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Microbial and pest contamination in nuts: Radio frequency disinfestation and controlled atmosphere preservation – A review

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ABSTRACT

Nuts are increasingly recognized for their rich nutritional profile and bioactive potential, making them a significant economic contributor globally. However, the commercialization of nuts necessitates stringent quality control measures to mitigate infestations by insect pests and microorganisms, which can lead to rapid deterioration both pre- and post-harvest. Contamination often arises from inadequate practices in harvesting, packaging, storage, and transportation, heightening the risk of pathogen infection and mycotoxin contamination. To address these challenges, innovative preservation techniques are essential for enhancing food safety and extending shelf-life without compromising quality. Radiofrequency (RF) technology has emerged as a promising solution in food processing, utilizing volumetric heating for effective disinfestation, pathogen pasteurization, drying, and blanching while maintaining product integrity. In contrast, Controlled Atmosphere (CA) storage employs gas composition control to create low-oxygen environments that inhibit microbial growth during storage. This review aims to provide a comprehensive overview of nut safety and preservation by identifying key contamination sources and the microorganisms that target nuts. It will analyze the effectiveness of RF and CA technologies in preserving and decontaminating nuts. By exploring these advanced methods, this study highlights their potential to surpass conventional processes, ultimately improving nut safety and quality throughout the supply chain.

1. Introduction

Nuts have gained worldwide popularity due to their appealing taste and numerous health benefits (Chen et al., 2020). The global market of nuts was valued at US$ 295.8 billion in 2022 and is expected to grow exponentially to US$ 459.1 billion in 2030, highlighting their significant economic importance (Intrado GlobeNewswire, 2023). Some of the most consumed nuts include almonds, walnuts, and cashews (Brar & Danyluk, 2018) offering a rich nutritional profile that includes proteins, fats, fiber, essential vitamins (C and E), and micronutrients such as potassium, copper, calcium, and magnesium (Gama et al., 2018; Gonçalves et al., 2023). Nuts also contain bioactive compounds like phenolic acids, flavonoids, and tannins, making them popular as healthy snacks and ingredients in various food products (Marchetti et al., 2018; Wang et al., 2017).

Nuts are usually harvested in relatively short periods, typically between late summer and early fall. Yet, their ear-round availability is highly desired due to their popularity (Chen & Pan, 2022). The quality and shelf-life of nuts are significantly influenced by pre- and post-harvest conditions, affecting their physicochemical composition (Gama et al., 2018; Yen & Chen, 2022). At harvest, most nut species are composed of a thick, moist shell that surrounds the husk and kernel and hold high moisture content and water activity. These features make fresh nuts especially vulnerable to microbial deterioration, requiring artificial drying to preserve their quality (Chen & Pan, 2022). However, drying alone is not enough for appropriate microbial decontamination and disinfestation. Traditional hot air-drying methods, while necessary, can be time-consuming for large volumes and may compromise nut's quality (Ling et al., 2020). However, nuts are rich in unsaturated fatty acids and sensitive to heat treatments, emphasizing the importance of applying suitable post-harvest preservation methods to ensure quality, safety, and market value for these products (Chen & Pan, 2022).

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These limitations have spurred research into innovative technologies that can ensure optimal decontamination and disinfestation while preserving the nutritional integrity, sensory attributes, and market value of nuts. Radiofrequency (RF) is an advanced dielectric heating technique that uses electromagnetic waves (1–300 MHz) to penetrate food and produce internal heat (Jiao et al., 2018). As a type of dielectric heating, RF heats the ingredients by ionic conduction and/or dipole rotation, with the absorbed energy being transformed into thermal energy inside the matrices (Huang et al., 2018). Compared to traditional heating techniques, RF energy can penetrate deeper and faster into thick matrices, promoting volumetric heating. This differs from conventional heating, which relies on thermal conduction, surface convection, or radiation (Macana & Baik, 2018). Radiofrequency energy can also penetrate conventional packaging without needing any contact between the product and the electrodes, making it particularly suitable for processing large matrices and bulk materials (Chen et al., 2019).

Several studies have investigated the suitability of RF energy for processing and preservation of agricultural and food products, namely in different nut species. In this field, highly satisfactory results were achieved in the drying (Wang et al., 2014; Zhang et al., 2016), decontamination/disinfestation (Appugol et al., 2022; Gao et al., 2010; Ling et al., 2016), and pasteurization (Zhang et al., 2019) of different types of products. To make the RF technique viable and acceptable for the nut industry, it is essential to determine optimal operating conditions for various nut matrices. This optimization should ensure uniform heating with favorable drying and decontamination/disinfestation rates, while simultaneously preserving the quality of the products (Yen & Chen, 2022). Ongoing research aims to refine RF applications for various nut types, optimizing processing parameters to meet industry standards and consumer expectations.

Controlled atmosphere (CA), in turn, is an advanced preservation technique that involves maintaining specific levels of gases, typically high carbon dioxide (CO_2) and low concentrations of oxygen (O_2) around stored products. This artificially created atmosphere alters the internal gas composition of the stored products, effectively slowing down their metabolic activity and postponing its senescence and/or deterioration (Falagán & Terry, 2018). The efficacy of CA storage is influenced by specific characteristics of each food matrix and storage conditions, including relative humidity and ethylene concentration (Falagán & Terry, 2018). When optimized, CA storage can significantly extend the seasonal availability of food products by reducing enzymatic activity responsible for browning and maintaining their physicochemical and functional characteristics. Additionally, CA storage can mitigate or prevent infestations, reduce storage disorders, and minimize food waste, thereby enhancing the overall quality and shelf life of stored produce (Alamar et al., 2018; Singh & Singh, 2013). Recent studies have explored the application of CA in maintaining the quality of different species of nuts. Ribeiro and colleagues (2022) found that CA storage maintained kernel quality of pecan nuts and extended their shelf-life by up to 18 months, while other authors demonstrated that this technique effectively reduced pathogens such as *Escherichia coli* in almonds (Cheng et al., 2017), *Hypothenemus obscurus* in macadamia (Delate et al., 1994), *Tribolium castaneum* in cashew nuts (Navarro & Navarro, 2020), among others, with excellent results being achieved in these fields without compromising the quality of nuts.

In this context, this review aims to address key aspects of nut safety and preservation comprehensively. First, it will identify the primary sources of contamination in nuts, shedding light on critical points in the production and supply chain where interventions may be most effective. Second, the review will determine which microorganisms are most likely to infect nuts, providing valuable information for targeted prevention and control strategies. Third, it will individually analyze RF technology for nut preservation, decontamination, and disinfestation, exploring its efficacy and potential applications in the industry and the CA system's role in controlling pests and microorganisms during nut storage, offering insights into long-term preservation techniques. By exploring these advanced techniques, this review highlights their potential to surpass conventional processes in ensuring nut safety and quality throughout the supply chain, from production to consumption.

2. Quality and shelf-life of tree nuts

2.1. Sources of microbial contamination and insect pests

Nuts are highly valued natural food products subject to rigidly ruled quality standards. A key quality indicator is the absence of any pest infestation, which may result in considerable economic losses throughout the supply chain (De Souza et al., 2017; Johnson, 2013) identified some of the most common insect pests that may infest tree nuts, presented in Table 1. Each species presents unique challenges in detection, prevention, and eradication, and their potential to infiltrate nut crops at various stages underscores the need for comprehensive, multi-stage pest management strategies (De Souza et al., 2017). Contamination of nuts can occur in several ways, influenced by complex interactions between crop characteristics, cultivation practices, environmental factors, and post-harvest conditions (Brar & Danyluk, 2018).

Postharvest infestations in nuts can originate from two primary sources: field-to-storage transfers and direct storage contaminations. Field pests that infest nuts before harvest typically struggle to reproduce in storage environments, making a single disinfestation treatment often sufficient. However, these infestations can render nuts inedible, as seen with navel orangeworm (*Amyelois transitella*) and codling moth (*Cydia pomonella*) infestations. Conversely, pests that infest nuts after harvest are well-adapted to storage conditions, allowing them to reproduce rapidly and spread throughout the commercial chain (De Souza et al., 2017). Common storage pests include beetles and moths, such as the indianmeal moth (*Plodia interpunctella*) (Johnson, 2013), which can infest all stored nuts, and *Oryzaephilus* species, frequently found in nut storage facilities. While storage pests are shared across various nut types, field pests often specialize in specific nut varieties. The closeness of nuts to the soil during production, harvesting, and post-harvest handling can affect the type and population of colonizing microorganisms. Fungal spores, for example, can contaminate nuts through soil, insects, and air transmission. Environmental parameters such as temperature, humidity, atmospheric composition, and moisture content of stored products also play crucial roles in microbial growth (Qiu et al.,

Table 1
Common post-harvest insect and mite pests that infest tree nuts.

Common name	Scientific name	Nuts
Field pests		
Chestnut moths	*Cydia splendana, Cydia flagiglandana*, and *Pammene fasciana*	Chestnut
Chestnut weevil	*Curculio elephas*	Chestnut
Codling moth	*Cydia pomonella*	Walnut
Filbertworm	*Cydia latiferreana*	Hazelnut
Navel orangeworm	*Amyelois transitella*	California almond, walnut, pistachio
Peach twig borer	*Anarsia lineatella*	Almond
Tropical nut borer	*Hypothenemus obscurus*	Macadamia
Various nut weevils	*Curculio* spp.	Pecan, chestnut, hazelnut
Carob moth	*Ectomyelois ceratoniae*	Almond
Storage pests		
Chestnut moths	*Cydia splendana* and *Cydia flagiglandana*	Chestnut
Chestnut weevil	*Curculio elephas*	Chestnut
Almond moth	*Cadra cautella*	Peanuts and other nuts
Indianmeal moth	*Plodia interpunctella*	All stored nuts
Grain and flour beetles	*Oryzaephilus* spp.	Common in stored nuts
Various bettles	*Cryptolestes* spp. *Cryptophagus* spp. *Trogoderma* spp.	Occasional pests on stored nuts

2022). Traditionally, these factors have been managed through various processing techniques, including fungicides and insecticides. However, increasingly stringent regulations are limiting the application of chemical disinfestation methods. It's noteworthy noting that insect or bird damage to nuts can accelerate fungal invasion rates and aflatoxin production (Safe Food Alliance, 2025). Some of the most common toxicogenic fungi found on tree nuts are presented in Table 2.

Fungi of the genus *Aspergillus* are the most prevalent contaminants in several nut species, playing a significant role in food product deterioration and mycotoxin production (Musangi et al., 2024; Ramadan et al., 2022). Recent studies have shown that small raises in moisture content during storage or transport can improve water activity in nuts, possibly leading to mycotoxin development despite (Klich, 2007). *A. flavus* is the predominant species infecting nuts, including almonds, walnuts, pistachios, cashews, hazelnuts, Brazil nuts, and peanuts, often resulting in high levels of aflatoxin contamination (Ünüsan, 2019). While surface contamination can be addressed using various techniques, research has revealed that *Aspergillus* spp., *Penicillium* spp., and *Rhizopus* spp. can penetrate nut shells, colonizing the internal tissues of almonds, Brazil nuts, pistachios, and walnuts (Klich, 2007). Significant differences were detected in the genera of fungal microorganisms that populate distinct species of nuts. *A. niger* and *Rhizopus* spp. are commonly found in store-bought nuts, while *Penicillium* spp. are more prevalent in field-harvested nuts (Bayman et al., 2002). Peanuts, due to their underground growth, are particularly susceptible to contamination by aflatoxin-producing fungi, with *A. flavus* and *A. parasiticus* being the most common perpetrators. A recent investigation on cashew nuts is coastal Kenya (Musangi et al., 2024) revealed a different *Aspergillus* population, with sections Flavi, Nigri, and Terrei denoted. The report found that 22.22 % of isolates were aflatoxigenic, all belonging to section Flavi.

Table 2
Common toxicogenic fungi that infect tree nuts.

Main source	Fungi species	Reference
Almonds	*Aspergillus* sp. *Penicillium* sp. *Yeast*	Khosravi et al. (2007)
Brazil nut	*Aspergillus flavus* *Aspergillus bombyces* *Aspergillus caelatus* *Aspergillus nomius* *Aspergillus tamarri*	Calderari et al. (2013)
Cashew nut	*Aspergillus section flavi* *Aspergillus section nigri*	Lamboni et al. (2016)
Chestnut	*Alternaria alternata* *Cladosporidium cladosporoides* *Fusarium oxysporium* *Mucir mucedo* *Rhizopus stolonifer*	Kačániová et al. (2014)
Hazelnut	*Aspergillus flavus* *Aspergillus parasiticus*	Ozay et al. (2008)
Peanut	*Aspergillus restrictus* *Aspergillus flavus* *Aspergillus fumigatus* *Aspergillus* sp. *Rhizopus nigricans* *Rhizopus arrhizus* *Mucor pusillus* *Aspergillus tamari* *Penicillium citrinum* *Aspergillus ochraceus* *Penicillium* sp.	Adebajo and Diyaolu (2003)
	Aspergillus parasiticus *Fusarium* sp. *Macrophomina phaseolina* *Botryodiplodia theobromae*	McDonald (1970)
Pecan nut	*Aspergillus wenti* *Aspergillus ruber* *Aspergillus pseudoglaucus* *Aspergillus chevalier* *Clodosporium* sp. *Fusarium* sp. *Penicillium* sp.	Garcia et al. (2019)
Pistachio	*Aspergillus* sp. *Penicillium* sp. *Mucor* sp. *Fusarium* sp. *Parcilomyces*	Bahkali et al. (2013)
Walnut	*Aspergillus flavus* *Aspergillus niger* *Aspergillus fumigatus* *Aspergillus parasiticus* *Penicillium* sp.	Tournas et al. (2015)

Foodborne pathogens also represent a significant source of nut contamination, potentially occurring at any stage of production or consumption, requiring the implementation of vigorous food safety strategies to prevent contamination issues. At the same time, the high fat content characteristic of many nuts is a crucial factor in increasing pathogen resistance, which is further enhanced in pathogens that have infiltrated the nut, compared to those present on the surface (Beuchat et al., 2013; Beuchat & Mann, 2011a). *Salmonella* is often considered the target organism due to its persistence for long periods and its high heat resistance (Beuchat & Mann, 2011b; Brar et al., 2015). Other foodborne pathogens found in nuts may include *Bacillus cereus*, *Clostridium botulinum*, *Clostridium perfringens*, *Cronobacter*, *Escherichia coli* O157:H7, *L. monocytogenes* and *Staphylococcus aureus* (Beuchat et al., 2013). *Enterococcus* and coliform microorganisms, in turn, are the major bacteria found on nuts surfaces (Al-Moghazy et al., 2014; King et al., 1970). Other common bacteria genera identified on nuts may include *Streptococcus*, *Staphylococcus*, *Bacillus*, *Xanthomonas*, *Achromobacter, Pseudomonas*, *Micrococcus*, and *Brevibacterium* species (Al-Moghazy et al., 2014; King et al., 1970).

Contamination of nuts can occur at various stages of production, with pre-harvest being a critical period. Orchard soil serves as a primary source of contamination (Brar & Danyluk, 2018), which can be transferred to nuts when they fall to the ground during harvesting or through the dispersion of contaminated dust (Uesugi et al., 2007). Likewise, rainfall during harvest periods can increase the adherence of nuts to the soil, increasing the frequency of pathogens. Moreover, the presence of soluble sugars in some wet nut shells can stimulate the growth of pathogens both in the shell and in the soil where sugar-laden rainwater may leach (Danyluk et al., 2008). The invasion of animals into the tree nut orchards also remains a significant food safety concern. given that foodborne pathogens sheltered by animals can contaminate orchard soils through faecal deposition, mainly rats and mice (Quinn & Baldwin, 2014). It is worth mentioning that, until the time of harvest, nuts do not have any kind of contact with the soil, equipment's, or humans (all important sources of contaminants). Thus, to maintain the safety of the products, the harvesting must be carried out in dry weather and with clean equipment, minimizing the potential for cross-contamination. Humid conditions can lead to the adherence of various materials (leaves, soil, debris) to nut surfaces, increasing contamination probability (Brar & Danyluk, 2018).

Post-harvest storage conditions are equally critical. Nuts must be stored in dry environments, protected from rain, groundwater drainage, and pest infestation. Constant temperature maintenance and regular monitoring are essential to prevent microbial growth and insect infestations (Christopoulos et al., 2024). These findings emphasize the complexity of maintaining nut safety throughout the production chain and highlight the importance of integrating cutting-edge research into agricultural practices to enhance food safety in the nut industry.

2.2. Environmental factors influencing preservation of nuts

2.2.1. Moisture content

The shelf-life and quality of nuts are significantly influenced by storage conditions, necessitating adherence to stringent and product-specific protocols, specific to each type of food matrices (Srichamnong et al., 2010). In this field, one of the prominent issues is the moisture content of the food products, which must be reduced to acceptable values soon after harvesting, with the risk of otherwise compromising the quality of the food products, specifically nuts (Wall, 2013). These values can differ between different nut species. For dried pistachios, for example, a moisture content of 4 % provides greater crispness, firmness, and sweetness while less bitterness and rancidity levels than those with 11 % (Kader et al., 2022). Overall, the moisture content is closely related to the water activity of the nuts, which represents the amount of available free water capable of participating in enzymatic, physical, and chemical reactions. Consequently, nuts with lower water activity values have a longer shelf-life, the development of aflatoxins being also influenced by higher values of this parameter (Venkatachalan & Sathe, 2006).

2.2.2. Storage temperature

Storage temperature remains a critical factor in determining the shelf-life of nuts, significantly influencing enzymatic activity, metabolic reactions involved in food deterioration, and chemical composition (Monsef et al., 2020). Specifically, oxidation and rancidity have a direct dependency on both low temperatures (0–5 °C) and storage time. For example, walnuts stored at 5 °C showed markedly lower peroxide values and hexanal content, which are key indicators of oxidative rancidity, compared to those stored at 25 °C (Mitcham et al., 2022). The increase in peroxide occurs with the oxidation of fats and the increase in the enzymatic activity of lipoxygenase and lipase verified at higher storage temperatures (Arena et al., 2013; Ozturk et al., 2016), which manifests as off-flavors and texture degradation (Mitcham et al., 2022).

While low temperatures extend shelf life, improper humidity control can negate these benefits, which is a clear drawback (Christopoulos & Tsantili, 2015; Ghirardello et al., 2016; Moscetti et al., 2012). High relative humidity (RH $\geq$ 80 %) promotes mold growth and textural changes, as observed in cashews and walnuts (Ajith et al., 2015). While raw cashew nuts stored at 86–90 % RH developed mold within 24–48 h, 67 % RH at 30 °C maintained stable moisture and quality. Similarly, walnuts stored at 80 % RH developed mold after 6–12 months, with water activity being more strongly correlated with textural degradation (Mitcham et al., 2022).Thus, the synergy between temperature and humidity is critical, with cold storage ranging from 0 to 2 °C combined with RH between 40 and 60 % being ideal for slowing oxidation and prevent moisture absorption, respectively. These effects were observed in walnuts, which storage at 15 °C and 80 % RH promoted the development of mold, whereas those at 5 °C and 40 % RH retained sensory quality for up to 12 months (Mitcham et al., 2022; Monsef et al., 2020).

2.2.3. Oxygen availability

Oxygen availability remains a critical factor affecting nut shelf-life during storage, as it promotes lipid oxidation when oils, oxygen, and catalysts interact (Choe & Min, 2006; Raisi et al., 2015). The larger the oxygen concentration, temperature, and presence of light and specific metals, such as iron and copper, the larger is that effect (Choe & Min, 2006). Bakkalbaşi, Yilmaz, Javidipour, and Artik (2012) found that the concentration of hexanal in stored pistachios and nuts was higher under high oxygen conditions, fact also exhibited by pistachios stored at $<$ 2 % oxygen, for which the shelf-life was extended relatively to those stored at 8 % (Sedaghat, 2010). Also, material packages that have high oxygen permeability can increase the concentration of the mentioned compounds in food matrices (Lal et al., 2023). On the other hand, storage of shelled nuts reduces oxygen permeability, consequently reducing lipid oxidation and oxidative rancidity (Li et al., 2019). Lipid oxidation is also caused by exposure of nut oils to light, given that nuts stored under these conditions have higher peroxide and hexanal values, rancidity, and bitterness when compared to those stored in the dark, regardless of temperature (Shahidi & John, 2013). Thus, the efficient management of this parameter is of particular importance to minimize its harmful effects on the quality of the nuts.

2.2.4. Relative humidity

During short-term storage in open systems or after opening nuts for consumption, relative humidity is also a highly important parameter (Ajith et al., 2015; Phatanayindee et al., 2012). Although its influence on the quality of the nuts during their commercial and retail periods is reduced, since the packaging materials used in sale points prevent the product from being exposed to rapid changes, the nuts reabsorb moisture which is responsible for the development of molds and the sudden aging of nuts (Ajith et al., 2015; Venkatachalan & Sathe, 2006). Also, nuts stored at lower relative humidity hold higher concentrations of polyunsaturated fatty acids and lower levels of free fatty acids, peroxide, and iodine (Ajith et al., 2015; Christopoulos & Tsantili, 2015). This loss of quality during storage is directly associated with increased oxidative and hydrolytic rancidity, because of higher relative water availability (Ajith et al., 2015; Phatanayindee et al., 2012). Therefore, relative humidity levels must be closely monitored during storage, and packages resealed after opening, avoiding mass and quality losses and fungal growth due to water absorption (Gama et al., 2018).

3. Technologies for preservation and decontamination/disinfestation of nuts

The food industry has made significant advances in producing high-quality, safe foods and ingredients with extended shelf lives, largely through the application of various processing and preservation techniques. Traditionally, thermal processing techniques have been the basis of food preservation and decontamination, utilizing steam, water, or hot air to inactivate bacteria, insects, and enzymes (Jiao et al., 2018). However, recent research has highlighted both the benefits and limitations of these methods. Thermal diffusion directly depends on the food matrices' solid nature, being lower for solid or semi-solid foods. To guarantee that all the points of the food matrix receive enough heat, it may signify that the quality of some points of the food matrix may be compromised (Jiao et al., 2018). Therefore, joint efforts have been made to investigate, develop, and apply new thermal and non-thermal processing technologies, with or without the use of chemicals, to preserve and decontaminate different types of foods, including nuts, preserving their safety and improving quality (Jiao et al., 2018).

3.1. Conventional techniques

Traditional approaches to processing and preserving nut quality have evolved to incorporate a combination of cultural practices, biological control, and pest monitoring. These methods include both chemical and non-chemical treatments, with a focus on minimizing damage to the nuts. However, recent research suggests that these individual approaches may be insufficient to fully preserve nut quality, necessitating additional treatments (Sánchez-Bravo et al., 2022).

Conventional methods for storing nuts focus on preserving their quality and extending shelf-life through various techniques. These methods typically include drying, proper packaging, and maintaining optimal storage conditions. Drying is one of the most important steps in nut storage, which reduces moisture content to levels that restrain microbial growth and oxidation (Li et al., 2019; Turan, 2018). After drying, nuts should be stored in sealed containers or vacuum-sealed packaging, which lessens exposure to oxygen that promotes rancidity and spoilage (Lal et al., 2023). Also, the storage environment may ideally involve keeping nuts in a cool, dark place with low humidity, blocking the growth of molds and other microorganisms that could compromise food safety (Christopoulos et al., 2024). More recently, metal silos are increasingly being recognized as an effective storage solution for nuts due to their ability to control temperature and humidity while providing excellent ventilation (Silos Spain, 2023).

Biological control agents, including parasitoids and predators, play a significant role in conventional field pest management programs. However, due to the low tolerance of insects in harvested products, naturally occurring biological agents often struggle to provide sufficient control on their own. Instead, these agents should be integrated with sanitation practices, early harvesting, and pest monitoring to enhance their effectiveness (He et al., 2021). In addition to traditional biological controls, the application of pathogenic organisms such as viruses, bacteria, fungi, and nematodes has emerged as a viable strategy for pest management (Lacey & Shapiro-Ilan, 2008). These microbial pesticides are commercially available and can effectively target pests when applied at the right developmental stages, particularly against newly hatched eggs and larvae (Tadesse Mawcha et al., 2024).

While synthetic pesticides and fumigants are used for pest control, their use must be carefully regulated to avoid negative impacts. However, while broad-spectrum insecticides can effectively control pests, they may harm beneficial insects and lead to pest resistance if overused (Samanta et al., 2023). Fumigants, in turn, although effective, are highly toxic and must be used cautiously. Methyl bromide was one of the most widely used fumigants in stored nuts until its use was banned due to ozone depletion concerns (UNEP, 2006), Alternative fumigants like phosphine or sulfuryl fluoride are currently used, although many chemical fumigants remain unregistered due to safety concerns, including potentially explosive effects, flammability, and release of toxic or carcinogenic residues (Fields & White, 2002). Thus, while synthetic pesticides offer quick results and a cost-effectiveness approach to disinfestation, they pose significant environmental and health risks. In this field, natural methods, though potentially slower-acting, provide a safer and a more sustainable approach to pest control.

In a pre-harvest context, synthetic sex pheromones have also been used to control pests, by interrupting the reproductive cycle of lepidopteran pest populations, and control codling moths. One of the main advantages of this method is that it does not affect beneficial insects, being also effective against populations of pesticide-resistant moths (Rizvi et al., 2021).

Some other processing methods that do not target insects for control can also cause considerable mortality rates, which can help reduce their populations. High temperatures, for example, used during the mechanical drying of food matrices, can result in total or partial mortality of insects (Johnson et al., 1996). Some methods approved by the Almond Board of California for decontaminating almonds from *Salmonella* include traditional practices of oil and dry roasting, blanching, and steam pasteurization. Refrigerated storage, used to maintain quality characteristics of food matrices, also prevents the infestation of clean products or the development of pest populations (Johnson et al., 1997, 1998, 2002), and, depending on the storage time, may disinfest food products (Johnson, 2007).

Different techniques have also been used to control the contamination of nuts by microorganisms, such as the utilization of specific fungi and bacteria. Chemical treatments include the use of compounds such as citric, propionic, and lactic acids, sodium hypochlorite, and propylene oxide (Pankaj et al., 2018). The treatment of food matrices with citric and lactic acids results in the degradation of aflatoxin B1 into less toxic products. In this sense, Pao et al. (2006), used citric acid sprays to treat almonds contaminated with *Salmonella*, verifying a 5-log reduction in these samples. Other chemical compounds used in the decontamination of nuts include sodium hypochlorite, peracetic acid, and propylene oxide (the latter has been found to reduce foodborne pathogens in almonds) (Danyluk et al., 2005). Although chemical treatments are one of the simplest and most economical methods used to decontaminate nuts and inactivate pathogens, their use is not allowed by health organizations.

Walnut shells have a high content of natural antioxidants that protect the kernel from external natural oxidation (Medic et al., 2021; Zaini et al., 2020). However, these give them a bitter taste that reduces sensory satisfaction and palatability (Li et al., 2020). Physical peeling of walnut shells involves bleaching and mechanical abrasive peeling, which is the recommended method in the almond industry (Shakerardekani & Mohamadi, 2019). However, the latter is not recommended for walnuts, as the kernels have an irregular shape, and abrasion can result in significant loss of the kernel pulp. When blanched, walnut kernels are subjected to immersion in water or steam at high temperatures, causing the shell to swell and crack. Blanching is effective not only in protecting the colour of the kernels (Bolling, 2017), but also in controlling the cross-contamination of aflatoxins in almonds (Mahoney et al., 2020). These methods, however, promote an increase in the moisture content of the nuts, as well as the softening of the pulp and the release of polyphenols into the processing water (Hughey et al., 2012). Chemical peeling, in turn, usually refers to the use of hot caustic soda, with the grains being soaked in this solution for a few minutes, and then rinsed with water (ShiLan et al., 2013). Although effective, caustic soda treatment significantly deteriorates the quality of nut kernels and may also cause additional food safety concerns (Liu et al., 2021).

Regulatory, environmental, and resistance issues relating to fumigants and other chemical products used to disinfest nuts and other food products have driven research into technologies that act without the use of chemical agents and are not detrimental to the quality parameters of food matrices. Most non-chemical treatments however require more treatment time, storage space, and investment in expensive equipment.

3.2. *Emergent techniques*

3.2.1. *Radiofrequency*

Radiofrequency (RF) treatments represent a cutting-edge approach to thermal processing in the food industry, offering an efficient, safe, and environmentally friendly alternative for pest control and food preservation. While traditional methods such as hot air, hot water, and steaming have been widely used, they come with certain limitations, including lengthy treatment times for large volumes and the need for additional drying of samples treated with water or steam (Appugol et al., 2022). Developed at the beginning of the 20th century, RF is a form of dielectric heating (DH) technology that utilizes specific electromagnetic (EM) waves, typically at 13.56, 27.12, and 40.68 MHz, for both domestic and commercial applications. This innovative method generates heat within the samples by inducing the rotation of polar molecules and the movement of ions, resulting in volumetric heating effects. With its longer wavelength, RF treatment offers greater penetration depth, making it particularly effective for processing larger volume samples compared to microwave (MW) treatments (Gao et al., 2023). Additionally, RF energy can penetrate non-metallic packaging, allowing for non-contact heating, which enhances its versatility in food processing applications (Ling et al., 2020).

In the food industry, RF was primarily exploited in the blanching, cooking, and dehydration of foods (Moyer & Stotz, 1947; Proctor & Goldblith, 1948), and later used in the thawing and final drying of baked goods (Mermelstein, 1998). From the 90s onwards, the advent of computing and control systems together with the experimental measurements of dielectric properties for an increasing number of food and pest materials boosted the study of RF applied to post-harvest disinfestation of agricultural products (Mitcham et al., 2004; Monzon et al., 2019; Wang et al., 2002, 2003), sterilization, and pasteurization of foods (Wang et al., 2002, 2003). Despite the investment, the industrial use of RF for disinfestation is still incipient and requires a deeper knowledge on the food materials and pests' properties (Jiao et al., 2018).

When test samples are exposed to RF fields, two key phenomena occur simultaneously. The first is ionic depolarization within the samples. The second involves dipole rotation, where dipolar molecules strive to align themselves with the shifting polarity of the electromagnetic field

(Ling et al., 2023). The rapid and continuous movement of these ions and dipoles, driven by the electromagnetic fields, produces volumetric heating within the sample. Although these two phenomena occur simultaneously during dielectric heating, dipolar polarization is the main factor generating heat at RF frequencies (Jiao et al., 2018).

Several factors may impact the RF heating performance in food products. When a food matrix is positioned in an electromagnetic field, it acts as an electrical capacitor, capable of storing energy, and as a resistor, able to convert it into thermal energy, generating heating. The interaction between a material and an electromagnetic field is described by the dielectric properties (Içier & Baysal, 2004), which are crucial to understand the interactions between RF energy and that materials that, together with the electromagnetic field characteristics, determine the absorption of electromagnetic energy. The retained electromagnetic energy, in turn, coupled with thermal and physical characteristics of the material shape the heating performance of food matrices. The dielectric properties of foods depend significantly on the amount of water molecules present in the matrices, with low-moisture foods showing a negligible dipole dispersion of free water molecules and, hence, low values of dielectric properties. Here, the bound water, a form of water that has its mobility between ice and free water, plays a critical role in the frequency range of 20–300 MHz, displaying a lower relaxation frequency than free water (100 MHz; 20 °C) (Huang et al., 2018). Alongside with its moisture content, there are other factors that strongly affect the dielectric properties of a material, such as the frequency of the alternating electric field, the temperature, as well as the density, composition, and structure of the food material (Hou et al., 2016). The dielectric properties include the permeability and permittivity. Permeability of food matrices is usually the same as the one of the empty spaces and is considered to not have significant effect on dielectric heating. In opposition, permittivity has a significant effect on dielectric heating. It is a complex variable that describes the dielectric properties related to the reflection of electromagnetic waves at interfaces and the attenuation of energy in materials (Sosa-Morales et al., 2010). The permittivity can be expressed in a dimensional way as the relative permittivity (**Supplementary material (SM), Equation 1**), which is the ratio between the permittivity of a material and the permittivity in vacuum.

The dielectric permittivity (**SM, Equation 2**) of a material (namely of food matrices) includes the dielectric constant (ε'), which describes the energy storage capacity of the material when subjected to an electric field, influencing the field distribution and the phase of the waves that pass through it, and the dielectric loss factor (ε), which impacts both the absorption and attenuation of energy and describes its dissipation capacity in response to an electric field (Routray & Orsat, 2018). These two components of permittivity are expressed through a complex number, by its real (dielectric constant) and imaginary (dielectric loss factor) parts.

The power dissipation per volume unit, also known as the power density, P_V (W/m3), can be expressed by **Equation 3 (SM).**

During dielectric heating, a part of the electromagnetic energy is absorbed by the material and converted into heat, but another part is blocked and reflected on the surface of the food matrix, with a gradual decrease in intensity of energy that reaches inner parts of the material. When this energy is reduced to $1/e$ ($e = 2.718$) of its surface value, the distance through the material over which the electromagnetic wave passes is called penetration depth, which also depends on the dielectric properties of a given material. The penetration depth (d_p) can be expressed mathematically by **Equation 4 (SM)**.

Based on **Equation 4** the penetration depth is inversely proportional to the frequency of electromagnetic waves and therefore, for a given material, is higher for lower frequencies — reason why RF can heat thicker products than microwave. Additionally, the dielectric properties of food matrices with higher water content are normally greater than those with lower values, despite the d_p being lower than in samples with lower humidity. Therefore, RF energy can be a potential heating method for large food matrices with low water content (Ling et al., 2020). Considering that the heat loss to the environment during RF heating is negligible, from an energy balance to the food material it is possible to see that the temperature of the material will change according to **Equation 5 (SM).**

According to **Equation 3**, the frequency and voltage are fixed for a given RF heating unit, the higher the material's dielectric loss factor (ε''), the more energy it absorbs. From **Equation 5**, in turn, it is possible to observe that the heating rate is directly proportional to ε'' values and to the electrical intensity, and inversely dependent on the density and thermal capacity of the same material (Hou et al., 2016).

3.2.2. Radiofrequency heating systems

Available RF systems for the conversion of electrical energy to thermal energy can be categorized into two groups: the free-running oscillator (FRO) system (a conventional equipment device) and the power-regulated 50 Ω system (Awuah, Koral, & Guan, 2014).

In an FRO system, the RF energy produced in a standard oscillator circuit is then applied to the food material using two electrodes and the products charged between them can form an output circuit, ending in the generation of heat. The energy stored in the product is adjusted by a movable top electrode and the products are moved through the electromagnetic RF field by a conveyor belt to obtain continuous heating (Awuah, Koral, & Guan, 2014).These systems are characterized by their high efficiency, structure simplicity, and low cost; however, the circuit capacitance can be changed during their operation due to changes of the electrode gaps and even changes of the dielectric properties of the products, which can provoke a change of the system frequency (Zhao et al., 2000). This obviously represents a disadvantage of FRO system.

In what concerns the 50 Ω systems, and despite their main structure be similar to the that of the FRO systems, the automatic impedance matching system can be automatically rotated while maintaining the general impedance of the circuit at 50 Ω. Therefore, the system can maintain the power coupling into stable matrices during heating, providing a fixed frequency and strictly controlling its power (Zhou et al., 2017), in opposition to what happens with the FRO system.

From these two systems, the FRO is the most widespread in industry with heating purposes, namely in the drying of food products. In fact, since the RF energy gets concentrated mainly in areas with higher moisture of the matrices, it tends to homogenize the water content over the whole food material, as more water will evaporate in the parts receiving more energy (Ling et al., 2020). This particularity of the FRO system makes it highly preferable in the drying industry, as it protects food from overheating, reducing moisture variation in the final product, ultimately controlling the growth of fungi, and preventing the loss of volatile components. The 50 Ω system, in turn, is suitable for handling food matrices with more stable moisture content, particularly in pasteurization and sterilization processes. However, these are more expensive systems with complex configuration and maintenance being, therefore, less used industry (Ling et al., 2020).

Although RF heating is a fast process, it does not preclude the existence of temperature heterogeneity in the heated material. Moreover, the uneven temperature distribution promotes itself an even stronger non-uniform heating, since many materials exhibit changes of the dielectric properties with temperature. The uniformity of the heating process depends on different parameters, such as physical, dielectric, and thermal properties, distance between the product and the electrodes, chemical properties of the medium, and even the system itself (Fu, 2008). Non-uniformity of RF heating can, in turn, cause damage to the product and packaging; To overcome this failure, different strategies have been suggested, such as placing the matrix in hot water, hot air, or saline water, as well as rotating, stirring and mixing the products passing between the electrodes (Birla et al., 2008; Ling et al., 2016; Wang et al., 2010).

This problem has merited the interest of the scientific community, as it represents a serious drawback of the technology. In order to quantify this issue, a uniformity index, λ, was proposed, defined according to

(SM, Equation (6)).

Due to the complexity of this question, computer simulation has also been used to improve the uniformity of RF heating, through the development of several models that allow the concomitant study of different factors applied to several food matrices (Huang et al., 2016). A smaller value of UI indicates a more uniform RF heating (ideally, the index would be 0, indicating complete uniformity of temperature over the material).

Most cellulose-based plastic materials used in packaging are generally inactive or transparent to RF. Other types of materials, such as dry foods, grains and nuts, on the other hand, quickly absorb RF energy and are consequently heated at a fast pace (Bermudez-Aguirre & Niemira, 2023; Costa & Marra, 2024). In the latter, the penetration of RF energy photons occurs easily, allowing their processing in large fluxes while heating the material entirely.

RF energy can also be delivered in ultrashort pulses, typically micro to milliseconds (μs to ms), creating considerable and instantaneous RF power peaks. When the energy supply time is ultra-short, targets, such as insects and mites, are subjected to instantaneous high temperatures, without however compromising the host material, generating non-thermal effects (Bermudez-Aguirre & Niemira, 2023; Costa & Marra, 2024). During the application of pulses, intense electrical fields induce dipolar polarization, making this the main energy transfer mechanism, responsible for the disinfection of biological materials that cause cellular changes in food matrices (Bermudez-Aguirre & Niemira, 2023; Costa & Marra, 2024). For pulsed RF systems to be reliable and successful, with high repetition rates, more investment is needed in the study of this system in order to allow a deep understanding of its mechanisms that base the development of engineering models capable of reproducing the complex behaviour of the system and can complement the efforts to unlock the potential for non-thermal and free disinfection system, free from chemicals, of fresh food products.

Table 3

Effect of Radiofrequency treatments in different physicochemical and biological parameters of nuts.

Samples/Species	Objectives	Treatment parameters	Main results	Reference
Walnuts (*Juglans regia* L.)	Drying Disinfection	**Power** – 2 kW **Frequencies** 6.78, 13.56, 27.12, and 40.68 MHz	No significant effect of frequency on the cracking ratio and color Pest mortality increased with increasing drying time for all systems of the 4 frequencies 100 % insect mortality provided acceptable peroxide value, free fatty acids, and *L*-values	Mao et al. (2021)
Chinese Chestnuts (*Castanea mollissima* Blume)	Disinfestation	**RF heating** - 55 °C with forced hot air, **Conveyor speed** - 9.2 m/h **Duration** - 0, 1, 3 and 5 min Forced room air cooling in single-layer samples	100 % mortality of *C. punctiferalis* No significant differences were observed in the quality/nutritional parameters of RF-treated and control chestnuts.	Hou et al. (2015)
Peanut (*Arachis hypogaea* L.)	Disinfestations Effect on quality	**Least electrode height** - 180 mm **Conveyor speed** – 5 m/h **Temperature** – 89.96 °C	100 % mortality of *Caryedon serratus* Reduction of aflatoxin B1 and B2 contents Significant decrease in moisture and protein content No significant differences in color values	Appugol et al. (2022)
Almond (*Prunus amygdalus* Batsch)	Pasteurization	**Frequency** - 27 MHz **Power** - 6 kW **Temperature** - 55 °C **Electrode gap** – 10.5 cm (pasteurization) −12 cm (drying) Forced room air cooling in 3 cm thick samples	1.5 min achieved 5-log reductions of *E. coli* ATCC 25922 8.5 min reduced the moisture content of almond shell back to 5.08 % wet basis Kernel color, peroxide value, weight loss, fatty acid value and fatty acid composition met good quality standards	Li et al. (2017)
Pistachio (*Pistacia vera* L. Kerman variety)	Investigation of heating rate Develop an effective cooling method after heating Disinfestation Effect on quality	**Frequency** - 27 MHz **Power** - 6 kW **Electrode gaps** - 11.5 and 10.5 cm **Heating rate** - 5.4 °C/min	100 % mortality of fifth-instar *Plodia interpunctella* (Hübner) No significant differences in weight loss, peroxide values, fatty acid values, fatty acid composition and kernel color	Ling et al. (2016)
Macadamia (*Macadamia tetraphylla* L.A.S. Johnson)	Investigate the heating and drying uniformity Study the influence of Hot Air Radio Frequency (HARF) drying time on the nut quality	**Frequency** - 27.12 MHz **Power** - 6 kW **Electrode gap** - 15.5 cm **Hot-air temperature** - 50 °C	HARF treatments could shorten drying of macadamia nuts by half when compared to hot-air drying alone The drying uniformity was acceptable Overall quality was reduced for HARF drying, but remained within accepted limits to the nut industry	Wang et al. (2014)
Hazelnuts (*Corylus avellana* L.)	Blanching	**Frequency** - 13.56 and 27.12 MHz **Holding time –** 0 or 5 min at target temperature **Target temperature** – 70, 80, and 90 °C	A 5-min holding time at the target temperature resulted in better heating uniformity and lower peroxidase (27–35 %) and polyphenol oxidase (40–45 %) activities	Dag et al. (2023)
Cashew nut (*Anacardium occidentale* L.)	Impact of the heating uniformity Effect on physicochemical properties, sensory quality, and antioxidant activity	**Frequency** - 27.12 MHz **Power** - 12 kW **Chamber capacity** - 310 × 100 × 165 cm^3 **Temperature of hot air** - 20–80 °C **Area of top electrode** - 75.0 × 55.0 cm^2	Peroxide and acid values of roasted samples were significantly lower than those roasted by conventional hot air, indicating better physicochemical quality. Sensory attributes and antioxidant activity of the kernels roasted by HARF were in well acceptable range	Liao et al. (2018)

3.2.2.1. Disinfestation using RF heating in the food industry. During the production, storage and marketing of agricultural products, one of the main problems responsible for damage and losses is pest infestation. These include nutritional losses, low germination rate, and reduced weight of agricultural products (Yuya et al., 2009), with pests still producing sticky substances and faeces that promotes microbial growth and reduce the market price of these types of products. RF heating represents different advantages compared to conventional methods, namely the selective heating of insect pests, which promotes the destruction of insects while keeping a tolerable, or even inexistent, thermal degradation of quality of the food matrices (Bermudez-Aguirre & Niemira, 2023; Costa & Marra, 2024). This phenomenon occurs due to differences in the permittivity (namely the loss factor) between the pest (high) and the food matrix (low), which foster the so-called "selective or differential RF heating" (Hou et al., 2015). In general, complex organisms, such as arthropod pests, are more aggressively and easily affected by high temperatures, which results in a bigger difference of the thermal sensitivity between the pests and the food matrices, offering a window of opportunity for the success of the RF heating disinfestation process (Bermudez-Aguirre & Niemira, 2023; Costa & Marra, 2024). Insect inactivation occurs through thermal damage caused by RF energy to the insect's constituent carbohydrates, proteins, DNA, RNA and lipids. RF disinfestation thus offers a green alternative to conventional approaches using chemical fumigants, since this technology is contact-free and waste-free (Jiao et al., 2021).

3.2.2.2. Effects of RF treatment in the quality of nuts. In the last few decades, several studies on the potential of RF energy in the processing and preservation of nuts have been performed, some of the most recent ones being described in Table 3. One of the main advantages of applying RF energy to a number of varieties of nuts is related to the high rate of disinfection/disinfestation, without however negatively impacting the quality of the food matrices. Hou et al. (2015) investigated the effect of RF heating on the pests and on the quality of the host during the disinfestation of chinese chestnuts (*Castanea mollissima*). They observed an increasing mortality of *C. punctiferalis* (the least thermal tolerant species among the pests under analysis) with an increasing holding time at 55 °C, having observed 100 % mortality for a holding time of 5 min. Their results showed no significant differences in quality parameters, such as color, fat, firmness, moisture content, protein, and soluble sugar content of chestnuts treated with RF when compared to those not submitted to such treatment. Although the moisture content of chestnut shells was in fact reduced after the RF treatments, these losses are not significant in what concerns the moisture of the treated kernels. The same was observed when peanuts (*Arachis hypogaea*) (Appugol et al., 2022) and pistachios (*Pistacia vera* L. Kerman variety) (Ling et al., 2016) were subjected to RF treatments, with 100 % mortality of *Caryedon serratus* and fifth instar *Plodia interpunctella* (Hübner) being achieved in both nut species, respectively. In Appugol et al. (2022), the ability of RF heating in detoxifying peanuts from aflatoxins was also verified and the potential of this technology in safeguarding the microbiological safety of the samples was proven. In both studies Appugol et al. (2022) and Ling et al. (2016), no significant differences in quality parameters of the nuts were verified, namely regarding weight loss, peroxide values, fatty acid values, fatty acid composition and kernel color. RF energy was also shown to be able to reduce the prevalence of *E. coli* ATCC 25922 in almonds (Li et al., 2017), with a 5-log reduction being achieved in 1.5 min of treatment, without compromising the quality parameters of the almonds.

Enzymatic activity in food products is one of the biggest obstacles to maintaining their quality and shelf-life. In this context, RF energy has also been used to inactivate enzymes responsible for the deterioration of the quality of nuts. Dag et al. (2023) investigated the ability of RF energy in blanching of hazelnuts using frequencies of 13.56 and 27.12 MHz, and target temperatures of 70, 80, and 90 °C. Their results showed the ability of the employed RF system in reducing the activity of peroxidase (27–35 %) and polyphenol oxidase (40–45 %) for a 5 min holding time, apart from a better heating uniformity.

Overall, most studies show the effectiveness of RF energy in maintaining quality parameters of different varieties of nuts, when subjected to different processes, that allow to extend the shelf-life of these highly appreciated products in terms of its diverse sensorial, nutritional, chemical and bioactive properties.

3.2.3. Controlled atmosphere chamber

In the last few decades, food retail has undergone transformations that have driven the development of technologies that allow the safe transport and storage of agricultural products, allowing them to be supplied throughout the year. These types of products are naturally highly perishable, since metabolic processes, such as respiration and transpiration, lead to the consumption of substrates (like sugars and organic acids) and the loss of water, that promote their ripening and post-harvest senescence (Falagán & Terry, 2018). To overcome this natural deterioration of fruits and vegetables, the development of advanced post-harvest technologies has become urgent, ultimately allowing the reduction of food waste and the maintenance of safety and quality standards of different agricultural products.

Modified atmospheres (MA) designate artificially created mixtures of gases whose composition differ from that of normal air. Food is sealed in containers or chambers that restrict the entry and exit of gases, resulting in the creation of an environment with O_2 consumption and CO_2 generation, a consequence of the respiratory activity of the food products (Yahia et al., 2019) and therefore leading to a permanently changing composition of the gaseous mixture. The controlled atmosphere (CA), in turn, differs from MA since the latter are closed loop systems (that is, they work under the action of a control system) while the former are, as seen above, merely open-loop systems (that is, they work without any control system). Thus, CA includes a control system that maintains the composition of the gaseous mixture constant (in previously fixed set-points). Apart from the controller unit itself, the control system comprises a set of sensors for measurement and an atmosphere generation mechanism (including a set of valves) to act on the system. In this technology, the atmosphere is maintained at established values (set-points) throughout the storage period, which is why it is usually used to preserve food products for long periods in refrigerated and airtight installations (Yahia et al., 2019). The first CA storage was implemented by Benjamin Nyce in 1860, in the United States, although the technology was only successful with studies by Franklin Kidd and Cyril West, between 1910 and 1920 (Kidd & West, 1927). They hypothesized that the composition of the gaseous mixture surrounding the food products in what concerns O_2 and CO_2 affect the storage capacity of fruits since these gases influence the metabolic processes. Kidd and West's studies on "gas storage" evolved rapidly into a successful industry based on CA technology in the 1930s. The technique has been refined along the years and is currently extremely important in the preservation of different food products (Prange et al., 2006).

The behaviour of fresh food matrices under CA conditions is determined by the relationship between the composition of the external and internal atmosphere of plant tissues, which is controlled by: (1) the product's respiration, namely by O_2 consumption and CO_2 production, (2) ethylene production, (3) permeability and resistance to diffusion of natural tissue barriers to gases (epidermis, cuticles, cell wall, among others), (4) difference in partial pressure inside and outside the food matrix (Yahia et al., 2019).

Some of the variations that occur in fresh agricultural products during ripening may include changes in colour (due to alterations in pigments), flavour (due to transformations in starch, sugars, phenolic compounds, among others), texture (due to variations in the constituent compounds of cell walls, gaseous alterations, by the influence of gases from the surrounding CA atmosphere), and nutritional variations (specifically in the composition of polyphenols, vitamins and minerals)

(Falagán & Terry, 2018; Yahia et al., 2019). Therefore, extending the shelf-life of food products and maintaining their quality implies minimizing these changes, given that in agricultural products these cannot be interrupted. Reducing temperature is crucial for minimizing damage, making it possible to slow down chemical reactions that occur within the tissues of food matrices. CA further reduces these variations/changes by reducing the availability of O_2, inhibiting reactions that generate CO_2, and specifically by reducing or inhibiting the production of ethylene, its synthesis being sensitive to both O_2 reduction and elevated CO_2 (Yahia et al., 2019). The CA storage of shelled "Barton" pecan nuts at low oxygen 2 kPa O2) and high CO2 (15 kPa CO_2) at 10 °C for six months maintained lower acidity values and peroxide values, indicating better quality preservation (Ribeiro et al., 2022).

Appropriate humidity management is also crucial for maintaining quality and extending shelf life of nuts, as high relative humidity (around 90–95 %) helps prevent moisture loss and preserves texture, but excessive levels can promote mold growth. Thus, balancing humidity with low oxygen and high CO_2 levels in CA storage may slow down respiration and transpiration, reducing metabolic activity. A study on peanuts found that maintaining relative humidity between 55 % and 70 % at 1–5 °C kept peanut moisture content at 7–7.5 %, which is optimal for quality preservation (van der Sluis, 2013).

Furthermore, CA storage is responsible for several other benefits for food matrices. By providing an atmosphere with low partial pressure of O_2 and high partial pressure of CO_2, food matrices reduce the metabolic rate, delaying the phenomena that promote the ripening of agricultural products. However, it must be considered that very low levels of O_2 and/or very high levels of CO_2 can increase the production of the latter, due to the fermentation of the products (Pasteur effect), this process being dependent on the species and variety of the food product (Yahia et al., 2019). The decrease in enzymatic activity and oxidation processes, resulting from the decrease in the concentration of O_2, are also clear consequences of CA storage. This is a relevant issue as enzymatic and non-enzymatic oxidation are one of the most important causes of food spoilage due to the production of reactive oxygen species (Falagán & Terry, 2018; Prange et al., 2006; Yahia et al., 2019). CA storage also can be used for the control of insects and pathogens in food matrices by applying an atmosphere with low partial pressure of O_2 (1 kPa) and high partial pressure of CO_2 (10 kPa), which has fungistatic effects. In what concerns fungi and bacteria, the molecules of CO_2 that permeate the cell membrane change their pH, giving rise to carbonic acid, which causes metabolic changes that culminate in the mortality of those microorganisms (Falagán & Terry, 2018; Yahia et al., 2019). Insects' mortality, in turn, is dependent on the species, their stage of development, partial pressure of O_2 and CO_2, temperature, relative humidity and duration of treatment, with insect mortality increasing with a decrease in the partial pressure of O_2 (0.5 kPa) and with increasing temperature and partial pressure of CO_2 (50 kPa).

However, most agricultural products do not tolerate such extreme atmospheric conditions for long periods of time (Falagán & Terry, 2018; Yahia et al., 2019). Despite the many advantages arising from CA storage for fresh agricultural products, it can also cause negative effects, including tissue anaerobiosis (which drives the fermentation process), changes in the flavour of the food product (since long periods of CA storage can reduce the ability of foods to develop specific flavours and aromas), physiological disorders (such as browning and abnormal ripening due to inaccurate gas concentrations), and enhanced sensitivity to decay (since inadequate gas composition may promote the entry of fungi and other microorganisms as bacteria into the tissues) (Yahia et al., 2019; Falagán & Terry, 2018b).

Although CA storage technology has proven beneficial in different areas of conservation of agricultural products, it should be complemented with the implementation of good conservation practices, namely special treatments during harvest and before storage (Bodbodak & Moshfeghifar, 2016). Despite this, it is always advisable to store agricultural products as soon as possible after harvesting. It has also been shown that exposing crops to high temperatures and humidity for a few days after storage can induce healing of damaged tissues and reduce post-harvest losses. Pre-storage by immersing and brushing nuts in hot water is also used to control infections by microorganisms before storage (Bodbodak & Moshfeghifar, 2016; Raghavan et al., 2021). Research on almonds demonstrated that hot water treatment at 85 °C for 40 s followed by infrared drying for 70 s reduced pathogens to undetectable levels by direct plating, thus improving their shelf-life (Bari et al., 2009).

3.2.3.1. Generation of the controlled atmosphere. The technology requires several units/components that allow the addition of O_2, removal of excess CO_2, removal of C_2H_4 and, in some cases, addition of CO_2. The choice of devices suitable for CA storage will always depend on the food matrices to be stored and, therefore, the conditions required for their proper loading (Yahia et al., 2019).

Different phenomena and/or mechanisms contribute for reducing O_2 levels in CA storage, including the respiration of agricultural products (especially at the beginning of storage) leading to a rapid reduction of O_2 levels in storage compartments (Malcolm, 2005) and the reduction of O_2 levels through N_2 flushes (a common practice in reducing the partial pressure of O_2 to 3–5 kPa). Until the 1990s, propane burners were used to convert O_2 into CO_2, operating based on the "open flame" or catalytic burner principle, although this was (Falagán & Terry, 2018b; Yahia et al., 2019). An alternative system based on the cracking of ammonia (NH_3) at high temperatures into N_2 and H_2 was then proposed, in which the molecules of O_2 from the deposit react with the molecules of H_2 and are converted into water. This method surpasses the previous one in terms of advantages mainly because it does not produce CO_2 and C_2H_4, in addition to the fact that any C_2H_4 present in the compartment's atmosphere is destroyed. Releasing N_2 into the atmosphere of the CA storage compartment is another method of rapid O_2 removal. N_2 can be supplied as a gas or liquid or alternatively produced on-site (since the use of liquid nitrogen is expensive) (Dilley, 2006; Malcolm, 2005). To remove CO_2 from the CA compartment, Purification systems based mostly on the utilization of an aqueous solution of caustic soda (NaOH) are used (Raghavan et al., 2021). However, the use of NaOH and potassium hydroxide (KOH) was suspended due to their high corrosivity and potential hazards in handling and disposal. The caustic soda was then replaced by the use of hydrated lime [$Ca(OH)_2$], placed directly inside the CA compartment, which transforms into limestone ($CaCO_3$) in the absorption process. Although hydrated lime is still used today, it is gradually being replaced by activated carbon (Raghavan et al., 2021; Yahia et al., 2019). Other purifiers, such as sodium or aluminium silicate zeolites, have also been used to remove CO_2 from CA storage compartments, but their use is limited by the large energy expenditure needed for their regeneration. Washing with N_2 also allows to decrease the CO_2 level and therefore it can be used as an alternative way of controlling the partial pressure of CO_2although in a less efficient way than the achieved by the CO_2 purifier (Bodbodak & Moshfeghifar, 2016). Finally, Marcellin and Leteinturier (1967) proposed diffusion units as a method of CO_2 removal, consisting of gas diffusion panels in an airtight container with two independent air flow paths.

In addition to abovementioned variables (directly connected to the composition of the gaseous mixture surrounding the food product), there are others that also play an important role towards the good performance of a CA storage system. One of those is the temperature of the chamber, as refrigeration is the main and most effective way of preserving agricultural products in storage or during transport over long distances. In fact, controlled atmosphere packaging and refrigeration act complementarily (Bodbodak & Moshfeghifar, 2016; Raghavan et al., 2021). CA storage is only effective when applied at low temperatures, which is why refrigeration units are integral components of CA systems. The most common refrigerants include ammonia or chlorofluorocarbons; however, due to the harmful effects of the latter on the ozone layer, a new generation of reagents (*e.g.,* R410A) was introduced.

Another crucial variable to be controlled is the humidity of the gaseous mixture. Efficient CA storage requires high relative humidity levels to maintain the quality of most stored agricultural products. Therefore, it is recommended to maintain the atmosphere with high relative humidity levels although without reaching saturation in order to avoid moisture condensation in food matrices (Bodbodak & Moshfeghifar, 2016; Yahia et al., 2019). Secondary cooling and ice bank cooling are techniques used to allow the retention of high humidity levels in the stored compartments (Bodbodak & Moshfeghifar, 2016).

3.2.3.2. Types of controlled atmosphere systems. With the development of CA storage technology, there has been, on one hand, a faster establishment of gas compositions that longer storage potential and, on the other hand, an evolution in what concerns the precise control of gases composition, even at extreme conditions, previously considered impractical or risky notwithstanding their absence be detrimental to the quality of food matrices. Hence, the CA system chosen will always depend on the type of food matrices, the objective intended, and the required storage duration. Similarly, the choice of gas composition to use and the setpoints will also depend on the food matrix and its stage of ripeness at harvest. These factors promoted the gradual evolution of the CA storage concept, with the following types being considered today.

- Conventional CA (CCA; ~3 kPa O_2 and ~3 kPa CO_2);
- Rapid CA (RCA);
- Low-oxygen CA (LO; ~2 kPa O_2 and 2 kPa CO_2);
- Ultra-low oxygen CA (ULO; ~1 kPa O_2 and ~1–1.5 kPa CO_2);
- Hyper-low oxygen CA (HLO; (<1 kPa O_2 and <1 kPa CO_2);
- Low-oxygen stress (LOS; (<0.7 kPa O_2 for several days prior to switching to higher O_2 for the remainder of storage);
- Initial low-oxygen stress (ILOS; gaseous stress at the start of storage with low levels of oxygen: <0.5 kPa O_2 for 15–20 days);
- Dynamic CA (DCA; HLO atmosphere (<0.6 kPa O_2 and <0.9 kPa CO_2) is maintained until a physiological measurement);
- High initial carbon dioxide CA (HCCA; 15–20 kPa for 1 or 2 weeks prior to establishment of the normal, long-term storage atmosphere);
- Low-ethylene CA (LECA; <1.0 ppm);
- Insecticidal CA (ICA; O_2 < 1.0 kPa and CO_2 ~50 kPa);
- Low-pressure storage or hypobaric storage (LP; O_2 partial pressure in 1/10 normal).

3.2.3.3. Effects of CA in the physicochemical parameters of nuts. Controlled atmosphere storage has been one of the most successful technologies applied to agricultural products in the 20th century. Although few studies have been conducted in nut species, its beneficial effects in these types of low moisture food matrices have already been object of investigation (Table 4). Similarly, to what happens with RF treatments, CA storage also holds ability to disinfect several nut species. For example, Delate et al. (1994), investigated the influence of CA storage with a CO_2 concentration of ≥95 % in the disinfestation of

Table 4
Effect of controlled atmosphere treatments in different physicochemical and biological parameters of nuts.

Samples/Species	Objectives	Treatment parameters	Main results	Reference
Pecan nut (*Carya illinoinensis* (Wangenh.) K.Koch)	Effects of low pO_2 isolated or in combination with high pCO_2 under different temperatures, in quality parameters	Airtight 20L containers Temperatures - 20 and 10 °C pO_2 inside containers reduced by flushing with N_2, High pCO_2 levels obtained by flushing with CO_2	Lower temperatures (10 °C) are ideal and the most effective strategy to maintain pecan quality attributes Low pO_2 and high pCO_2 values better maintain nut quality than storage under normal pO_2 conditions (20 kPa)	Ribeiro et al. (2022)
Almond (*Prunus amygdalus* Batsch)	Pasteurization	Temperatures - 65, 70, 75 or 80 °C Heating rate - 5 °C/min Mesh bags immersed in an ice-water bath (about 4 °C, for at least 2 min) O_2 concentrations - 0, 2, 5, 10, 15, and 21 %; O_2Flow rate - 950–1000 ml/min under no CO_2 conditions CO_2 concentrations - 0, 5, 10, 15, 20, and 25 %; CO_2Flow rate -1000-1100 ml/min under 2 % O_2 concentration.	CA could be used in determining thermal inactivation of *E. coli* ATCC 25922 The D- and z-values of *E. coli* ATCC 25922 under the regular atmosphere treatments were significantly higher than those under the controlled atmosphere CA concentration of 2 % O_2/20 % CO_2 held at 75 °C for 43 min could reach 5-log reduction of *E. coli* ATCC 25922 for achieving pasteurization requirement	Cheng et al. (2017)
Macadamia nuts (*Macadamia integrifolia* Maiden & Betche)	Disinfestation	**Chamber concentrations** - ≥95 % CO_2 **Temperatures** - 24 to 30 °C **Duration** - 2–14 days When removed from the chambers, samples were held for 1 day in air at ambient temperatures	Exposure of infested nuts in-husk to ~95 % CO_2 at ambient temperatures (24–30 °C) for 6 days resulted in 97.3 % mortality of *Hypothenemus obscurus* A 14-d treatment of ~95 % N_2 was required for 100 % mortality in unhusked nuts	Delate et al. (1994)
Cashew nut (*Anacardium occidentale* L.)	Disinfestation	O_2 concentrations - 1 % in 1L glass jars N_2 concentrations – 99 % Incubation - 7–10 days of at 28 °C and 43 °C (control); Relative humidity - 60 ± 5 %	Increased mortality observed in 43 °C exposure to air (control) compared to exposure to 28 °C Adult stage of *O. surinamensis* was the most tolerant with 99.5 % mortality after 48h treatment 100 % mortality of larval and pupal stages Average egg mortalities were counted as 97.5 % for *T. castaneum* and 98 % for *O. surinamensis*	Navarro and Navarro (2020)
Chestnut (*Castanea sativa*, Miller)	Effect on quality	O_2 concentrations - 3.04 kPa CO_2 concentrations - 15.20 kPa Storage time – 2 months	CA helped maintain the organoleptic quality of chestnuts CA promote slightly higher overall quality than the air-stored technique Incidence of moldy nuts under CA was considerably reduced Color was more homogeneous, Production of acetaldehyde and ethanol was slightly higher than normal.	Cecchini et al. (2011)

macadamia nuts. These were kept in treatment for 2–14 days at 20–30 °C and, after this time, the samples were removed from the chambers and kept in air for 1 day at room temperature. Their results showed that a 6-day exposure of infested nuts in husk to ~95 % CO_2 at ambient temperatures (24–30 °C) resulted in 97.3 % mortality of *Hypothenemus obscurus*. Moreover, these authors also verify that a 14-day treatment of the same samples within a chamber with an ~95 % N_2 atmosphere was required for 100 % mortality of. *H. obscurus* in unhusked nuts. Thus, their study proved the potential of CA storage for an effective postharvest treatment of *H. obscurus* in dried macadamia nuts or in unhusked nuts, using two different approaches (high levels of CO_2 and N_2) since, as previously mentioned, different food matrices may respond differently to the same treatments. The lethal effect was also observed by Navarro et al. (2020) in cashew nuts, where a CA storage under N_2 concentrations of 99 % for 48h reached a 99.5 % mortality of adult *O. surinamensis,* and 100 % mortality of larval and pupal stages.

The effect of CA storage in the pasteurization of in-shell almonds (*Prunus amygdalus*) was studied by Cheng et al. (2017), whose investigation intended to use different concentrations of O_2 (0, 2, 5, 10, 15, and 21 %) and CO_2 (0, 5, 10, 15, 20, and 25 %) and high temperatures (65, 70, 75 or 80 °C) to achieve thermal inactivation of *E. coli* ATCC 25922. Their results showed that a CA concentration of 2 % O_2 and 20 % CO_2 held at 75 °C for 43 min could reach a 5-log reduction of *E. coli* ATCC 25922, thus proving the potential of CA storage in the proper pasteurization of in-shell nuts. In most studies, CA storage technology has shown to be highly effective in the disinfestation and pasteurization of different varieties of nuts. These studies also enlightened the role of different concentrations of gases in maintaining the quality and safety parameters of these type of food products. Furthermore, different studies have shown the reliability of the CA technique in extending the shelf-life of nuts, allowing them to be stored for long periods, without compromising their quality parameters.

4. Conclusion

Microbial and pest contamination in nuts presents significant challenges throughout the supply chain, originating from various sources including crop interactions, cultivation practices, environmental factors, and post-harvest conditions. Common pests such as *Cydia* spp. and *Curculio* spp., are some of the most prevalent species that can affect nuts both in the field and during storage. Additionally, fungi like *Aspergillus* and *Penicillium* are prevalent, while bacteria such as enterococci and coliforms frequently contaminate the surfaces of nuts. The shelf-life of nuts is primarily influenced by moisture content, storage temperature, and oxygen availability, which affect water activity prompting their spoilage. Conventional storage techniques typically involve drying, sealing, and controlling temperature, humidity, and light exposure. For disinfestation, traditional methods include the use of biological agents (viruses, bacteria, parasites), synthetic pesticides, fumigants, sex pheromones, and other conventional techniques, such as roasting, blanching, and pasteurization. However, these methods can sometimes compromise the nutritional and sensory qualities of the nuts, mainly by the application of high processing temperatures. Emerging technologies such as RF treatment and CA storage offer promising alternatives for preserving and disinfecting nuts. RF has been studied for its effectiveness in disinfesting various nut species without significantly altering their quality attributes. Meanwhile, CA storage utilizes modified gas compositions to create low-oxygen environments that inhibit microbial growth and reduce spoilage while maintaining product integrity. Despite the potential benefits of RF and CA technologies, challenges remain regarding their implementation on a commercial scale. Non-uniform heating in RF treatments can pose risks to product quality and safety. Similarly, while CA storage has shown effectiveness in extending shelf-life for certain food products, its application to nuts requires further research to determine optimal gas levels that prevent physiological disturbances.

In conclusion, addressing microbial and pest contamination in nuts necessitates a multifaceted approach that combines traditional methods with innovative technologies like RF and CA storage. Continued research is essential to optimize these techniques for broader industrial application, ensuring the safety and quality of nut products in the global market.

CRediT authorship contribution statement

Ângela Liberal: Writing – original draft, Data curation. **Ângela Fernandes:** Writing – review & editing, Supervision, Conceptualization. **Jorge Moreira:** Writing – review & editing. **Natércia Fernandes:** Writing – review & editing. **Alexandre Gonçalves:** Writing – review & editing. **Isabel C.F.R. Ferreira:** Visualization. **Lillian Barros:** Writing – review & editing, Visualization, Supervision, Project administration, Funding acquisition, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.foodcont.2025.111328.

Data availability

Data will be made available on request.

References

Adebajo, L. O., & Diyaolu, S. A. (2003). Mycology and spoilage of retail cashew nuts. *African Journal of Biotechnology, 2*(10), 369–373.

Ajith, S., Pramod, S., Prabha Kumari, C. P., & Potty, V. P. (2015). Effect of storage temperatures and humidity on proximate composition, peroxide value and iodine value of raw cashew nuts. *Journal of Food Science and Technology, 52*(7), 4631–4636. https://doi.org/10.1007/s13197-014-1476-6

Al-Moghazy, M., Boveri, S., & Pulvirenti, A. (2014). Microbiological safety in pistachios and pistachio containing products. *Food Control, 36*(1), 88–93. https://doi.org/10.1016/j.foodcont.2013.07.030

Alamar, M. del C., Falagán, N., Aktas, E., & Terry, L. A. (2018). Minimising food waste: A call for multidisciplinary research. *Journal of the Science of Food and Agriculture, 98*(1), 8–11. https://doi.org/10.1002/jsfa.8708

Appugol, K. A., Mangang, I. B., Shanmugasundaram, S., & Manickam, L. (2022). Radiofrequency heating: A novel thermal treatment on the quality of peanut during disinfestation of *Caryedon serratus* and its potential in reducing aflatoxin. *Journal of Food Processing and Preservation, 46*(11), Article e17029. https://doi.org/10.1111/JFPP.17029

Arena, E., Ballistreri, G., & Fallico, B. (2013). Effect of postharvest storage temperatures on the quality parameters of pistachio nuts. *Czech Journal of Food Sciences, 31*(5), 467–473. https://doi.org/10.17221/69/2013-cjfs

Awuah, G. B., Koral, T., & Guan, D. (2014). Radio-frequency baking and roasting of food products. In *Radio-frequency heating in food processing: Principles and applications* (pp. 231–243). https://doi.org/10.1201/b17740

Bahkali, A., El-Samawaty, A. E. R. M. A., Yassin, M. A., El-Naggar, M. A., & Mahmoud, M. H. (2013). Toxigenic fungal biota associated with walnut in Saudi Arabia. *Journal of Pure and Applied Microbiology, 7*(2), 1079–1086.

Bakkalbaşi, E., Yilmaz, Ö. M., Javidipour, I., & Artik, N. (2012). Effects of packaging materials, storage conditions and variety on oxidative stability of shelled walnuts. *Lebensmittel-Wissenschaft & Technologie, 46*(1), 203–209. https://doi.org/10.1016/j.lwt.2011.10.006

Bari, M. L., Nei, D., Sotome, I., Nishina, I., Isobe, S., & Kawamoto, S. (2009). Effectiveness of sanitizers, dry heat, hot water, and gas catalytic infrared heat treatments to inactivate *Salmonella* on almonds. *Foodborne Pathogens and Disease, 6*(8), 953–958. https://doi.org/10.1089/fpd.2008.0219

Bayman, P., Baker, J. L., & Mahoney, N. E. (2002). Aspergillus on tree nuts: Incidence and associations. *Mycopathologia, 155*(3), 161–169. https://doi.org/10.1023/A:1020419226146

Bermudez-Aguirre, D., & Niemira, B. A. (2023). Radio frequency treatment of food: A review on pasteurization and disinfestation. *Foods, 12*(16), 3057. https://doi.org/10.3390/foods12163057

Beuchat, L. R., Komitopoulou, E., Beckers, H., Betts, R. P., Bourdichon, F., Fanning, S., Joosten, H. M., & Kuile, B. H. T. (2013). Low-water activity foods: Increased concern as vehicles of foodborne pathogens. *Journal of Food Protection, 76*(1), 150–172. https://doi.org/10.4315/0362-028X.JFP-12-211

Beuchat, L. R., & Mann, D. A. (2011a). Inactivation of Salmonella on in-shell pecans during conditioning treatments preceding cracking and shelling. *Journal of Food Protection, 74*(4), 588–602. https://doi.org/10.4315/0362-028X.JFP-10-411

Beuchat, L. R., & Mann, D. A. (2011b). Inactivation of Salmonella on pecan nutmeats by hot air treatment and oil roasting. *Journal of Food Protection, 74*(9), 1441–1450. https://doi.org/10.4315/0362-028X.JFP-11-080

Birla, S. L., Wang, S., & Tang, J. (2008). Computer simulation of radio frequency heating of model fruit immersed in water. *Journal of Food Engineering, 84*(2), 270–280. https://doi.org/10.1016/j.jfoodeng.2007.05.020

Bodbodak, S., & Moshfeghifar, M. (2016). Advances in controlled atmosphere storage of fruits and vegetables. In *Eco-friendly technology for postharvest produce quality* (pp. 39–76). https://doi.org/10.1016/B978-0-12-804313-4.00002-5

Bolling, B. W. (2017). Almond polyphenols: Methods of analysis, contribution to food quality, and health promotion. *Comprehensive Reviews in Food Science and Food Safety, 16*(3), 346–368. https://doi.org/10.1111/1541-4337.12260

Brar, P. K., & Danyluk, M. D. (2018). Nuts and grains: Microbiology and preharvest contamination risks. In *Preharvest food safety* (pp. 105–121). https://doi.org/10.1128/9781555819644.ch6

Brar, P. K., Proano, L. G., Friedrich, L. M., Harris, L. J., & Danyluk, M. D. (2015). Survival of salmonella, escherichia coli O157:H7, and listeria monocytogenes on raw peanut and pecan kernels stored at 224, 4, and 22uC. *Journal of Food Protection, 78*(2), 323–332. https://doi.org/10.4315/0362-028X.JFP-14-327

Calderari, T. O., Iamanaka, B. T., Frisvad, J. C., Pitt, J. I., Sartori, D., Pereira, J. L., Fungaro, M. H. P., & Taniwaki, M. H. (2013). The biodiversity of *Aspergillus* section Flavi in Brazil nuts: From rainforest to consumer. *International Journal of Food Microbiology, 160*(3), 267–272. https://doi.org/10.1016/j.ijfoodmicro.2012.10.018

Cecchini, M., Contini, M., Massantini, R., Monarca, D., & Moscetti, R. (2011). Effects of controlled atmospheres and low temperature on storability of chestnuts manually and mechanically harvested. *Postharvest Biology and Technology, 61*(2–3), 131–136. https://doi.org/10.1016/j.postharvbio.2011.03.001

Chen, C., & Pan, Z. (2022). Processing of tree nuts. In *Postharvest technology - recent advances, new perspectives and applications*. https://doi.org/10.5772/intechopen.102623

Chen, L., Wei, X., Irmak, S., Chaves, B. D., & Subbiah, J. (2019). Inactivation of Salmonella enterica and Enterococcus faecium NRRL B-2354 in cumin seeds by radiofrequency heating. *Food Control, 103*, 59–69. https://doi.org/10.1016/j.foodcont.2019.04.004

Chen, C., Weipeng, Z., Venkitasamy, C., Khir, R., McHugh, T., & Pan, Z. (2020). Walnut structure and its influence on the hydration and drying characteristics. *Drying Technology, 38*(8), 975–986. https://doi.org/10.1080/07373937.2019.1605610

Cheng, T., Li, R., Kou, X., & Wang, S. (2017). Influence of controlled atmosphere on thermal inactivation of *Escherichia coli* ATCC 25922 in almond powder. *Food Microbiology, 64*, 186–194. https://doi.org/10.1016/J.FM.2017.01.007

Choe, E., & Min, D. B. (2006). Mechanisms and factors for edible oil oxidation. In *Comprehensive reviews in food science and food safety* (Vol. 5, pp. 169–186). https://doi.org/10.1111/j.1541-4337.2006.00009.x, 4.

Christopoulos, M. V., Kafkaletou, M., Velliou, A., & Tsantili, E. (2024). Short cold storage as a sustainable postharvest handling method for natural enrichment in antioxidants of fresh and dried walnut kernels—cultivar effect. *Sustainability, 16*(11), 4727. https://doi.org/10.3390/su16114727

Christopoulos, M. V., & Tsantili, E. (2015). Oil composition in stored walnut cultivars-quality and nutritional value. *European Journal of Lipid Science and Technology, 117*(3), 338–348. https://doi.org/10.1002/ejlt.201400082

Costa, J. M., & Marra, F. (2024). Advances in food processing through radio frequency technology: Applications in pest control, microbial and enzymatic inactivation. *Food Engineering Reviews, 16*(3), 422–440. https://doi.org/10.1007/s12393-024-09372-8

Dag, D., Farmanfarmaee, A., Kong, F., Jung, J., McGorrin, R. J., & Zhao, Y. (2023). Feasibility of simultaneous drying and blanching inshell hazelnuts (*Corylus avellana* L.) using hot air–assisted radio frequency (HARF) heating. *Food and Bioprocess Technology, 16*(2), 404–419. https://doi.org/10.1007/s11947-022-02946-6

Danyluk, M. D., Nozawa-Inoue, M., Hristova, K. R., Scow, K. M., Lampinen, B., & Harris, L. J. (2008). Survival and growth of *Salmonella Enteritidis* PT 30 in almond orchard soils. *Journal of Applied Microbiology, 104*(5), 1391–1399. https://doi.org/10.1111/j.1365-2672.2007.03662.x

Danyluk, M. D., Uesugi, A. R., & Harris, L. J. (2005). Survival of *Salmonella enteritidis* PT 30 on inoculated almonds after commercial fumigation with propylene oxide. *Journal of Food Protection, 68*(8), 1613–1622. https://doi.org/10.4315/0362-028X-68.8.1613

De Souza, R., Schincaglia, R., Pimentel, G., & Mota, J. (2017). Nuts and human health outcomes: A systematic review. *Nutrients, 9*(12), 1311. https://doi.org/10.3390/nu9121311

Delate, K. M., Armstrong, J. W., & Jones, V. P. (1994). Postharvest control treatments for *Hypothenemus obscurus* (F.) (Coleoptera: Scolytidae) in macadamia nuts. *Journal of Economic Entomology, 87*(1), 120–126. https://doi.org/10.1093/JEE/87.1.120

Dilley, D. R. (2006). Development of controlled atmosphere storage technologies. *Stewart Postharvest Review, 2*(6), 1–8. https://doi.org/10.2212/spr.2006.6.5

Falagán, N., & Terry, L. A. (2018). Recent Advances in Controlled and Modified Atmosphere of Fresh Produce Postharvest technologies to reduce food waste and maintain fresh produce quality. *Technology Review, 62*(1), 107–117.

Fields, P. G., & White, N. D. G. (2002). Alternatives to methyl bromide treatments for stored-product and quarantine insects. *Annual Review of Entomology, 47*, 331–359. https://doi.org/10.1146/annurev.ento.47.091201.145217

Fu, Y.-C. (2008). Fundamentals and industrial applications of microwave and radio frequency in food processing. In *Food processing* (pp. 79–100). https://doi.org/10.1002/9780470290118.ch4

Gama, T., Wallace, H. M., Trueman, S. J., & Hosseini-Bai, S. (2018). Quality and shelf life of tree nuts: A review. *Scientia Horticulturae, 242*, 116–126. https://doi.org/10.1016/j.scienta.2018.07.036

Gao, M., Tang, J., Wang, Y., Powers, J., & Wang, S. (2010). Almond quality as influenced by radio frequency heat treatments for disinfestation. *Postharvest Biology and Technology, 58*(3), 225–231. https://doi.org/10.1016/j.postharvbio.2010.06.005

Gao, Wu, M., Du, S., Zhang, H., Wang, S., & Ling, B. (2023). Recent advances in food processing by radio frequency heating techniques: A review of equipment aspects. *Journal of Food Engineering, 357*, Article 111609. https://doi.org/10.1016/j.jfoodeng.2023.111609

Garcia, M. V., Moraes, V. M., Bernardi, A. O., Oliveira, M. S., Mallmann, C. A., Boscardin, J., & Copetti, M. V. (2019). Mycological quality of pecan nuts from Brazil: Absence of aflatoxigenic fungi and aflatoxins. *Ciência Rural, 49*(6). https://doi.org/10.1590/0103-8478cr20190076

Ghirardello, D., Bertolino, M., Belviso, S., Dal Bello, B., Giordano, M., Rolle, L., Gerbi, V., Antonucci, M., Spigolon, N., & Zeppa, G. (2016). Phenolic composition, antioxidant capacity and hexanal content of hazelnuts (*Corylus avellana* L.) as affected by different storage conditions. *Postharvest Biology and Technology, 112*, 95–104. https://doi.org/10.1016/j.postharvbio.2015.09.039

Gonçalves, B., Pinto, T., Aires, A., Morais, M. C., Bacelar, E., Anjos, R., Ferreira-Cardoso, J., Oliveira, I., Vilela, A., & Cosme, F. (2023). Composition of nuts and their potential health benefits—an overview. *Foods, 12*(5), 942. https://doi.org/10.3390/foods12050942

He, D.-C., He, M.-H., Amalin, D. M., Liu, W., Alvindia, D. G., & Zhan, J. (2021). Biological control of plant diseases: An evolutionary and eco-economic consideration. *Pathogens, 10*(10), 1311. https://doi.org/10.3390/pathogens10101311

Hou, L., Hou, J., Li, Z., Johnson, J. A., & Wang, S. (2015). Validation of radio frequency treatments as alternative non-chemical methods for disinfesting chestnuts. *Journal of Stored Products Research, 63*, 75–79. https://doi.org/10.1016/j.jspr.2015.07.004

Hou, L., Johnson, J. A., & Wang, S. (2016). Radio frequency heating for postharvest control of pests in agricultural products: A review. *Postharvest Biology and Technology, 113*, 106–118. https://doi.org/10.1016/j.postharvbio.2015.11.011

Huang, Z., Marra, F., Subbiah, J., & Wang, S. (2018). Computer simulation for improving radio frequency (RF) heating uniformity of food products: A review. *Critical Reviews in Food Science and Nutrition, 58*(6), 1033–1057. https://doi.org/10.1080/10408398.2016.1253000

Huang, Z., Marra, F., & Wang, S. (2016). A novel strategy for improving radio frequency heating uniformity of dry food products using computational modeling. *Innovative Food Science and Emerging Technologies, 34*, 100–111. https://doi.org/10.1016/j.ifset.2016.01.005

Hughey, C. A., Janusziewicz, R., Minardi, C. S., Phung, J., Huffman, B. A., Reyes, L., Wilcox, B. E., & Prakash, A. (2012). Distribution of almond polyphenols in blanch water and skins as a function of blanching time and temperature. *Food Chemistry, 131*(4), 1165–1173. https://doi.org/10.1016/j.foodchem.2011.09.093

Içier, F., & Baysal, T. (2004). Dielectrical properties of food materials - 2: Measurement techniques. *Critical Reviews in Food Science and Nutrition, 44*(6), 473–478. https://doi.org/10.1080/10408690490892361

Intrado GlobeNewswire. (2023). Global edible nuts market to reach $459.1 billion by 2030. https://www.globenewswire.com/news-release/2023/03/15/2628035/0/en/Global-Edible-Nuts-Market-to-Reach-459-1-Billion-by-2030.html.

Jiao, S., Salazar, E., & Wang, S. (2021). Radio frequency. In *Electromagnetic technologies in food science* (pp. 272–297). Wiley. https://doi.org/10.1002/9781119759522.ch11.

Jiao, Tang, J., Wang, Y., & Koral, T. L. (2018). Radio-frequency applications for food processing and safety. *Annual Review of Food Science and Technology, 9*, 105–127. https://doi.org/10.1146/annurev-food-041715-033038

Johnson, J. A. (2007). Survival of indianmeal moth and navel orangeworm (Lepidoptera: Pyralidae) at low temperatures. *Journal of Economic Entomology, 100*(4), 1482–1488. https://doi.org/10.1603/0022-0493(2007)100[1482:SOIMAN]2.0.CO;2

Johnson, J. (2013). Pest control in postharvest nuts. In *Improving the safety and quality of nuts*. https://doi.org/10.1533/9780857097484.1.56

Johnson, J. A., Gill, R. F., Valero, K. A., & May, S. A. (1996). Survival of navel orangeworm (*Lepidoptera pyralidae*) during pistachio processing. *Journal of Economic Entomology, 89*(1), 197–203. https://doi.org/10.1093/jee/89.1.197

Johnson, J. A., Vail, P. V., Brandl, D. G., Tebbets, J. S., & Valero, K. A. (2002). Integration of nonchemical treatments for control of postharvest pyralid moths (*Lepidoptera pyralidae*) in almonds and raisins. *Journal of Economic Entomology, 95*(1), 190–199. https://doi.org/10.1603/0022-0493-95.1.190

Johnson, J. A., Vail, P. V., Soderstrom, E. L., Curtis, C. E., Brandl, D. G., Tebbets, J. S., & Valero, K. A. (1998). Integration of nonchemical, postharvest treatments for control of navel orangeworm (*Lepidoptera pyralidae*) and indianmeal moth (Lepidoptera: Pyralidae) in walnuts. *Journal of Economic Entomology, 91*(6), 1437–1444. https://doi.org/10.1093/jee/91.6.1437

Johnson, J. A., Valero, K. A., & Hannel, M. M. (1997). Effect of low temperature storage on survival and reproduction of Indianmeal moth (*Lepidoptera pyralidae*). *Crop Protection, 16*(6), 519–523. https://doi.org/10.1016/S0261-2194(97)00037-9

Kačániová, M., Sudzinová, J., Kádasi-Horáková, M., Valšíková, M., & Kráčmar, S. (2014). The determination of microscopic fungi from Chestnut (*Castanea sativa* Mill.) fruits, leaves, crust and pollen. *Acta Universitatis Agriculturae et Silviculturae Mendelianae Brunensis, 58*(4), 73–78. https://doi.org/10.11118/actaun201058040073

Kader, A. A., Heintz, C. M., Labavitch, J. M., & Rae, H. L. (2022). Studies related to the description and evaluation of pistachio nut Quality1. *Journal of the American Society for Horticultural Science, 107*(5), 812–816. https://doi.org/10.21273/jashs.107.5.812

Khosravi, A. R., Shokri, H., & Ziglarí, T. (2007). Evaluation of fungal flora in some important nut products (pistachio, peanut, hazelnut and almond) in Tehran, Iran. *Pakistan Journal of Nutrition, 6*(5), 460–462. https://doi.org/10.3923/pjn.2007.460.462

Kidd, F., & West, C. (1927). *Atmosphere control in fruit storage*.

King, A. D., Miller, M. J., & Eldridge, L. C. (1970). Almond harvesting, processing, and microbial flora. *Applied Microbiology, 20*(2), 208–214. https://doi.org/10.1128/aem.20.2.208-214.1970

Klich, M. A. (2007). *Aspergillus flavus* : The major producer of aflatoxin. *Molecular Plant Pathology, 8*(6), 713–722. https://doi.org/10.1111/j.1364-3703.2007.00436.x

Lacey, L. A., & Shapiro-Ilan, D. I. (2008). Microbial control of insect pests in temperate orchard systems: Potential for incorporation into IPM. *Annual Review of Entomology, 53*, 121–144. https://doi.org/10.1146/annurev.ento.53.103106.093419

Lal, S., Chand, L., Kumawat, K. L., & Sharma, O. C. (2023). Effect of packaging system and storage conditions on quality retention of shelled walnut. *International Journal of Bio-Resource and Stress Management, 14*(Mar, 3), 407–413. https://doi.org/10.23910/1.2023.3309

Lamboni, Y., Frisvad, J. C., Hell, K., Linnemann, A. R., Nout, R. M. J., Tamo, M., Nielsen, K. F., van Boekel, M. A. J. S., & Smid, E. J. (2016). Occurrence of Aspergillus section Flavi and section Nigri and aflatoxins in raw cashew kernels (Anacardium occidentale L.) from Benin. *Lebensmittel-Wissenschaft & Technologie, 70*, 71–77. https://doi.org/10.1016/j.lwt.2016.02.017

Li, R., Kou, X., Cheng, T., Zheng, A., & Wang, S. (2017). Verification of radio frequency pasteurization process for in-shell almonds. *Journal of Food Engineering, 192*, 103–110. https://doi.org/10.1016/j.jfoodeng.2016.08.002

Li, Liu, Y., & Chen, F. (2019). Effect of storage temperature on lipid oxidation and changes in nutrient contents in peanuts. *Food Science and Nutrition, 7*(7), 2280–2290. https://doi.org/10.1002/fsn3.1069

Li, C., Zhang, S., Sun, H., Zhao, H., Chen, C., & Xing, S. (2020). Study on a two-dimensional correlation visible–near infrared spectroscopy kinetic model for the moisture content of fresh walnuts stored at room temperature. *Journal of Food Process Engineering, 43*(12). https://doi.org/10.1111/jfpe.13551

Liao, M., Zhao, Y., Gong, C., Zhang, H., & Jiao, S. (2018). Effects of hot air-assisted radio frequency roasting on quality and antioxidant activity of cashew nut kernels. *Lebensmittel-Wissenschaft & Technologie, 93*, 274–280. https://doi.org/10.1016/j.lwt.2018.03.047

Ling, B., Cheng, T., & Wang, S. (2020). Recent developments in applications of radio frequency heating for improving safety and quality of food grains and their products: A review. In *Critical reviews in food science and nutrition* (Vol. 60, pp. 4631–4636). https://doi.org/10.1080/10408398.2019.1651690, 15.

Ling, B., Hou, L., Li, R., & Wang, S. (2016). Storage stability of pistachios as influenced by radio frequency treatments for postharvest disinfestations. *Innovative Food Science and Emerging Technologies, 33*, 357–364. https://doi.org/10.1016/j.ifset.2015.10.013

Ling, B., Ramaswamy, H. S., Lyng, J. G., Gao, J., & Wang, S. (2023). Roles of physical fields in the extraction of pectin from plant food wastes and byproducts: A systematic review. *Food Research International, 164*, Article 112343. https://doi.org/10.1016/j.foodres.2022.112343

Liu, M., Li, C., Cao, C., Wang, L., Li, X., Che, J., Yang, H., Zhang, X., Zhao, H., He, G., & Liu, X. (2021). Walnut fruit processing equipment: Academic insights and perspectives. *Food Engineering Reviews, 13*(4), 822–857. https://doi.org/10.1007/s12393-020-09273-6

Macana, R. J., & Baik, O. D. (2018). Disinfestation of insect pests in stored agricultural materials using microwave and radio frequency heating: A review. *Food Reviews International, 34*(5), 483–510. https://doi.org/10.1080/87559129.2017.1359840

Mahoney, N. E., Cheng, L. W., & Palumbo, J. D. (2020). Effect of blanching on aflatoxin contamination and cross-contamination of almonds. *Journal of Food Protection, 83*(12), 2187–2192. https://doi.org/10.4315/JFP-20-218

Malcolm, G. L. (2005). Advancements in the implementation of CA technology for storage of perishable commodities. *Acta Horticulturae, 682*, 1593–1598. https://doi.org/10.17660/ActaHortic.2005.682.212

Mao, Y., Wang, P., Wu, Y., Hou, L., & Wang, S. (2021). Effects of various radio frequencies on combined drying and disinfestation treatments for in-shell walnuts. *Lebensmittel-Wissenschaft & Technologie, 144*, Article 111246. https://doi.org/10.1016/j.lwt.2021.111246

Marcellin, P., & Leteinturier, J. (1967). *Premières applications industrielles des membranes en caoutchouc de silicone à l'entreposage des pommes en atmosphere contrôlée*.

Marchetti, L., Califano, A. N., & Andrés, S. C. (2018). Partial replacement of wheat flour by pecan nut expeller meal on bakery products. Effect on muffins quality. *Lebensmittel-Wissenschaft & Technologie, 95*, 85–91. https://doi.org/10.1016/j.lwt.2018.04.050

McDonald, D. (1970). Fungal infection of groundnut fruit before harvest. *Transactions of the British Mycological Society, 54*(3), 453–460. https://doi.org/10.1016/s0007-1536(70)80160-7

Medic, A., Jakopic, J., Hudina, M., Solar, A., & Veberic, R. (2021). Identification and quantification of the major phenolic constituents in Juglans regia L. peeled kernels and pellicles, using HPLC–MS/MS. *Food Chemistry, 352*, Article 129404. https://doi.org/10.1016/j.foodchem.2021.129404

Mermelstein, N. (1998). Microwave and radio frequency drying. *Food Technology, 52*, 84–86.

Mitcham, E., Adkison, C., Lingga, N., & Bikoba, V. (2022). Storage temperature, relative humidity, and time effects on the organoleptic profile of walnut kernels. *Journal of the American Society for Horticultural Science, 147*(6), 291–299. https://doi.org/10.21273/JASHS05196-22

Mitcham, E. J., Veltman, R. H., Feng, X., De Castro, E., Johnson, J. A., Simpson, T. L., Biasi, W. V., Wang, S., & Tang, J. (2004). Application of radio frequency treatments to control insects in in-shell walnuts. *Postharvest Biology and Technology, 33*(1), 93–100. https://doi.org/10.1016/j.postharvbio.2004.01.004

Monsef, A. M., Shaghaghian, S., & Sharafati-Chaleshtori, R. (2020). The effect of various shelf life and conditions on storage of walnuts walnut storage shelf life temperature aflatoxin. *Int J Nutr Sci, 5*(3), 134–141. https://doi.org/10.30476/IJNS.2020.87611.1084

Monzon, M., Biasi, B., Wang, S., Tang, J., Hallman, G., & Mitcham, E. (2019). Radio frequency heating of persimmon and guava fruit as an alternative quarantine treatment. *HortScience, 39*(4), 879C–879. https://doi.org/10.21273/hortsci.39.4.879c

Moscetti, R., Frangipane, M. T., Monarca, D., Cecchini, M., & Massantini, R. (2012). Maintaining the quality of unripe, fresh hazelnuts through storage under modified atmospheres. *Postharvest Biology and Technology, 65*, 33–38. https://doi.org/10.1016/j.postharvbio.2011.10.009

Moyer, J. C., & Stotz, E. (1947). The blanching of vegetables by electronics. *Food Technology, 1*(2), 252–257.

Musangi, C. R., Juma, B. S., Mukhebi, D. W., Isoe, E. M., Kibiti, C. M., & Mbinda, W. M. (2024). *Aspergillus* population diversity and its role in aflatoxin contamination of cashew nuts from coastal Kenya. *PLoS One, 19*(1), Article e0292519. https://doi.org/10.1371/journal.pone.0292519

Navarro, H., & Navarro, S. (2020). Efficacy of controlling two stored cashew nut insects in 1% O 2 and 99% N 2 at 43 C. In *Proceedings of the 11th international conference on controlled atmosphere and fumigation in stored products* (pp. 23–28).

Ozay, G., Seyhan, F., Pembeci, C., Saklar, S., & Yilmaz, A. (2008). Factors influencing fungal and aflatoxin levels in Turkish hazelnuts (*Corylus avellana* L.) during growth, harvest, drying and storage: A 3-year study. *Food Additives & Contaminants Part A Chemistry, Analysis, Control, Exposure and Risk Assessment, 25*(2), 209–218. https://doi.org/10.1080/02652030701711016

Ozturk, I., Sagdic, O., Yalcin, H., Capar, T. D., & Asyali, M. H. (2016). The effects of packaging type on the quality characteristics of fresh raw pistachios (Pistacia vera L.) during the storage. *Lebensmittel-Wissenschaft & Technologie, 65*, 457–463. https://doi.org/10.1016/j.lwt.2015.08.046

Pankaj, S. K., Shi, H., & Keener, K. M. (2018). A review of novel physical and chemical decontamination technologies for aflatoxin in food. *Trends in Food Science & Technology, 71*, 73–83. https://doi.org/10.1016/j.tifs.2017.11.007

Pao, S., Kalantari, A., & Huang, G. (2006). Utilizing acidic sprays for eliminating Salmonella enterica on raw almonds. *Journal of Food Science, 71*(1), M14–M19. https://doi.org/10.1111/j.1365-2621.2006.tb12394.x

Phatanayindee, S., Borompichaichartkul, C., Srzednicki, G., Craske, J., & Wootton, M. (2012). Changes of chemical and physical quality attributes of macadamia nuts during hybrid drying and processing. *Drying Technology, 30*(16), 1870–1880. https://doi.org/10.1080/07373937.2012.703275

Prange, R. K., DeLong, J. M., Daniels-Lake, B. J., & Harrison, P. A. (2006). Innovation in controlled atmosphere technology. *Stewart Postharvest Review, 1*(3), 1–11. https://doi.org/10.2212/spr.2005.3.9

Proctor, B. E., & Goldblith, S. A. (1948). Radar energy for rapid food cooking and blanching, and its effect on vitamin content. *Food Technology, 2*(2), 95.

Qiu, Y., Zhou, Y., Chang, Y., Liang, X., Zhang, H., Lin, X., Qing, K., Zhou, X., & Luo, Z. (2022). The effects of ventilation, humidity, and temperature on bacterial growth and bacterial genera distribution. *International Journal of Environmental Research and Public Health, 19*(22), Article 15345. https://doi.org/10.3390/ijerph192215345

Quinn, N., & Baldwin, R. A. (2014). Managing roof rats and deer mice in nut and fruit orchards. In *Managing roof rats and deer mice in nut and fruit orchards*. https://doi.org/10.3733/ucanr.8513

Raghavan, G. S. V., Vigneault, C., Gariépy, Y., Markarian, N. R., & Alvo, P. (2021). Refrigerated and controlled/modified atmosphere storage. In *Processing fruits*. https://doi.org/10.1201/9781420040074-7

Raisi, M., Ghorbani, M., Sadeghi Mahoonak, A., Kashaninejad, M., & Hosseini, H. (2015). Effect of storage atmosphere and temperature on the oxidative stability of almond kernels during long term storage. *Journal of Stored Products Research, 62*, 16–21. https://doi.org/10.1016/j.jspr.2015.03.004

Ramadan, E. A., Ramadan, N. A., & Mohammed, A. A. H. (2022). Aflatoxigenic fungi in nuts and dried fruits in mosul and DuhokCity. *Military Medical Science Letters, 91*(3), 224–234. https://doi.org/10.31482/mmsl.2021.049

Ribeiro, S. R., Klein, B., Santos, I. D. dos, Thewes, F. R., Brackmann, A., Both, V., & Wagner, R. (2022). Effects of controlled atmosphere and storage temperature on the quality of shelled 'Barton' pecan nuts during long-term storage. *Food Research International, 158*, Article 111498. https://doi.org/10.1016/j.foodres.2022.111498

Rizvi, S. A. H., George, J., Reddy, G. V. P., Zeng, X., & Guerrero, A. (2021). Latest developments in insect sex pheromone research and its application in agricultural pest management. *Insects, 12*(6), 484. https://doi.org/10.3390/insects12060484

Routray, W., & Orsat, V. (2018). Recent advances in dielectric properties–measurements and importance. *Current Opinion in Food Science, 23*, 120–126. https://doi.org/10.1016/j.cofs.2018.10.001

Safe Food Alliance. (2025). Aflatoxin guide for almonds and pistachios. Retrieved January 7, 2025, from https://safefoodalliance.com/testing-analysis/aflatoxin-and-exports-for-almonds-and-pistachios/.

Samanta, S., Maji, A., Sutradhar, B., Banerjee, S., Shelar, V. B., Khaire, P. B., Yadav, S. V., & Bansode, G. D. (2023). Impact of pesticides on beneficial insects in various agroecosystem: A review. *International Journal of Environment and Climate Change, 13*(8), 1928–1936. https://doi.org/10.9734/ijecc/2023/v13i82149

Sánchez-Bravo, P., Noguera-Artiaga, L., Gómez-López, V. M., Carbonell-Barrachina, Á. A., Gabaldón, J. A., & Pérez-López, A. J. (2022). Impact of non-thermal technologies on the quality of nuts: A review. *Foods, 11*(23), 3891. https://doi.org/10.3390/foods11233891

Sedaghat, N. (2010). Pistachio nuts shelf life based on sensory evaluation. *American-Eurasian Journal of Agricultural & Environmental Sciences, 8*(5), 570–575.

Shahidi, F., & John, J. A. (2013). Oxidative rancidity in nuts. In *Improving the safety and quality of nuts* (pp. 198–229). Elsevier. https://doi.org/10.1533/9780857097484.2.198.

Shakerardekani, A., & Mohamadi, A. (2019). Determination of peeling efficiency, free fatty acid, peroxide value and sensory evaluation of peeled pistachio kernel using hot water. *Journal of Nuts, 10*(2), 175–185. https://doi.org/10.22034/jon.2019.1877513.1067

ShiLan, W., LiKang, Q., ChengGang, J., & ShuAi, Z. (2013). Dynamic changes of nutritional and functional components of walnut kernel during lye peeling. *China Oils and Fats, 38*(2), 84–87.

Silos Spain. (2023). Advantages of drying and storing nuts in a metal silo. https://silosspain.com/grain-storage/advantages-of-drying-and-storing-nuts-in-a-metal-silo/.

Singh, S. P., & Singh, Z. (2013). Controlled and modified atmospheres influence chilling injury, fruit quality and antioxidative system of Japanese plums (*Prunus salicina* Lindell). *International Journal of Food Science and Technology, 48*(2), 363–374. https://doi.org/10.1111/j.1365-2621.2012.03196.x

Sosa-Morales, M. E., Valerio-Junco, L., López-Malo, A., & García, H. S. (2010). Dielectric properties of foods: Reported data in the 21st century and their potential applications. *In LWT, 43*(8), 1169–1179. https://doi.org/10.1016/j.lwt.2010.03.017

Srichamnong, W., Wootton, M., & Srzednicki, G. (2010). Effect of nut-in-shell storage conditions on volatile profile in macadamia nuts. *Julius-Kühn-Archiv, 425*, 270.

Tadesse Mawcha, K., Malinga, L., Muir, D., Ge, J., & Ndolo, D. (2024). Recent advances in biopesticide research and development with a focus on microbials. *F1000Research, 13*, 1071. https://doi.org/10.12688/f1000research.154392.3

Tournas, V. H., Niazi, N. S., & Kohn, J. S. (2015). Fungal presence in selected tree nuts and dried fruits. *Microbiology Insights, 8*. https://doi.org/10.4137/mbi.s24308. MBI-S24308.

Turan, A. (2018). Effect of drying methods on nut quality of hazelnuts (*Corylus avellana* L.). *Journal of Food Science and Technology, 55*(11), 4554–4565. https://doi.org/10.1007/s13197-018-3391-8

Uesugi, A. R., Danyluk, M. D., Mandrell, R. E., & Harris, L. J. (2007). Isolation of Salmonella Enteritidis phage type 30 from a single almond orchard over a 5-year period. *Journal of Food Protection, 70*(8), 1784–1789. https://doi.org/10.4315/0362-028X-70.8.1784

Unep, U. N. E. P. (2006). Handbook for the Montreal protocol on substances that deplete the ozone layer. In *The Montreal Protocol*.

Ünüsan, N. (2019). Systematic review of mycotoxins in food and feeds in Turkey. *Food Control, 97*, 1–14. https://doi.org/10.1016/j.foodcont.2018.10.015

van der Sluis, A. (2013). Quality of peanuts, walnuts, pistachio's and raisins. A review of optimal storage conditions. In *Food & biobased research*. www.wur.nl.

Venkatachalan, M., & Sathe, S. K. (2006). Chemical composition of selected edible nut seeds. *Journal of Agricultural and Food Chemistry, 54*(13), 4705–4714. https://doi.org/10.1021/jf0606959

Wall, M. M. (2013). Improving the quality and safety of macadamia nuts. In *Improving the safety and quality of nuts* (pp. 274–296). https://doi.org/10.1533/9780857097484.2.274

Wang, Lu, F., Li, Z., Zhao, L., & Han, C. (2017). Recent developments in gluten-free bread baking approaches: A review. *Food Science and Technology, 37*, 1–9. https://doi.org/10.1590/1678-457X.01417

Wang, S., Tang, J., Cavalieri, R. P., & Davis, D. C. (2003). Differential heating of insects in dried nuts and fruits associated with radio frequency and microwave treatments. *Transactions of the American Society of Agricultural Engineers, 46*(4), 1175. https://doi.org/10.13031/2013.13941

Wang, S., Tang, J., Johnson, J. A., Mitcham, E., Hansen, J. D., Cavalieri, R. P., Bower, J., & Biasi, B. (2002). Process protocols based on radio frequency energy to control field and storage pests in in-shell walnuts. *Postharvest Biology and Technology, 26*(3), 265–273. https://doi.org/10.1016/S0925-5214(02)00048-0

Wang, S., Tiwari, G., Jiao, S., Johnson, J. A., & Tang, J. (2010). Developing postharvest disinfestation treatments for legumes using radio frequency energy. *Biosystems Engineering, 105*(3), 341–349. https://doi.org/10.1016/j.biosystemseng.2009.12.003

Wang, Y., Zhang, L., Johnson, J., Gao, M., Tang, J., Powers, J. R., & Wang, S. (2014). Developing hot air-assisted radio frequency drying for in-shell macadamia nuts. *Food and Bioprocess Technology, 7*(1), 278–288. https://doi.org/10.1007/s11947-013-1055-2

Yahia, E. M., Fadanelli, L., Mattè, P., & Brecht, J. K. (2019). Controlled atmosphere storage. In *Postharvest technology of perishable horticultural commodities* (pp. 439–479). Elsevier. https://doi.org/10.1016/B978-0-12-813276-0.00013-4.

Yen, Y.-F., & Chen, S.-D. (2022). Influence of radio frequency heating on the pasteurization and drying of solid-state fermented wolfiporia cocos products. *Foods, 11*(12), 1766. https://doi.org/10.3390/foods11121766

Yuya, A. I., Tadesse, A., Azerefegne, F., & Tefera, T. (2009). Efficacy of combining Niger seed oil with malathion 5% dust formulation on maize against the maize weevil, Sitophilus zeamais (*Coleoptera curculionidae*). *Journal of Stored Products Research, 45*(1), 67–70. https://doi.org/10.1016/j.jspr.2008.09.003

Zaini, P. A., Feinberg, N. G., Grilo, F. S., Saxe, H. J., Salemi, M. R., Phinney, B. S., Crisosto, C. H., & Dandekar, A. M. (2020). Comparative proteomic analysis of walnut (*Juglans regia* L.) pellicle tissues reveals the regulation of nut quality attributes. *The Life, 10*(12), 314. https://doi.org/10.3390/life10120314

Zhang, L., Lyng, J. G., Xu, R., Zhang, S., Zhou, X., & Wang, S. (2019). Influence of radio frequency treatment on in-shell walnut quality and Staphylococcus aureus ATCC 25923 survival. *Food Control, 102*, 197–205. https://doi.org/10.1016/j.foodcont.2019.03.030

Zhang, S., Zhou, L., Ling, B., & Wang, S. (2016). Dielectric properties of peanut kernels associated with microwave and radio frequency drying. *Biosystems Engineering, 145*, 108–117. https://doi.org/10.1016/j.biosystemseng.2016.03.002

Zhao, Y., Flugstad, B., Kolbe, E., Park, J. W., & Wells, J. H. (2000). Using capacitive (radio frequency) dielectric heating in food processing and preservation - a review. *Journal of Food Process Engineering, 23*(1), 25–55. https://doi.org/10.1111/j.1745-4530.2000.tb00502.x

Zhou, H., Guo, C., & Wang, S. (2017). Performance comparison between the free running oscillator and 50 Ω radio frequency systems. *Innovative Food Science and Emerging Technologies, 39*, 171–178. https://doi.org/10.1016/j.ifset.2016.12.003