*, e14546, doi:10.1111/jfpe.14546.
35. Bagheri, H.; Kashaninejad, M.; Ziaifar, A.M.; Aalami, M. Textural, Color and Sensory Attributes of Peanut Kernels as Affected by Infrared Roasting Method. *Information Processing in Agriculture* **2019**, *6*, 255–264, doi:10.1016/j.inpa.2018.11.001.
36. Binello, A.; Giorgis, M.; Cena, C.; Cravotto, G.; Rotolo, L.; Oliveri, P.; Malegori, C.; Cavallero, M.C.; Buso, S.; Casale, M. Chemical Modifications of Tonda Gentile Trilobata Hazelnut and Derived Processing Products under Different Infrared and Hot-Air Roasting Conditions: A Combined Analytical Study. *Journal of the Science of Food and Agriculture* **2018**, *98*, 4561–4569, doi:10.1002/jsfa.8984.

37. Bermudez-Aguirre, D.; Niemira, B.A. Radio Frequency Treatment of Food: A Review on Pasteurization and Disinfestation. *Foods* **2023**, *12*, 3057, doi:10.3390/foods12163057.
38. Di Rosa, A.R.; Bressan, F.; Leone, F.; Falqui, L.; Chiofalo, V. Radio Frequency Heating on Food of Animal Origin: A Review. *Eur Food Res Technol* **2019**, *245*, 1787–1797, doi:10.1007/s00217-019-03319-8.
39. Liao, M.; Zhao, Y.; Gong, C.; Zhang, H.; Jiao, S. Effects of Hot Air-Assisted Radio Frequency Roasting on Quality and Antioxidant Activity of Cashew Nut Kernels. *LWT* **2018**, *93*, 274–280, doi:10.1016/j.lwt.2018.03.047.
40. Coffee Bean Heating Uniformity and Quality as Influenced by Radio Frequency Treatments for Postharvest Disinfestations.
41. Megahed, M.G. Microwave Roasting of Peanuts: Effects on Oil Characteristics and Composition. *Food / Nahrung* **2001**, *45*, 255–257, doi:10.1002/1521-3803(20010801)45:4<255::AID-FOOD255>3.0.CO;2-F.
42. Nüchter, M.; Ondruschka, B.; Bonrath, W.; Gum, A. Microwave Assisted Synthesis – a Critical Technology Overview. *Green Chemistry* **2004**, *6*, 128–141, doi:10.1039/B310502D.
43. Sruthi, N.U.; Premjit, Y.; Pandiselvam, R.; Kothakota, A.; Ramesh, S.V. An Overview of Conventional and Emerging Techniques of Roasting: Effect on Food Bioactive Signatures. *Food Chemistry* **2021**, *348*, 129088, doi:10.1016/j.foodchem.2021.129088.
44. Milczarek, R.R.; Avena-Bustillos, R.J.; Peretto, G.; McHugh, T.H. Optimization of Microwave Roasting of Almond (*Prunus Dulcis*). *Journal of Food Processing and Preservation* **2014**, *38*, 912–923, doi:10.1111/jfpp.12046.
45. Smith, A.L.; Barringer, S.A. Color and Volatile Analysis of Peanuts Roasted Using Oven and Microwave Technologies. *Journal of Food Science* **2014**, *79*, C1895–C1906, doi:10.1111/1750-3841.12588.
46. Sithole, T.R.; Ma, Y.-X.; Qin, Z.; Liu, H.-M.; Wang, X.-D. Technical Aspects of Peanut Butter Production Processes: Roasting and Grinding Processes Review. *Journal of Food Processing and Preservation* **2022**, *46*, e16430, doi:10.1111/jfpp.16430.
47. E. Newton, A.; J. Fairbanks, A.; Golding, M.; Andrewes, P.; A. Gerrard, J. The Role of the Maillard Reaction in the Formation of Flavour Compounds in Dairy Products – Not Only a Deleterious Reaction but Also a Rich Source of Flavour Compounds. *Food & Function* **2012**, *3*, 1231–1241, doi:10.1039/C2FO30089C.
48. van Boekel, M.A.J.S. Formation of Flavour Compounds in the Maillard Reaction. *Biotechnology Advances* **2006**, *24*, 230–233, doi:10.1016/j.biotechadv.2005.11.004.
49. Cui, H.; Yu, J.; Zhai, Y.; Feng, L.; Chen, P.; Hayat, K.; Xu, Y.; Zhang, X.; Ho, C.-T. Formation and Fate of Amadori Rearrangement Products in Maillard Reaction. *Trends in Food Science & Technology* **2021**, *115*, 391–408, doi:10.1016/j.tifs.2021.06.055.
50. Wang, X.; Lu, J.; Cai, G.; Wu, D. Advances in Maillard Reaction Products on Color, Flavor and Biological Activity of Specialty Malt. *Syst Microbiol and Biomanuf* **2024**, *4*, 500–510, doi:10.1007/s43393-023-00211-1.
51. Shakoor, A.; Zhang, C.; Xie, J.; Yang, X. Maillard Reaction Chemistry in Formation of Critical Intermediates and Flavour Compounds and Their Antioxidant Properties. *Food Chemistry* **2022**, *393*, 133416, doi:10.1016/j.foodchem.2022.133416.
52. Shahidi, F.; Hossain, A. Role of Lipids in Food Flavor Generation. *Molecules* **2022**, *27*, 5014, doi:10.3390/molecules27155014.
53. Müller, R.; Rappert, S. Pyrazines: Occurrence, Formation and Biodegradation. *Appl Microbiol Biotechnol* **2010**, *85*, 1315–1320, doi:10.1007/s00253-009-2362-4.
54. Agila, A.; Barringer, S. Effect of Roasting Conditions on Color and Volatile Profile Including HMF Level in Sweet Almonds (*Prunus Dulcis*). *Journal of Food Science* **2012**, *77*, C461–C468, doi:10.1111/j.1750-3841.2012.02629.x.
55. Zyzak, D.V.; Sanders, R.A.; Stojanovic, M.; Tallmadge, D.H.; Eberhart, B.L.; Ewald, D.K.; Gruber, D.C.; Morsch, T.R.; Strothers, M.A.; Rizzi, G.P.; et al. Acrylamide Formation Mechanism in Heated Foods. *J. Agric. Food Chem.* **2003**, *51*, 4782–4787, doi:10.1021/jf034180i.
56. Acrylamide in Roasted Almonds and Hazelnuts | Journal of Agricultural and Food Chemistry Available online: https://pubs.acs.org/doi/full/10.1021/jf051132k?casa_token=08HijXt0EL0AAAAA%3A3dkLSzILSx6pBfrjINFwh9hTFynQ9iyCQDMdYgmk_OvPVwNQE4isOU_yKxUzum7iteNSgeBJ1zwEt (accessed on 12 December 2024).

57. Valdés García, A.; Sánchez Romero, R.; Juan Polo, A.; Prats Moya, S.; Maestre Pérez, S.E.; Beltrán Sanahuja, A. Volatile Profile of Nuts, Key Odorants and Analytical Methods for Quantification. *Foods* **2021**, *10*, 1611, doi:10.3390/foods10071611.
58. Kesen, S.; Amanpour, A.; Selli, S. Comparative Evaluation of the Fatty Acids and Aroma Compounds in Selected Iranian Nut Oils. *European Journal of Lipid Science and Technology* **2018**, *120*, 1800152, doi:10.1002/ejlt.201800152.
59. Alasalvar, C.; Shahidi, F.; Cadwallader, K.R. Comparison of Natural and Roasted Turkish Tombul Hazelnut (*Corylus Avellana* L.) Volatiles and Flavor by DHA/GC/MS and Descriptive Sensory Analysis. *J. Agric. Food Chem.* **2003**, *51*, 5067–5072, doi:10.1021/jf0300846.
60. Burdack-Freitag, A.; Schieberle, P. Characterization of the Key Odorants in Raw Italian Hazelnuts (*Corylus Avellana* L. Var. Tonda Romana) and Roasted Hazelnut Paste by Means of Molecular Sensory Science. *J. Agric. Food Chem.* **2012**, *60*, 5057–5064, doi:10.1021/jf300908d.
61. Marzocchi, S.; Pasini, F.; Verardo, V.; Ciemnińska-Żytikiewicz, H.; Caboni, M.F.; Romani, S. Effects of Different Roasting Conditions on Physical-Chemical Properties of Polish Hazelnuts (*Corylus Avellana* L. Var. *Kataloński*). *LWT* **2017**, *77*, 440–448, doi:10.1016/j.lwt.2016.11.068.
62. Erten, E.S.; Cadwallader, K.R. Identification of Predominant Aroma Components of Raw, Dry Roasted and Oil Roasted Almonds. *Food Chemistry* **2017**, *217*, 244–253, doi:10.1016/j.foodchem.2016.08.091.
63. Xiao, L.; Lee, J.; Zhang, G.; Ebeler, S.E.; Wickramasinghe, N.; Seiber, J.; Mitchell, A.E. HS-SPME GC/MS Characterization of Volatiles in Raw and Dry-Roasted Almonds (*Prunus Dulcis*). *Food Chemistry* **2014**, *151*, 31–39, doi:10.1016/j.foodchem.2013.11.052.
64. Franklin, L.M.; Mitchell, A.E. Review of the Sensory and Chemical Characteristics of Almond (*Prunus Dulcis*) Flavor. *J. Agric. Food Chem.* **2019**, *67*, 2743–2753, doi:10.1021/acs.jafc.8b06606.
65. Rodríguez-Bencomo, J.J.; Kelebek, H.; Sonmezdag, A.S.; Rodríguez-Alcalá, L.M.; Fontecha, J.; Selli, S. Characterization of the Aroma-Active, Phenolic, and Lipid Profiles of the Pistachio (*Pistacia Vera* L.) Nut as Affected by the Single and Double Roasting Process. *J. Agric. Food Chem.* **2015**, *63*, 7830–7839, doi:10.1021/acs.jafc.5b02576.
66. Noguera-Artiaga, L.; Salvador, M.D.; Fregapane, G.; Collado-González, J.; Wojdyło, A.; López-Lluch, D.; Carbonell-Barrachina, Á.A. Functional and Sensory Properties of Pistachio Nuts as Affected by Cultivar. *Journal of the Science of Food and Agriculture* **2019**, *99*, 6696–6705, doi:10.1002/jsfa.9951.
67. Hojjati, M.; Calín-Sánchez, Á.; Razavi, S.H.; Carbonell-Barrachina, Á.A. Effect of Roasting on Colour and Volatile Composition of Pistachios (*Pistacia Vera* L.). *International Journal of Food Science & Technology* **2013**, *48*, 437–443, doi:10.1111/j.1365-2621.2012.03206.x.
68. Hojjati, M.; Noguera-Artiaga, L.; Wojdyło, A.; Carbonell-Barrachina, Á.A. Effects of Microwave Roasting on Physicochemical Properties of Pistachios (*Pistaciavera* L.). *Food Sci Biotechnol* **2015**, *24*, 1995–2001, doi:10.1007/s10068-015-0263-0.
69. Gogus, F.; Ozel, M.Z.; Kocak, D.; Hamilton, J.F.; Lewis, A.C. Analysis of Roasted and Unroasted *Pistacia Terebinthus* Volatiles Using Direct Thermal Desorption-GC×GC-TOF/MS. *Food Chemistry* **2011**, *129*, 1258–1264, doi:10.1016/j.foodchem.2011.05.003.
70. Sonmezdag, A.S.; Kelebek, H.; Selli, S. Pistachio Oil (*Pistacia Vera* L. Cv. Uzun): Characterization of Key Odorants in a Representative Aromatic Extract by GC-MS-Olfactometry and Phenolic Profile by LC-ESI-MS/MS. *Food Chemistry* **2018**, *240*, 24–31, doi:10.1016/j.foodchem.2017.07.086.
71. Oliveira, I.; Malheiro, R.; Meyer, A.; Pereira, J.; Gonçalves, B. Application of Chemometric Tools for the Comparison of Volatile Profile from Raw and Roasted Regional and Foreign Almond Cultivars (*Prunus Dulcis*). *Journal of Food Science and Technology* **2019**, *56*, doi:10.1007/s13197-019-03847-x.
72. Zhang, H.; Wang, M.; Xiao, J. Chapter One - Stability of Polyphenols in Food Processing. In *Advances in Food and Nutrition Research*; Toldrá, F., Ed.; Academic Press, 2022; Vol. 102, pp. 1–45.
73. Alean, J.; Chejne, F.; Rojano, B. Degradation of Polyphenols during the Cocoa Drying Process. *Journal of Food Engineering* **2016**, *189*, 99–105, doi:10.1016/j.jfoodeng.2016.05.026.
74. Król, K.; Gantner, M.; Tatarak, A.; Hallmann, E. The Content of Polyphenols in Coffee Beans as Roasting, Origin and Storage Effect. *Eur Food Res Technol* **2020**, *246*, 33–39, doi:10.1007/s00217-019-03388-9.

75. Chang, S.K.; Alasalvar, C.; Bolling, B.W.; Shahidi, F. Nuts and Their Co-Products: The Impact of Processing (Roasting) on Phenolics, Bioavailability, and Health Benefits – A Comprehensive Review. *Journal of Functional Foods* **2016**, *26*, 88–122, doi:10.1016/j.jff.2016.06.029.
76. Bagheri, H.; Kashaninejad, M.; Ziaifar, A.M.; Aalami, M. Novel Hybridized Infrared-Hot Air Method for Roasting of Peanut Kernels. *Innovative Food Science & Emerging Technologies* **2016**, *37*, 106–114, doi:10.1016/j.ifset.2016.08.014.
77. Pelvan, E.; Alasalvar, C.; Uzman, S. Effects of Roasting on the Antioxidant Status and Phenolic Profiles of Commercial Turkish Hazelnut Varieties (*Corylus Avellana* L.). *J. Agric. Food Chem.* **2012**, *60*, 1218–1223, doi:10.1021/jf204893x.
78. Król, K.; Gantner, M.; Piotrowska, A.; Hallmann, E. Effect of Climate and Roasting on Polyphenols and Tocopherols in the Kernels and Skin of Six Hazelnut Cultivars (*Corylus Avellana* L.). *Agriculture* **2020**, *10*, 36, doi:10.3390/agriculture10020036.
79. Lucchetti, S.; Ambra, R.; Pastore, G. Effects of Peeling and/or Toasting on the Presence of Tocopherols and Phenolic Compounds in Four Italian Hazelnut Cultivars. *Eur Food Res Technol* **2018**, *244*, 1057–1064, doi:10.1007/s00217-017-3028-6.
80. Chandrasekara, N.; Shahidi, F. Effect of Roasting on Phenolic Content and Antioxidant Activities of Whole Cashew Nuts, Kernels, and Testa. *J. Agric. Food Chem.* **2011**, *59*, 5006–5014, doi:10.1021/jf2000772.
81. Lin, J.-T.; Liu, S.-C.; Hu, C.-C.; Shyu, Y.-S.; Hsu, C.-Y.; Yang, D.-J. Effects of Roasting Temperature and Duration on Fatty Acid Composition, Phenolic Composition, Maillard Reaction Degree and Antioxidant Attribute of Almond (*Prunus Dulcis*) Kernel. *Food Chemistry* **2016**, *190*, 520–528, doi:10.1016/j.foodchem.2015.06.004.
82. Oliveira, I.; Meyer, A.S.; Afonso, S.; Sequeira, A.; Vilela, A.; Goufo, P.; Trindade, H.; Gonçalves, B. Effects of Different Processing Treatments on Almond (*Prunus Dulcis*) Bioactive Compounds, Antioxidant Activities, Fatty Acids, and Sensorial Characteristics. *Plants* **2020**, *9*, 1627, doi:10.3390/plants9111627.
83. Bolling, B.W.; Blumberg, J.B.; Oliver Chen, C.-Y. The Influence of Roasting, Pasteurisation, and Storage on the Polyphenol Content and Antioxidant Capacity of California Almond Skins. *Food Chemistry* **2010**, *123*, 1040–1047, doi:10.1016/j.foodchem.2010.05.058.
84. Yuan, W.; Zheng, B.; Li, T.; Liu, R.H. Quantification of Phytochemicals, Cellular Antioxidant Activities and Antiproliferative Activities of Raw and Roasted American Pistachios (*Pistacia Vera* L.). *Nutrients* **2022**, *14*, 3002, doi:10.3390/nu14153002.
85. Amaral, J.S.; Casal, S.; Seabra, R.M.; Oliveira, B.P.P. Effects of Roasting on Hazelnut Lipids. *J. Agric. Food Chem.* **2006**, *54*, 1315–1321, doi:10.1021/jf052287v.
86. Schlörmann, W.; Birringer, M.; Böhm, V.; Löber, K.; Jahreis, G.; Lorkowski, S.; Müller, A.K.; Schöne, F.; Gleis, M. Influence of Roasting Conditions on Health-Related Compounds in Different Nuts. *Food Chemistry* **2015**, *180*, 77–85, doi:10.1016/j.foodchem.2015.02.017.
87. Cui, N.; Zhao, T.; Han, Z.; Yang, Z.; Wang, G.; Ma, Q.; Liang, L. Characterisation of Oil Oxidation, Fatty Acid, Carotenoid, Squalene and Tocopherol Components of Hazelnut Oils Obtained from Three Varieties Undergoing Oxidation. *International Journal of Food Science & Technology* **2022**, *57*, 3456–3466, doi:10.1111/ijfs.15669.

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