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Review Article

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Review of Some Thermal Methods in Drying and Roasting Processes

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Abstract

Thermal processing is a routine procedure in food science, with two important methods being drying and roasting. During thermal processing, simultaneous heat and mass transfer occur, where the distribution of heat and humidity depends on effective diffusivity. Various methods exist for achieving this, each differing in efficiency and energy consumption. The conventional method of thermal processing involves hot air (HA) or convection, which typically requires significantly more energy and time (at least 25%). However, there are newer thermal processing methos based on radiation, each with their own advantages and disadvantages. Nevertheless, all radiation-based methods generally consume less time and energy compared to the HA method. Different thermal processing methods have been studied and reviewed with regard to their energy consumption and effective diffusivity. In summary, while HA remains the routine method in industries, it demands considerably more energy and time compared to radiation-based methods. Radiofrequency is a non-thermal method that can also be employed to enhance the efficiency of various processing techniques.

Keywords

Thermal processing, Infrared, Ultra sound, Hot air, Microwave, Drying, Roasting

Introduction

Global warming is a serious problem worldwide. It is changing climate, and we need to produce crops that have a higher resistance to climate changes, while having a higher production efficiency, and also control the reduction of the heat produced by various industries, including the food industry [1-5].

The oldest method in food preservation is drying. Over time the drying process has changed and could be applied by different methods. The aim of drying process is reducing fresh crops moisture content, while during roasting the products moisture, texture, and aroma is changed [5-8]. Vaporizing the moisture in different fresh foods using temperature by different method occurs during drying and roasting.

The significant factors determining the profitability of a processing method are energy consumption, color, texture, and sensory properties. Heat transfer typically occurs through three basic methods: conduction, convection, and radiation [9].

Various food products, vegetables, fruits, and nuts are perishable and require thermal processing for preservation [10]. One of the oldest and simplest preservation methods is drying. Sun drying is a traditional method used for preserving various foods, especially agricultural products. However, it suffers from unavoidable disadvantages such as undesirable changes in food quality, lengthy processing time, uncontrollable process, and environmental pollution. The drying method removes moisture from food through evaporation [11, 12], thereby limiting microbial growth but necessitating high energy consumption [13]. Two crucial features of dried products are their low porosity and high apparent density, while the color of foods may also change during drying process [14].

During the drying process, simultaneous heat and mass transfer occur. The distribution of heat and humidity depends on effective diffusivity [10, 15]. Initially, heat converts moisture in the food into steam, which is then transferred to the food's surface [10, 13, 15]. Consequently, the variation among different heating methods lies in their heat distribution and effective diffusivity.

Roasting is another thermal processing method that significantly alerts the digestibility, sensory properties, and texture of food. During roasting, food is exposed to dry HA, facilitating cooking from all sides [16]. Advantages of roasting and drying process include color development, formation of taste compounds, aroma enhancement, volume and weight loss, and expansion of food materials (pop/puff) [11, 16]. Traditional roasting typically employs HA, where the precise combination of temperature and time is crucial. Raw nuts are typically pale in color, but as they are roasted, they undergo a Maillard reaction and caramelization process. This reaction causes the nuts to turn golden brown or even darker depending on the roast level. The longer and hotter the roasting process, the darker the nuts become. Roasting affects the texture of nuts by altering their moisture content and structure. Initially, nuts are soft and pliable. During roasting, the heat causes the moisture inside the nuts to evaporate, leading to a crunchy texture. The proteins and sugars undergo changes due to Maillard reactions and caramelization, further contributing to the crunchiness and overall texture [17, 18]. However, increasing the temperature can reduce the processing time, albeit at the expense of physicochemical and structural properties of the final products. Fortunately, novel techniques often result in fewer adverse effects on foods while requiring shorter processing times [19-26].

Numerous studies have investigated various heating methods (Table 1), including HA, infrared (IR), microwave (MW), and radio frequency (RF). These methods differ significantly in terms of effective diffusivity, energy consumption, processing time, and their effect on the ingredients of different types of foods.

The objective of this study is to review the most extensively researched methods of drying and roasting, including their associated mathematical equations.

HA

Conductional and conventional air-drying or HA method, represents the most commonly used technique for drying and roasting (Figure 1). In this method, alongside material characteristic dimensions, air temperature, velocity, and humidity play pivotal roles [13]. Equation 1 describes thermal energy transferred by convection HA; while equation 2 addresses thermal energy transferred by conduction method.

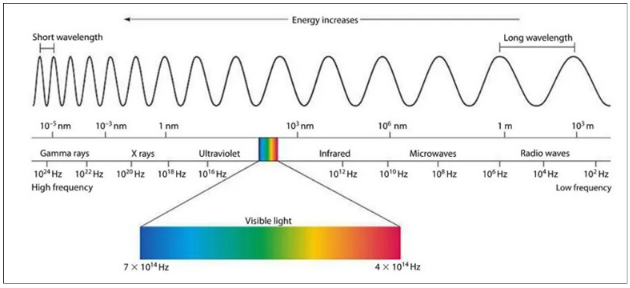

Figure 1: Electromagnetic spectrum.

$$Q = h(A \times \Delta T) \tag{1}$$

Where: Q represents thermal energy (W); h is the heat transfer coefficient (W/m^2 °C); A denotes surface area (m^2); and Δ T signifies the temperature difference (°C) [27, 28].

$$Q = KA\frac{\Delta T}{\Delta x} \tag{2}$$

Where: Q represents thermal energy (W); K denotes thermal conductivity (W/m °C); Δ T signifies temperature differences (°C); and Δx presents thickness (m) [29, 30].

Some researchers have highlighted several consequences of slow heat transfer, including browning, pitting, color changes, surface hardening, solute migration, and loss of aroma. This damage occurs because thermal energy is transferred from the surface of the food to its interior layer by layer, followed by the migration of moisture from inside to outside the food [13, 31].

Temperature plays a crucial role in this process, as indicated by various studies. Krokida et al. [13] found that temperature had a significant impact on the drying process of different vegetables, with air velocity contributing less compared to other factors. Similarly, other researchers reported that increasing air velocity led to decreased process time but increased energy consumption [11, 32].

These findings suggest that optimizing temperature conditions while considering air velocity and humidity levels can help improve the efficiency of the HA heating method in food processing, potentially reducing process time and minimizing damage to the food product.

Roasting nuts is needed as a traditional process, commonly carried out using either HA or hot plate methods. However, both methods have their challenges, practically concerning achieving even roasting throughout the nuts [22, 33].

HA drying, while widely used in various industries for drying purposes, does come with some disadvantages:

Uneven drying: Depending on the design of the drying equipment and the characteristics of the material being dried, HA drying may result in uneven drying. This can lead to some

Table 1: Various heating methods.

Product	Method	Aim of study
Different vegetables	HA	Different air features (temperature, humidity, and velocity) effect on drying process
Kiwi	HA	Different temperature and fruit slices size effect on process time
Berberi	HA	Effect of drying conditions on energy consumption
Pumpkin	HA	The process modeling
Vegetables	HA	The process effect on physicochemical
Moslae herba	HA	The drying effect on volatile compounds and flavor
Potato, garlic, and cantaloupe	HA	The drying process energy consumption
Fruits	HA	The drying process effect on final quality
Nuts	HA	Reviewing IR nut roasting
Food	IR	Overview in IR heating
Peanut kernel	IR	Roasting of peanut kernel
Ginkgo biloba	IR	The process effect on physico-chemical properties
Jackfruit	IR	The drying process effect on microstructure and quality properties
Turmeric	IR	IR assisted HA drying process effect on quality parameters
Mango	IR	IR drying effect on bioactive compounds
Blueberries	IR	The drying process effect on quality attributes
Rose	IR	The drying process effect on color, time, and total phenolic compounds
Food texture	MW	The process effect on food texture
Pecan nut	MW	The roasting process effect on quality and aroma
Extruded foods	MW	Feasibility study
Pistachio kernel	MW	The drying process effective moisture diffusivity, energy consumption, shrinkage, and color
Apple	MW	The drying process effect on rehydration characteristics
Orange slices	MW	The drying process effect on quality and process kinetics
Thompson naval orange	MW	The drying process effect on essential oil
Laurus nobilis leaves	MW	Drying kinetics and effect on phenolic compounds
Potato peel	MW	Kinetic and modeling of drying process and its effect on antioxidant content
Inshell hazelnut	RF	The drying effect on quality
Cashew nut	RF	The roasting process effect on antioxidant activity and quality
Cashew nut	RF	The roasting effect on aroma
Food	RF	Recent developments
Paddy	RF	HA assisted RF drying process effect on quality factors and heating uniformity
Potato flour	RF	Drying process effect on structure and gelatinization properties
Carrot cubes	RF	HA assisted RF of drying process
Carrot pomace	RF	HA assisted RF drying process effect on quality and its kinetics
Apple slices	RF	Drying process effect on quality improvement
Food	US	US usage in food production
Carrot slices	US	The IR assisted US drying process effect on quality and moisture migration
Nectarine slice	US	The pre-treatment of HA drying process effect on quality and thermodynamic properties
Strawberry slice	US	US pre-treatment of HA drying process effect on quality attributes
Blackberry	US	Studying US pre-treatment assisted HA drying process heat and mass transfer, energy consumption, and kinetics
Apple slices	US	The drying process effect on quality attributes
Carrot	US	US assisted HA drying process effect on product structure, quality, and energy consumption
Pumpkin	US	US pre-treatment HA drying process effect on carotenoid content
Hawthorn fruit	US	US assisted vacuum drying process effect on quality

parts of the material being over-dried (resulting in quality degradation) while other parts remain under-dried [34].

Loss of nutrients: In food and agricultural products, HA drying can cause degradation of heat-sensitive nutrients, vitamins, and antioxidants. The prolonged exposure to high temperatures can lead to loss of nutritional value in the dried product [35, 36].

Potential for oxidation: Some materials are sensitive to oxidation reactions when exposed to HA, which can lead to undesirable changes in flavor, color, and texture. One critical quality factor is oil oxidation, which occurs during the HA roasting process and can impact the shelf life of the nuts. This is particularly true for sensitive oils and fats. Heat triggers various physicochemical changes, such as enzymatic browning (Millard reaction), which contributes to the aroma, taste, and color of the roasted nuts. Additionally, non-enzymatic browning process form antioxidants, which can be beneficial [33, 37].

However, high temperatures during roasting can also lead to the formation of unpleasant compounds like acrylamides, particularly in certain types of nuts such as almonds [33]. Therefore, controlling the heat during the roasting process is crucial for maintaining food quality.

HA drying processes can be energy-intensive, especially if large volumes of air need to be heated to high temperatures. This can result in higher operational costs and environmental impact, especially if the energy source is not renewable [38]. The high energy consumption associated with HA treatment can be attributed to various factors. Firstly, heating air to the required temperature demands significant energy input. Additionally, maintaining the desired temperature throughout the process duration requires continuous energy supply. Moreover, the need for adequate ventilation and airflow control adds to the energy requirements.

Longer drying times: Compared to other drying methods such as freeze drying or vacuum drying; HA drying may require longer drying times to achieve the desired moisture content. This extended drying period can increase production time and reduce overall throughput [20].

Potential for contamination: In industrial settings, HA-drying systems can sometimes contribute to contamination risks if not properly maintained. There may be issues with microbial growth or cross-contamination if hygiene standards are not strictly adhered to [39].

Limited application to heat-sensitive materials: Some materials, such as certain pharmaceuticals or delicate organic compounds, cannot tolerate high temperatures without degradation. For these materials, alternative drying methods that involve lower temperatures or vacuum conditions may be more suitable [40].

Energy efficiency: As energy efficiency becomes increasingly important in food processing industries, researchers and practitioners are exploring ways to minimize energy consumption in HA treatment methods. This may involve optimizing process parameters, enhancing insulation and airflow management, and incorporating innovative technologies to improve energy utilization.

By addressing energy consumption challenges, advancements in thermal processing methods can not only reduce operational costs but also contribute to sustainability efforts by minimizing environmental impact [20, 22, 41-43].

Despite these disadvantages, HA drying remains a popular choice in many industries due to its simplicity, effectiveness with certain materials, and relatively lower initial investment compared to more specialized drying methods. The key is to carefully consider the specific characteristics of the material being dried and the requirements of the final product when selecting a drying method [18].

In summary, while traditional nut roasting methods have their challenges, advancements in heat control techniques can help achieve more consistent and high-quality roasted nuts, while also minimizing the formation of the undesirable compounds.

It's well-established that HA treatment, whether in drying or roasting process, is among the most energy-intensive methods in thermal processing. Several studies, including those by Bagheri [22], Boateng et al. [41], Nejad et al. [42], Morshedi et al. [20], and Xie et al. [43], have highlighted this fact.

IR

IR radiation is indeed a part of electromagnetic spectrum, with wavelengths ranging from 0.78 - 100 (μm). When IR radiation is applied to food materials, the generated heat energy is absorbed by the bipolar molecules present in food, leading to heating. This process has been studied and documented by researchers like Krishnamurthy et al. [9].

IR radiation can be categorized into different types based on their wavelengths. These categories include:

Near IR (NIR): NIR radiation has wavelengths ranging from approximately 0.78 to 3 μm. It is commonly used in various applications, including food processing, due to its ability to penetrate food materials to some extent and heat them effectively.

Mid IR (MIR): MIR radiation typically ranges from 3 - 50 μm in wavelength. It is also utilized in food processing, albeit to a lesser extent compared to NIR radiation.

Far IR (FIR): FIR radiation has longer wavelengths, typically ranging from 50 - 100 μm. FIR radiation is known for its deep penetration capabilities, making it suitable for certain food processing applications [44].

Understanding the characteristics and applications of these different categories of IR radiation allows for the optimization of heating process in food processing, contributing to improved efficiency and quality of the final food products [44]. Produced thermal energy by IR could be calculated by equation 3:

$$q'' = -k\frac{A}{\Delta x}(T2 - T1) \qquad 3$$

Where: q'' is heat transfer rate (W); Δx is thickness (m); k is thermal conductivity (W/m °C); A is cross sectional area (m^2); and (T2 - T1) is temperature difference (°C) [9].

Thermal process based on IR is completely different from HA heating. IR heating, indeed, operates by allowing electromagnetic waves to penetrate the food, leading to more uniform heating and potentially higher quality products compared to HA methods decreased [9, 22, 33, 44]. Additionally, IR heating tends to be more energy-efficient [20, 22, 45]. However, limitations such as low penetration depth and the potential for structural damage to the food over prolonged exposure are important considerations [22, 46].

IR heating comparing HA and freeze-drying needs less energy, highest drying rate, and reduced drying time besides higher quality in final product [20, 22, 41]. IR heating has some disadvantages, as well:

Potential for overheating: If not controlled properly, IR drying can lead to localized overheating of the material, which may cause degradation of heat-sensitive compounds or even combustion in extreme cases [47, 48].

Equipment cost: IR drying equipment can be more expensive to purchase and maintain compared to conventional drying methods, which might be a consideration for some industries [49].

Uneven heating: IR drying can sometimes result in uneven heating of the material being dried, especially if the surface of the material absorbs heat differently than its interior. This can lead to inconsistencies in the final product quality [50, 51].

MW

MW are categorized in electromagnetic waves as well (Figure 1). Their wavelengths are longer than those of IR radiation, and they penetrate food deeply [44]. Food material absorbs MW radiation, a portion of which dissipates converts to heat. The moisture content or water in food causes dielectric heating due to the dipolar nature of water. The dielectric property of water varies depending on its state in the food, whether it is free or bound [52]. MW includes movement in molecules through the migration of ionic particles or rotation of dipolar particles [53]. This energy absorption can be calculated by equation 4:

$$P = 2\pi f \varepsilon_0 \varepsilon'' \left|E\right|^2 \qquad 4$$

Where: P represents the developed energy per unit volume (W/m^3); f is the frequency (Hz); ε_0 is the absolute permittivity of vacuum (8.854188 × 10^{-12} F/m); ε'' is the loss factor; and |E| is the electric field strength [52, 54].

Dielectric constant (ε'), governs the electromagnetic field, while the loss factor (ε'') plays an important role in MW interaction and are physical parameters [54].

Dielectric properties change with temperature and moisture. To control the temperature during the MW vacuum drying process, it is recommended to select intermittent mode of MW power. A combination of MW intermittent and continuous modes will accelerate the drying rate. During MW drying, MW energy converts to heat by molecular excitation and this heat causes liquid water molecules to change to vapor, which then moves to the surface of the food and passes into the air. Therefore, the most efficient method for increasing the drying rate is using "MW convective drying" [54].

Various studies have demonstrated that MW heating significantly depends on the size and shape of materials, in addition to the radiation frequency. Lower frequencies penetrate more deeply than higher frequencies wavelengths [55-59].

MW drying offers several advantages, such as faster drying times and reduced energy consumption compared to conventional methods. However, it also has some potential disadvantages, which include:

Uneven heating: MW energy can penetrate unevenly into materials, leading to uneven drying. This can result in areas of the material being over-dried or under-dried, affecting product quality [60, 61].

Dependence on material properties: MW drying effectiveness can vary depending on the material's composition, moisture content, and geometry. Some materials may absorb MW more readily than others, affecting drying efficiency [62, 63].

Potential for hot spots: MW drying can create localized hot spots within the material, especially if the material does not have uniform dielectric properties or if MW distribution is not uniform [63, 64].

Equipment design complexity: Designing and maintaining MW drying equipment can be more complex and expensive compared to conventional drying methods. Specialized knowledge and equipment are often required for proper operation and maintenance [60, 64].

Initial investment costs: The initial investment cost for MW drying equipment can be higher than for conventional drying methods, which might be a barrier to adoption for some industries [60, 65].

Quality issues: In some cases, MW drying may lead to changes in product quality, such as texture, color, flavor, or nutrient content, due to the rapid and intense heat transfer involved [60, 66, 67].

RF

RF has been regarded as a new method in non-thermal processing. This method features high efficiency and deep penetration depth [23, 68]. In this method, heat is generated by the friction of molecules inside the foods due to dipole reactions and ionic conduction [68]. RF has a long wavelength range (3 KHz - 300 MHz) and deeper penetration compared to electromagnetic waves. The longest wavelength in electromagnetic waves belong to RF waves, as depicted in (Figure 2) [44, 69].

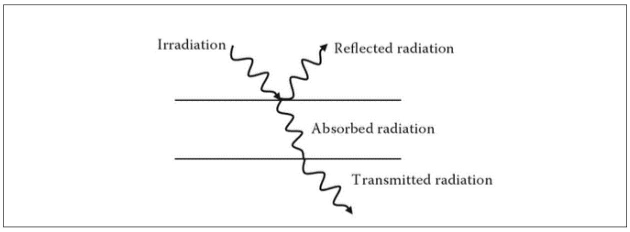

Figure 2: Conduction and convection heating schematic.

The most significant problem in RF heating is non-homogeneous diffusion of temperature; consequently, damaging the quality of products [70]. Equation 5 demonstrates the governing equation:

$$0 = -\nabla.((\sigma + j2\pi f \varepsilon_0 \varepsilon')\nabla V) \qquad 5$$

Where: j = $\sqrt{-1}$; ε' represents the dielectric constant; σ is related to the dielectric loss factor (sm^{-1}); $2\pi f \varepsilon_0 \varepsilon'$ is the temperature-dependent conductivity; E is ∇V; and V(V) is voltage potential [71].

Some scientists have suggested fruit immersion in fluid (water or air) to achieve temperature homogenous [70-72]. In this situation energy conservation equation will change (Equation 6):

$$\partial t / \partial \rho + \nabla(\rho v) = \nabla(K \nabla T) + S \qquad 6$$

Where: ρ represents the density of the material (fruit in case); t is time; v is the velocity of the fluid (water or air) surrounding the fruit; K is the thermal conductivity tensor, which describes how heat is transferred through the material; T is the temperature of the fruit; and S represents any heat sources or sinks within system.

This equation essentially states that the change in energy density within the system over time is equal to the divergence of the energy flux, which includes both the advective transport of energy by the fluid and the conductive transport of energy through the material, along with any heat sources or sinks present.

The specific form of the energy conservation equation for fruit immersion in a fluid under RF heating will depend on various factors such as the properties of the fruit, the fluid medium, and the specific RF heating process being used. It may involve additional terms to account for the absorption of RF energy by the fruit and its subsequent conversion into heat [70-72].

RF drying, while an emerging technology in food processing, also presents certain disadvantages and challenges, which include:

Uneven heating: Similar to MW drying, RF drying can lead to uneven heating within the material. This uneven heating may result in localized hot spots and areas that are under-dried, affecting product quality and consistency [73, 74].

Material penetration and absorption: The penetration depth of RF waves into materials varies depending on their dielectric properties. Some materials may absorb RF energy more effectively than others, leading to variations in drying efficiency and uniformity [75, 76].

Equipment design and costs: RF drying equipment can be complex and expensive to design, install, and maintain. The need for specialized equipment and expertise may increase initial investment costs for adopting RF drying technology [77, 78].

Energy efficiency: While RF drying can be efficient in terms of energy utilization compared to conventional methods, optimizing energy use and minimizing losses can be challenging. This efficiency can vary depending on factors such as material properties and process parameters [69, 79, 80].

Potential for product quality changes: RF drying may affect the sensory attributes of food products, including texture, color, flavor, and nutritional content. Careful control of process parameters is required to minimize these changes and preserve product quality [76, 78, 81].

Safety considerations: RF radiation poses potential safety risks to operators and workers if not properly shielded or controlled. Safety regulations and guidelines must be followed to ensure safe operation of RF drying equipment [82].

Ultra sound (US)

Sound waves greater than 20 kHz are categorized as "US". The US is a relatively new source of energy that has gained attention in the food industry as a non-thermal and thermal method [83]. Its applications are diverse, but its combination with other thermal processing notable. The US causes vibration in molecules as well. It can be used in various food processing applications as an effective and eco-friendly method; in particular, it reduces the process time while maintaining the fresh-like texture, flavor, taste, and quality of products [84, 85].

When US penetrates the food, it causes compressions and decompressions in the particles. Therefore, a high amount of energy is released as turbulence, and after that, mass transfer occurs. Combining US with pressure and temperature is named as manosonication, and with thermosonication respectively. US application in the food industry is divided into two general categories: high and low-intensity US [84].

US thermal processing involves the application of US waves to induce and control temperature changes in a medium. The mathematical equations governing US thermal processing depend on various factors such as the intensity and frequency of the US waves, the properties of the medium being processed, and the desired temperature changes. Here are some key equations commonly used in US thermal processing:

Acoustic intensity (I): I represent the power per unit area carried by the US wave [85]. It's typically measured in watts per square meter (W/m^2). I can be calculated using the equation 7:

$$I = \frac{P}{A} \quad \mathbf{7}$$

Where: P = Acoustic power (W); A = Cross-sectional area of the US beam (m^2).

Acoustic pressure (P): P represents the amplitude of the US wave [86]. It's typically measured in pascals (Pa). The relationship between I and P is given by equation 8:

$$I = \frac{P^2}{\rho c} \quad 8$$

Where: ρ is the density of the medium (kg/m^3); and c is the speed of sound in the medium (m/s).

Temperature rise (ΔT): ΔT induced by US depends on factors such as I, absorption coefficient of the medium (°C), and exposure time [84]. The ΔT can be estimated using the equation 9:

$$\Delta T = \frac{I \times t}{\rho c \times Cp} \quad 9$$

Where: t is exposure time (s); and Cp is specific heat capacity of the medium (J/kg °C).

Bioheat equation

The bioheat equation describes the distribution of temperature within a biological tissue subjected to US heating. It takes into account factors such as heat generation due to US absorption, heat conduction, and blood perfusion [84]. The general form of the bioheat equation 10:

$$\rho c \partial T / \partial t = \nabla(k \nabla T) + Qm \quad \mathbf{10}$$

Where: ρ is density of the tissue (kg/m^3); c is specific heat capacity of the tissue (J/kg °C); T is temperature (°C); t is time (s); k is thermal conductivity of the tissue (W/m °C); and Qm is metabolic heat generation (W/m^3).

These equations provide a basic framework for understanding the principles of US thermal processing and can be adapted based on specific applications and conditions. However, like any emerging technology, it has its disadvantages and challenges. Here are some potential disadvantages of US drying:

Limited penetration depth: US waves have limited penetration depth into materials, typically only a few millimeters. This limits their effectiveness for drying materials with larger dimensions or complex geometries [86].

Surface drying dominance: US energy primarily affects the surface layers of the material, leading to rapid surface drying. However, this can result in moisture gradients within the material, which may require additional processing steps to achieve uniform drying throughout [80].

Equipment complexity and cost: Designing and implementing US drying equipment can be complex and expensive. Specialized transducers and control systems are often required, which may increase initial investment costs [85].

Energy efficiency: Achieving optimal energy efficiency in ultrasound drying can be challenging. The conversion of electrical energy into US waves and their propagation through the material may lead to energy losses if not carefully managed [81].

Conclusion

Drying and roasting are two important processes in food industry and there are different methods for accomplishing them. The oldest industrial method involves using HA in various types of dryers, which requires significant heat and energy usage. However, there are newer methods of heat transfer such as IR, MW, US and RF. These methods can be utilized separately or in combination with HA or each other. One notable aspect of these new methods is their reduced time and energy consumption. However, a drawback of the new method is their unfamiliarity. One of the most problem with utilization of new methods is their cost and equipment. On the other hand, higher knowledge is necessary for designing and studying optimization of different products drying process. Therefore, this area of the food industry requires further study and research.

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None.

Conflict of Interest

None.

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