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REVIEW

Thermal and Non-thermal Processing on the Physical and Chemical Properties of Tree Nuts: A Review

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Abstract

Tree nuts are an essential component of the modern diet and are consumed worldwide for their health benefits and great taste. The quality and nutritional value of nuts can be altered by processing. Therefore, it is important to understand nut processing methods and resulting property changes. In this review, thermal processing (drying, roasting, blanching) and non-thermal processing (HPP, irradiation, cold plasma, PEF, radio frequency heating) effects on the physicochemical properties of tree nuts are summarized. Different thermal and non-thermal methods employed in the last ten years are compared and perspectives on their current challenges and future prospects are given. The review reveals that, although, thermal processing can enhance the dark brown color, crispy texture, and flavor of nuts, its impact on nutritional quality (e.g. vitamins, lipids, and phytochemicals) can be undesirable due to the effect of heat. In contrast, non-thermal processing has little effect on losses in the nutritional quality of nuts; yet, it has other limitations, e.g. incomplete inactivation of pathogens, unexpected chemical reactions, and non-robust process control. Considering these challenges, future perspectives are described and discussed, including the application of newly developed thermal techniques (e.g. superheated steam roasting, cooling with dehumidification) in nut processing, integration of thermal and non-thermal processing methods with enhanced efficiency, and the use of artificial intelligence and mathematical models for optimization of processing parameters, amongst others. This review will benefit nut researchers and help the industry develop and optimize nut processing strategies.

Keywords Tree nuts · Thermal and non-thermal processing · Nut properties · Nut quality · Phytochemicals · Artificial intelligence

Abbreviations

a*	Part of the CIELAB color space. The a*-axis is the green-red axis, with greenness to redness values of –128 to + 127
b*	Part of the CIELAB color space. The b*-axis is the blue-yellow axis, with blueness to yellowness values of –128 to + 127
CWD	Cooling with dehumidification
DPPH•	2,2́-diphenyl-1-picrylhydrazyl radical
FAO	Food and Agricultural Organization of the United Nations
FRAP	Ferric reducing antioxidant power
HAHA	Hot-air-hot-air
HAMW	Hot-air-microwave
HARF	Hot-air-radiofrequency
HPP	High-pressure processing
IR	Infrared
L*	Part of the CIELAB color space. The L*-axis denotes the lightness: a white object has an L* value of 100 and the L* value of a black object is 0
LDL	Low-density lipoprotein
LPCP	Low-pressure cold plasma
MDA	Malondialdehyde
MUFAs	Monounsaturated fatty acids
ORAC	Oxygen radical absorbance capacity
PEF	Pulsed electric field

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PUFAs	Polyunsaturated fatty acids
RF	Radio frequency
SFAs	Saturated fatty acids
TFC	Total flavonoids content
TPC	Total phenolics content
WHO	World Health Organization

Introduction

The majority of culinary nut varieties belong to the order Fagales, which contains eight families, including *Rosaceae* (almond drupe), *Betulaceae* (hazelnut), *Juglandaceae* (pecan and walnut drupes), and *Fagaceae* (chestnut). *Fabaceae* (peanut) is a legume from the order Fabales, and *Anacardiaceae* (pistachio) is a drupe from the order Sapindales (Jonas da Rocha Esperança et al., 2022). Culinary nuts are also classified as tree nuts (e.g., almonds, pecans, walnuts, cashews) or groundnuts (e.g., peanuts and tiger nuts). The production of nuts has increased significantly over the past ten years and accounted for 5.13 million metric tons in 2021–2022 (FAOSTAT, 2022). The global market value of nuts and seeds is forecasted to increase from $1.3 trillion in 2018 to $1.4 trillion in 2023 (Market data forecast, 2022). In 2021, the United States was the largest exporter of nuts, with ~1.6 billion kg, followed in order by Turkey, China, and Chile (Koç Güler et al., 2017; Market data forecast, 2022).

Nuts are one of the most consumed seeds worldwide. Health benefits afforded by nut consumption is a significant factor driving for their increased demand (Lu et al., 2022). When consumed in moderation, nuts can provide many health benefits. They are an excellent source of protein, with ~20–40% protein content when de-oiled by pressing. In addition, they are also rich in dietary fiber and contain polyunsaturated fatty acids (PUFAs), such as linoleic acid and α-linolenic acid (Dobhal et al., 2018; Sari et al., 2022). Nut dietary fiber is reported to help improve digestion and reduce constipation. Linoleic and α-linolenic acids are essential fatty acids in human nutrition that can reduce the risk of diabetes and coronary heart diseases (Afshin et al., 2014). The B vitamins (niacin, pyridoxine, folate), vitamin E, as well as considerable amounts of minerals such as calcium, potassium, and magnesium, are present in nuts (Chang et al., 2016). Nut consumption purportedly reduces neurological damage, cardiovascular diseases, inflammation, as well as oxidative stress and ameliorates type-2 diabetes and some types of cancer (Gervasi et al., 2021; Nunzio, 2019). Phytochemicals or bioactives such as polyphenols, phytosterols, and carotenoids in nuts qualify them as functional foods (Rábago-Panduro et al., 2020). Certain phenolic compounds possess both antioxidant and anti-inflammatory properties and confer other beneficial effects, including reducing cardiovascular diseases, preventing DNA damage, and suppressing tumor cell growth (Gervasi et al., 2021). Phytosterols are responsible for lowering low-density lipoprotein (LDL) levels in blood plasma, which may help treat hypercholesterolemia and cardiovascular disease (Trautwein et al., 2018). Carotenoids are promising lipophilic antioxidants that can be converted to retinol, which promotes vision, immune response, reproduction, as well as embryonic growth and development (Albuquerque et al., 2020).

After harvest, the perishability of nuts necessitates techniques for their preservation. The high lipid content (40–80%) and considerable amount of moisture (6–25%) of tree nuts render them highly vulnerable to degradation through lipid oxidation, enzymatic reactions, and microorganisms, notably fungi (Barbhuiya et al., 2021; Mirzabe et al., 2013). Consequently, processing tree nuts promptly is crucial to preserve their quality, restrict lipid oxidation, and microbial activity before storage and/or subsequent applications.

There are two main approaches for nut processing: thermal and non-thermal. Thermal processing involves the application of heat on raw nuts via techniques such as drying, blanching, and roasting to achieve a desired product quality (for instance, roasted flavor during roasting) and to destroy detrimental microorganisms, enzymes, and pathogens in the nuts (Štěrbová et al., 2017). However, thermal processing increases the extent of lipid oxidation, the formation of toxicants (e.g., acrylamide), and the degradation of certain micronutrients and phytochemicals (Lu et al., 2022). On the other hand, non-thermal processing techniques such as pressurization, irradiation, and cold plasma are applied to raw tree nuts as a means to preserve their freshness/quality by destroying pathogens and spoilage microorganisms as well as inactivating enzymes (i.e., preservation of heat-sensitive compounds) before storage (Thirumdas et al., 2014). For example, high-pressure processing (HPP) and irradiation technologies have been used to disinfect nuts, with minimizing the negative effect of heat (Chen & Pan, 2022). Koç Güler et al. (2017) reported that irradiation effectively preserves protein contents in hazelnuts for long-term storage (6 months), and other studies confirmed irradiation deactivates pathogens (*E. coli*, *Salmonella* spp., *Listeria monocytogenes*) in pistachio nuts, with minimal alteration in nut color (Koç Güler et al., 2017; Song et al., 2019). Despite these advantages, non-thermal food processing technologies have drawbacks, such as incomplete inactivation of pathogens, scale-up issues, unexpected chemical reactions, and unreliable process control.

In the last decade, growing attention has been paid to the topic of tree nut processing among researchers. Figure 1a illustrates the trend in research published over the past ten

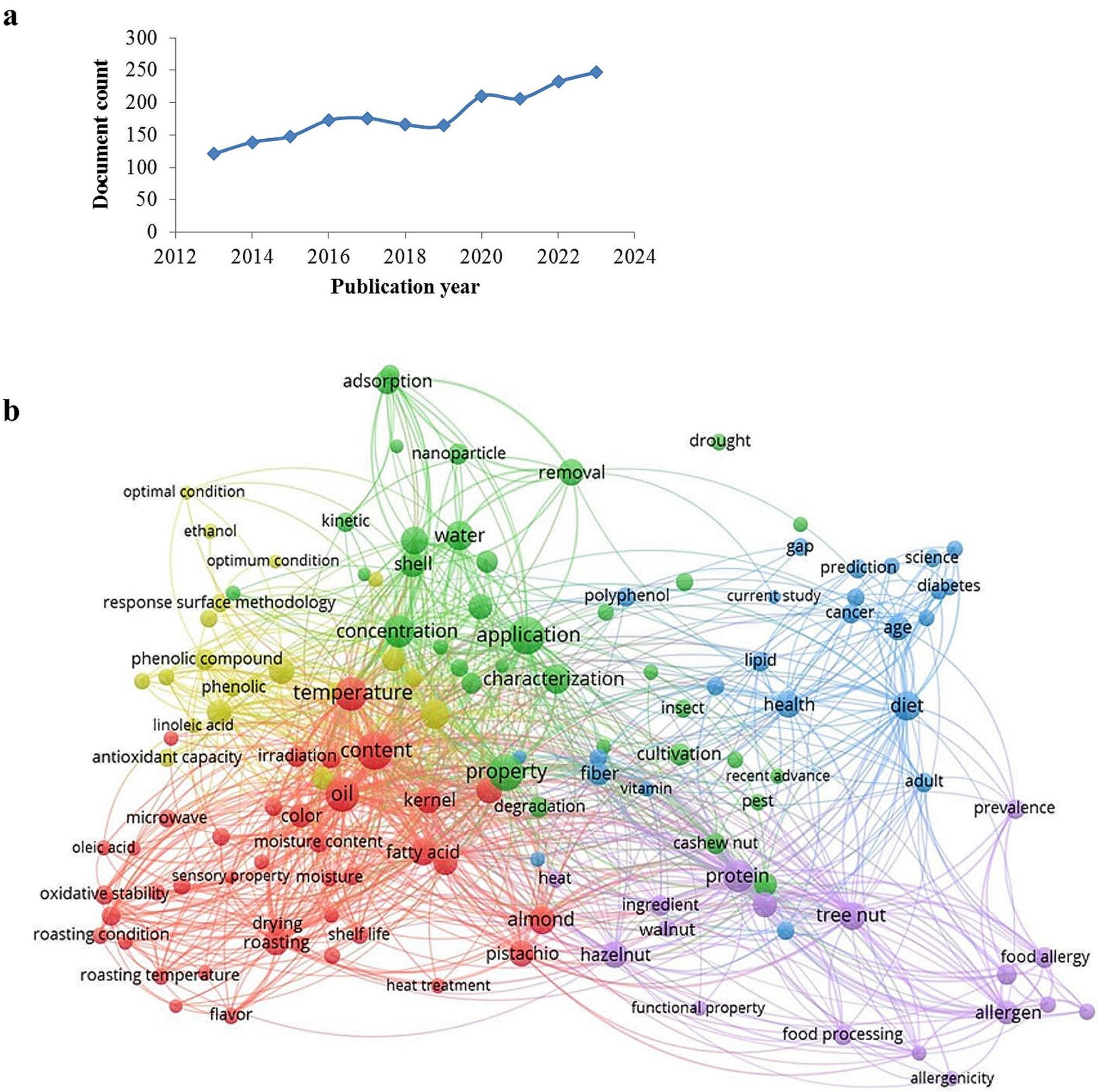

Fig. 1 Research trend in tree nut processing showing (**a**) the number of scientific articles published over the past ten years (2013–2023) and (**b**) the corresponding network visualization

years on this subject using the keyword "tree nut processing" (data was processed using 'The Lens' tool, provided by Lens.org [https://www.lens.org/]). The increasing number of publications indicates the continued relevance of this topic. A total of 1984 research and review articles involving tree nut processing were published between 2013 and 2023. Figure 1b depicts the topic network associated with this research area. Each circle represents a term extracted from the titles and abstracts of the publications within the dataset. The placement of terms is determined by their co-occurrences in the dataset, with closer proximity indicating higher co-occurrence. Larger circles denote a higher frequency of terms. Most reviews focus primarily on thermal technologies involving the following topics: nut safety during processing and storage (Chen & Pan, 2022); nut processing and phytochemicals (Lu et al., 2022); roasting and phenolic compounds (Chang et al., 2016); the effect of nut structure and processing on lipid bioavailability (Li et al., 2023); and pre- and post-harvest effects on pecan quality (Siebeneichler et al., 2023). Recently, Sáchez-Bravo et al.

(2022) reviewed non-thermal technologies in nut processing, but focused only on food safety impacts (i.e., microorganism deactivation and inhibition). To date, no review has focused on the physicochemical property changes in nuts due to both thermal and non-thermal processing.

In this article, commonly consumed tree nuts (i.e., almonds, hazelnuts, pecans, cashews, walnuts, pistachios) and selected properties/characteristics of them are examined. The current technological status of (1) thermal processing (i.e., drying, roasting, blanching) and (2) non-thermal processing (i.e., high-pressure, irradiation, cold plasma, pulsed electric field (PEF), radio frequency heating) for tree nuts (including some minor nuts like pine nuts) is evaluated. Importantly, we focus on the physical (color, flavor, and texture) and chemical (lipids, proteins, and phytochemicals) changes that nuts undergo as a consequence of processing. Finally, challenges and future perspectives in this area are discussed.

Tree Nuts and Their Physical and Chemical Properties

Tree nuts come in different colors and flavors depending on their type, origin, and the processing method employed. For instance, almonds with their brown skin removed have a beige to light brown color, while walnut halves have a golden brown to dark brown color (Chen & Pan, 2022; Das et al., 2014). Nuts contain high amounts of lipids, primarily unsaturated fatty acids, which confer their unique flavor (buttery, nutty) and health benefits; however, these PUFAs are particularly vulnerable to oxidation. Nuts also contain protein, dietary fiber, vitamins, minerals, and a variety of phytochemicals (e.g., phenolics) (Bolling et al., 2011; Chang et al., 2016).

Almonds

Almonds (*Prunus amygdalus*) are drupes consisting of an edible kernel with two cotyledons. The pericarp of almonds contains a green hull, which turns brown when dried, and a hard, pitted shell. The outer skin of almonds comprises a thin layer known as the testa (Grundy et al., 2016). Almonds originated from Asia and are the most produced tree nut globally, with over 1.6 million metric tonnes produced in 2021 (International Nut & Dried Fruit Council, 2022). Almonds transform into seeds with a light brown outer layer and a creamy-colored inner core when fully dried. They possess a desirable nutty, creamy flavor and succulent mouthfeel due to their high-fat content. Chemically, almonds are a good source of lipids, proteins, dietary fiber, phytochemicals (phenolics), and minerals (Bernat et al., 2015). Key phenolic compounds present in almonds include flavan-3-ols (e.g., catechin), flavanones (e.g., naringenin), flavonols (e.g., dihydroflavonol), hydroxycinnamic acids (e.g. ferulic, sinapic, *p*-coumaric acid), and high-molecular-weight compounds such as procyanidins, prodelphinidins, and propelargonidins (Chang et al., 2016; Xie & Bolling, 2014). (+)-Catechin has been detected at high levels in almond cultivars (Massantini & Frangipane, 2022), while ferulic acid, naringenin, and *p*-coumaric acid were reported to be present at relatively low quantities compared to other phenolics. Several studies confirmed that almonds are rich in α-tocopherol (vitamin E; natural antioxidant), suggesting that almonds could be stored under ambient conditions for extended periods because of the presence of this fat-soluble natural antioxidant (Çelik et al., 2019; Kodad et al., 2011, 2018; Massantini & Frangipane, 2022).

Hazelnuts

Hazelnuts (*Corylus avellana*) are mostly grown in Turkey as well as temperate forests of the United States (Dobhal et al., 2018). They are edible nuts with a pleasant flavor, making them economically significant to the food industry (López et al., 2012). The color of the seed skin of freshly harvested hazelnuts is light to medium brown, and the mesocarp is a creamy white. During storage, the color of the skin tends to darken. Hazelnuts taste best shortly after harvest with a mild aromatic flavor, which fades unfortunately during storage (Kurzawa & Ehrke, 2014). Hazelnuts are often added to confections (e.g., chocolate), baked goods, ice cream, and dairy products (Costa et al., 2013; Guiné & Correia, 2020). Hazelnut oil has a low viscosity (i.e., ~ 60 cP at 25 °C), which is suitable for producing margarine and butter-like products that require spreadability as a physical property (Bagheri, 2020). Hazelnuts contain lipids (mainly PUFAs), proteins, vitamins (B and E), and minerals. (Dobhal et al., 2018). Hazelnuts also possess phytochemicals, including flavonoids and other phenolics, such as gallic acid, stilbenes, coumarins, tannins, and lignans. Among these, gallic acid was reported to be most abundant (Guiné & Correia, 2020).

Pecans

Pecans (*Carya illinoinensis*) are grown in the southern United States and northern Mexico. The increased demand for pecans has triggered their cultivation in South American countries (e.g., Chile, Uruguay, Argentina, and Brazil) and Eastern Asian countries, such as China (Bilharva et al., 2018; Kang & Suh, 2022). Pecans are characterized by their mild nutty flavor, and their kernel size typically ranges from 3 to 6 g. The kernel color varies from light amber to amber.

Moisture affects kernel texture and flavor; therefore, pecans are usually stored in low-moisture environments (i.e., moisture level < 3–5%) (Kurzawa & Ehrke, 2014). Pecans contain high lipid levels (~ 70%; mainly PUFAs) and other constituents (proteins, carbohydrates, dietary fiber, vitamins, minerals, and phytochemicals/bioactives) (Alvarez-Parrilla et al., 2018). The primary nutrients are vitamins B, E, and choline (Durazzo et al., 2021; Rábago-Panduro et al., 2020). Pecans also possess abundant levels of polyphenols, carotenoids, and phytosterols, which exhibit high antioxidant activity and are a good source of proanthocyanidins (Carey et al., 2012; Chang et al., 2016; Robbins et al., 2015, 2016; Rusu et al., 2018).

Cashews

Cashews (*Anacardium occidentale*) are the third most economically valuable tree nut species in international trade after hazelnuts and almonds (Chandrasekara & Shahidi, 2011). 5% of the cashew nut (by weight) is wrapped in a thin, hard-to-remove peel (Gadani et al., 2017). Cashews have a mild, sweet taste and nutty aroma. Raw cashew kernels contain 5–6% moisture and exhibit a slightly off-white color (Minh et al., 2019b). The odor of cashews can range from nutty to slightly fishy (Kurzawa & Ehrke, 2014). They are never consumed raw and require processing before consumption. Cashews are used in confections and baked goods, such as cakes, candies, chocolates, cookies, and cereal bars (Gadani et al., 2017). Like other tree nuts, cashews are a rich source of lipids (e.g., MUFAs and PUFAs), vitamins, minerals, and dietary fiber. They also provide certain phytochemicals/bioactives (e.g., polyphenols, phytosterols) that benefit health.

Walnuts

Studies report that English walnuts (*Juglans regia*) have been cultivated since the Neolithic age. They are hard-shelled nuts with a broad global growth distribution (Guney et al., 2021; Kafkas et al., 2020). China is the top producer of walnuts, constituting > 50% of global production, followed by the United States (mainly situated in California), which accounts for ~ 33% (Colak et al., 2021). When mature, walnuts weigh ~ 10–13 g, while the kernels mass is ~ 5–7 g. The walnut kernel is round, light brown, and irregularly shaped. Walnuts taste bitter and astringent to some due to the abundance of phytochemicals, such as tannic acids (Hayes et al., 2016). Walnuts are rich in lipids (~ 65%) and proteins (15%) and possess all indispensable amino acids, with a relatively low amount of carbohydrates. Compared to other nuts, walnuts are an abundant source of vitamins (predominantly the B vitamins thiamine, riboflavin, niacin, pantothenic acid, pyridoxine, and folate, as well as vitamin E), minerals (potassium, phosphorous, calcium, and magnesium), dietary fiber, and phytochemicals/bioactives (catechin, ellagic acid, ellagitannins, juglone, and phytosterols).

Pistachios

Pistachios (*Pistacia vera*) are tree nuts that belong to the cashew family (*Anacardiaceae*). Pistachios originated from Iran and are primarily grown in the Mediterranean-type climate of California (Kola et al., 2018). Pistachios are consumed fresh or roasted and are mainly used in desserts. Pistachios are round, almond-shaped nuts with a mild spicy taste (Alinezhad et al., 2020). For confectionary products, pistachios are used as a colorant due to the yellowish-green color of their kernel and tightly adhering reddish skin. The pistachios kernel possesses a mild resinous flavor and unique texture (Kola et al., 2018). Pistachios are characterized by lipids (predominantly MUFAs and PUFAs), carotenoids, chlorophylls (i.e., providing the green color), vitamins (pyridoxine and vitamin E), and minerals (copper, manganese, potassium, and phosphorous) (Chaharbaghi et al., 2017; Kola et al., 2018). Pistachios contain various phytochemicals (e.g., phytosterols, phenolics) that confer antioxidant and anti-inflammatory properties (Mokhtarian et al., 2017).

Effect of Thermal Processing on Tree Nut Quality

Drying

Drying is a preservation technique that has been used for centuries to extend the shelf life of nuts and facilitate their storage and transport. The process improves nut quality and ensures their safety for consumption (Mokhtarian et al., 2017). There are several approaches at hand for drying nuts. Sun drying involves spreading the nuts outside for days at temperatures above 35 °C and humidity levels below 60%. The two primary heat transfer parameters affecting sun drying are temperature and airflow. Solar radiation heats the surface of the nut, which then penetrates the nut via conduction, promoting water vaporization (Ahmed et al., 2013). Higher airflows lower the vapor concentration at the nuts' surface by convectively removing water vapor, which ultimately increases the evaporative drying rate. Although sun drying is simple and economical, it has limitations. For example, dust or microorganisms contaminate the nuts during drying. Additionally, sunlight is unidirectional, while nuts are spheroidal, leading to uneven heating and possibly incomplete drying. Hot air drying has been employed as an alternative method to overcome these limitations. During hot air drying, nuts are loaded into a drying chamber or onto a conveyor belt, where fans circulate hot, dry air to evaporate moisture (more uniformly) from the nuts' surface (Ahmed et al., 2013) (Fig. 2a). This approach provides more controlled drying environments compared to sun drying, reducing the risk of contamination and promoting uniform drying. However, hot air drying requires considerable energy, making it relatively inefficient. Also, the processing parameters applied during hot air drying vary depending on the application, making it challenging to achieve optimal drying outcomes.

More advanced drying methods have been introduced in tree nut processing in response to these challenges. Examples of such methods include vacuum, microwave, infrared, and hybrid drying techniques (Lu et al., 2022). In vacuum drying, nuts are placed in a closed chamber and exposed to low pressures. The low-pressure environment reduces the vaporization temperature of the water, allowing evaporation (i.e., drying) to occur at relatively low temperatures. A condenser removes the evaporated moisture from the chamber to maintain a low vapor partial pressure. Due to the reduced processing temperature, vacuum drying retains more volatile compounds than other drying methods (Folasade & Subomi, 2016). Moreover, the vacuum removes oxygen, which helps mitigate lipid oxidation during drying. In microwave drying, heat is generated within the nuts, leading to a rapid rise in temperature. The mechanism responsible for heat generation through microwaves is dielectric heating, where dipole rotation of the water molecules (with a frequency range of 300–30,000 MHz) causes friction with neighboring molecules and atoms in the material, generating heat. This technique can reduce drying time and improve product quality, which was demonstrated when microwave-drying pistachios (Balbay & Şahin, 2013; Kermani et al., 2016). Similarly, infrared drying has been employed to dry walnuts, almonds, and pistachios (Dolgun et al., 2021; Safary & Chayjan, 2016; Venkitasamy et al., 2018). Infrared drying uses an electric or catalytic emitter to transmit electromagnetic radiation to the nut kernel, generating thermal energy (Abbaspour-Gilandeh et al., 2019). Electromagnetic radiation causes internal heating and molecular oscillation, heating the bulk material of the granule and any internal moisture. The induced internal heating drives the moisture out of the granule into a passing stream of cooler, dryer air, thereby removing moisture continuously from the granule. The advantages of infrared drying are uniform heating, high heat transfer rates, and reduced processing times and energy consumption (Ding et al., 2015; Pan et al., 2019; Venkitasamy et al., 2017).

Effect of Drying on the Physical Properties of Tree Nuts

In terms of physical properties, drying impacts the texture of nuts considerably. Depending on the technique, heating intensity and duration, drying can also affect the nuts' color, taste, and flavor (Chen & Pan, 2022). Rogel-Castillo et al. (2017) reported an increase in brown color intensity (decrease in L*, increase in a* and b* values) and loss in aroma-generating compounds of almonds in oven drying conditions (temperature range 45 to 95 °C). The increase in brown coloration is related to the concealed damage (discoloration) of nuts. The concealed damage was low at low drying temperatures (45–65 °C), while increased damage was observed at temperatures greater than 65 °C (Rogel-Castillo et al., 2017). Similarly, Turan reported that fast oven-drying (air velocity > 1.4 m/s) and higher temperatures altered hazelnut flavor undesirably, while lower temperatures and slower drying led to better nutty flavor perception (Turan, 2018). In a study on walnuts, oven drying decreased the bitter taste and increased the sweet taste of the nut (Zhou et al., 2017). For the flavor of nuts, drying nuts at low temperatures tend to conserve flavors; thereby, yielding a strongly flavored product. In contrast, drying at high temperatures (e.g., hot air drying) tends to exacerbate flavor loss, yielding a weakly flavored product. Currently, the prevailing drying techniques used in the nut industry are traditional methods such as oven drying due to its simplicity and cost-effectiveness. Nevertheless, the limitations of conventional drying techniques (e.g., deterioration in nut quality) underscore the

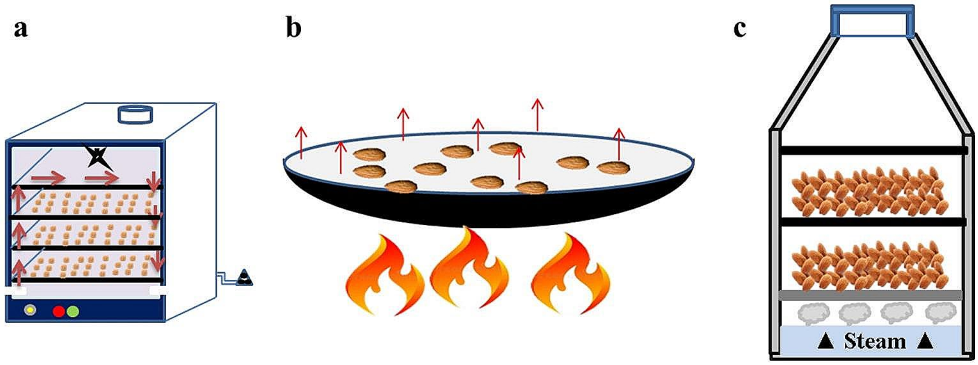

Fig. 2 Schematic diagram of thermal processing of tree nuts: (**a**) oven drying, (**b**) roasting, and (**c**) blanching

need for advanced drying techniques to minimize the quality loss of nuts.

As mentioned earlier, advanced drying techniques applied in nut processing include microwave and infrared drying. Although these techniques have only been employed at a pilot scale, they provided nuts of superior quality compared to conventional drying techniques. Abbaspour-Gilandeh et al. (2019) reported a decrease in walnut shrinkage and color loss (ΔE) when using microwave drying (microwave power: 270, 450, and 630 W) compared to oven drying. Similar results were achieved in cashew nuts from a study by Das et al. (2014). The reduced physical deterioration in dried nuts may be attributed to more uniform heating during microwave drying (Celen, 2019; Das et al., 2014). Venkitasamy et al. (2017) reported that infrared heating of pistachios at temperatures between 60 and 70 °C resulted in better physical qualities (e.g., color) with faster moisture removal rates compared to oven drying. The research team also identified and characterized the linear relationship between the total color change of nuts and drying temperature and duration.

Summarily, the extent and nature of physical changes vary by (1) nut type, (2) techniques applied, and (3) processing conditions (Turan, 2018). Temperature, air velocity, and applied power and uniformity (for advanced drying techniques) during drying are factors that directly affect heat transfer, which has a corresponding direct effect on the texture (such as hardness, shrinkage), color (as in non-enzymatic browning), and retention of flavor during nut processing. Drying concentrates the natural sugars in nuts, intensifying their sweetness and flavor, but prolonged exposure to high temperatures can lead to the development of undesirable off-flavors or even bitterness. Balancing preservation, enhancement of natural flavors, and maintaining visual appeal is crucial for consumer acceptability.

Effect of Drying on the Chemical Properties of Tree Nuts

In addition to alterations in physical and sensory properties, drying affects the chemical composition of nuts. Han et al. (2019) reported some positive effects of oven drying on the nutritional qualities of walnuts, with higher levels of chemical components, such as minerals and phenolics. A positive correlation between process temperature and phenolic level has also been shown in hazelnuts (Marzocchi et al., 2017; Özcan et al., 2018; Štěrbová et al., 2017). The process of removing moisture increases the concentration or nutrients relative to the raw nut concentration. Additionally, heat during processing may aid in the release of certain compounds (phenolics) that are bound to the nut matrix (e.g., proteins) (Juhaimi et al., 2017). However, this trend is not in agreement with Campidelli et al. (2020), who reported a decline in phenolic levels of almonds dried at 65 °C as compared to raw samples: these included caffeic, chlorogenic acid, *p*-coumaric, and ferulic acids. The reductions in these compounds are ascribed to the impact of heat, which may concurrently occur with protein denaturation (Shahidi & Yeo, 2016). The optimal oven-drying temperature for most nuts is 105°C because, at this temperature, nutrients such as proteins, soluble sugars, and fatty acids reach their highest levels (Mokhtarian et al., 2017). On the other hand, a number of nutrients and bioactives are sensitive to heat and degrade at these higher temperatures. For example, tocopherols (vitamin E) readily are oxidized at higher temperatures during drying. Minh et al. (2019b) investigated the effect of heat pump oven drying on the tocopherol content of cashews and found that they decreased exponentially with increasing temperature. High temperatures are thought to facilitate tocopherols oxidation resulting in their breakdown (Han et al., 2019). Similarly, the heat-drying process promotes the oxidation of PUFAs in nuts. Turan (2018) compared the effects of hot air and sun drying on hazelnuts and found that both approaches caused MUFA and PUFA losses via lipid oxidation: the unsaturated fatty acids – oleic, linoleic, and α-linolenic – were the most affected. The decomposition of these fatty acids will result in the generation of alcohols (1-propanol, 2,3-butanediol, aldehydes (hexenal, nonanal), ketones, and other products, as the drying temperature increases. Hexanal is a common oxidation product of linoleic acid and it has been related to rancid off-flavors in tree nuts. These chemical changes result in decreased stability of tree nuts during storage by promoting early rancidity development.

Despite limited data, advanced drying techniques might be a solution to reduce the chemical changes in nuts. Das et al. (2014) reported a decrease in peroxide and free fatty acid values (related to lipid oxidation and decomposition) in microwave-dried cashew nuts, and they confirmed these values can remain stable over a six-month storage period. This result suggests microwave treatment may deactivate lipase enzymes responsible for lipid oxidation and decomposition, thereby preventing chemical deterioration in nuts during storage. The ability of microwave drying to reduce moisture rapidly may help extend the shelf life of nuts and preserve their chemical qualities (Das et al., 2014). More research is needed, however, to characterize how advanced drying techniques affect the chemical properties of nuts, i.e., changes in phenolics, minerals, and vitamins.

Application of Novel Drying Techniques to Tree Nuts

Recently, drying methods have further improved, although they have not been studied yet in nut processing. Examples include cooling with dehumidification (CWD), supercritical CO_2 drying, and combining two or more drying techniques, often called hybrid or hurdle drying. CWD dries food by pumping the surrounding air through a condenser to remove moisture. The CWD technique can be applied to heat-sensitive food products (Uthpala et al., 2020). CWD is reported to yield consistent product quality in terms of color, aroma, taste, and texture, with better preservation of heat-sensitive nutrients and phytochemicals/bioactives (Ng et al., 2017). Supercritical-CO_2 drying employs CO_2 as a drying medium, resulting in minimal product shrinkage, improved rehydration capacity, and better preservation of heat-sensitive compounds. Hurdle or hybrid drying techniques, such as a traditional drying method combined with solar-assisted drying, heat pump-assisted drying, or microwave-assisted drying, also have gained attention due to their potential to reduce quality degradation and maintain process efficiency with less energy input and shorter processing time (Lv et al., 2022; Thamkaew et al., 2021). Each of these newer drying technologies has special merits (e.g., preservation of bioactive compounds, retention of textural and microstructural properties) (Xu et al., 2020), thus warranting further investigation for tree nut processing applications.

Roasting

Roasting of nuts has been employed for centuries as a thermal processing technique. Unlike drying, the primary objective of roasting is not to eliminate moisture, rather to impart nuts with characteristic color and flavor (Chen & Pan, 2022). Tree nuts can be roasted in different ways (e.g. hot air vs. oil roasting, variations in heating times and duration) resulting in a light, medium, or dark roast depending on the color and moisture content (Grundy et al., 2016). Roasting involves applying heat > 90 °C (194 °F) conductively and convectively to a desired level of doneness (Fig. 2b). Different roasting conditions, either by low temperature (120–140 °C), moderate temperature (140–160 °C), or high temperature (160–180 °C), are applied depending on the nut type.

Effect of Roasting on the Physical Properties of Tree Nuts

Roasting confers various consumer-preferred tastes, aromas, and colors (yellow-to-brown), improving the nuts' appeal. During roasting, moisture loss results in a crunchy texture, and high temperatures trigger reactions between sugars and amino acids, leading to non-enzymatic browning reactions (i.e., Maillard browning). Consequently, the Maillard reaction initiates the formation of various volatile heterocyclic by-products (e.g., pyrazines, furans, pyrroles) that give rise to pleasant roasted flavor notes (Chen & Pan, 2022). Nuts roasted at low-to-moderate temperatures tend to appeal more to consumers. High-temperature drying has been reported to impart a bitter taste and over-roasted aroma in nuts such as pistachio (Schlörmann et al., 2015). Grundy et al. (2016) applied a two-step roasting technique to almonds. The first step involved using an intermediate temperature to stabilize the microstructure of the nut, while the second step, conducted at a higher temperature, was intended to generate a distinctive roasted flavor and brown color. Moisture loss and the Maillard reaction occurred during the roasting process (Grundy et al., 2016). Roasting can also lead to the coalescence and formation of larger oil droplets in nut cells, resulting in brittle, crunchy products that create more loose particles while chewing, compared to their whole, raw nut counterparts (Grundy et al., 2016; Karaosmanoğlu, 2022; Olatidoye et al., 2020). Karaosmanoğlu (2022) compared the effect of different roasting temperatures (e.g., 140 °C, 160 °C) on the color and browning index of hazelnuts. As the temperature increased, a decrease in the L* value and an increase in a* and b* values were observed. The browning index also increased under high-temperature conditions. For roasting, applied temperatures and duration are considered the primary factors influencing the physical characteristics of nuts. At elevated temperature conditions (> 150 °C), another type of browning reaction starts to occur alongside the Maillard reaction, referred to as caramelization (decomposition of sugars). Caramelization might contribute to the bitter taste and over-roasted aroma associated with the high-temperature roasting of nuts. The above factors and reactions collectively impact the texture, flavor, and color of the roasted nuts (Karaosmanoğlu, 2022; Marzocchi et al., 2017).

Effect of Roasting on the Chemical Properties of Tree Nuts

Like heat-induced drying, roasting can cause the degradation of beneficial nutrients and bioactives (e.g., vitamins, carotenoids, and unsaturated fatty acids). One study found that almonds lost up to 50% of their α-tocopherol (vitamin E) by roasting (170 °C for 20 min). Tocopherols comprise four isoforms (α, β, ϒ, δ): α-tocopherol is abundant in hazelnuts and almonds, and ϒ- tocopherol is moderately present in pecans, pistachios, and walnuts. The level of α-tocopherol decreased significantly in hazelnuts with an increase in roasting temperature (Stuetz et al., 2017). Results also show roasting duration affect tocopherol content. The observed trend in tocopherol is due to one or more of the following factors which include the following: heat-induced degradation, oxidation, reaction with volatile compounds, Maillard reaction, and surface migration (Çelik et al., 2019). Generally, longer roasting periods at higher temperatures resulted in more significant losses of these compounds (Stuetz et al., 2017). Cai et al. (2013) reported a gradual decrease in ϒ-tocopherol in pine nuts when roasted at 150 °C between

10 and 60 min. Interestingly, α-tocopherol initially decreased at 10 to 30 min and then slightly increased after 60 min. Prolonged heating may have liberated α-tocopherol bound to the nuts' structural wall components (kernel) (Cai et al., 2013). In addition, Durmaz & Gomen (2011) measured a dramatic loss of carotenoids (antioxidants; some are vitamin A provitamins) in pistachios during drying and roasting (Durmaz & Gökmen, 2011). The level of polyphenols and their antioxidant activities decreased in pecans under high temperatures and prolonged heat exposure during roasting (Amarowicz & Pegg, 2019).

In addition to nutritional loss, roasting can give rise to toxic compounds, such as 2'-thiobarbituric acid reactive substances (TBARS) and acrylamide, a Group 2a carcinogen, according to the World Health Organization (WHO). Acrylamide is formed during the Maillard reaction, starting from interactions between α-amino acids (primary amino acids in nuts: lysine, arginine, histidine, cysteine) and carbonyl carbons of reducing sugars (sugars in nuts: glucose and fructose). Roasting temperatures > 120 °C accelerate these reactions, yielding larger amounts of acrylamide. Studies show acrylamide formation in nuts (e.g., almonds, pistachios) is driven primarily by roasting temperature rather than roasting time (Schlörmann et al., 2015). TBARS can also be generated in nuts during roasting: TBARS decrease the nutritional value of nuts, and some of these compounds can harm human health (Minh et al., 2019a). Malondialdehyde (MDA) – the primary indicator of TBARS – is produced by lipid oxidation, predominantly PUFAs (omega-3 and −6 fatty acids) oxidation. Hence, high roasting temperatures also cause a reduction in nutritional quality (loss of PUFAs) by lipid oxidation. Indeed, many studies have reported significantly increased TBARS levels in nuts (e.g., almonds and hazelnuts) due to roasting (Barreira et al., 2008; Cai et al., 2013; Vera et al., 2018). To summarize, roasting is a double-edged sword: careful consideration of the temperature, duration, and methods employed is essential to optimize the desirable quality, nutrition, and safety of roasted tree nuts. Striking a balance between the benefits and challenges of roasting is crucial for both consumers and the food industry. Minimizing the formation of undesired adducts and nutritional loss during roasting requires further research in process optimization, new approaches, and technology integration.

Application of Novel Roasting Techniques to Tree Nuts

The growing demand for roasted foods, together with concern for food safety, has led to novel roasting techniques and equipment. Like drying, newer roasting technologies have been introduced for different foods (e.g., coffee, cocoa beans), but have not yet been applied in tree nut processing. Technologies include superheated steam roasting and infrared (IR) roasting. Roasting by superheated steam is a technology whereby the steam is heated beyond the saturated vapor point. This processing requires a relatively short contact time, which minimizes the loss of heat-sensitive compounds (Yodkaew et al., 2017). Similarly, IR roasting heats the product by applying IR radiation, with reduces roasting time and energy consumption (Bagheri, 2020; Mazaheri et al., 2019). In the electromagnetic spectrum, IR radiation exists across a wavelength range of 0.5 to 1000 µm. IR radiation is categorized into three distinct regions: near-IR (0.78–1.4 µm), medium-IR (1.4-3 µm), and far-IR (3-1000 µm). Selecting the appropriate wavelength for a specific food-related task is of paramount importance, as it significantly affects the temperature, emissivity of the emitter, and the absorption intensity of food components (Sruthi et al., 2021). The two aforementioned techniques involve rapid surficial heating that could better preserve food aromas and sensory qualities. Given the advantages of superheated steam and IR roasting, it is worth developing specific applications for nut processing.

Blanching

Blanching involves applying mild heat to fresh agricultural commodities to denature enzymes so as to maintain product quality during storage. In nut processing, blanching serves as a pretreatment step prior to drying or roasting. Raw nuts are exposed to hot water or steam around 100 °C for short periods (i.e., 2–10 min), then rapidly cooled to room temperature before drying or roasting (Folasade & Subomi, 2016; Kumar et al., 2021). Nuts destined to be used for other products such as nut butters can be dry-blanched (hot air for 2-10 min) to facilitate removal of nut skins as well as to inactivate enzymes and microorganism prior to shipping and storage.

Effect of Blanching on the Physical Properties of Tree Nuts

Blanching helps increase cell membrane permeability; thus, increasing moisture removal rates during drying or roasting (Xiao et al., 2017). (Oliveira et al., 2020) conducted a study in which they compared raw almonds with two different roasted almond varieties: blanched-roasted almonds (30 s in hot water) and unblanched-roasted almonds. The findings revealed significant improvements in several aspects for the blanched-roasted almonds, including enhanced skin color lightness, skin integrity, increased chew hardness, and a reduction in both bitter taste and bitter almond flavor, when compared to the unblanched almonds. Consumer testing revealed a positive rating for blanched-roasted almond in terms of crispiness, crunchiness, and sweet taste as compared to unblanched counterparts. Recently, Luo et al. (2023) investigated the effect of different blanching methods (IR blanching, hot-water blanching) on pecan quality. An increase in L* and a* values were observed in the hot-water blanched samples, compared to the IR blanched samples, which is likely as a result of the inactivation of lipoxygenase and polyphenol oxidase, and a decreased chlorophyll content in hot-water blanched pecan kernels. The color difference (ΔE) value was greater in the hot-water blanched samples than the IR blanched samples.

Effect of Blanching on the Chemical Properties of Tree Nuts

Blanching significantly reduces the antioxidant activity of almonds as compared to unblanched samples. This may be as a result of antioxidant leaching such as β-carotene during the blanching operation. Lipid oxidation was not significantly affected by blanching. When nuts are to be processed into beverages, blanching is often used to remove the outer skins of tree nuts, leaving behind the inner creamy white kernel. Blanching was reported to substantially reduce specific allergens in almonds, hazelnuts, and walnuts (Vanga & Raghavan, 2017). Shakerardekani and Abdolhossein found no significant difference in the physical properties of pistachios after blanching at mild temperatures (75–95 °C) (Shakerardekani & Abdolhossein, 2019). Yet, blanching still seems to impact certain heat-sensitive nutrients adversely. For instance, blanching decreased the antioxidant activity of flavonoids and other phenolic compounds in almonds (Franklin & Mitchell, 2019). Cam and Kilic (2009) also measured decreased phenolic and flavonoids in blanched hazelnut. In general, blanching has been used on nuts to enhance drying rate and product quality, such as color, sweet flavor, and texture; however, water-soluble compounds and heat-sensitive antioxidant constituents are depleted during the process. Water blanching may be responsible for the leaching of vitamins, minerals, proteins, and some sugars, thereby lowering the nutritional quality of the nuts. To mitigate this challenge, the choice of temperature/time of exposure and method of cooling is very crucial to reduce the losses of water-soluble nutrients. It is also noteworthy to point out that traditional blanching generates a high volume of effluent that requires additional cost of treatment before discharging into water bodies.

Application of Novel Blanching Techniques to Tree Nuts

Emerging blanching technologies such as ohmic, IR, gas, microwave, high humidity hot air blanching, and novel hybrid (thermal blanching with ultrasound, steam-blanching with vacuum) have been developed. They have been reported to significantly accelerate heat transfer, be energy efficient, reduce blanching time and nutritional losses thereby yielding a higher quality product (Bassey et al., 2021). To date, these emerging blanching techniques have rarely been applied to tree nuts. Exploring the relationship between these technologies and the product quality, safety, large scale practicability and cost efficiency of tree nuts will provide substantial data that could be useful for nut industries. A summary of thermal processing effects of tree nuts is presented in Table 1.

Effect of Non-thermal Processing on Tree Nut Quality

Non-thermal processing technologies use mechanisms other than temperature to inactivate microorganisms and enzymes in foods, with minimal effects on color, texture, flavor and heat-sensitive bioactive compounds (Rajashri et al., 2020; Roselló-Soto et al., 2018). Although some limitations exist (e.g., incomplete inactivation of pathogens), the development and advancement of non-thermal technologies have opened up new opportunities in food processing, which could extend the shelf life of foods and improve food safety while mitigating nutritional losses (Barbhuiya et al., 2021; Sánchez-Bravo et al., 2022). The study of non-thermal technologies applied to tree nuts is still in its nascent stages, resulting in limited research regarding their impact on their physicochemical properties. Non-thermal processing techniques employed on nuts include HPP, irradiation, PEF, cold plasma, and radio frequency heating. (Fig. 3; Tables 2 and 3).

HPP

HPP applies pressures ranging from 100 to 1200 MPa to food products for short periods (typically 3–5 min) (Ekezie et al., 2018). An HPP system includes a water-filled chamber pressurized by mechanical compression (Fig. 3a). Pressure is swiftly and consistently distributed throughout the food system, regardless of the food product's size and geometry. This is in contrast to heat processing, where heat gradually spreads through the food system. This rapid pressure transmission results in shorter processing times, reduced energy consumption, and a decreased likelihood of over-processing bulky food items (Barba et al., 2015). High pressures inactivate microorganisms and macromolecules by altering cell wall/membrane and destroying molecular structures (Jadhav et al., 2021). Primarily, HPP has been utilized to enhance food safety and prolong the shelf life of premium food products. This technique can be applied to whole raw nuts or nut products such as nut milks and nut butters (Sánchez-Bravo et al., 2022).

Table 1 Summary of thermal processing applications involving tree nuts

Tree nuts	Processing techniques	Treatments	Effect on physical and sensory properties	Effect on chemical properties	References
Almond	roasting	roasting at 146 °C for 14 min hot air roasting at 165 °C for 20 min	brown roasted color ↑ nutty flavor ↑ L*↓, a*↑, b*↑ hardness↓, chocolate, woody, nutty flavor↑, citrus and lemon flavor↓	amadin (almond protein) structure disruption, TPC and FRAP ↓ lipid oxidation and TBARS ↑ SFA↑, MUFA and PUFA↓, aldehydes, pyrazine↑, lipid oxidation ↑	(Grundy et al., 2016) (Hojjati et al., 2016)
	drying	forced air oven-drying at 65 °C for 30 min hot air drying at 85 °C for 30 min	not determined L*, a* ↑ b* value ↓	protein denaturation↑ caffeic acid, chlorogenic acid, *p*-coumaric acid, ferulic acid, quercetin, anthocyanins, and PUFA ↓, lipid oxidation↑	(Campidelli et al., 2020; Rogel-Castillo et al., 2017)
	blanching	immersed in boiling water for 30 s	fruity and bitter almond flavor ↑ first chew hardness↑ bitter taste↓	protein content—, lipid content ↓, TPC, TFC, DPPH•↓ SFA, MUFA,↓, PUFA↑	(Folasade & Subomi, 2016; Oliveira et al., 2020)
Walnut	drying	vacuum drying and hot air drying	not determined	TPC, TFC, and fatty acids, sugar ↑	(Han et al., 2019)
	roasting	two step roasting; HAHA, HARF, HAMW	roasted, milky, nutty and fatty flavors ;HAMW > HAMW > HAHA brittleness and chewiness, HARF > HAMW > HAHA	not determined	(Jia et al., 2023)
Pistachio	roasting	roasting at 120 °C for 30 min (control; unroasted)	brown color ↑, L*↓, a*↑, b*↓ nutty flavor ↑	TPC↑ and DPPH• —, tocopherols, lutein and β-carotene↓ fatty acid—	(Durmaz & Gökmen, 2011)
	drying	drying at 45 °C for 34 h (control; raw pistachio)	sweet taste ↑	TPC, TFC, FRAP, and DPPH•↓	(Tsantili et al., 2011)
	blanching	blanched in boiling water containing 0.5% citric acid	hardness↓ brown color —	protein content, oleic and linoleic acids ↓	(Luh et al., 2007)
Hazelnut	roasting	roasting at 140 °C for 15 min	roasted nutty flavor ↑	TPC ↓	(Schmitzer et al., 2011)
	blanching	heat treated in an incubator at 120 °C	hardness ↓ brown color —	PUFA ↓	(Cam & Kilic, 2009)
Pecan	drying	oven drying (control; raw pecan)	not determined	lipid content —, TPC TFC, condensed tannins, DPPH•, and ORAC —	(Rábago-Panduro et al., 2020)
	roasting	stir-frying at 200 to 400 °C for 10 to 30 min	dark color ↑ buttery flavor↑	tocopherols, TPC, and TFC ↓	(Yang et al., 2015)
	blanching	hot-water blanching at 90 °C for 60s (control; unblanched) IR blanching (600 W for60s)	L*↓ a* b*↑, browning index↑ L*a*↑b*— browning index ↑	lipid oxidation rate ↓, TPC, DPPH•↑ TPC, DPPH•↑	(Luo et al., 2023)
Cashew	drying	drying at 35 °C followed by 125 °C for 25 min	crispiness ↑ buttery flavor —	tocopherols, TPC, and TFC —	(Minh et al., 2019b)
	roasting	roasting at 130 °C for 30 min	brown color ↑ nutty flavor ↑	TPC, and DPPH•↓ proanthocyanidins, and flavonoids ↑	(Chandrasekara & Shahidi, 2011)

TBARS = 2'-thiobarbituric acid reactive substance; TFC = total flavonoids content; TPC = total phenolics content; FRAP = ferric reducing antioxidant power; SFA = saturated fatty acids; MUFA = monounsaturated fatty acids; PUFA = polyunsaturated fatty acids; DPPH• = 2,2-diphenyl-1-picrylhydrazyl radical assay; ORAC = oxygen radical absorbance capacity, HAHA = hot-air-hot-air; HAMW = hot-air-microwave; HARF = hot-air-radiofrequency ↑=increase, ↓=decrease, —=unchanged

Effect of HPP on the Physical Properties of Tree Nuts

While HPP is not typically used for disinfecting whole raw nuts, it has found application in the treatment of nut beverages such as nut milks. HPP has a minimal effect on the nuts' color and flavor. Tsai et al. (2018) compared the effect of HPP and thermal processing on hazelnut milk: thermal processing yielded darker product (ΔE = 17.05),

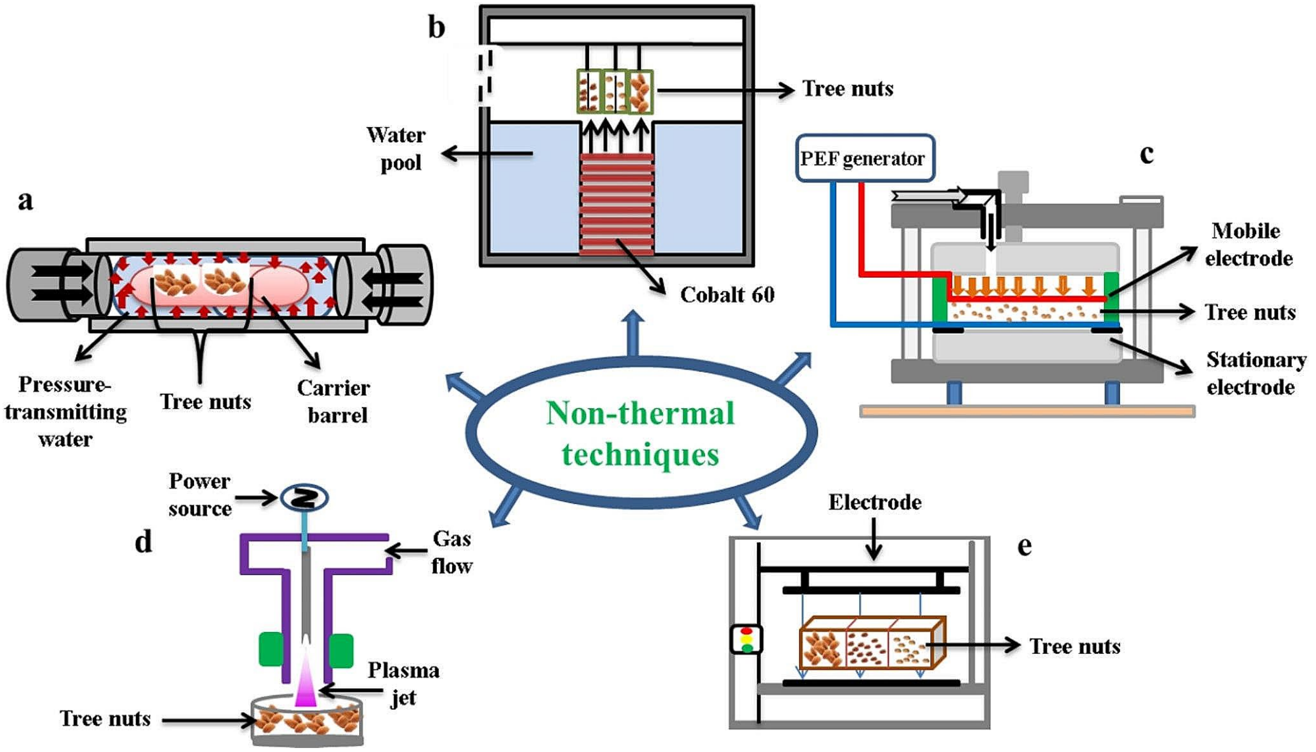

Fig. 3 Schematic diagram of non-thermal processing of tree nuts: (**a**) HPP, (**b**) irradiation, (**c**) PEF, (**d**) cold plasma, and (**e**) radio frequency heating

Table 2 Summary of the non-thermal processing on tree nuts

Tree nuts	Processing techniques	Treatments	Effect on physical and sensory properties	Effect on chemical properties	References
Almond	HPP	high pressure at 62, 103, and 172 MPa	whiteness index ↑ chroma↓, L* —, hue↓	denaturation of proteins at 103 and 172 MPa	(Bernat et al., 2015)
	PEF	electric field strength of 18 kV/cm for 500 µs, pulse frequency of 1 kHz	L*—, a*↓, b*↑, hue —, chroma and browning index↑	TPC, TFC, condensed tannins, anthocyanins, and DPPH ↑	(Manzoor et al., 2019)
	cold plasma	argon cold plasma	L*a*b*, hue — hardness —	peroxide value —	(Sánchez-Bravo et al., 2022; Shirani et al., 2020)
Walnut	irradiation	1–7 kGy using ^{60}Co (12 mo)	not determined	proteins, and stearic, oleic, palmitic acids —	(Gecgel et al., 2011)
	cold plasma	low-pressure cold plasma	L*↓, a*—, b*↓ chroma, hue ↓ ↑ firmness ↑	peroxide value —	(Ahangari et al., 2020)
Pistachio	γ-irradiation	1–6 kGy using ^{60}Co	L*↓, a*↑, b*—, chroma — hardness—, crunchiness ↑	TPC, DPPH, ↑fatty acids↑, soluble proteins, and carotenoids ↓	(Alinezhad et al., 2020)
	cold plasma	dielectric barrier discharge cold plasma	L*—, a*↑, b*↓ hardness —	soluble proteins ↓ TPC —, DPPH↑	(Makari et al., 2021)
Hazelnut	HPP	high pressure at 200, 400, and 600 MPa	color (ΔE)↑	TPC and TFC, SFA, MUFA, PUFA —	(Tsai et al., 2018)
Pecan	PEF	electrical conductivity in tap water at 463 µS/cm	brown color —	TPC, TFC, and tannins ↑	(Rábago-Panduro et al., 2021)
Cashew	γ-irradiation	0.25-1 kGy using ^{60}Co	not determined	lipid oxidation ↑ antioxidant activity ↓	(Mexis & Kontominas, 2009)
	radio frequency heating	12 kW, 27.12 MHz RF system with parallel electrodes	nutty flavor ↑ crispiness ↑	DPPH — peroxide value ↓	(Liao et al., 2018)

TFC = total flavonoids content; TPC = total phenolics content; DPPH = 2,2′-diphenyl-1-picrylhydrazyl antioxidant capacity; ↑=increase, ↓=decrease, ━=unchanged

Table 3 Comparison of non-thermal processing techniques in nut processing

Processing Techniques	Advantages	Disadvantages	References
Non-thermal processing	• retention of heat-sensitive compounds • preservation of sensory and nutritional quality • no toxic compounds generated from heat-induced chemical reactions • improved shelf life stability (compared to thermal processing) • applicable for whole nut, nut oil, and beverages	• incomplete inactivation of pathogens • hard to achieve the desired physical appearance and sensory properties (e.g., roasted flavor) • unwanted chemical reactions • insufficient data and industrial applications • initial cost is expensive	(Chacha et al., 2021) (Mandal & Kant, 2017) (Boye & Arcand, 2012) (Picart-Palmade et al., 2018) (Kurpiewska et al., 2019) (Pal, 2017) (Bhat et al., 2020) (Shorstkii et al., 2020) (Handayani & Permawati, 2017) (Zinoviadou et al., 2015; Ziuzina et al., 2015) (Altemimi et al., 2019)
	[HPP] • additional energy (e.g., cooling) not required • reuse of transmission and pressurization water • environment-friendly	• batch processing (not continuous processing)	
	[irradiation] • efficient detoxification of aflatoxins	• alterations in functional and sensory qualities at high doses	
	[PEF] • high yields of oil extraction from nuts • extraction of bioactive compounds • minimal energy requirements	• incomplete inactivation of microbial spores • high cost of scaling for industrial processing	
	[cold plasma] • modify protein (allergen) structure and solubility • decreased antigenicity of nuts • minimal waste or residue generation	• lack of plasma chemistry knowledge • possibility of free radical generation (lipid oxidation with off flavor formation)	
	[radio frequency heating] • precise power control	• lack of knowledge and data	

compared to a product from HPP ($\Delta E = 3.92$). Furthermore, the taste of thermally processed samples was perceived less sweet than that of HPP samples, suggesting that fructose and glucose levels decrease as a consequence of thermal processing, maybe due to Maillard browning. There is currently limited information on the effect of HPP on physical properties of tree nuts. Further physical parameters such as alterations in texture of nuts by HPP need to be elucidated.

Effect of HPP on the Chemical Properties of Tree Nuts

HPP can affect macromolecules such as proteins. Hydrogen bonds can form between amino acid side chains or backbone atoms in proteins subjected to HPP. High pressures disrupt the electrostatic interactions that ordinarily stabilize amino acid side chains within the protein structure, compromising its structure and function. While HPP is typically applied to fruit juices and beverages, several HPP applications involving tree nuts also exist.

For instance, Cuadrado et al. (2018) investigated the effect of HPP on the proteins of cashews, almonds, pistachios, and hazelnuts (Cuadrado et al., 2018; Pérez-Andrés et al., 2018). These researches showed protein degradation increased via HPP, including allergenic proteins, and decomposition behaviors differed between nut types. Under HPP, hydrogen bonds within the proteins' secondary structure (e.g., α-helix, β-sheet) break down, leading to structural modifications (Pérez-Andrés et al., 2018). High pressures exceeding 500 MPa were also reported to cause lipid oxidation in almonds and walnuts (Medina-Meza et al., 2014). Here, HPP is thought to break down lipid molecules into smaller, reactive compounds that more readily oxidize (Medina-Meza et al., 2014). Most low-molecular-weight compounds are unaffected by HPP (Barba et al., 2015). Finally, a study revealed that HPP does not alter the vitamin content of almond milk, implying this method can preserve heat-sensitive nutrients (Briviba et al., 2016).

Advantages, Limitations, and Applicability of HPP to the Tree Nut Industry

HPP offers several distinct advantages in terms of food preservation. First, the application of high pressure is not contingent on the size or geometry of the food, making it a versatile technique to the nut industry due to variation in geometry of tree nuts. It also holds the potential to reduce or even eliminate the need for chemical disinfectants, enhancing nuts' overall nutritional quality and safety during storage. HPP is further advantageous due to its uniformity, ensuring that no nut particles escape during treatment. Despite these advantages, HPP still has drawbacks that limit its commercial application to the nut industry. Commercial benefits of HPP technology require more research to fill the gaps, to fully understand the process, and to reduce production costs. In terms of applicability, HPP has the potential to be used as a pre-treatment prior to drying and roasting of nuts. The growing demand of tree nuts as a functional ingredient in food products will also require improved functionality. HPP can thus be employed to improve nutritional retention and extraction, rehydration capacity, as well as texture and color optimization of tree nuts to fit specific applications.

Irradiation

Food irradiation involves exposing foods to doses of ionizing radiation (e.g., γ-rays, X-rays, electron beams) (Fig. 3b) (Rajashri et al., 2020). The irradiation dose is a function of radiation intensity and duration. Food irradiation is also called 'cold pasteurization', because it takes place at low temperatures (Alinezhad et al., 2020). Impinging radiation excites or liberates electrons, generating high-energy molecular ions and highly reactive free-radical species that deactivate microorganisms and interact with food components (Fan & Niemira, 2020). Irradiation is controversial, because consumers equate irradiation with radioactivity and fear that the process induces radioactivity in foods. After considerable research, the Food and Agricultural Organization of the United Nations (FAO) and the WHO unilaterally concluded that irradiated foods are safe to eat, and pose no toxicological or nutritional hazards. Irradiation has also been proven to inactivate foodborne pathogens and toxins (e.g., mycotoxins) without altering the foods' physical or chemical properties.

Effect of Irradiation on the Physical Properties of Tree Nuts

Koç Güler et al. (2017) reported that irradiated hazelnuts did not undergo significant changes in their water activity, moisture content, and color during long-term storage (6 months). Furthermore, an effective deactivation of pathogens (*E. coli*, *Salmonella* spp., *Listeria monocytogenes*) in pistachio nuts with minimal alteration in nut color was reported after irradiation (Koç Güler et al., 2017; Song et al., 2019). Other irradiation studies involving walnuts and cashews gave similar results (no color changes); however, some off-flavor notes were detected. Most likely, the free radicals generated during irradiation caused these off-flavors via non-specific lipid oxidation (Ma et al., 2013).

Effect of Irradiation on the Chemical Properties of Tree Nuts

Regarding chemical properties, γ-rays were reported to preserve the overall nutritional quality of pistachios, hazelnuts, cashews, walnuts, almonds, as well as other beneficial attributes such as total phenolics content, antioxidant activity, and sensory properties (Alinezhad et al., 2020; Koç Güler et al., 2017; Ma et al., 2013; Mexis & Kontominas, 2009). In one study, raw tree nut samples were compared with irradiated samples at different dosages. The results showed that using low- to moderate-irradiation doses (up to 5 kGy) did not change the quantities of MUFAs and PUFAs in the samples. Yet, higher doses did cause PUFA contents to decrease (Alinezhad et al., 2020). It is possible that γ-irradiation interacts with lipid molecules and accelerates reactions like oxidation, decarboxylation, dehydration, and polymerization, thereby resulting in changes to constituents of the lipid fraction (Gecgel et al., 2011). Moreover, increased irradiation doses resulted in reduced protein solubility due to γ-irradiation's proteolytic and structural effects. This phenomenon involves the conversion of low-molecular-weight proteins into less soluble high-molecular-weight aggregates. Additionally, radiation-induced unfolding disrupts hydrophobic interactions, diminishing water binding. The same trend was observed in the total phenolics content, which could be attributed to the upregulation of antioxidative pathways and the liberation of phenolic compounds resulting from irradiation-induced breakdown of glycosides (Alinezhad et al., 2020).

Advantages, Limitations, and the Applicability of Irradiation to the Tree Nut Industry

Irradiation technology holds great promise for preserving tree nuts. It is an environmentally friendly technique, leaving no residues and requiring minimal energy and materials. γ-Irradiation, when used at appropriate doses, extends the shelf life of tree nuts without introducing radioactivity (Handayani & Permawati, 2017). This process can be customized to ensure even treatment of each kernel, and importantly, it does not raise the kernel's temperature. It offers a non-chemical alternative to fumigation and is highly efficient in combating insect pests. Nevertheless, irradiation still suffers some limitations, as it was reported that it does significantly affect the tocopherol content in tree nuts (Mei et al., 2020). In terms of applicability, treatment can be carried out on bulk nuts or after packaging, with irradiation's deep penetration making it especially suitable for in-shell nuts. Moreover, depending on the volume, the cost of irradiation can be competitive compared to other treatment methods. It enhances tree nut safety while preserving the nutritional and chemical composition (Pi et al., 2022).

PEF

The PEF method involves subjecting foods to a repeating electric field (0.5 to 40 kV/cm) during short-time intervals (< 1 s) between two electrodes (Fig. 3c). PEF has emerged as a promising alternative to conventional preservation techniques such as pasteurization (Gómez-López et al., 2022). The stored electric energy in the capacitor is discharged in short, intermittent pulses, which can be tuned to prevent undesirable heating effects. During exposure to high electric field pulses, food cells undergo electroporation, establishing temporary or permanent pores within the cell membrane. The creation of these pores may cause a redistribution of the electric charge across the cell membrane, inducing secondary effects, such as membrane depolarization or electrophoresis of charged molecules (Ranjha et al., 2021).

Effect of PEF on the Physical Properties of Tree Nuts

Although the effect of PEF is still at the nascent stage, reports have shown little alteration in color, texture, and flavor of tree nuts. Manzoor et al. (2019) investigated the impact of PEF on almonds as compared to untreated samples. It was noted that L* and a* values decreased slightly; whereas, the b* value (denoting an increase in yellowness), hue, and browning index increased marginally. The alteration in color induced by PEF treatment might be associated with electroporation and the subsequent release of intracellular content. Furthermore, bioactive compounds have the potential to interact with one another as well as other biomolecules, including artificial polymeric compounds formed during processing through non-enzymatic reactions (Manzoor et al., 2019;(Mtaoua et al., 2017).

Effect of PEF on the Chemical Properties of Tree Nuts

The physicochemical effects of PEF treatment on nuts have not been elucidated, because the subject has been poorly investigated. Yet, one study suggested the interaction between the electric field and proteins might ionize carboxylic and amino moieties in proteins, resulting in protein denaturation/aggregation and disrupting their secondary (α-helix) structures (Ashogbon & Akintayo, 2014). Another study revealed that when assisted by ultrasound, PEF could efficiently retain bioactive compounds, such as phenolics, tannins, and anthocyanins (and their antioxidant activity) in almonds, possibly due to a synergistic effect (Manzoor et al., 2019). Furthermore, low-intensity PEF treatment seems to preserve the chemical integrity of nuts better than high-intensity treatment. Rábago-Panduro et al. (2021) tested PEF intensities ranging from 0.5 to 17.6 kJ/kg, and they observed 0.8 kJ/kg conserved the highest amount of total phenolics and condensed tannins.

Advantages, Limitations, and the Applicability of PEF to the Tree Nut Industry

PEF processing holds great promise for decontaminating heat-sensitive foods such as tree nuts, and offers a safe and non-toxic method (Bassey et al., 2021). The main challenge in implementing this technology for pasteurizing tree nuts is the high initial investment. The equipment needed for PEF processing, including benchtop units, lab-scale pulsers, and treatment chambers, comes at a cost. For instance, a pilot-sized pulser for nut processing can require an investment of roughly $250,000, while larger industrial units range anywhere from $450,000 to $2,000,000 (Pal, 2017).

Cold Plasma

Cold plasma has gained interest recently as a novel processing technique for decontaminating food products during processing and packaging (Hertwig et al., 2017; Pankaj et al., 2014). Cold plasma employs partially ionized gases to inactivate microbes and toxins (Bora et al., 2022). It is generated by applying an electric field to a pure gas or a mixture of gases. Under an electric field, gas molecules partly ionize, forming ions, electrons, reactive species, and excited-state molecules that comprise the plasma (Fig. 3d). Air, nitrogen, oxygen, helium, or argon are typically used as the gas medium (Barbhuiya et al., 2021).

Effect of Cold Plasma on the Physical Properties of Tree Nuts

Cold plasma does not leave behind residuals and it minimally impacts the nutritional properties of foods during and after processing. It was employed to inactivate *Aspergillus* and *Salmonella* species in almonds (Sánchez-Bravo et al., 2022). Shirani et al. (2020) reported that cold plasma had little effect on the almonds' physical and sensory qualities (i.e., hardness, color, flavor, crispiness, crunchiness). The yellowish brown color and hardness increases in almonds as the amount of time cold plasma exposure increased. Two explanations are possible for this effect: (1) the reaction between the plasma species and the moisture content, and subsequent conversion to other compounds, and (2) the breakdown of proteins, carbohydrates, and glycosides, which liberate phenols that in turn inhibit the Maillard reaction (Shirani et al., 2020). Previous research also demonstrated that cold plasma treatment did not alter the texture (hardness) of walnuts and almonds measurably (Shirani et al., 2020; Thirumdas et al., 2014). Another study investigated the effect of low-pressure cold plasma (LPCP) treatment on microbial decontamination and the physicochemical properties of dried walnut kernels. They found that LPCP effectively inactivated microorganisms with minimal impact on the color of walnuts. Samples treated at 20 W for 10 min (2.82 N) were reported to have the highest firmness as compared to untreated samples. Moreover, there was a slight increase in the L* and a* values and a decrease in b* value. The assessment of ΔE values revealed slight differences in the overall color when compared to the control, particularly in samples processed for 20 min. Among these, samples treated at 20 W for 20 min exhibited the greatest ΔE values. It is worth noting that the chroma index, which signifies color intensity or saturation, followed the same trend: this might be linked to surface oxidation and a reduced moisture content (Ahangari et al., 2020).

Effect of Cold Plasma on the Chemical Properties of Tree Nuts

Cold plasma can interact with specific proteins and lipids and may alter their structure and functionality. Protein modification occurs in cold plasma due to reactive species (e.g., reactive oxygen species) that trigger oxidative reactions and cross-linking of amino acid side chains within the proteins (Barbhuiya et al., 2021; Ulbin-Figlewicz & Jarmoluk, 2016). The alteration in the three-dimensional protein structure during cold plasma treatment is attributed to the formation of $HO^{\bullet}$. These radicals have the capability to cleave peptide and disulfide bonds, resulting in changes to the protein's configuration. This process can also lead to the oxidation of amino acids, with a particular impact on aromatic amino acids such as tryptophan (Bora et al., 2022). Cold plasma can also induce lipid oxidation in nuts during prolonged exposure and high voltage. Moreover, findings revealed a reduction in the fatty acid composition, notably in linoleic acid, which is an essential fatty acid for human nutrition (Ulbin-Figlewicz & Jarmoluk, 2016). Thus, low voltage (less than 20 kV) is recommended to avoid these effects (Amini et al., 2017).

Advantages, Limitations, and Applicability of Cold Plasma in Tree Nut Industry

Cold plasma offers varying and important advantages such as uniformity during processing, reproducibility, short reaction time, and environmental safety. Because nuts are rich in MUFAs and PUFAs, high voltages and processing times can accelerate oxidation. Applying cold plasma treatment to tree nut packaging materials offers potential benefits by enhancing their barrier properties. Whether utilized for sterilization or surface modification of packaging, cold plasma treatment influences mechanical traits and mass transfer properties, encompassing barrier functionality and substance migration (Pankaj et al., 2014). In the nut industry, cold plasma is used to deactivate pathogens and mycotoxins in nuts, with increasing their shelf life. Previous studies demonstrating the effective removal of pathogens such as *Escherichia coli*, *Salmonella*, and *Listeria* from nuts (e.g., walnuts, hazelnuts) by cold plasma treatment support its application potential to ensure nut safety and quality (Bassey et al., 2021; Rao et al., 2023). One major factor that is limiting the application of cold plasma to the nut industry is the high cost of the equipment, lack of enough information on validation, process control, and safety (Boateng, 2022). When considering industrial applications of cold plasma, it is important to consider the health and safety of the operators. Cold plasma contains reactive gas species, such as ozone, nitrogen oxides, and peroxide at considerable concentrations, which are injurious to human health during long-time exposure. To mitigate this, design engineers must put in place necessary safety measures to destroy reactive species and ozone before being discharged to the atmosphere (Boateng, 2022; Noor et al., 2019).

Radio Frequency (RF) Heating

RF heating is an indirect dielectric heating process classified as non-thermal. High-frequency electromagnetic waves ranging from 10 to 300 MHz are applied in short intervals to heat food rapidly (Ling et al., 2020). The wave penetrates the core of food products generating heat via internal conduction, surface convection, and radiation (Fig. 3e). Only select RF frequencies (13.56, 27.12, and 40.68 MHz) are permitted for industrial, scientific, and medical applications (Zhang et al., 2019). RF heating demonstrates the capability to preserve product quality while meeting stringent pasteurization criteria (with microbial reductions of at least ≥ 4 log). This is particularly advantageous for low-moisture products like raw tree nuts (Zhang et al., 2019). Recent studies have explored the utilization of RF energy in various food processing applications, blanching, drying, roasting, and pasteurization (Guo et al., 2019).

Effect of RF Heating on the Physical Properties of Tree Nuts

RF heating has been applied to certain nuts, including almonds, walnuts, and cashews. Studies indicated that RF heating improved the nuts' physical, compositional, and sensory qualities (Liao et al., 2018; Ling et al., 2020). Zhang et al. (2019) investigated the effect of RF on the quality of in-shell walnuts and reported no significant differences in L* values of kernel color after RF drying as compared to untreated samples. Liao et al. (2018) reported a higher hedonic score for taste, color, crispiness, of cashew kernels roasted with hot air-assisted RF roasting as compared with conventional oven roasting. It was also observed that the brown color was more uniform than that from conventional roasting. This could be that browning reactions occurred promptly and uniformly in the whole kernels, because the heat was generated inside the samples volumetrically (Guo et al., 2019). In a study conducted by Lian and Chen (2022), RF roasting protocols were developed for almonds. The findings revealed that roasting enhanced the crispness of almonds and created a distinctive roasted flavor. Higher L*, a*, and b* values were reported for RF-roasted almonds, as compared to oven-roasted almonds, which showed the lowest brightness. Even though the RF roasting was conducted at a higher temperature of 120 °C compared to the oven roasting at 105 °C, the color change in the almonds treated by RF was closer to that of untreated almonds, largely due to the shorter duration of RF roasting (Lian & Chen, 2022).

Effect of RF Heating on the Chemical Properties of Tree Nuts

Although very few information is available on the impact of RF heating on the proteins, fatty acids and bioactive compounds in tree nuts, RF heat treatment at s temperature up to 60 °C caused no significant changes in the proteins and fatty acids of nuts. Ling et al. (2016) reported that the water activity and fatty acid compositions showed no significant change between the control (i.e., no RF treating) and RF-treated samples during a 3-month storage period. The data also illustrated that the mean peroxide and free fatty acid values increased only after 3 months of storage for RF-treated pistachios, thereby suggesting that the inactivation of lipoxygenase occurred after RF heating. In a study by Wang et al. (2013), it was found that as the treatment time for RF-treated nuts increased, both the mean peroxide and free fatty acid values increased. This phenomenon is likely attributed to the oxidation of the PUFAs in the nut oil, which occurs more prominently at extended exposure times and higher temperatures (Wang et al., 2013).

Advantages, Limitations, and Applicability of RF Heating to the Tree Nuts Industry

RF heating boasts advantages over microwave heating due to its longer wavelength and penetration depth (Altemimi et al., 2019). This results in a more even electric field distribution and uniform heating, making RF heating particularly well-suited for bulk sample treatments in the nut industry. RF heating operates volumetrically, allowing for rapid heating of the entire sample (Lian & Chen, 2022). Primarily, RF waves excite bound water molecules making it an ideal technology for low-moisture foods, such nuts, which contain more bound water than free water (Liao et al., 2018). In nut industry, the RF heating can be used for the sterilization of bulk raw nuts as an alternative to chemical fumigation, with the extension of the shelf life of nuts. One notable example of its application includes the removal of *Salmonella* in almonds (Poltronieri et al., 2015). Just like other novel techniques, RF heating suffers some limitations. One notable one is a reduction in power density. Furthermore, the equipment needed for RF heating is costly compared to traditional heating systems. In terms of applicability, RF has the potential to be used for disinfecting, drying, and roasting different tree nuts (Zhang et al., 2019). It is also noteworthy that RF heating operations depend on several factors such as the dielectric properties of the food product in question, the gap between electrodes, the specific configurations of the top electrode, and the voltage applied to the top electrode within a free-running oscillator utilizing a two parallel-plate system (Guo et al., 2019). Collectively, these variables impact the efficiency and effectiveness of RF heating processes. Research advancement in optimizing these parameters will be germane in adoption of this technique to the nut industry.

Challenges and Future Perspectives

Thermal methods represent the traditional approach to processing nuts for safe consumption. During processing, raw nuts are heated not only to destroy pathogens, spoilage microorganisms, and to inactivate enzymes, but also to impact some physical qualities such as aroma and texture. Although such properties are desirable, as seen in roasted nuts, thermal treatment can significantly alter other characteristics (both physical and chemical) in undesirable ways, like resulting in an increase in dark-brown color as a result of Milliard browning, loss of heat sensitive bioactive compounds and generation of health challenging compounds such as acrylamide. Non-thermal techniques have been introduced as safe alternatives to processing raw nuts while offering additional benefits, including improved nutritional attributes, and increased processing efficiency. However, most of these non-thermal techniques can only preserve the nuts without spoilage during storage but cannot impact desirable properties such as described above. Emerging technologies (e.g. RF heating, IR drying), have offered unique potentials (both singly and in combination with existing technologies) to greatly maximize the advantages and to minimize the disadvantages of traditional nut processing methods for improved quality, safety of tree nuts and consequently reducing processing time and cost. Despite the level of research that has been reported on the impact of thermal and non-thermal techniques on tree nuts, many questions still remain unanswered, which future researches can explore.

Comprehensive Nut Quality Assessment

The qualities of dried foods are determined by six major indices. These include the following: (1) retention of flavoring substances; (2) retention of heat and oxygen sensitive compounds (nutrients), (3) browning inhibition closely related to color desirability and food protection; (4) rehydration capacity, which allows for application as food ingredient; (5) textural properties that result from complex interactions between food components at micro- and macro-structural levels, which can be reported as a measure of force-to-grind hardness, such as toothpack (i.e., the amount of product left in the teeth crevices after it has left the mouth), persistence of crunch (i.e., number of chews that the sample still has to give a crunchy sound), crispiness (i.e., the amount of high pitched sound during mastication) and shrinkage; and (6) modification of nutritional components such as protein and lipids. These qualities are affected largely by the choice of processing techniques that are employed and differ depending on the types of nuts. Much research has reported on the impact of processing on the properties of tree nuts, predominantly focusing on color, hardness, flavor, and nutrient retention. However, to date, no report has been conducted on other areas of quality parameters (e.g., rehydration capacity). Exploring quality measurement using different thermal and non-thermal techniques will help us understand in more detail the extent of the impact traditional and novel processing methods on the quality of tree nuts.

Integrated Approaches to Nut Preservation

Typically, thermal and non-thermal technologies have been used independently for the preservation of tree nuts. Yet, this approach lacks the potency of yielding desirable product qualities, energy consumption, processing time, and throughput. Future advancement should be channeled towards intelligent combination of more than one processing method on different types of tree nuts in order to balance out the advantages/disadvantages of an individual technology. For instance, the combination of hot-air with RF drying. This approach can foster the emergence of a wide range of hybrid technologies. Application of various non-thermal processing methods as a pretreatment prior to drying or roasting has shown greater advantage in preserving dried foods qualities. No research has been reported on the use of non-thermal techniques as a pretreatment in tree nuts. Successful integration of these methods is crucial, so as to develop a feasible and comprehensive postharvest technology for tree nuts. It is also noteworthy to facilitate public education efforts to teach the basic principles behind thermal and non-thermal processing technologies, as this will benefit both consumers and stakeholders to overcome common misconceptions.

Accessing the Adoption and Economic Viability of Novel Processing Technologies

In adopting a new technology, industries are interested not only in the improvement of the quality of the products, but also on the sustainability, economic feasibility, and viability of the technology. Although there is a quest to use indirect heating or non-thermal processing methods to preserve the quality of tree nuts, it is very crucial for research to focus on how adoptable they are to the nut industries. Many of the novel indirect heating and non-thermal technologies are still used solely for research purposes because of their cost. Research should focus on economic evaluation that accounts for capital and operating costs, run-time efficiency, energy usage, and maintenance costs. It is useful to improve and optimize design parameters for different techniques, such that laboratory and pilot-scale test systems can be transferred to large-scale industry implementation. Artificial intelligence and mathematical models may help to optimize processing parameters and inform regulatory guidelines.

Conclusions

This review has summarized thermal and non-thermal processing and their effects on the physicochemical properties of tree nuts. Figure 4 provides a summary of our evaluation. Each processing method has its benefits and limitations. Overall, thermal processing approaches (drying, roasting, blanching) have favorable effects on the nuts' physical (brown color, crisp texture) and sensory properties (roasted, nutty flavor), but adversely affect nutritional value because many beneficial chemical components such as vitamins and phytochemicals are heat sensitive. Applying novel drying and roasting technologies that reduce heat loads or intensity could help mitigate these limitations. Non-thermal processing approaches such as HPP, irradiation, PEF, cold plasma and RF heating are promising alternatives, as they seem to preserve these nutritional properties. To select appropriate processing techniques, nut processors should define the desired product properties, consider the specific effects of processing on each property, and then weigh potential trade-offs. In addition to the physical/chemical properties of the product, nut processors must consider process efficiency, resource requirements, food safety, and consumer acceptance. Given the further advancements in research and development cited above, thermal and non-thermal

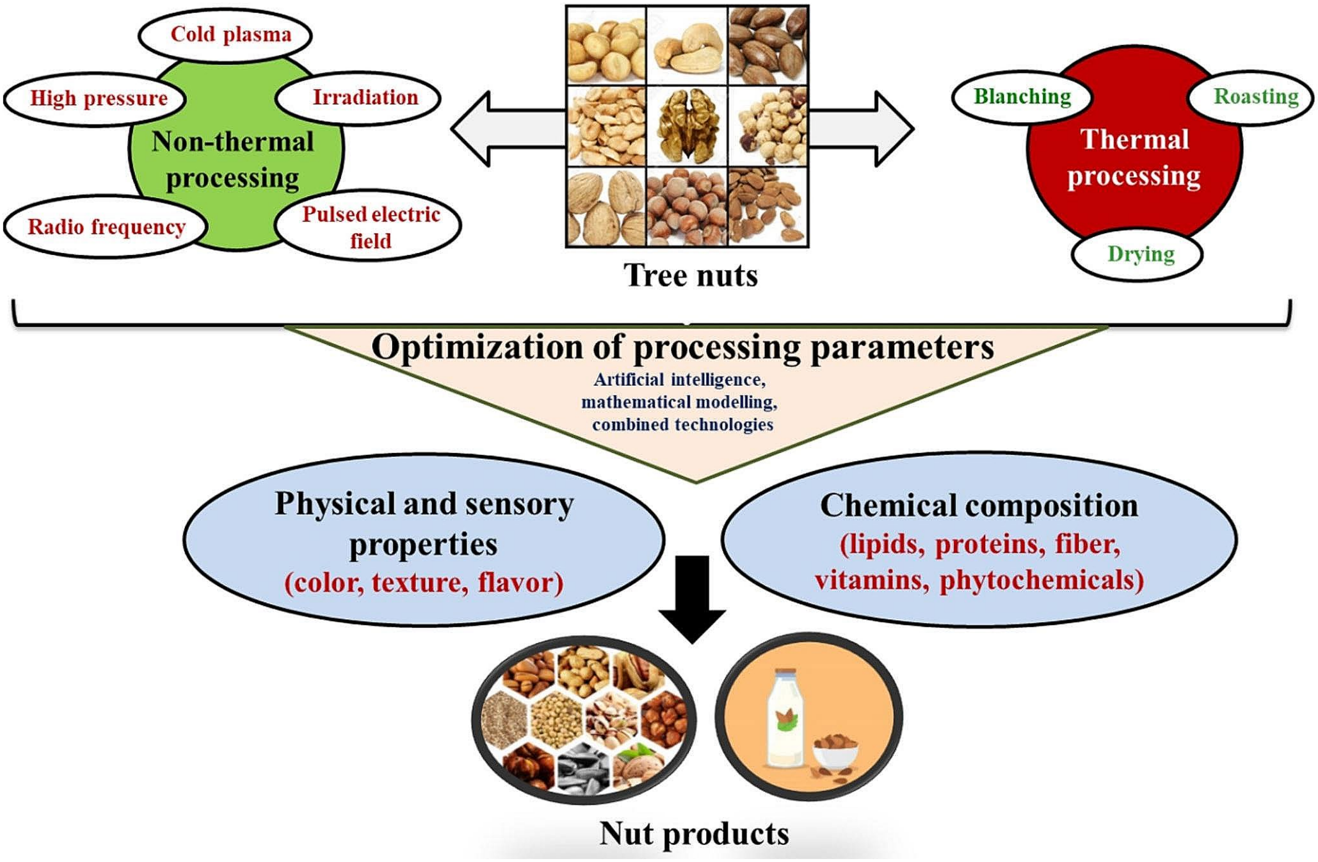

Fig. 4 Effect of thermal and non-thermal processing on the quality of tree nuts

processing will hold a bright future in nut processing fields and promise to advance our ability to maintain/improve the quality of nuts for consumers.

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