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Processing of Tree Nuts

Chang Chen and Zhongli Pan

Abstract

Tree nuts are consumed as healthy snacks worldwide and are important economic crops. In this chapter, post-harvest processing technologies of tree nuts are discussed, with focus on the drying, disinfection, disinfestation, and downstream processing technologies (blanching, kernel peeling and roasting) for the control and preservation of product quality and safety. Almonds, walnuts, and pistachios are selected as the representative crops for the discussion. Current status, recent advances, and challenges in the scientific research, as well as in the industrial productions are summarized. Some new perspectives and applications of tree nut processing waste and byproducts (such as shells and hulls) are also introduced. The contents presented in this chapter will help both scientists and stakeholders to better understand the tree nut processing and provide technological recommendations to improve the throughput, efficiency, and sustainability of the processes, and preserve the quality and safety of the products.

Keywords: tree nuts, drying, disinfection, disinfestation, food safety, food quality, energy, sustainability

1. Introduction

Tree nuts have high nutrient contents, including oils, proteins, and carbohydrates [1]. Due to their high pleasant flavor and various benefits for human health, tree nuts have gained increasing popularities worldwide, and are consumed as healthy snacks or food ingredients for cooking [2]. The global market of tree nuts was reported at US\$88.8 billion in 2020, and it is expected to grow continuously to US\$103 billion by 2027 [3]. Commonly consumed tree nuts include almonds, walnuts, pistachios, pecans, macadamia nuts, hazelnuts, and cashews, etc. Among them, almonds, walnuts, and pistachios are the most popular types, accounting for almost 70% of total tree nuts production in the world [4]. The global production mass of almonds, walnuts, and pistachios in 2020 were: 1,700,000, 2,300,000 and 985,000 metric tons, respectively, which increased 15%, 20% and 37%, respectively, compared to the 2019 harvest season [5].

Tree nuts are usually harvested in a relative short harvest season (about 1–2 months from late summer to early fall). The harvested nuts need to fulfill the year-round consumption. Almost all tree nuts are composed of a thick and wet hull that wraps the shell and kernel inside at harvest (**Figure 1**). As the result, freshly harvested tree nuts usually have high initial moisture contents (IMCs) and water activity. Such characteristics make fresh tree nuts vulnerable to spoilage and quality deterioration after harvesting [7, 8]. Therefore, artificial drying is critical to preserve the quality and safety of the nuts. Meanwhile, since tree nuts are rich in unsaturated fatty acids [9, 10], their oil quality is sensitive to the thermal drying

Figure 1.

The photos of walnut, almond and pistachio at different stages of drying (in-hull, in-shell, unpeeled kernel, and peeled kernel) [6].

process [11–13]. Thus, tree nuts need to be dried appropriately and efficiently after harvesting to ensure the quality, safety, and market value of dried products [14–18].

Prior to harvest, plants usually have very good natural defense mechanisms against microbial spoilage. After harvesting, the high moisture contents (MCs) and nutrient contents make them vulnerable to microbial spoilages. Any food safety problems associated with the regional tree nuts production could cause international outbreaks and significantly impact the human health [19–21]. Drying alone usually cannot achieve adequate disinfection and disinfestation. Therefore, further disinfection and disinfestation are critical for extending the shelf life and safety of the dried products [22, 23]. Depending on the type of the final products, further processing, such as roasting, blanching and kernel peeling, may also be needed to produce desired products for consumption.

In addition, thermal and chemical processing of tree nuts are energy intensive and cause significant environmental impacts [24, 25]. It is worthy of noticing that the food production sector is responsible for one-quarter of the world's total greenhouse gas emissions [26] and consumed 200 EJ energy per year [27]. The fast-growing population, increasing production volume and market demands for food production will put more pressure and challenges on the industries for higher processing throughput and efficiency [28]. In the 2021 United Nations Climate Change Conference (COP 26), the world leading countries have committed to achieve 'net zero' carbon neutrality goals by 2050 [29, 30], which needs contributions from all sectors, including the postharvest processing of tree nuts.

In the following sections, the current status, recent advances, and challenges in the postharvest processing technologies are summarized using walnuts, almonds and pistachios as examples.

2. Conventional harvest and postharvest processing methods

Due to similar hull-shell-kernel multiplayer structures (**Figure 1**), the post-harvest processing operations, including cleaning, dehulling and drying, etc. are similar for different types of tree nuts. Meanwhile, due to the differences in the shell conditions, MCs and lipid compositions, the processes have some differences.

In California and Australia, almonds are shaken off trees when they are mature and dried on-ground in orchards (**Figure 2**), taking advantage of the hot and dry

Figure 2.
 Harvesting and post-harvest processing of almonds: (A) almond shaking; (B) on-ground drying; (C) stockpiling; (D) off-ground harvester (figures obtained from industrial partner or taken by the author's lab).

weather during the harvest season [31, 32]. Conventional drying process takes 7–14 days depending on the weather condition, until the overall MC of whole almonds achieved about 12% on wet basis (while the kernel moisture reaches about 6%). Dried almonds are swept together into windrows and picked up by machineries, which are then stockpiled outdoor for temporary storage. The stockpiles are aerated, which allows the product moisture to equilibrate before mechanically cleaned and de-hulled with abrasive huller [33]. Currently, two major problems with this procedure are: (1) the sweeping and picking up generate large amount of dust, which spreads away in the air and causes pollution [34]; (2) almonds contact the soil directly while drying on-ground, which induces severe insect damage and microbial spoilage [35, 36]. In Europe (mainly Spain), almonds are harvested off-ground and de-hulled in-field, which are then dried in silo dryers with air [31]. Recently, the Almond Board of California (ABC) and Almond Board of Australia are also supporting research in developing off-ground harvesting technology to mitigate the problems of conventional harvesting [37]. Meanwhile, it brings up critical needs to dry the high-moisture almonds artificially and efficiently and to handle the large volume of production in the short harvest season for product quality and safety.

The harvesting method of walnuts are similar to almonds. However, since walnut shell is harder and thicker than that of the almond, natural drying is not efficient enough to dry the inside of them. If the walnuts stay too long on the ground, microbial spoilage becomes significant. Therefore, after drying on the orchard floors for several days, the walnuts are mechanically swept and transferred for washing, mechanical de-hulling and artificial drying of in-shell walnuts with hot air (HA) heating [38]. Typically, walnuts are dried at around 43°C (110°F) until the MC of the walnuts are below 8% (w.b.) in the bin dryers (**Figure 3**).

Figure 3.
Typical harvesting and postharvest processing of walnuts: (A) walnut shaking; (B) hulling and washing section; (C) hot air drying bins.

This process can take as long as 24 h [39]. This conventional heated air drying method has the advantages of large processing capacity and relatively low operating cost [2]. Currently, there are three major concerns with this process: (1) the efficiency and throughput of the current drying method may not fulfill the growing production volume, resulting in significant product loss due to insufficient or inappropriate drying [5]; (2) walnut drying is very energy-intensive [2, 40] and causes large amount of carbon emission, thus efficient drying methods are needed to improve the sustainability; (3) freshly harvested walnuts have wide distribution of IMCs [41]. Drying the walnuts with different MCs together leads to over-dried or under-dried products, causing quality deterioration, food safety risk, and energy waste [42]. Therefore, it is desirable to sort the walnuts with different MCs first based on MCs and conduct the drying separately to improve moisture uniformity in products and avoid problems from current drying methods.

Pistachios are commonly harvested off-ground and dried artificially (**Figure 4**). Pistachio nuts have hard and naturally enclosed shell, which significantly restrict the moisture transfer rate, and natural drying is not popular [44]. In a typical process, pistachios are firstly de-hulled, washed, and dried with HA to pop-open the shells. A second hulling process is then used to remove the remaining hulls to obtain the in-shell pistachios. After that, the open-shell nuts and closed-shell nuts are separated with a rotating sieve [45]. After removing the remaining foreign

Figure 4.
Harvesting and post-harvest processing of pistachios in California: (A) off-ground harvesting [43]; (B) mechanical dehulling; (C) cylindrical hot air drying.

materials, defected or stained nuts, the pistachios may be further dried in batch or continuous dryers with HA the kernel reaches 5% MC to ensure the safety of the dried nuts [46–48].

3. Drying technologies

Current drying methods have drawn increasing concerns due to low efficiency, high energy consumption, large carbon footprint and risks of causing quality and safety deterioration. As the results, the tree nut industries are under the pressure to develop more efficient and sustainable drying technologies that can preserve the quality and safety of dried products. In recent years, research works have been conducted mainly in two aspects: (1) to improve or optimize the operating conditions of the current HA drying practice; (2) to develop novel drying technologies based on thermal and non-thermal methods.

3.1 Improve the hot air drying process

Elevating the drying temperature is a potential approach to reduce the drying time and improve the efficiency of the current HA drying practices. However, keeping the nuts at high temperatures for long times is not desirable, as it may induce significant quality deterioration to nuts, such as lipid oxidation and browning [23, 49]. Enhancing the drying rates by intensifying the heat and moisture transfer during the drying while maintaining the product qualities has become the key approach. Since the hull and shell have much higher IMCs than the kernel [2, 42], most thermal energy in the heated air is consumed for raising the temperature and evaporating moisture in the hull and shell, particularly in initial drying stages [50, 51]. As the results, the temperature increase in kernels is significantly slowed down, and the moisture removal from kernel to the environment is greatly restricted due to the reverse moisture gradient from the hull to the kernel [50]. Based on these characteristics, Chen [15] developed a new drying strategy by using high temperature heating in the beginning of drying to quickly heat up and partially dry the hull and shell; at the same time, due to the relatively low thermal conductivity of the kernel and shell, the kernels should not be over-heated; then before kernels reached a temperature that was high enough to cause significant oil quality deterioration, drying temperature was decreased to finish the drying. With the aids of experimental studies and mathematical modeling of the heat and moisture transfer (**Figure 5**) during the drying, the feasibility of this new drying strategy was verified [51, 52]. Drying in-shell walnuts by HA with step-down temperatures reduced the drying time and energy consumption by up to 40% and 24%, respectively, and obtained similar oil quality and kernel color in the dried products compared to the conventional practice. Similarly, using HA drying with step-down temperature and tempering for in-hull almonds significantly reduced the drying time and did not affect the quality of the dried almonds in terms of oil quality or incidence of concealed damage [13].

Sorting the nuts into different groups based on IMCs first and then drying them separately is another strategy of improving the drying efficiency, moisture uniformity and product quality. Khir et al. [42] studied the correlation between the MCs of walnuts and terminal velocities and developed a sorting method called the ‘air knife’. The walnuts were separated into low and high MC groups and dried separately, which resulted in 18–28% energy saving compared to without sorting. Meanwhile, the uniformity of moisture in the dried products was greatly improved. This technology has been commercialized and installed in-line in walnut hulling and drying facilities in California (**Figure 6**). Similarly, the correlations between

Figure 5. Modeling results showing: (A) schematic diagram of pilot-scale column dryer; (B) mesh grid of the modeled system; (C) distribution of moisture and (D) temperature profile within the column and within single walnuts the moisture and temperature distribution within single walnut located in a pilot-scale column dryer [51, 52].

Figure 6. Photo of the (A) 'air knife' sorter and (B) SIRHA dryer for walnuts.

terminal velocities of pistachios and almonds with their MCs have also been studied [44, 53]. Chen et al. [13, 54] have shown that in-hull almonds, in-shell almonds and loose hulls at harvest could be separated based on the thickness and terminal velocities of different groups, and suggested sorting and removing almond hulls prior to drying benefited the improvement of moisture uniformity and energy saving.

3.2 Novel thermal and non-thermal drying technologies

Infrared (IR) heating has the advantage of high heating intensity compared to convective heating. IR radiation could penetrate 2–5 mm depth into food surface [55], which matches the typical thickness of the nut hull and shell. Therefore, IR heating was an ideal technology to pre-dry the tree nuts. A commercial-scale sequential infrared and hot air (SIRHA) drying technology (**Figure 6**) was developed by Chen [15] and Atungulu et al. [40], which had 14.2 ton/h throughput and achieved 13.6–26.5% drying time reduction and 10–20% energy savings, respectively. Venkitasamy et al. [22, 23] used SIRHA drying for pistachios and almonds, and

achieved 9% and 40%, respectively, compared with HA drying only. Additionally, research has shown that the percentage of shell splitting for pistachios increased with drying rates, and thus spray-rinsing with water and then IR drying could effectively improve the shell splitting [56].

Heat pump drying utilizes the thermal energy in the air flowing out of the dryer by dehumidifying and condensing the water vapor containing in the outflow air, retrieving the enthalpy of heat evaporation, then circulating the heat back to the dryer inlet [57]. HA heat pump drying was used for walnuts and higher drying efficiency was achieved without affecting the product quality [58, 59]. IR-assisted heat pump drying for walnuts reduced 20% drying time and 10% energy consumption compared to HA drying [60]. Solar heat pump drying reduced the drying time and increased the energy utilization ratio of pistachios [61, 62].

Dielectric heating such as microwave (MW, wavelength range: 300 MHz–300 GHz) and radiofrequency (RF, wavelength range: 3 kHz–300 MHz) can penetrate the foods. The electromagnetic wave activates the water molecules through dipole rotation and/or ionic polarization, generating heat volumetrically within foods, while non-polar molecules are not affected [63]. HA drying at 50°C assisted with RF heating at 27.12 MHz and 6 kW reduced 58.3% drying time of walnuts compared to HA drying only [64]. Intermittent MW drying could be used to dry pistachios without affecting the nut quality [65].

Some non-thermal technologies have also been studied as assistance to conventional drying processes. For example, high-power ultrasound treatments improved the drying rate and energy efficiency of pistachios [66]. The drying time of almonds was reduced by 58.33% with 40 min ultrasound treatment [67]. Such phenomena should be attributed to the enhancement of moisture transfer by the molecule vibrations induced by ultrasonic field. Under vacuum, the boiling point of water and vapor pressure in the drying chamber were significantly lower, and thus increase the driving force of moisture transfer during the drying process [12]. Vacuum drying was able to dry walnuts in a shorter time compared with conventional practice [68]. IR- and MW-assisted vacuum drying improved the drying efficiency of almonds [69].

4. Food safety processing: disinfection and disinfestation

Tree nuts are vulnerable to contamination by pathogenic microbes, such as *Salmonella* species, *Escherichia coli* strains and *Aspergillus flavus*, as well as molds and mildew [70, 71]. Two severe worldwide outbreaks of *Salmonella* occurred in 2001 and 2004 that were traced back to California almonds, which caused more than 200 illness cases in more than 15 US states or countries [72]. In response, ABC and United States Department of Agriculture (USDA) required all raw almonds to be pasteurized with at least 4-log reduction in the *Salmonella* population [73]. Additionally, aflatoxins are usually generated associated with the mold growth, which cause even more severe food safety risks. Insect damages (webbing, cast skins, frass, etc.) by field pests, such as Codling moth, (*Cydia pomonella* [L.]), navel orange worm (*Amyelois transitella* [Walker]), and storage pests, such as Red flour beetle and Indianmeal moth (*Plodia interpunctella* [Hübner]) have raised additional food safety concerns [74]. For example, navel orange worms lay eggs while the almonds are on tree, and hatch while they are dried on-ground. The insects could hide in dried nuts for a long time. In recent years, damaged nuts and live insects have been found in dried nuts or nut-containing products [35]. Insect infestation is also favorable for mold growth [75]. Although drying reduces water activity of nuts and can inhibit the microbial growth, drying alone is not enough to sufficiently

disinfect and disinfest the tree nuts [13]. Thus, additional disinfection processing is needed to ensure the microbial safety of the products.

4.1 Conventional disinfection and disinfestation technologies

Conventionally disinfection and disinfestation technologies can be classified into chemical and thermal treatments, which are similar for different tree nuts. Chemical treatments refer to fumigation. The commonly used disinfectants and pesticides for fumigation of tree nuts include sulfuryl fluoride, aluminum phosphide and magnesium phosphide [74, 76]. Nowadays, there are increasing concerns of the chemical residues on tree nuts after fumigation as they are classified as 'probably carcinogenic to human', and excessive chemical use is not desired for the clean labeling of the products.

Thermal treatment is another type of disinfection and disinfestation method for tree nuts. High temperature heating kills the pathogenic microorganisms by denaturing their proteins and nucleic acids. For example, hot water blanching at 88°C for 1.6 min reduced 4-log *Salmonella* levels on the surface of almond kernels [73]. Oil roasting at 127°C for 53 s reduced 4-log *Salmonella* level on almonds and achieved effective disinfection of pistachios and walnuts [77].

4.2 Emerging disinfection and disinfestation technologies

In recent years, many emerging technologies have been studied and developed to improve the safety of tree nuts. It is generally agreed that 'moist heating' at high temperature and humidity conditions are effective for pasteurizing foods due to the high heat capacity and penetration depth. In addition, since 'moist heating' does not use harmful chemicals, it is more environmentally friendly and considered safer [78, 79]. Chen et al. [13, 37] applied step-down temperature HA heating with tempering for the simultaneous drying and disinfection of in-hull almonds that were harvested off-ground. When the average processing temperature was higher than 50°C, the insect eggs in the almonds were completely killed as no new larva was observed during the incubation and storage of dried nuts.

Radiative heating technologies have been proven to effectively pasteurize and disinfest the nuts. For example, IR preheating followed by temperature holding achieved 7.5-log reduction of *Salmonella enterica* on almonds owing to the intensive thermal effects [80]. SIRHA heating pasteurized pistachios and almonds with up to 6.1 and 4.7 log CFU/nut reductions in *Salmonella* level, respectively [22, 23]. MW and RF heating can penetrate the nuts and achieve rapid volumetric heating. As the results, 2–4 min of RF treatment was able to reduce 5-log *Salmonella* in the almonds [81]. RF heating could also kill the larvae of *Ceraphron cephalonica* and rice moth in walnuts [82], and *Indianmeal* moth in pistachios [83]. Nonetheless, due to the high temperature, thermal processing may damage the quality and reduce the shelf life of tree nuts, particularly causing lipid oxidation. Therefore, non-thermal disinfection technologies are gaining increasing interests.

Irradiation technologies have been used for disinfection for tree nuts. Ultraviolet (UV) illumination destructs the DNA structure of microorganisms and degrades the toxins. Particularly, Aflatoxin B1 (AFB1) absorbs UV radiation strongly at wavelengths of 362 nm and degrades rapidly under acidic (pH < 3) or alkaline (pH > 10) conditions [84]. Pulsed light treatment illuminates high intensity UV and/or visible light to target foods, which can also destruct the DNA structure in microbials and leads to effective disinfection [85]. Electron beam irradiation and Gamma irradiations have also been applied to disinfect tree nuts effectively [73, 86]. Low pressure

cold plasma can generate UV radiation and reactive chemical species that destroy the protein and DNA structure within bacteria and fungi that infect the nuts [87]. However, it has also been reported that increased irradiation dose caused decrease in the nutrient contents in tree nuts, such as α -tocopherol [88, 89]. Therefore, these irradiation disinfection technologies need further investigation to maintain both the safety and quality of tree nuts.

Some other emerging technologies, such as nanoparticles (NPs), electrolyzed oxidized water (EOW) and ozone treatments have also been researched. Photocatalytic NPs can be used as a disinfectant alone or combined with other materials due to the oxidative stress arising from reactive oxygen species (ROS) that are generated under visible or UV lights [90]. Among which, silver NPs show antimicrobial properties against several bacteria including *Escherichia*, *Pseudomonas*, *Salmonella*, *Bacillus*, *Clostridium*, *Enterococcus*, *Listeria*, and *Streptococcus* [91], and different fungus, including *Aspergillus niger*, *Candida albicans*, and *Saccharomyces cerevisiae* [92, 93]. Some metal oxide photocatalytic NPs, such as titanium dioxide (TiO_2), also show potential disinfection functions [94, 95]. However, excessive use of NPs has raised concerns for their accumulation in foods that may cause toxicity.

EOW is normally obtained by passing the saltwater solution through an electrolysis system containing a cathode, an anode and a selective-permeable membrane [96]. The electrolysis of saltwater generates oxidizing species, such as O_2 and Cl_2 gases, and HOCl , at the anode. The redox potential of the EOW solution ranged from +700 to +800 mV with a pH of 4, which indicates high oxidizing ability [97]. These oxidizing species damage the cell wall and the metabolic process of a variety of pathogenic bacteria, such as *E. coli* O157:H7, *Listeria monocytogenes*, *Bacillus cereus*, and *Salmonella typhimurium* [98, 99]. Although EOWs are accepted as an antiseptic agent in food production, their toxicity needs further investigation.

Ozone is another ROS that has been used for food safety improvement. As a strong oxidant, ozone destructs cell wall, cell membrane and other cell constituents in microorganisms [100, 101]. Ozone could also effectively degrade mycotoxins and aflatoxins in foods by reacting with the alkene double bonds [102]. Ozone is relatively unstable, and can spontaneously decompose into oxygen, thus do not generate hazardous residues in foods [101]. However, ozone is a greenhouse gas with strong global warming potential, and thus its application and emission may need to be regulated. Although not yet reported, these emerging technologies also show potentials to be used for the disinfection of tree nuts, and thus more research works are needed.

5. Further processing

Depending on the types of final products, 'raw nuts' (dried and disinfested) may be sold directly or further processed with the methods of blanching, kernel peeling and roasting.

5.1 Blanching and kernel peeling

Tree nut kernels with bright and white color are appealing to the consumers and are typically required for producing meals or milk, or consuming raw in salads [103]. For this purpose, blanching and peeling of kernels are usually needed. The peel on the kernel surface, also known as 'pellicle', has dark color and usually has high contents of natural antioxidants, such as tannins, phenolics and flavonoids

[104]. They protect the kernel from natural oxidations and show good antibacterial activities [105]. However, due to the abundant antioxidants and fiber, pellicles usually have bitter taste, high chewiness, and low solubility in drinks, which lowers the sensory satisfaction and affect the palatability [106]. Kernel peeling is mainly accomplished by physical or chemical methods.

Physical peeling involves blanching and mechanical abrasive peeling [107] and is the recommended method in the almond industry [108]. However, abrasive peeling is not recommended for walnut kernels since walnut kernel has irregular shape and abrasion may also result in significant loss of nut flesh. During blanching, nut kernels are subjected to either water soaking or steaming at high temperatures, which cause the pellicle to swell and crack [109]. After blanched, the tree nuts go through soft rubber rollers to mechanically peel off the pellicle by abrasion [106]. Besides, blanching also showed the capability to protect the color of the tree nut kernels [110], and control the cross-contamination of aflatoxins in almonds [111]. The disadvantages of blanching include the increase of MCs, softening of the nut flesh and leakage of polyphenols into the water [112], which brings up the need to further dry the kernels after peeling and loss of antioxidant activities. The large water consumption is another concern for the sustainability, particularly in the drought regions.

Chemical peeling usually refers to the hot lye peeling by NaOH, Na₂CO₃, and Ca(OH)₂, etc. [113, 114]. In a typical process, nut kernels are soaked in hot lye solutions for several minutes to corrode the pellicles, then rinsed with water [109]. Factors, such as alkali type, concentration, temperature, and soaking time, are important for the peeling performance [115]. Although lye peeling is efficient and effective, it may cause significant quality deteriorations, such as texture softening, surface browning, loss of crude protein and fat, decrease of antioxidant activities, and increased oxidation [113]. If the rinsing of peeled nuts was not performed adequately, the chemical residues on the nut surface cause additional food safety concerns. More importantly, disposal of the wastewater from lye peeling requires excessive use of chemicals and may cause severe environmental impacts.

For these reasons, novel and safe peeling methods have been studied and developed. IR radiation can penetrate the pellicle and heat up the kernel, which cause moisture evaporation and accumulation of vapor pressure under the pellicle. Meanwhile, IR heating may cause pyrolysis of pectin substances. When the vapor pressure reaches a critical level, the pellicles crack and can be peeled [109, 116]. Zhao et al. [117] developed a cryogenic peeling system for walnuts, in which the walnuts were held at -160°C by cold gas/liquid N₂ and moved dynamically downwards, and the shrinking pellicles were removed by upflowed air. Studies have shown that walnuts and almonds with their pellicles peeled off had shorter shelf life compared to the unpeeled ones [106, 118]. Therefore, applications of edible coatings containing antioxidant substances, such as Mastic gum, chitosan incorporated with green tea extract, walnut phenolic extracts, and mango kernel starch, etc. are popular research topics in recent years [118–121]. Meanwhile, the sensory quality of the nuts with edible coatings should not be compromised.

5.2 Roasting

Roasting is a commonly used processing to improve the palatability of tree nuts, which is usually done at a temperature higher than 90°C [122]. Maillard reaction between the carbonyl group of reducing sugars and the amino groups of proteins in the nuts is responsible for the nonenzymatic browning and formation

of substances with desired ‘roasted aroma and flavor’ (e.g., pyrazines, furans, and pyrroles) [123–125]. During roasting, nuts are further dried and are subjected to some change in texture properties, which gives rise to the crunchy mouthfeel. The texture properties of tree nuts (hardness, fracture force, firmness, etc.) are significantly affected by the roasting temperatures [126, 127]. Meanwhile, roasting is also an effective measure to reduce the aflatoxin contents in tree nuts [128].

Conventionally, tree nuts are roasted by HA or oil [129]. HA roasting is usually performed at a temperature ranging from 100 to 180°C for up to 60 min [130]. The main problems with this method are the long processing time, high energy consumption and non-uniform roasting, which should be attributed to the slow convective and conductive heat transfer with HA heating. During oil roasting, tree nuts are immersed and fried in a vegetable oil at a temperature near 180°C for 7–8 min, followed by drying to remove the oil from surface [131]. Although the roasting process do not significantly reduce the contents of macronutrients, it also has some disadvantages. The major concern associated with roasting are the severe oxidation of polyunsaturated fatty acids that give rise to ‘off-flavor’ and the risk of toxin generation over the smoke point under the high temperature processing [132]. Some main chemical reactions related to the quality change during tree nut roasting are shown in **Figure 7**. In addition, oil roasting results in high oil intake in the products. Therefore, new roasting technologies need to be more efficient and cost effective, while not compromising the product quality and safety.

Formation of acrylamide, a group 2a carcinogen by WHO, from the free asparagine and reducing sugars in the nuts arises another food safety concern. Asadi et al. [133] found IR roasting caused the highest acrylamide content in pistachios, and MW roasting led to the lowest. Increasing the roasting temperature and time, and MW power facilitated acrylamide formation, since the formation rate of acrylamide increased with temperature [134]. Milczarek et al. [135] suggested that MW roasting was a promising method to replace the conventional HA roasting for almonds. Adding of salt during roasting can mitigate the acrylamide formation in tree nuts, which should be due to the prevention of intermediate (such as Schiff base) formation under the inhibition of cations [136]. In response, ABC [137] suggested that almonds should be roasted at the lowest possible temperature to minimize the acrylamide formation. Corradini and Peleg [138] found that using a step-down temperature heating may reduce the acrylamide contents in baked goods. Bagheri [139] suggested that use of IR heating together with HA or MW heating reduced the roasting time while obtaining similar product quality. Future research

Figure 7.
Main chemical reactions related to quality change of nuts during roasting.

in tree nut roasting should focus on the development of novel roasting methods that combine the advantage of different heating methods, optimization of roasting parameters (using stepwise temperature roasting strategy) and addition of appropriate food-safe additives to preserve product quality, reduce acrylamide formation, and improve microbial safety and energy efficiency.

6. Utilization of tree nut processing wastes for value-added byproducts

Besides kernels, a large amount of waste materials, mainly the shells and hulls, is generated during tree nut processing and production. In fact, the tree nut hulls and shells account for 70% of the harvested weight [140], but currently have low economic values. Utilization of these wastes for producing value-added byproducts or bioenergy should benefit the stakeholders economically and reduce the environmental impacts of tree nut processing industry.

Hulls usually have high contents of natural antioxidants, such as tannins and phenolics [141]. Extraction of these antioxidants and then adding them as functional additives to other foods may improve the economic value of the crop [142]. Extracts from walnut and pistachio hulls exhibit good antibacterial and anti-inflammatory properties [143]. Walnut hull also contains juglone, a compound with high pharmaceutical value, which can be extracted and used in medicines [144]. Almond hulls weights over 60% at harvest and are conventionally used as cattle feed in California and Australia [145]. However, they are normally sold at a very low price. In addition, hulling and shelling of almonds cost about \$0.30/kg, being one of the most expensive operations in the almond industry. Therefore, these processes need to be optimized to reduce the processing cost. Besides, off-ground harvested almonds have much higher MCs in the hulls at the time of harvest [54]. Wet dehulling of the almonds will be needed, as drying the hulls consumes more

Source	Valuable substance	Application	Reference
Walnut husk	Juglone and antioxidant	Enhance antioxidant and antimicrobial properties of ketchup	[141, 142]
Pistachio hull	Phenolic compound	Improve antibacterial and anti-inflammation properties	[143, 144]
Almond hull	Soluble sugar	Culture and produce edible fungi for foods	[148, 150]
Almond hull	Soluble sugar	Culture microorganisms that produce biodegradable plastics	[149]
Pistachio shell	Woody biomass	Biogas production	[146]
Almond hull	Soluble sugar and polysaccharides	Bioenergy production	[147]
Walnut and pistachio shell	Woody biomass	Biogas production	[152, 153]
Walnut shell	Cellulose	Reinforcement for biodegradable packaging	[154]
Pistachio processing waste	Starch, fiber and bioactive compounds	Biodegradable packaging for foods, active packaging	[155]

Table 1.
Valuable substances and potential applications of wastes and byproducts from tree nut processing.

than half of the total drying energy and leads to extra drying time and costs [24]. Meanwhile, since the high moisture hulls have high sugar contents, they can be used for fermentation and bioenergy production, and culturing certain microorganisms for producing value-added foods or biodegradable plastics without the need of drying [146–150]. Tree nut shells are mainly composed of cellulose, hemicellulose, and lignin [151], and thus can be used as woody biomass for biogas production through combustion or pyrolysis [152, 153]. The natural biopolymers from the tree nut production wastes and byproducts, such as polysaccharides, fibers, and proteins could also be utilized and manufactured into thin films as biodegradable packaging for foods [154]. The natural bioactive compounds in the hulls can be added into the packaging to improve the antioxidative and antimicrobial functions [155]. **Table 1** provides a summary of the potential values and applications of tree nut production wastes and byproducts.

7. Conclusion

Tree nuts are healthy foods with significant economic values. Postharvest processing technologies are essential in preserving the quality and safety of tree nuts. In this chapter, the status, recent advances, and challenges of drying, disinfection, disinfestation, blanching, peeling, and roasting of almonds, walnuts, and pistachios in scientific research, as well as in industrial productions are summarized. Current processing practices can be improved by optimizing the operating parameters. Novel thermal and non-thermal drying technologies, such as IR, MW, RF, ultrasound, vacuum, etc. and combined technologies, have shown great potential to improve the drying efficiency and safety of nuts without compromising the nut quality. It was noted that the postharvest processing methods of different tree nuts share some similarities but are also different due to the differences in physical properties and chemical compositions. Each processing practice has significant impacts on the quality and safety of the final products, such as lipid oxidation, loss of nutrients and formation of acrylamide. Therefore, suitable processing technologies and operating conditions must be carefully selected. Additionally, processing wastes of tree nuts, such as hulls and shells, have potential to be utilized as high value bioresources for producing value-added products. Being important economic crops with large market size, improvements in the postharvest processing technologies of tree nuts could translate into significant global influence in reducing the energy consumption and environmental impacts for improved sustainability, economic values, and competitiveness of tree nut industry.

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