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Review

Individual and interactive effect of ultrasound pre-treatment on drying kinetics and biochemical qualities of food: A critical review

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ABSTRACT

One of the earliest and most prevalent processing methods to increase the shelf-life of foods is drying. In recent years, there has been an increased demand to improve product quality while lowering processing times, expenses, and energy usage in the drying process. Pre-treatments are therefore effectively used before drying to enhance heat and mass transfer, increase drying efficiency, and lessen degradation of final product quality. When food is dried, changes are expected in its taste, color, texture, and physical, chemical, and microbial properties. This has led to the need for research and development into the creation of new and effective pre-treatment technologies including high-pressure processing, pulsed electric field, ultraviolet irradiation, and ultrasound. Sound waves that have a frequency >20 kHz, which is above the upper limit of the audible frequency range, are referred to as "ultrasound". Ultrasonication (US) is a non-thermal technology, that has mechanical, cavitational, and sponge effects on food materials. Ultrasound pre-treatment enhances the drying characteristics by producing microchannels in the food tissue, facilitating internal moisture diffusion in the finished product, and lowering the barrier to water migration. The goal of ultrasound pre-treatment is to save processing time, conserve energy, and enhance the quality, safety, and shelf-life of food products. This study presents a comprehensive overview of the fundamentals of ultrasound, its mechanism, and how the individual effects of ultrasonic pre-treatment and the interactive effects of ultrasound-assisted technologies affect the drying kinetics, bioactive components, color, textural, and sensory qualities of food. The difficulties that can arise when using ultrasound technology as a drying pretreatment approach, such as inadequate management of heat, the employment of ultrasound at a limited frequency, and the generation of free radicals, have also been explained.

1. Introduction

One of the earliest methods of food preservation that has been modernized by technology in the past century is drying. Reducing water activity and extending the shelf life of the food are the main goals of drying, which is described as the process of using controlled heat to

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evaporate the significant portion of water present in a product. Microorganism and enzyme activity both decrease as water activity decreases [1]. Due to their high water content, fresh fruits and vegetables quickly lose quality if not dried in a timely manner. Furthermore, some food products have a very limited harvest time; thus, a highly effective drying method is required to better preserve a large quantity of harvested foods [2]. Moisture removal keeps microorganisms from growing, which also makes the product lighter, cuts down on the space it takes up in packaging, and saves money on shipping and storage [3].

The process of drying is essential since it also has a big impact on the final product's sensory and nutritional qualities [4]. Drying can be easily accomplished using traditional methods or a variety of modern techniques, such as hot air drying with or without pre-treatments to save time and energy while retaining the dried product's quality [5]. Since drying necessitates a considerable amount of energy and time, there are a number of different pre-treatment procedures that can be used before fruit and vegetables are dried. Pulsed electric fields, microwaves, infrared, ultrasound, high pressure and high humidity hot air impingement blanching are among the pre-treatments used to accelerate heat and mass transfer and improve the quality of dried products [6,7]. When compared to other techniques for drying, the impacts of electrohydrodynamic (EHD), pulsed electric field (PEF), ultrasound waves, microwaves, and radio frequency (RF) have garnered the most attention due to their superior effectiveness and shorter amount of time spent in operation [1].

In fields such as food science, nanotechnology, and alternative medicine — all of which place a premium on the efficient extraction of bioactive compounds — ultrasond is an environmentally friendly method that offers prospects for a wide range of applications. In addition to this, the technology has a low cost of both energy and maintenance, which contributes to its many positive effects on the economy [8]. Researchers have recently used both physical and chemical pre-treatments of foods extensively. They discovered that while chemical pre-treatment can accelerate the drying process, it also diminishes soluble nutrients and raises concerns about chemical residuals affecting food safety. The utilization of non-thermal technologies, such as pulsed electrical fields and ultrasound, can be a better solution to these problems [3]. Recently, ultrasound pre-treatment has been applied to many agro-food products, including kiwifruit [7], sweet potatoes [5], Jerusalem artichokes [9], olives [10,11], celery [12], strawberries [13,14] and saffron [4] to improve the drying rate and enhance the quality characteristics of the final products. Also, related protocols for the application of ultrasound as a drying pre-treatment have been developed recently [4]. There are several papers that have recently discussed the application of ultrasound pre-treatment for the drying process [6]. However, there is a need to reveal the individual and interactive effects of ultrasound pre-treatment on biochemical qualities and drying kinetics of foods. Therefore, the purpose of this review was to provide an overview of the effects that ultrasound has on the drying kinetics, energy effectiveness, and quality of foods, including the bioactive components, color, textural, and sensory qualities of finished food products. In addition, the potential applications of these compounds in the food drying industry, as well as the associated action mechanisms, were reviewed with reference to the data that was found in the relevant published literature.

2. Ultrasound

One of the most common non-thermal techniques for "green" chemistry that uses sound waves of various frequencies for particular purposes is called ultrasonication (US) [15]. Ultrasound is described as the energy created by sound waves at frequencies higher than those audible to humans (20 kHz to 20 MHz range) [16]. Ultrasound is classified into two types based on frequency range: low energy, low strength (frequency: 20–100 kHz) and high frequency, high strength [5].

High-power ultrasound (HPU) with a frequency range of 20 kHz to 100 kHz is a potential non-thermal technology for food preservation that involves applying pressure waves known as cavitation to change the mechanical, chemical, and biological properties of foods and beverages [18].

The two distinct types of ultrasound devices that are frequently used for ultrasound applications are the ultrasonic bath and the ultrasound probe (Fig. 1) [17]. A supply of high-energy vibrations and a propagation medium are two essential components for using HPU in industrial processes. High-energy ultrasonic pressure waves are transmitted through the medium by the source or transducer, which transforms electrical generating power into mechanical vibrations [16].

When ultrasonic waves are applied, the material undergoes a sequence of fast compressions and expansions, much like a sponge being repeatedly squeezed and released, which aids in the transfer of water within the substance. Because of the mechanical tension, also known as the "sponge effect," liquid water or vapor can be more easily drawn out of the solid particle [16,19]. Through the sponge effect, microchannels are formed, which aid in the transfer of intracellular water to the surface. It has also been shown that dissolved oxygen in the intracellular region of plant tissue can be eliminated with US treatment, which improves heat and mass transmission during drying [7].

In recent years, ultrasound pre-treatment has become one of the most common mechanical pre-treatments, and it has shown encouraging results in terms of enhancing the drying properties of fruits and vegetables. Before drying, food samples are often ultrasonically pretreated in the 20–40 kHz range [6]. Although some research are using osmotic solution or ethanol, ultrasound technology is typically performed using water as the medium to deliver the mechanical waves to the foods. In this instance, ethanol impregnation prior to drying is improved by ultrasound pre-treatment [12]. Additionally, ultrasound with a high intensity induces a phenomenon known as cavitation, which is useful to remove the contents of moisture that are firmly bound to the cell. Cavitation can be achieved through the use of ultrasound [17]. Ultrasound devices are capable of producing acoustic cavitation, which is the production and collapse of air bubbles within a system. There are two types of acoustic cavitation: transient and steady [20]. The former happens when gas- or vapor-filled cavitation bubbles suffer erratic oscillations and then implode. When a bubble in a liquid system explodes, it causes an accumulation of energy, which in turn causes the formation of local hot spots with temperatures of approximately 4000 Kelvin and pressures of >1000 atm [21]. This generates high local temperatures and pressures that would denature enzymes and destroy biological cells. The exploding bubble also generates significant shear forces and liquid jets in the utilized solvent, which may have adequate energy to destroy the wall and the membrane of cell. Stable cavitation, on the other hand, refers to bubbles that oscillate in a consistent manner for a significant number of acoustic cycles [22]. The procedure of using ultrasound has all these additional benefits as well. When compared to the improvement in drying rate that can be reached through airborne ultrasound, the improvement in drying rate that can be achieved through contacting ultrasound is superior in the vast majority of circumstances [3].

2.1. Ultrasound applications in foods

Over the past few decades, ultrasound, as one of the alternative green technologies, has been widely used in food technology. It is utilized for a variety of tasks, including extraction [23–25], freezing [26–28], removal of pesticides [29–31], cleaning [32], emulsification [22], degassing [16,26], homogenization [33], thawing [34], extraction, preservation [35], crystallization [36], filtration [17,27], preservation [37] and drying [3,12,38]. Ultrasound primarily uses acoustic waves to generate mechanical and chemical effect that are fundamentally different from those used in conventional methods in order to accomplish these goals [27]. This technology's guiding idea is to reduce processing time, conserve energy, and enhance food product quality, safety, and shelf life [19].

The mechanism by which ultrasound power generates powerful

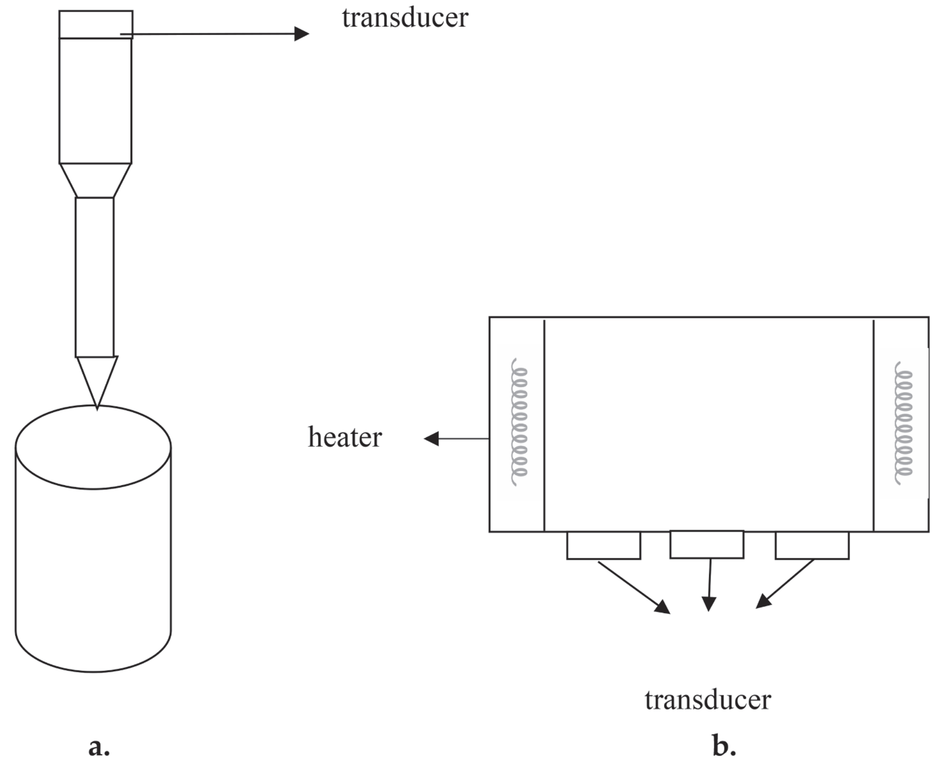

Fig. 1. Illustrations for an ultrasonic probe (a) and ultrasonic bath (b) [17].

waves from cavitation in liquid solutions is dependent on the properties of the liquid, the presence of air, and the acoustic power of the ultrasonic system. The use of ultrasound (US) causes cavitation by producing micro gas bubbles within a liquid. These bubbles, when they burst, release powerful shock waves and free radicals across the cell membrane, both of which contribute to the inactivation of microorganisms [37].

When comparing the individual effect of US, the interactive effect of US with other processing methods (high temperature, high pressure, or a combination of temperature and pressure), this increases the inactivation efficacy. However, this is only possible when the ultrasonic treatment is performed in conjunction with the other processing methods. They are able to be categorized as ultrasonication, which involves the use of ultrasound at a low temperature; thermosonication, which involves the use of ultrasound in conjunction with a high temperature; manosonication, which involves the use of ultrasound in conjunction with pressure; and manothermosonication, that is, ultrasound, pressure, and temperature [39].

Table 1 provides some examples of how the US has been used to enhance and improve various processes. This technology has been implemented in the food sector as a result of the mechanical and/or chemical impacts that ultrasound has on the procedures of homogenization, mixing, extraction, filtering, crystallization, drying, fermentation, and degassing. Antifoaming actions, reduction of particle sizes, temporary or permanent modifications of viscosity, modulation of the growth of living cells, cell destruction and dispersion of aggregates, inactivation of microorganisms and enzymes, and sterilization are some of the effects that can be caused by these effects [40].

Table 1
Chemical and mechanical effects of ultrasound used in Food Science [1].

Chemical and Biochemical Effects	Mechanical Effects
Microbiological inactivation	Crystallization
Sterilization	Degassing
Enzyme inactivation	Foaming
Pesticide removal	Drying
Wastewater treatment	Emulsification
	Freezing
	Filtration
	Extraction
	Tenderization
	Homogenization

The current focus of food technologists is on producing foods that are not only long-lasting and safe against microorganisms, but also have improved appearence, mouthfeel, nutritional content, and taste [41]. Industries are also looking for effective technologies with environmentally friendly and sustainable characteristics to satisfy customer demands and legal requirements [42]. Although ultrasound was initially used to deactivate microorganisms, current research is primarily focused on extracting beneficial nutraceutical compounds from plants to be encapsulated in regularly consumed food products, formulating new stable products using emulsification, and enhancing the mouth feel and digestibility of food [43].

3. Utilization and effect of ultrasound Pre-treatment on drying of foods

Drying is the most common approach to preserving fresh foods, and it has a number of significant advantages, including the facilitation of early harvesting, a reduction in shipping weights and costs, a reduction in the amount of packaging that is required, and an extension of shelf life [44]. There are a variety of drying processes, each of which has its own set of benefits. The drying equipment required for hot air drying is straightforward, risk-free, and inexpensive to a significant degree. Due to cell collapse brought on by moisture loss, hot air drying causes significant product shrinkage. It can also result in negative changes to the dried product's color, texture, flavor, and nutritional content [3]. The process of freeze drying (FD) is particularly well suited for materials that are sensitive to heat, since it may maintain the color, smell, and nutritional value of food. However, the drawback of FD is its high energy use and prolonged drying period, as well as the abundance of bacteria that are present in foods [45]. The method of vacuum drying has been modified to work with the materials that easily oxidize [12]. The rate at which microwave technology dries things out is very quick, and the product's quality is consistent throughout. However, the biggest drawback of the microwave is the possibility of burns due to excessive moisture content, electromagnetic field, drying time, or product shape [15].

Deng et al. conducted a review of the chemical and physical pre-treatments that were performed on fruits and vegetables. They discovered that despite the fact that chemical pre-treatment can speed up the drying process, it results in the loss of soluble nutrients and poses issues with food safety due to chemical residuals. A pre-treatment with heat can eliminate germs, make the texture more manageable, and speed up the drying process. On the other hand, it causes products to have an undesirable quality [44]. Thus, non-thermal, green, and innovative solutions (such as ultrasound, microwave, pulsed electrical field, etc.) can be a better alternative to address these shortcomings [2,8,32]. The use of ultrasound in the pre-treatment of food products before drying has become increasingly popular in recent years and has demonstrated the potential to significantly decrease the amount of time required for drying [46]. As was previously indicated, the cavitation, microchannel production and sponge effect that ultrasonic pre-treatment has on food material has led to its widespread application prior to the drying process (Fig. 2). The inertial flow and the sponge effect are examples of the direct mechanisms that contribute to mass transfer. The microchannels formed as a result of the rupture of tissues and cells caused by acoustic cavitation are an example of the structural changes created by ultrasound, which constitute the indirect processes [47].

As a pre-treatment step prior to the convective drying of carrot slices, studies were conducted with the use of ethanol and/or ultrasound. Following the application of pre-treatments, the ethanol pre-treatment resulted in a 6 % reduction in carrot moisture, whereas the ethanol plus US pre-treatment resulted in a 21 % reduction [47]. Pei et al. conducted research to determine how the drying rate, color difference, and microstructure of saffron were affected by a pre-treatment with ultrasound, which was then followed by drying in the far infrared. In addition, the impact of pre-treatment length (30 and 60 s) and drying temperature (50, 60, 70, and 80 °C) on saffron's primary chemical composition, total flavonoid content, antioxidant activity, and volatile aroma components was analyzed. According to the findings, the length of time spent in pre-treatment led to a reduction in the overall amount of time required for drying. After a pre-treatment of sixty seconds, the drying time was reduced by 21.05 %, especially when the temperature was set to 50 °C [4].

Drying is another term for the process of limiting the growth of microorganisms and prolonging the shelf life of fruit and vegetables by lowering the water content from 80 to 95 % down to 10–20 % [46]. The main objective of the study by Rani et al. was to investigate the influence of potassium metabisulfite (KMS solution, 0.25 % w/v) and ultrasonic (20 and 30 min) pre-treatment on the features and quality of pineapple slices after exposure to drying. The ultrasound-treated samples, according to the findings, had a faster drying rate, a lighter color, better moisture diffusivity, and lower hardness than the control samples. It was noted that pre-treatment with KMS and ultrasound for 20 to 30 min resulted in a reduction in drying time [6].

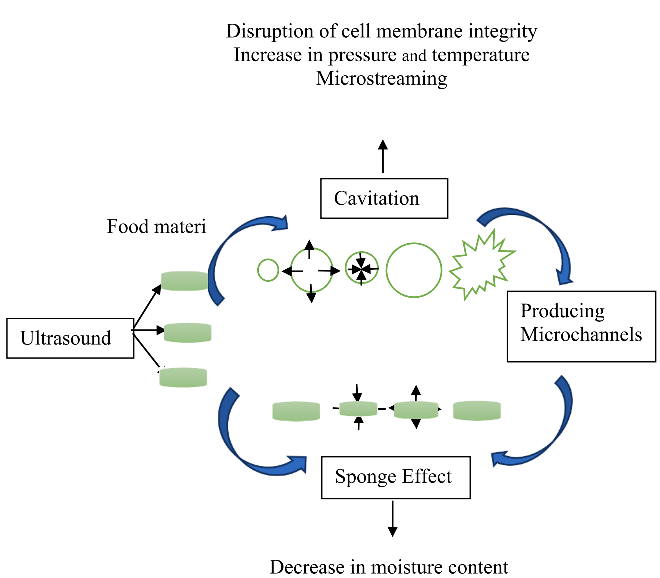

Fig. 2. The effects of ultrasound on food materials before drying [48].

It was discovered that the use of ultrasonic considerably accelerated drying at every temperature evaluated; the lower the evaluated temperature, the quicker the drying process. The use of ultrasonics hence resulted in a 32 % reduction in the amount of time necessary for drying in order to get a moisture content of 0.2 kg water/kg dry matter when the drying was carried out at 70 °C. In the experiments conducted at 50 °C, this reduction rose to 62 %. The authors observed that there was no noticeable difference between the times required for the US-50 and AIR-70 studies ($p > 0.05$). This indicates that using ultrasound caused the drying of red pepper to intensify, which is equivalent to an increase in drying temperature of 20 °C [19].

When performing drying operations like freezing, atomization, and blanching that are employed in freeze-drying, spray-drying, and other drying techniques, indirect effects of ultrasonic pretreatment can be applied. Researchers examined the impact of ultrasonic (US) pretreatment before spray drying on the powder flow and moisture sorption behavior of micellar casein concentrate. US pretreatment raised average particle size (D50) from 82.46 m to 100.73 m and reduced surface fat content from 19.2 % to 13.8 %, reducing basic flow energy, cake energy, and cohesion. US-treated samples had a lower ability to absorb atmospheric moisture than the control. Protein structural study indicated that as US power rose, α-helix reduced and β-sheet and surface hydrophobicity increased, exposing hydrophobic groups and slowing water sorption. US pretreatment improves powder flow and reduces cake formation at high humidity [123]. In another study, microfiltered casein micelle retentates were treated with ultrasound 15 min before spray drying. The effect of ultrasound pretreatment on the physicochemical, functional, and digestion properties of the resulting micellar casein concentrates was studied. The results showed that when the ultrasound pretreatment time was increased from 2 to 6 min, the intrinsic fluorescence intensities of the casein samples went up, but they went down when the pretreatment time was increased even more. This was also accurate for the oil absorption capacity [124].

Ultrahigh pressure (UHP), ultrasound (US), and the combination of the two (UHP-US) were studied as pre-treatments to determine their impact on the drying characteristics of vacuum-freeze dried strawberry slices. For the control sample and the samples pretreated with UHP, US, and UHP-US, the drying times were 20 h, 16 h, 18 h, and 14 h, respectively, to achieve a moisture content of less than 8 % [13]. The drying time of yellow cassava was significantly impacted by the application of two ultrasound pre-treatment methods, namely osmotic dehydration with ultrasound (ODU) and distilled water with ultrasound (DWU), during the process of convective hot air drying. When compared to the untreated ones, the samples of DWU and ODU had a drying time that was 29 % and 35 % faster, respectively, than before treatment. Because ultrasound caused cavitation in the yellow cassava tissue, microscopic channels were made, which led to a higher effective moisture diffusion rate than in the untreated [49].

As described in more detail in the preceding sections, the pressure wave propagating through a liquid medium causes oscillating bubbles, which cause the acoustic cavitation phenomenon. Therefore, the dynamics of acoustic cavitation and the results of macroscopic processing are greatly influenced by the physicochemical characteristics of the surrounding liquid media [43]. As a result, in addition to water, numerous other solvents, such as methanol and ethanol, were utilized to pre-treat liquid media with ultrasound [47,50]. To improve the drying process and the quality of the final products, tri-frequency (20, 40, and 60 kHz) ultrasound-ethanol pre-treatment, ultrasound-water pre-treatment, and ethanol pre-treatment have been utilized before infrared convection drying (ICD). When compared to the control, the drying time was reduced by 33.34 %-83.34 % following each of the pre-treatments; however, the ultrasound-ethanol pre-treatment resulted in the greatest reduction in drying time (83.34 %). Because of the volatile nature of ethanol, air has been replaced in the tissue, which has resulted in a more effective osmotic dehydration effect. Additionally, the cavitation effect of ultrasound has altered the cell function of the material, causing the food tissue to be rapidly compressed and expanded, which has led to damage to the cell structure [50].

Many agricultural goods, including pineapple [6], melon [51,52], mushroom [53], garlic [54], olive [10,11,55] celery [12], saffron [4], almond kernel [56], strawberry [13,14] Jerusalem arthichoke [9], scallion stalk [50], yellow cassava [49], carrot [47,57], barley grass [45] goji berry [58], olive[10,11], kiwi fruit [7], and potato [59,60] have been reported to have their drying times shorten by applying ultrasonic pre-treatment before being subjected to higher temperatures in the hot air. After only 40 min of ultrasound pre-treatment, the drying time of almond kernels was lowered by 58.33 % compared to the control sample (without ultrasound pre-treatment). This may occur when ultrasonic waves cause a transformation (destruction) in the texture of the product. Drying time is reduced, and a hard surface layer is not generated in samples prepared with ultrasonic waves [56].

The findings demonstrated that contact ultrasound was effective in facilitating the accelerated mass transfer of the samples, and an increase in ultrasonic power was shown to drastically reduce the amount of time required for drying. The influence that ultrasonic reinforcement had on drying rate became less significant as the amount of moisture in the air decreased [60]. The rate at which the moisture ratio decreased under different pre-treatment conditions was ranked by ultrasonic power in the following order: 200 W > 250 W > 300 W > 150 W > 100 W and the rate at which the moisture ratio dropped when ultrasonic pre-treatment was used was much faster than the control. In the same study, treatment times of 30 min, 20 min, 10 min, 40 min, and 50 min showed the greatest reduction in moisture ratio across all pre-treatment conditions [58]. The above mentioned studies have indicated that the ultrasound power and treatment time had a significant effect on the drying rate and/or drying time.

3.1. Effect of ultrasound Pre-treatment on drying kinetics

The moisture ratio (MR) and drying rate (DR) are used in kinetic calculations and modeling of drying characteristics, which are calculated by using equations (1) and (2), respectively. In these equations, M_t is the moisture content of the food at a certain time t, M_e is the equilibrium moisture content of the food, M_0 is the initial moisture content of the food, $M_{t+\Delta t}$ is the moisture content of the food at t + Δt, and t is the time [10].

$$MR = \frac{M_t - M_e}{M_0 - M_e} \tag{1}$$

$$DR = \frac{M_{t+\Delta t} - M_t}{\Delta t} \tag{2}$$

The diffusivity of water is an important feature in food materials that can be useful in the forecast and engineering analysis of a variety of mass transfer activities, including drying, rehydrating, and storing [19,58] The moisture effective diffusivity (D_{eff}) can be measured by graphing the natural logarithm of the moisture ratio (MR) against the drying time (t). This will produce a linear line, and the slope of this line can be understood by considering the following:

$$Slope = \frac{\pi^2 D_{eff}}{4L^2} \tag{3}$$

Where L is half thickness of samples (m) [55]. A higher D_{eff} value indicated that the moisture removal rate in the green olive slices was greater, which would result in a reduction in the amount of time needed to dry the green olive slices to attain the final moisture content [11]. Important factors that have an effect on drying kinetics include the type of dried sample being used, the maturity index, the initial moisture content, any pre-treatments that are applied, the drying conditions, and the drying methods [61]. The conditions of ultrasound pre-treatment, such as ultrasonic power, sonication time, frequency, and sonicator probe amplitude, also have a considerable impact on the drying properties and quality of food items [3].

In order to determine which drying model most accurately represents the behavior of pretreated food components throughout the drying process, thin layer drying models are adapted to experimental drying data [10]. The most commonly used statistical parameters used to determine the best fit model are the coefficient of correlation (R^2), residual sum of squares (RSS), root mean square error (RMSE), modeling efficiency (EF), reduced chi-square (χ^2). The equations used to determine these parameters are as follows: 4, 5, 6, 7 and 8).

$$R^2 = 1 - \frac{\sum_{i=1}^{N}\left(MR_{\exp,i} - MR_{pre,i}\right)^2}{\sum_{i=1}^{N}\left(MR_{\exp,1} - MR_{pre,i}\right)^2} \tag{4}$$

$$RSS = \sum_{i=1}^{N}\left(MR_{\exp,i} - MR_{pre,i}\right)^2 \tag{5}$$

$$RMSE = \left[\frac{1}{N}\sum_{i=1}^{N}\left(MR_{\exp,i} - MR_{pre,i}\right)^2\right]^{1/2} \tag{6}$$

$$EF = \frac{\sum_{i=1}^{N}\left(MR_{\exp,i} - MR_{\exp,i_{mean}}\right)^2 - \sum_{i=1}^{N}\left(MR_{pre,i} - MR_{\exp,i}\right)^2}{\sum_{i=1}^{N}\left(MR_{\exp,i} - MR_{\exp,i_{mean}}\right)^2} \tag{7}$$

$$\chi^2 = \frac{\sum_{i=1}^{N}\left(MR_{\exp,i} - MR_{pre,i}\right)^2}{N - n} \tag{8}$$

In these formulas, $MR_{exp,i}$, $MR_{exp,imean}$ and $MR_{pre,i}$ are the experimental, mean value of experimental, and predicted moisture ratios at observation i, respectively. N is the number of experimental data points and n is the number of constants in the model. The higher values of R^2 and EF, lower values of RSS, χ^2, and RMSE should be chosen as the criteria for goodness of fit.

When trying to determine which model is best suited to representing the variations in moisture levels that occur during drying, the one that has the lowest RMSE and the highest R^2 is selected. Weibull, Verma et al, Newton, Page, Henderson and Pabis, Parabolic, Logistic, Logarithmic, Wang and Sing, Midilli et al., and Diffusion are just some of the models that have been used to describe the changes in the amount of moisture that is contained in food products [50,56]. The experimental data of ultrasound-pretreated olive drying were well predicted by the distribution and Midilli et al. models, with an R^2 value >0.992 and RMSE values less than 0.029 [10].

Effects of ultrasound parameters on the drying kinetics of food materials are summarized in Table 2. The use of ultrasound for pre-treatment to improve hot air drying of kiwifruit slices was investigated. The Weibull distribution model accurately described the moisture fluctuations of kiwifruit slices while drying, and the results suggested that ultrasound pre-treatment had a beneficial influence on drying rate [7]. Drying time was greatly decreased (up to 20 %), and control samples' rehydration ratios were determined to be lower than those of samples that had been pretreated with ultrasound [21].

As can be observed from the available research, whereas many studies have been conducted on the drying of food items, very few have examined the drying characteristics of sea products. To this end, researchers examined the effects of drying *Loligo vulgaris* with infrared

Table 2
Effect of ultrasound pretreatment on drying properties.

Material	Ultrasound parameters	Results
Saffron [2]	42 kHz, 0.4 W/cm^2	The overall drying time at 50C was reduced by 7.9 % and 21.05 %, respectively, following 30 s and 60 s of US pretreatment compared to the control samples (no ultrasound applied).
Yellow cassava [3]	20 kHz, 600 Watt	The effective moisture diffusivity of ultrasound treated samples significantly were higher than control samples.
Celery [4]	40 kHz, 32 W/L	Using the optimal combination (US + OH), the drying time of celery slices at 50 °C was reduced to roughly 45 min, while adding 5 min of pretreatment to the entire drying process.
Scallion stalk [5]	20, 40, 60 kHz	Drying time has been reduced by all pretreatment methods compared to the control, however the ultrasound-ethanol pretreatment yields the greatest reduction in time (83 %) compared to the control.
Strawberry [6]	40 kHz, 200 W	Drying times to achieve a moisture content of less than 8 % were 20 h for the control sample, 16 h for the UHP pretreatment sample, 18 h for the UHP-US pretreated sample, and 14 h for the UHP-US pretreated sample.
Barley grass [7]	20 kHz, 1500 W	In comparison to the case where there was no treatment, the utilization of ultrasound (45 W/L) resulted in a 14 % reduction in drying time and a 19 % reduction in energy usage.
Red pepper [8]	21.7 kHz, 20.5 kW/m^3	Ultrasound reduced drying time by 32 % at 70 °C to obtain 0.2 kg water/kg dry matter. At 50 °C, this reduction reached 62 %.
Apricot [9]	28 kHz, 50 W	Water activity decreased from 0.82 to 0.36 in ultrasound treated samples.
Pakchoi stems [10]	20 kHz, 300, 600, and 900 W	The initial moisture content (d.b.) was reduced by 53.68, 68.92, 72.93, and 74.93 %, respectively, as a result of ultrasound assisted osmotic dehydration pretreatments carried out at 0, 300, 600, and 900 W.
Pomegranate aril [11]	25 and 40 kHz, 100 W	In all of the treatments, the value of moisture loss from the arils increased with the amount of time they were immersed in the hypertonic solution. Additionally, utilizing ultrasonic wave to the arils while they were immersed in the solution increased the dehydration speed, which resulted in a greater amount of water loss in the same amount of time.
Okra [12]	25 kHz, 400 W	Weight loss increased with ultrasound power from 80 to 320 W and time from 5 to 15 min. Lower ultrasound power levels showed a greater effect of ultrasound duration on weight loss (80 W).
Carrot [13]	21 kHz, 180 W	Carrots treated with pulsed electric field followed by immersive sonication had the quickest drying time (180 ± 6 min) recorded. In this instance, drying took 40 % less time than it would have with untreated carrots (298 ± 3 min).
Carrot [14]	35 kHZ, 65, 75 and 85 W	The samples that were treated to ultrasound for 5 min at 10 °C showed the lowest rate of rehydration.
Garlic [15]	20 kHz, 1513.5 W/m^2	The amount of time required to dry garlic slices to a moisture content of 0.1 kg water/kg DM while maintaining a constant ultrasonic intensity level reduced as the temperature of the garlic slices increased.
Jerusalem arthichoke[16]	25 kHz, 150 W	The effective moisture diffusion coefficient increased with increasing ultrasonic duration. The samples that were treated with ultrasound and dried at 80 °C had a greater effective diffusion coefficient than the Jerusalem artichokes that underwent ultrasound treatment and dried at 60 °C.
Olive [17]	25 kHz, 150 W	It was discovered that the Deff values rose along with an increase in either the amount of time spent in ultrasonic pretreatment or the amount of microwave power. As the amount of ultrasonic time rose, both the effective moisture diffusion coefficient and the drying rate increased as well.
Olive [18]	25 kHz, 150 W	It was discovered that black olives have better rehydration properties than green olives. It was discovered that black olives have better rehydration properties than green olives.
Almond kernel [19]	28 kHz,70 W	It was shown that raising the drying temperature and ultrasonic time caused the Deff to rise because water vapor evaporation increased more quickly at the higher temperature and as a result of the ultrasound pretreatment.
Melon [20]	25 kHz, 154 W	In association with an increase in drying temperature, the drying time decreases proportionally with the duration of ultrasound exposure, achieving a 40 % decrease at 70 °C after 20 min of ultrasound treatment.
Bittter melon [21]	20 kHz, 1200 W	As the moisture level of the air decreased, so increased the ultrasonic reinforcing impact on the drying rate. Increases in ultrasound power resulted in Deff values between 1.15 and 1.96 × 10^{-10} m^2/s
Loligo vulgaris [22]	40 Hz, 120 W	Deff values for infrared drying with ultrasonic pretreatment are 5.11 × 10^{-10} m^2/s, 6.46 × 10^{-10} m^2/s, and 1.09 × 10^{-9} m^2/s at 60 °C, 70 °C, and 80 °C, respectively.
Goji berry [23]	40 Hz, 200 W	A combination of ultrasonic pretreatment and electrohydrodynamic drying technology greatly outperforms the control in terms of drying rate, time, and goji berry quality.
Kiwifruit [24]	20 kHz, 400 W	Kiwifruit slices dried between 16.67 and 25.00 % faster after being pretreated with ultrasound.
Mushroom [25]	28 kHz, 600 W	The samples that had been exposed to ultrasound pretreatment had the highest initial Mt (16.90 g water/g dry base), and the samples that had been exposed to infrared drying had the smallest final Mt (0.03 g water/g dry base), respectively, prior to and following infrared drying.

energy at 60, 70, and 80 °C [62]. The Mt of the samples that had been processed with ultrasound and then dried for 35 min resulted in a decrease to 4.60 g water/g dry base, which was a value that was smaller than that of the samples that had been dried using infrared drying without any prior pre-treatment. When compared to a control sample, the sample processed with ultrasound decreased the total drying time of shiitake mushrooms to 75 min [53].

3.2. Individual effects of ultrasound Pre-treatment on quality characteristics

3.2.1. Effects of ultrasound pre-treatment on food bioactive components

Recently, ultrasonication has been used as either a process or as part of a multi-stage methodology for the extraction of bioactive substances (including phenolics, antioxidant compounds, anthocyanins, chloropylls, carotenoids, flavonoids, etc.) from foods. This is because ultrasound enhances heat and mass transfer by breaking out the cell wall thanks to the cavitation effect [63]. Total phenol levels rose dramatically after ultrasound (US) pre-treatment, as predicted; the maximum total phenol was found in sonicated kiwifruit slices subjected to 30 min of pre-treatment. An increase in phenolics in US-treated samples is likely due to the release of phenolics that were bound within the cell walls [7]. Ascorbic acid is quickly dissolved in water and degrades at high temperatures, making it the most challenging vitamin to keep stable during food processing. However, the ultrasonic power had an inverse relationship with the amount of ascorbic acid that was retained after drying before ultrasound was applied. This result suggested that ascorbic acid was more likely to be preserved during rapid drying. Also, increasing the power of the ultrasonic waves helped separate ascorbic acid from its structural cellular wall binding [64].

The body of a human being is capable of converting beta-carotene into vitamin A, making it one of the hydrocarbon carotenoids. In vegetables, a higher beta-carotene content is typically correlated with a more intense yellow color. However, due to its sensitivity to heat, light, oxygen, and enzymes, this pigment, which gives carrots their distinctive orange hue, is easily destroyed. The beta-carotene retention of the samples that were pretreated with an ultrasonic probe at 65 W was better as the process duration got longer, but the same impact was not seen for the other power levels [21]. Changes in chlorophyll content were examined in numerous studies because chlorophyll was considered to be an important indicator of the overall quality of dried foods. The chlorophyll concentration of the ultrasound vacuum pre-treatment okra slices was 0.3788 mg/g, while the chlorophyll content of the untreated okra slices was 0.3016 mg/g. The reduced chlorophyll concentration of the control okra slices may be attributable to the longer drying time required for conventional drying [65]. There was a correlation between the ultrasonic power levels and the chlorophyll content changes of dried Pakchoi stems, with an increasing tendency as the ultrasonic power increased. It's possible that this is due to the successful removal of blocked oxygen from the sample, which was a crucial factor in determining how chlorophyll behaves over time [64].

Since flavonoids include several hydroxyl groups, they are highly susceptible to oxidation. The flavonoid content of the dried saffron that had been processed with ultrasound for 60 s was consequently greatly diminished. After being processed with ultrasound for 30 or 60 s, the flavonoid content of saffron at 50 °C increased by 1.57 mg/g and 0.45 mg/g, respectively. Perhaps this is because US pre-treatment at 50 °C requires much less time to dry. However, US pre-treatment weakened cell membranes, allowing intracellular contents to leak out [4]. Similar results were found in ultrasound vacuum pretreated (UVP) okra samples. In comparison to the control okra slices (4.68 mg/g and 1.75 mg/g, respectively), the UVP okra slices had greater total phenolic and total flavonoid contents, which were 6.48 mg/g and 2.00 mg/g, respectively [65].

3.2.2. *Effects of ultrasound pre-treatment on food color*

The color of food products is an indication of both their acceptance and their aesthetic worth [65]. Ultrasonic waves have led to an increase in the color intensity and overall visual appearance of numerous food products [27,63]. The dried shiitake mushrooms that were treated with ultrasound before being dried had a greater L* value compared to the other untreated samples. This was due to the shorter drying time necessary for these mushrooms. Furthermore, a little rise in the b* value of the mushrooms was observed compared to the samples that had not been treated, which also exhibited a decline in yellowness. This was the case when compared to the untreated samples [53]. It was discovered that a pre-treatment with ultrasonication for thirty minutes resulted in the least amount of total color change and a lower level of browning in the sample when it was dried. The untreated sample had the largest intensity of browning index (47.26 ± 1.12), followed by the US20 sample (42.07 ± 3.16) and then the US30 sample (36.02 ± 2.45). Because browning enzymes are deactivated when samples are subjected to ultrasonic waves, the amount of browning that occurs during the drying process of samples that have been prepared with ultrasound shows a significant reduction [6].

The results of an ultrasonic pre-treatment showed a rise in the value of whiteness, a reduction in the value of yellowness, and no significant influence on the redness value ($p > 0.05$). However, an increase in redness may also be observed because of the enzymatic browning that occurs during the drying process. The decrease in redness value indicates that heat degradation of carotenoids has occurred; however, an increase in redness may also be observed during drying. In the case of carrots, the majority of the pre-treatment samples were placed in the same group as the fresh sample; hence, the redness stayed rather consistent with the value that it had before drying [21].

When comparing processed samples to fresh ones, it is common practice to use the total color difference, abbreviated as ΔE, to determine the degree to which there has been an overall change in color. The kiwifruit samples that were dried without being subjected to an ultrasound pre-treatment got the biggest ΔE (32.45), which may be attributable to the fact that they were dried for the greatest amount of time [7]. The lowest ΔE value was also observed in 30 s US pretreated saffron drying samples, which was 26.32 ± 1.67. This shown that the proper pre-treatment time might not only expedite drying but also significantly lessen color change [4]. The variation in the amount of beta-carotene in carrot slices has a strong relationship with the change in the values of a* and b*. According to the findings of Wang et al., low frequency ultrasonic pre-treatment greatly enhanced the beta-carotene content, which resulted in an increase in b* values [57].

3.2.3. *Effects of ultrasound pre-treatment on textural properties*

Texture features are one of the most essential sensory attributes for dried products. These include hardness and crispness, both of which connect to a customer's level of happiness with the product. The peak number of compression forces is correlated with crispness, whereas the highest compression force represents the degree of the texture's hardness [53]. Many microscopic channels are formed as a result of the ultrasound treatment, resulting in a less concentrated sample. This results in a softer material with less resistance to the flow of moisture and a reduced level of hardness compared to the untreated samples [6]. According to the findings of some studies, the application of ultrasound, the strength of which may be adjusted according to the intensity, can have an effect on the firmness of freshly harvested fruits and vegetables [48]. It was found that the power of ultrasound and pre-treatment time have a big effect on the cavitation and deformation of the goji berry surface, but pre-treatment temperature doesn't have much of an effect on the cavitation of the goji berry surface [58].

As the sample is continuously altered in shape, size, and mechanical qualities as a result of drying processes, it affects the product's textural profile. The fresh pineapple slices were measured to have a hardness of 27.66 N, but this value increased dramatically to 167.70 N after drying. In comparison to fresh and pretreated dried samples, the hardness of the untreated dry sample is much higher. By causing tissue and cell membrane deterioration, ultrasound pre-treatment softens the sample, preventing it from stiffening when dried. As a result, the ultrasound-treated sample had significantly less hardness than the control samples [6]. It also appeared that the surface of the goji berry that was exposed to the control had a smoother texture and fewer holes, whereas the surface of the goji berry that was exposed to ultrasonic pre-treatment had an exceedingly uneven texture and a large number of cavitation bubbles. This suggests that sonication generates a number of physical and chemical reactions as well as deformation on the surface of the goji berry. These effects are beneficial in reducing the thickness of the surface layer and destroying the waxy layer that is present on the surface of the goji berry [58].

It was also demonstrated that there is a correlation between the microstructure, the amount of water present, the texture, and the rehydration ratio. In one study, ultrasound treatment of dried mushrooms resulted in the formation of a microstructure with uniform porosity. Additionally, the microstructure, which resembled a honeycomb, indicated better texture, that resulted in decreased hardness and increased crispness of dried foods [53]. In another study, Santos et al. determined the effect of ultrasound combined with ethanol on the cortex and core of carrots. The cortical texture profile was unaffected by ultrasonic treatment, and ethanol had a more profound effect on carrot morphology than ultrasound. Identical patterning and conduct were discovered in the core. In contrast to the cortex, the Water + US treatment exhibited greater structural rigidity than the control. It might be due to the increased cellular osmotic pressure that results from this pretreatment, which in turn increases the tissue's resistance to perforation [47]. There was a statistically significant ($p < 0.05$) decline in the firmness values of carrot samples that were treated with ultrasound when the ultrasound frequency was raised from 25 to 35 kHz. Additionally, greater cavities and fractures were created in ultrasound treated samples at 35 kHz. This is because the ultrasonic cavitation effect in the apricot tissue caused fractures and microchannels to emerge, which in turn led to a reduction in maximum force [66].

3.2.4. Effects of ultrasound pre-treatment on sensorial properties

It was hypothesized that the samples' comparatively low water content at their final stage was responsible for the crisp flavor [53]. Wang et al. conducted research in which they investigated the approaches in which ultra-high pressure (UHP), ultrasonic (US), and the combination of the two (US-UHP) could affect the sensory qualities of strawberry slices prior to vacuum-freeze drying (Fig. 3). In general, it was interesting to note that US samples demonstrated the highest aroma score (7.8) in all samples with fruity notes, such as ethyl acetate, methyl butyrate, ethyl hexanoate, and methyl hexanoate. Similar to aroma, taste scores of US, were also higher than control, UHP, and UHP-US samples [14].

In addition to the other sensory qualities, color is frequently listed as the main reason for people's willingness to consume dried food, particularly fruit. The high concentrations of sugars such as fructose, glucose, and sucrose as well as carbohydrates that are found in dried fruits are thought to be responsible for the color changes that occur in these fruits [67]. The UHP-US samples had the highest scores in color due to their brittleness and reddish color, both of which were related to the ruptures of partial cells that were responsible for the changes in color [14].

4. Ultrasound-Assisted food drying

4.1. Interactive effects of Ultrasound-Assisted food drying on drying kinetics

The effect of ultrasound-assisted drying on the moisture content of the dried food products was found to be significant [68–72]. Using ultrasonication instead of hot air drying at similar temperatures results in a higher reduction of moisture content. The cavitation bubbles created by ultrasound damage the cells and cause the water diffusion faster [3, 63, 73 87]. Aydar [55], in a study using green olives, applied ultrasonication pre-treatment (5 and 10 min; 32 kHz) before microwave drying and observed that untreated samples took longer to dry. In other words, a 42.5 % decrease in drying time was reported with the use of ultrasonication [11]. Similarly, Oladejo et al. [49] applied ultrasonication for yellow cassava at 600 W power for 10 min at 20 kHz before the hot-air drying process [49]. Thus, it has been reported that the drying time is reduced by 35 % in ultrasonicated samples when compared to untreated samples. The drying rate increased from 0.011 kg/kg dry matter.min to 0.018 kg/kg dry matter.min, an increase of 63 %. In ultrasound-assisted drying studies, when the variation of drying speed with time is examined, it can be said that two drying zones are generally observed. The first is the increasing rate period, which is observed for a relatively short period of time and depends on the difference in ambient and product surface moisture and is also known as the preheating period. The second is the ''falling rate period'', during which the actual drying process takes place and is observed for a longer time. Similar findings are reported by Wang et al. [14], Oladejo et al. [49], and Malvandi et al. [73]. In addition, higher water loss and solid gain are observed with ultrasonication during osmotic dehydration, thus positively affecting the drying kinetics. As mentioned before, this is due to the increase in density in heat transfer and moisture/steam migration

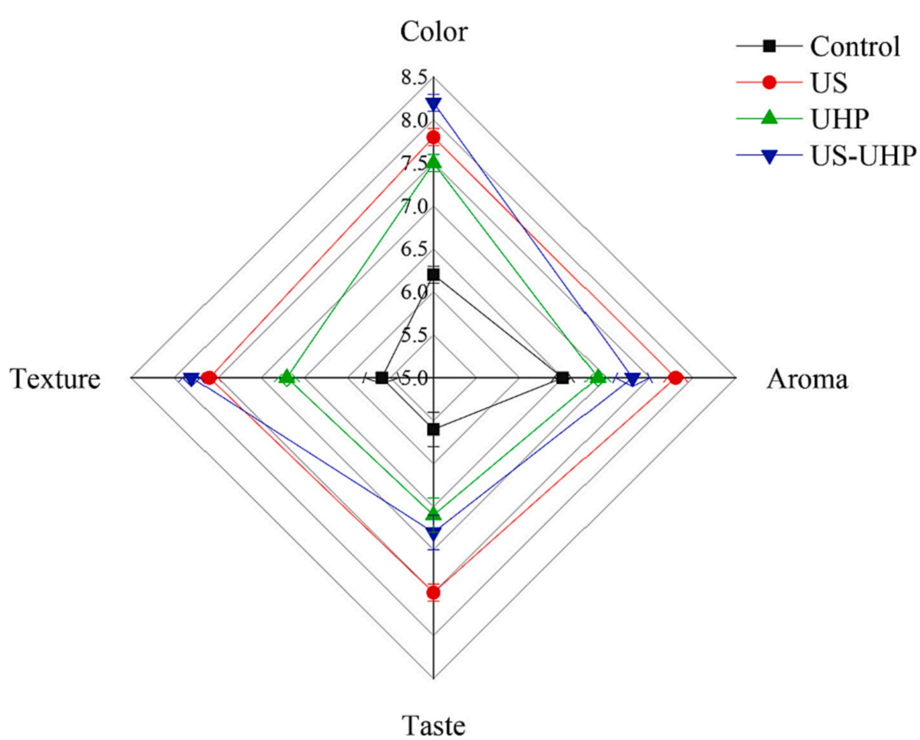

Fig. 3. Sensorial properties of different pretreated combined freeze dried strawberries [14].

by ultrasonication [74]. In addition to the use of ultrasonication as a pre-treatment, one of the sonication application methods has been airborne power ultrasound (APU). In the method, ultrasound waves are directed at the food material through the air. This method ensures that the product is dried without damaging the temperature-sensitive components, and with the help of mechanical effects, both the drying rate and energy costs are reduced. However, the most important disadvantage of this method is the capacity problem in industrial applications [75]. Studies to overcome this problem will be valuable in the future. Another type of application of ultrasonication is surface-contacting ultrasound. In a study, an 83.4 % decrease in drying rate was observed due to surface contact [76]. Wang et al. [89] carried out a very comprehensive study and used ultrasonication both as a pre-treatment and as the main treatment during the drying of lotus seed. As a result, it was reported that the drying time was 19 min when the pre-treatment was applied with 440 W of ultrasound power intensity before microwave vacuum drying. On the other hand, the drying time was found to be 15 min by ultrasound-assisted microwave vacuum drying. In the untreated method of ultrasonication, this time was recorded as 28 min. It is discovered that using ultrasonication as an assist to the drying method rather than pre-treatment has a better effect on drying time and rate. In addition, it was stated that as the strength of the ultrasonic power was increased from 120 W to 440 W, the drying rate also ascended [14].

The drying mechanism can be modeled by fitting thin layer models using the moisture data obtained in the drying process. Thin layer drying indicate a placement of the product in single layer. Thin layer models can be categorized as theoretical, empirical, or semi-empirical [77]. Thin layer models are frequently used in drying processes, and the equations of the models are given in Table 3. These mathematical models are usually derived using Fick's second law [73]. In these models, MR is the moisture ratio; a, b, n, k, g, and h are the model coefficients; and t is the drying time [77].

One of the constants in the thin layer models, k, is used to compare drying kinetics between different conditions. The higher the k value, the higher the drying rate and the shorter the drying time [73]. When examining the studies carried out in this context, Malvandi et al. [73] determined the kinetics of hot air drying and ultrasound-assisted drying at different temperatures (25, 50, and 75 °C). In a comparison of drying methods, it was seen that as the temperature increased (25, 50, and 75 °C), there was an increase of 18, 9, and 2 folds at the k values of the ultrasound-assisted method, respectively. This significant effect of ultrasound application on both drying rate and drying time at low temperatures is proof that the method is more economical than hot air drying [73]. However, it was seen that the ultrasonication process was not very effective in model selection. In a study on the drying of yellow cassava with hot air after ultrasonication pre-treatment, it was stated that Page was the model that best fitted the data obtained with pretreated and untreated samples [49]. In a different study on the ultrasound-assisted drying of unripe banana slices, it was reported that Midilli was the model that showed the best fit in all conditions [78].

Table 3
Most used thin layer models for drying.

Model names	Model equations
Newton	$MR = \exp(-kt)$
Page	$MR = \exp(-kt^n)$
Modified Page I	$MR = \exp[(-kt)^n]$
Modified Page II	$MR = \exp[-(kt)^n]$
Henderson and Pabis	$MR = a \exp(-kt)$
Modified Henderson and Pabis	$MR = a \exp(-kt) + b \exp(-gt) + c \exp(-ht)$
Midilli	$MR = a \exp(-kt^n) + bt$
Wang and Singh	$MR = 1 + at + bt^2$
Logarithmic	$MR = a \exp(-kt) + c$
Diffusion approaches	$MR = a \exp(-kt)+(1-a)\exp(-kbt)$
Two-term	$MR = a \exp(-k_o t) + b \exp(-k_1 t)$
Two-term exponential	$MR = a \exp(-kt)+(1-a)\exp(-kat)$
Verma	$MR = a \exp(-kt)+(1-a)\exp(-gt)$
Thompson	$MR = a \ln(MR) + b [\ln(MR)]^2$
Weibull distribution	$MR = a\text{-}b \exp[-(kt^n)$
Peleg	$MR = 1\text{-}t/(a + bt)$

The drying mechanism is generally complex. The drying kinetics of a product have a significant impact on the final product's properties. Although different rate periods are observed during the drying process, it is assumed that the drying essentially takes place during the falling rate period. In order to calculate the effective diffusion coefficients, it is necessary to make assumptions such as that the moisture distribution is homogeneous, there is no shrinkage, the medium and the product are in thermal equilibrium, and the drying time is too long [88].

It has been observed that a higher D_{eff} value was obtained because the products were dried after applying ultrasonication. This finding means that both the low moisture content in the final product and the shorter drying time [76]. In support of this finding, in a study performed by Aydar (2021), it was reported that the effective diffusion coefficient increased as the time of ultrasonication applied during the drying of green olives increased. Thanks to the ultrasonication application, the creation of microscopic paths in the product and the weakening of the cell structure reduce the internal resistance against moisture diffusion during drying with hot air [11]. In such a case, higher effective diffusion coefficients are achieved, according to Oladejo et al. (2021) as has been reported [49]. Wang et al. (2021), in a study on microwave-vacuum drying of lotus seeds, applied ultrasonication as a pre-treatment and assisted the method. It was observed that the effective diffusion coefficient increased by 30 % when ultrasonication was used as a pre-treatment and by 41 % when it was used as an assist to the method compared to the samples that were not applied to ultrasonication. This finding shows that assisting the ultrasound application during the relevant drying method instead of the pre-treatment has more positive results. They also reported that ultrasonication increased efficiency through "vibration," "heating", and "synergistic" effects, but the increase in drying efficiency was mainly attributed to the "vibration effect"[14]. On the other hand, Fernandes da Silva et al. [90] reported that the effective diffusion coefficient of dried melon as a result of ultrasound application at constant power and different temperatures decreases as the application temperature increases. The reason for this may be that the microstructure of the product to which the process is applied is very important, and there is a structure that will prevent water diffusion.

The variation of diffusion coefficients with applied temperature or power (or intensity) can be explained by Arrhenius-type exponential functions. This term is defined as the activation energy. The activation energy (E_A) can be interpreted as the minimum energy that must be overcome in the first step of the mass transfer process from inside the food product to the surface [91]. La Fuente and Tadini [78] reported that 20 min of low intensity ultrasonication pre-treatment applied before drying reduced the activation energy compared to unpretreated samples. This means that when ultrasound is used to dry the product, less energy is needed.

The rehydration capacity of the product after drying is also a very important characteristic. The rehydration rate gives information about the possibility of that product returning to its original form. This term can be used to understand whether the drying method and conditions are suitable [92]. The rehydration process may alter depending on the cellular and structural degradation of the food products [93]. Buvaneswaran et al. [93] treated ginger with different pre-treatments (traditional, microwave, and ultrasound) and dried it with hot air at different temperatures (40, 50, and 60 °C), and then investigated the shrinkage and rehydration kinetics of the product. The Peleg model was used to fit the data obtained during rehydration. When compared to other pre-treatments, the ultrasound was found to be better in terms of volumetric shrinkage and the rate of rehydration.

As a result, it has been seen that the use of ultrasonication alone (by direct surface contact or by air) or as an interactive effect during drying has a positive effect on drying kinetics. The application of ultrasonication during drying causes a decrease in the drying time and activation energy of the products and an increase in the drying rate, effective diffusion coefficient, and rehydration ratio. This way, it emerges as a more effective, fast, and low-energy method.

4.2. Interactive effects of Ultrasound-Assisted food drying on quality Characteristics

4.2.1. Interactive effect of ultrasound-assisted food drying on food bioactive components

The hybrid drying systems with co-application of US is being explored as alternative technique to improve the retention of food bioactive and nutrients [94,95]. Vallespir et al. [96] studied the effect of ultrasound application (20.5 kW/m^3, 22 kHz) on the ergosterol content (EC) and total polyphenolic content (TPC) of mushroom slices subjected to low temperature (5, 10 and 15 °C) drying. US-assisted drying resulted in better retention of mushroom's bioactives, with a significant increase of 24–27 % in EC and 15–41 % in TPC as compared to those without US exposure. In another study by Liu et al. [97], the changes in TPC, total flavonoid content (TFC), and vitamin C content of pear slices dried using contact US-assisted hot air drying (HAD) at three different temperatures (35, 45, and 55 °C) and ultrasonic powers (0, 24 and 48 W; 28 kHz) were investigated. US application of 24 W resulted in higher TPC at lower drying temperatures of 35 °C (408.88 mg GAE/100 g) and 45 °C (467.02 mg GAE/100 g) as compared to those subjected to HAD only (307.49 mg GAE/100 g at 35 °C and 344.27 mg GAE/100 g at 45 °C). The better preservation of TPC was attributed to less oxidation of phenolic compounds, which happened because drying time went down (the cavitation effect of the US made the space between cells bigger, which helped mass transfer). However, a significant decrease in TPC was observed at a higher temperature (55 °C) along with an increase in ultrasonic power (24–48 W) attributable to the increased cell damage causing higher oxidation of phenolics at the elevated drying temperature. A similar trend of improved retention of flavonoids (TFC) in US-assisted HAD of pear slices was found at lower drying temperatures, while a reduction in TFC at higher temperature and with US power was noticed as compared to their HAD only counterparts. Application of US was more effective in retaining vitamin C in pear slices at a lower drying temperature as compared to those without US exposure owing to the reduced drying time. However, a decrease trend was observed at higher temperatures and ultrasound power, which could be attributed to increased vitamin C degradation. The effect of application of US (20 kHz, 125.2 and 180.1 W/dm^2) in pulse mode (5 s on 5 s off) on bioactive compounds of HAD dried (70 °C; 2.0 m/s) broccoli florets was examined by Cao et al. [98]. Both HAD and US-assisted HAD caused a significant decrease in 4-hydroxyglucobrassicin, 4-methoxyglucobrassicin, and glucoraphanin, which was attributed to degradation by enzymatic/non-enzymatic reactions. Further, a slight decrease in gluconapin content (non-significant) and a significant increase in glucobrassicin content were observed in dried samples as compared to fresh broccoli florets. The increase in glucobrassicin content might be due to its synthesis (amino acid metabolism) during the drying process. Application of US didn't negatively affect the sulforaphane content, and the values (2.93 ± 0.28 – 3.30 ± 0.30 mg/g) were comparable to those subjected to HAD alone (3.01 ± 0.14 mg/g). The US treatment was found to better preserve the total thiosulfinates in HAD garlic slices (6.4 ± 0.2 – 7.3 ± 0.6 mmol/100 g) as compared to those subjected to HAD alone (6.0 ± 0.7 mmol/100 g) at 60 °C owing to the shortened drying time by the US intensification of drying process. The loss of organosulfur compounds such as methylene dithiocyanate, diallytrisulfide, 3-vinyl-1,2-dithiacyclohex-4-ene and 3-vinyl-1,2-dithiacyclohex-5-ene in garlic slices was alleviated by exposing it to US vibrations during HAD-drying [54]. Significant reduction in Vitamin C (2.06 ± 0.11–2.72 ± 0.18 mg L-ascorbic acid/g) and TPC (7.82 ± 0.15–7.97 ± 0.15 mg GAE/g) was observed after drying (both HAD and US-assisted HAD) of broccoli florets (Vitamin C, 13.62 ± 1.47 mg L-ascorbic acid/g; 11.09 ± 1.90 mg GAE/g). The decrease in vitamin C can be attributed to enhanced oxidation of ascorbic acid because of structural damage of cell wall by ultrasound energies [98].

The apple slices subjected to US (67.9 kW/m^3) assisted conductive hydro-drying (85.0 ± 0.5 °C) had significantly higher TPC (6.51 ± 0.31 mg GAE/g), TFC (1.75 ± 0.13 mg CE/g), and Vitamin C (7.59 ± 0.18 mg/100 g) than those subjected to HAD drying alone (TPC, 5.27 ± 0.31 mg GAE/g; TFC, 1.43 ± 0.13 mg CE/g; Vitamin C, 3.63 ± 0.18 mg/100 g) [79]. Further, TPC (4.5 ± 0.1 mg/g) was found to be better retained by the application of US (902.7 W/m^2) during HAD drying at 60 °C. However, with the increase in US intensity (1513.5 W/m^2) a significant reduction in TPC content (3.7 ± 0.1 mg/g) was observed [54]. Kroehnke et al. (2018) reported lower losses in TPC (34 %) of carrot slices subjected to high-power US (200 W) assisted HAD (45 °C, 4 m/s) as compared to 68 % and 42 % for those treated at low US power (75 W) or HAD only, respectively. The reduced drying time at high US power applications resulted in decreased degradation of polyphenolic compounds, thereby alleviating TPC content [80]. Cárcel et al. [19] reported US (20.5 kW/m^3) application at lower temperature (30 °C) had no significant effect on TPC and Vitamin C content of red pepper and influenced positively at intermediate drying temperature (50 °C) while a negative effect of US was observed at elevated temperature (70 °C) drying. The shortened drying time due to the application of US resulted in the protection of TPC during intermediate temperature drying. The decrease in TPC at elevated temperatures and US treatment can be attributed to increased cellular damage and polyphenolic compound degradation caused by mechanical stress and elevated drying temperature. Szadzinska et al. [99] reported significantly higher TPC content in dried mushroom slices (with US application at 100 W and 200 W) as compared to those subjected to HAD alone (both at 50 °C and 70 °C). Further, the retention of TPC was higher at a lower drying temperature (50 °C) and US power (100 W), owing to the lower degradation of polyphenolic compounds at a lower temperature. The application of US during HAD drying of orange peel resulted in better retention of TPC (38 %) as compared to 27 % in HAD alone. This can be attributed to the reduced degradation of orange peel polyphenols because of the lower exposure to drying air. However, no significant difference in vitamin C retention was observed between US-assisted HAD samples and HAD-only peel samples in spite of the reduced drying time in the former [81]. Rojas et al. [82] evaluated the effect of ethanol pre-treatment (0, 10, 20, and 30 min) on the TPC of US (21.77 kHz, 20.5 kW/m^3) assisted HAD (50 °C) of apple slices. Immersion of apple slices in a citric acid and ascorbic acid solution (1:2) resulted in a 2.4 % increase in TPC. Furthermore, when compared to samples treated only with HAD, the US application resulted in better preservation of TPC content of apple slices. Ethanol pre-treatment enhanced the US-assisted drying of an apple sample [82].

Gong et al. [83] evaluated the effect of co-pigmentation pre-treatment (ferulic acid or caffeic acid) with or without US (180.1 W/dm^2) application on the soluble and insoluble phenolic profiles of HAD (65 °C) blackberry pellets. A significant decrease in soluble catechin (fresh sample: 22.24 ± 3.63 mg/g) was observed in all the dried samples, owing to enzymatic or non-enzymatic degradation. However, the losses in sonicated blackberry samples (10.22 ± 2.18–13.63 ± 1.38 mg/g) were lower as compared to those subjected to HAD only (8.70 ± 2.14 mg/g). No-significant effect of US was observed on soluble phloretic acid content while a significant increase in ferulic acid content was observed on US application which can be due to breakdown of cell matrix releasing bound phenolic compounds or synthesis and degradation of anthocyanin into phenolic acids during drying. Furthermore, there was a weak effect of US application (with pre-treatment) on blackberry bound phenolics (phloretic acid, gallic acid, myricetin, caffeic acid, catechin). The loss of blackberry bound phenolics after drying might be due to the breakdown of the covalent bond between the cell wall and bound phenolics, thus resulting in the conversion of bound phenolics to soluble phenolics [83].

4.2.2. Interactive effect of ultrasound-assisted food drying on food color

During the conventional drying process, due to prolonged exposure of food to heat, the color undergoes degradation owing to oxidation of color pigments, enzymatic browning (polyphenol oxidase and peroxidase activity), and non-enzymatic browning (Maillard reaction, caramelization, ascorbic acid oxidation) reactions [63,100–102].

Several researchers have investigated the interactive effect of US drying on the color attributes of food material (Table 4). Significantly lower browning index (BI) values were reported for mushroom slices dried at lower temperatures (10 and 15 °C) with US application (20.5 kW/m^3, 22 kHz) as compared to samples subjected to drying alone. However, a reverse trend was observed for samples dried at 5 °C, owing to their longer exposure to US waves (sponge effect) [96]. Szadzińska et al. [99] also reported a significantly lower total color change (ΔE) value (15.57 ± 1.00) for red beetroot dried using US (26 kHz, 200 W) assisted convective drying (60 °C, 2 m/s) as compared to microwave (2.45 GHz, 500 W) assisted drying at the same temperature (ΔE = 29.42 ± 0.74). Further, US application resulted in higher retention (82 %) of betanin pigment as compared to those subjected to microwave-assisted drying or convective drying alone [84]. The greater change in color and lower betanin retention in microwave treated samples can be ascribed to heat generated within the beetroot sample upon exposure to microwave radiation. On a similar note, Mierzwa et al. [103] documented lower total color change (ΔE) and higher anthocyanin retention for US (200 W) assisted convective drying of raspberries (55 °C, 0.4 m/s) as compared to those without US exposure. In another study, Cao et al. [98] evaluated the effect of US (125.2 and 180.1 W/dm^2) assisted HAD (70 °C) on color attributes and pigments (chlorophyll and carotenoids)

Table 4
Effect of ultrasound assisted drying on the color attributes of food materials.

Food material	US device and conditions	Drying method and conditions	Color (Control sample)	Color (US assisted dried samples)	Reference
Orange peel (*Citrus sinensis*)	Vibrating drying chamber 21.9 kHz 20.5 kW/m^3	Convective drying Drying temperature = 50 °C	Fresh L* = 64.17 ± 1.77 a* = 25.93 ± 1.36 b* = 39.91 ± 3.76 C* = 47.60 ± 3.86 Hot air dried L* = 62.32 ± 0.63 a* = 27.30 ± 0.97 b* = 33.53 ± 0.68 C* = 43.24 ± 0.82	L* = 45.61 ± 2.34 a* = 11.88 ± 4.60 b* = 9.20 ± 3.87 C* = 34.90 ± 1.33	[81]
Broccoli floret (*Brassica oleracea* L.)	Probe in oven 20 kHz 125.2 W/dm^2 and 180.1 W/dm^2 Pulse mode: 5 s on and 5 s off	Convective drying Drying temperature = 70 °C Air velocity = 2.0 m/s	Freeze dried L* = 63.23 ± 0.69 a* = −14.47 ± 0.10 b* = 21.75 ± 0.14 Hot air dried L* = 43.87 ± 0.52 a* = −8.80 ± 0.43 b* = 16.59 ± 0.28 ΔE = 20.83 ± 0.83	L* = 43.96 ± 0.58 to 45.08 ± 0.57 a* = −9.03 ± 0.46 - − 9.39 ± 0.48 b* = 17.13 ± 0.20 – 17.19 ± 0.35 ΔE = 19.52 ± 0.83 – 20.45 ± 0.61	[98]
Garlic slices (*Allium sativum* L.)	Vibrating plate 20 kHz 216.8, 902.7 and 1513.5 W/m^2 Pulse mode = 3 s on and 1 s off	Convective drying Drying temperature = 50, 60 and 70 °C Air velocity = 2.5 m/s Humidity = 16.4 % (50 °C), 10.5 % (60 °C) and 8.5 % (70 °C)	Freeze dried L* = 84.3 ± 7.9 a* = 3.5 ± 0.4 b* = 5.8 ± 0.9 ΔE = 25.4 Hot air dried L* = 61.6 ± 4.9 a* = 3.4 ± 1.2 b* = 17.2 ± 2.3	L* = 61.8 ± 4.6 to 64.6 ± 4.8 a* = 2.7 ± 0.8 to 3.0 ± 0.9 b* = 17.0 ± 2.1 to 18.3 ± 1.5 ΔE = 3.0 to 4.2	[54]
Apple slices (*Malus domestica*)	25 kHz 67.9 ± 0.8 kW/m^3	Conductive hydro drying Air temperature: 25 ± 1 °C Relative humidity = 30 ± 1 % Air velocity = 0.55 ± 0.02 m/s Hot water temperature = 85.0 ± 0.5 °C, flow rate = 2.5 ± 0.1 m^3/hr Cooling temperature = 15.0 ± 0.5 °C and 1.0 ± 0.1 m^3/hr	Fresh L* = 66.03 ± 1.65 a* = −15.98 ± 0.58 b* = 17.52 ± 0.73 Hot air dried L* = 53.35 ± 1.65 a* = −12.37 ± 0.58 b* = 24.92 ± 0.73 ΔE = 15.12	L* = 55.45 ± 1.65 a* = −13.07 ± 0.58 b* = 12.91 ± 0.73 ΔE = 11.90	[79]
Goldenberry (*Physalis peruviana* L.)	20 kHz 1780.3 W/m^2	Drying temperature = 50 °C Air velocity = 1 m/s	Fresh L*= 59.47 ± 0.63 a*= 27.38 ± 0.45 b*= 59.01 ± 0.98 Hot air dried L*= 40.91 ± 1.77 a*= 33.84 ± 1.14 b*= 36.62 ± 1.34 ΔE = 29.85 ± 1.28	L*= 45.63 ± 1.08 a*= 38.07 ± 0.62 b*= 40.87 ± 2.28 ΔE = 25.28 ± 1.44	[110]

of broccoli floret. US treatment resulted in lower color change (L*, a*, b*, and ΔE values) as compared to samples dried by HAD alone (Table 4). Furthermore, US application negatively affected chlorophyll *a* (847.09 ± 3.33 – 1087.94 ± 36.94), chlorophyll *b* (250.94 ± 4.26 – 331.09 ± 36.86) and total chlorophyll content (1098.02 ± 7.59–1419.03 ± 0.08) as compared to HAD samples (chlorophyll *a*, 1128.39 ± 25.22; chlorophyll *b*, 357.35 ± 19.52; total chlorophyll,1485.75 ± 44.74) or fresh broccoli (chlorophyll *a*, 2317.14 ± 87.09; chlorophyll *b*, 749.79 ± 5.60; total chlorophyll, 3066.93 ± 92.69) and the losses increased with the increase in US power. The higher loss of chlorophyll pigment was attributed to the degradation of low-molecular-weight bioactives by physical energy. Additionally, US was found to alleviate losses in carotenoids (lutein, zeaxanthin, α-carotene, and β-carotene) in broccoli florets; however, the difference was non-significant as compared to the HAD sample. The protective effect of US on carotenoids was attributed to the lower drying time of US-treated samples resulting in lower exposure to hot air.

In a study by Tao et al. [54], lower power US (216.8 and 902.7 W/m^2) was found to be better at protecting the color of garlic slices during HAD. The color of US-assisted dried garlic slices was found to be whiter with higher L* and b* values as compared to those dried by HAD alone (Table 4) [54]. A similar trend was observed by Kroehnke et al. (2018) for US (75, 125, and 200 W) assisted HAD drying (45 °C, 4 m/s) of carrot slices, wherein US application resulted in lower total color change (ΔE) as compared to HAD- only samples. Further, the ΔE values increased with the increase in US power. The lower power US (75–125 W) resulted in higher retention of α-carotene (89–98 %), β-carotene (86–97 %), lutein (87–95 %), and total carotenoids (86–98 %) in carrot slices as compared to their HAD counterparts (α-carotene, 87 %; β-carotene, 68 %; lutein, 94 %; and total carotenoids, 73 % [80]. A similar trend was reported by Baeghbali et al. [79], wherein the color profile of apple slices dried using US (67.9 kW/m^3) assisted hydro-drying was found to be better as compared to the HAD (85 °C) sample (Table 4) [79]. During US-assisted HAD drying of white mushroom slices at a lower temperature (50 °C), the total color change (ΔE) was reported to decrease with an increase in US power (from 100 W to 200 W), while treatment at an elevated temperature (70 °C) and US power (200 W) resulted in greater color change (ΔE) in mushroom samples. The better preservation of color properties at lower drying temperatures combined with US application can be ascribed to lower drying times due to US intensification of the drying process [99]. Further, color attributes (L*, a*, b*, and C* values) of orange peel subjected to US-assisted HAD were found to be significantly lower as compared to the HAD samples (Table 4).

HAD of blackberry pellets at 65 °C (2 m/s air velocity) along with simultaneous US (180.1 W/dm^2) application with or without ethanol pre-treatment (ferulic acid or caffeic acid) alleviated the loss of anthocyanins. The protective effect of US and pre-treatment was ascribed to reduced exposure of sample to hot air (sonication) and synergistic effect between the phenolic acid co-pigmentation (pre-treatment). Further, lower losses in the two major blackberry anthocyanins, i.e., peonidin-3-*O*-glucoside (35.1 %) and cyanidin-3-*O*-glucoside (37.6 %) were observed after sonication [83].

4.2.3. *Interactive effect of ultrasound-assisted drying on textural properties*

The effect of ultrasound on the quality attributed to the dried food product is a major function of characteristics of the food product (microstructure, porosity, rigidity), as well as the process parameters (ultrasound frequency and intensity, time of ultrasonication process, medium of propagation) involved in the ultrasonication process during the drying. The utilization of ultrasound in the drying process allows for an improvement in the textural attributes and predominantly affects the hardness of the product [43,104]. In addition to hardness, ultrasound-assisted drying also shows improvement in other textural attributes like chewiness, gumminess, and brittleness [60,105]. The mechanism underlying the improvement in the texture using ultrasound-assisted drying is due to the formation of microscopic channels due to the compression and expansion cycles that results in the reduced hardness due to the consequent loss of turgor pressure due to the detachment of protoplasm from the cell wall, rapture of cellular structure and mild denaturation of proteins [87,106]. Ultrasound-assisted osmotic dehydration has been conducted for the drying of fruits and vegetables and showed better textural properties in comparison to simple osmotic dehydration [107]. Furthermore, the type of osmotic solution used for the ultrasound-assisted drying has also shown the variability of the textural attributes of the kiwi [85]. Table 5 presents a selection of recent studies on the effect of ultrasound-assisted drying on textural properties.

4.2.4. *Interactive effect of ultrasound-assisted drying on sensory properties*

The effect of ultrasound-assisted drying on the sensory properties has not been documented extensively in the literature. However, few studies have documented the effect of ultrasound-assisted drying on sensory characteristics like color, texture, taste, flavor, and overall acceptability. It is interesting to note that the effect of ultrasound- assisted drying was highly variable on the sensorial attributes of the kiwi depending on the process parameters. In the study conducted by Roueita et al. [85], it was observed that ultrasound application majorly affected appearance and texture scores, whereas the detrimental effect on sensorial attributes was less pronounced in grape and mulberry syrup as propagation medium due to masking of detrimental effects by the taste and flavour of grape and mulberry syrup [85]. In contrast to this, utilization of ultrasound in the drying of the sweet potato showed a positive influence on the sensory characteristics [86]. However, in one more study by da Silva et al. [108], no significant effect was observed on the sensory attributes of the melon. The effect of ultrasound-assisted drying on the sensory properties is summarized in Table 6.

5. Challenges associated with ultrasound Pre-treatment

As reviewed in the preceding sections, the use of ultrasonication as a pre-treatment technique in the drying of foods can significantly improve the process efficiency and facilitate the use of low drying temperatures that yield improved quality in the end products. Ultrasonication is an eco-friendly, non-thermal process that enhances the mass transfer properties of the foods to be dried and thus holds potential relevance in the food industry. However, there are a number of challenges that are restricting its widespread adoption. These are discussed under the following sub-headings:

5.1. *Improper temperature control or heat generation*

Ultrasound-assisted drying processes usually operate at lower temperatures than conventional methods to preserve thermo-labile nutritional components in the dried products. This is particularly facilitated by improved mass transfer during ultrasonication. However, the irradiation of high-intensity ultrasound waves generates additional heat in the treated foods because of acoustic cavitation. The heat generation during the process is unsteady and contributes to an increase in the process temperature at an uncontrolled rate. As such, proper temperature control mechanisms are required while using ultrasound as a pre-treatment in the drying process.

5.2. *Use of US at limited frequency*

As is evident from the reviewed literature, most of the research studies have been undertaken at a fixed ultrasonic frequency that is commercially available (20 or 40 kHz). However, frequency of US waves determines their energy flux and as such is also expected to substantially play a role in determining the process efficiency. The inclusion of frequency as a design variable along with intensity, exposure time and temperature during the conduct of experiments would thus be of a high interest in this relevance.

Table 5
Recent selected studies about the effect of ultrasound assisted drying on the textural properties.

Material	Processing parameters	Results	Reference
Sanhua plum (*Prunus salicina* L.)	Ultrasound Device: Ultrasound Bath Medium of Propagation: Sucrose solution (20∘Brix) Ultrasound Characteristics: Frequency: 40 kHz, Intensity: 0.45 W/g, 0.90 W/g and 1.35 W/g Time & Temperature of Ultrasound treatment: 15 min at 30 ∘C. Drying Conditions:50∘Brix osmotic solution, osmotic dehydration times (20, 40, 60, 80, 100, 120, 140, and 160 min) and drying temperature 60 ∘C.	Reduced hardness and chewiness in the dried plum due to ultrasound treatment. Lowest hardness and chewiness along with highest springiness was reported with 1.35 W/g for 15 min at 30 ∘C.	[111]
Kiwi	Ultrasound Device: Ultrasound Bath Medium of Propagation: Distilled water and sucrose solution, grape syrup, and mulberry syrup (50∘Brix) Ultrasound Characteristics: Frequency:27 kHz Time & Temperature of Ultrasound treatment: 20, 30 & 40 min at 30 ∘C. Drying Conditions: Drying temperature 50 ∘C (20 % m.c)	Ultrasonication resulted in increased firmness of the dried kiwi and increase in the sonication time resulted in increase firmness. Highest firmness was exhibited by samples in the grape syrup	[85106]
	Ultrasound Device: Ultrasound Bath Medium of Propagation: Distilled water Ultrasound Characteristics: Frequency: 35 kHz, Intensity: $8.4{\cdot}10^{-2}$, $9.7{\cdot}10^{-2}$ & $10.2{\cdot}10^{-2}$ W/g Time & Temperature of Ultrasound treatment: 10, 20& 30 & 40 min at 25 ∘C. Drying Conditions: Osmotic dehydration in 61.5 % sucrose solution for 120 min.	Ultrasound treatment for 10 mins exhibited lower values for firmness in comparison to 20 & 30 mins	
Chinese Yam	Ultrasound Device: Ultrasound Probe Medium of Propagation: 5 % NaCl Solution Ultrasound Characteristics: Frequency:20 kHz, Intensity: 1.52 W/g, 2.28 W/g and 3.04 W/g Time of Ultrasound treatment: 10 min Drying Conditions: Pulsed Fluidized Bed Microwave Freeze-Drying was employed. Freezing temperature − 67 ∘C, absolute pressure 80 ± 5 Pa, pulse interval and time 20 min & 0.1 *sec* respectively, microwave power 600 W and drying temperature 50 ∘C (7 % $m.c_{db}$)	Fresh sample was harder in comparison to samples treated at with ultrasound (1.52 &2.28 W/g). However, pronounced increase in the hardness was observed in the sample treated at the intensity of 3.04 W/g due collapse of the structure and shrinkage partial melting of ice crystals during drying.	[112]
Quince	Ultrasound Device: Ultrasound Bath Medium of Propagation: Water Ultrasound Characteristics: Frequency:28 kHz, Intensity: 100 kW/m3 Time & Temperature of Ultrasound treatment: 10,20 &30 min at 30 ∘C. Drying Conditions: Freeze-Drying was employed. Freezing temperature −70 ∘C, absolute pressure 48 Pa, shelf temperature − 25 ∘C, condenser temperature − 55 ∘C (12 ± 0.17 m.c)	Hardness of the freeze dried quince decreased with the increase in the time of ultrasound treatment.	[104]
Potato	Ultrasound Device: Ultrasound radiation disk using horn type ultrasound vibrator Ultrasound Characteristics: Frequency: 28 ± 0.5 kHz, Intensity: 0, 0.09, 0.17, 0.27 and 0.36 W/cm2 Drying Conditions: Far	Hardness and brittleness of potato slices decreased due to ultrasound treatment and it decreased linearly with the increase in the intensity of the ultrasound. Ultrasound treatment resulted	[60]

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Table 5 (*continued*)

Material	Processing parameters	Results	Reference
	Infrared radiation (FIR) drying was employed. Drying temperature 50 ∘C	in softer and crispier potato slices.	
Victoria Plum	Ultrasound Device: Ultrasound Bath Medium of Propagation: 50 % Glucose and sucrose solution Ultrasound Characteristics: Frequency: 25 kHz, Power: 40 and 99 % Time & Temperature of Ultrasound treatment: 30 and 60 min at 30 ∘C. Drying Conditions: Convective drying at 55 ∘C.	Hardness, gumminess, and chewiness of the plums decreased with ultrasound treatment with utilization of glucose solution whereas it increased by using sucrose solution. Adhesiveness decreased with ultrasound treatment regardless of osmotic solution used.	[105]
Pineapple	Ultrasound Device: Ultrasound Bath Medium of Propagation: Water Ultrasound Characteristics: Frequency: 40 kHz Time & Temperature of Ultrasound treatment: 20 & 30 min at 30 ∘C. Drying Conditions: Convective drying at 55 ∘C & 0.6 m/s air velocity (25 % $m.c_{wb}$)	Ultrasound treatment resulted in reduction in the hardness	[6]
Beetroot (*Beta vulgaris* L. var. Patryk	Ultrasound Device: Ultrasound Cylindrical Plate Medium of Propagation: Air Ultrasound Characteristics: Frequency: 26 kHz, Power: 200 W Time of Ultrasound treatment: 30 min Drying Conditions: Different techniques were used in drying viz. Convective drying, convective microwave drying (power 200 W), convective drying with intermittent microwave (1, 3 & 5 min) and ultrasound (330 min). Drying temperature 60 ∘C &2 m/s air velocity	Ultrasound resulted in reduction in the hardness of the dried sample in comparison to sample dried by convective drying. Lowest value of hardness by obtained by combination of ultrasonication with intermittent microwave treatment of 3 min.	[84]
Papaya	Ultrasound Device: Ultrasound Bath Medium of Propagation: Sucrose solution (20∘Brix) Ultrasound Characteristics: Frequency: 25 kHz, Intensity: 4870 W/m^2 Drying Conditions: Different techniques used for drying were, convective drying, vacuum drying (pressure 0.02–0.03 MPa), ultrasound assisted vacuum drying, ultrasound assisted drying. Drying temperature 60 ∘C	Ultrasound treatment reduced the hardness in comparison to convective and vacuum drying. Ultrasound treatment showed comparable values in combination with both convective and vacuum drying.	[113]
Tilapia fillets	Ultrasound Device: Ultrasound Bath Medium of Propagation: Trehalose solution (Concentration: 30, 50, 70, 90, 110, 130 & 150 g/L) Ultrasound Characteristics: Power: 200, 250, 300, 350, 400, 450 & 500 W Time of Ultrasound treatment: 30, 40, 50, 60, 70, 80 & 90 min. Drying Conditions: Drying temperature 45 ∘C & 2.5 m/s air velocity (0.3 ± 0.02 g/ $gm.c._{wb}$)	Ultrasound treatment (up to 60–70 min) improved the textural attributes of the fillets. Lowest value of hardness, elasticity and adhesiveness was obtained by employing 60 min of ultrasonication whereas chewiness was lowest after 70 mins. Ultrasonication beyond 70 mins resulted in detrimental effect on the texture	[114]
Sweet potato	Ultrasound Device: Ultrasonic probe Medium of Propagation: Distilled water & sucrose solution (35 % w/w) Ultrasound Characteristics: Frequency: 28 kHz, Power: 300 W Time & Temperature of Ultrasound treatment: 20, 30, 45 & 60 min at 30 ∘C. Experimental Conditions: Ultrasound treatment. Osmotic dehydration with and without ultrasound treatment	Ultrasound treatment resulted in reduction in the firmness (83.53 %) of fresh samples after 60 min of treatment. Marked reduction in the ultrasound assisted osmotically dehydrated samples (92.74 %) after 60 min of treatment. The combination of osmotic dehydration and ultrasound demonstrated marked reduction in the firmness	[107]
Okra	Ultrasound Device: Ultrasound Bath Medium of Propagation: Water (with and without vacuum packaging of	Hardness was reduced with ultrasound treatment and was lowest after treatment time of	[115]

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Table 5 (*continued*)

Material	Processing parameters	Results	Reference
	the samples) Ultrasound Characteristics: Frequency: 30 kHz, Power: 600 W Time of Ultrasound treatment: 30 & 60 min Drying Conditions: Microwave drying in Continuous Microwave Drier (MW Frequency: 2450 MHz, Power: 540 W, Belt speed: 5 mm/s)	60 and 30 min in ultrasound treated and ultrasound treated-vacuum packaged samples respectively. The hardness, gumminess and chewiness of these samples were nearly like fresh okra sample.	
Button Mushroom (*Agaricusbisporus*)	Ultrasound Device: Ultrasound Bath Medium of Propagation: Sucrose solution (50 % w/w) Ultrasound Characteristics: Frequency: 40 kHz, Power: 200 W Time & Temperature of Ultrasound treatment: 45 min at 30 ∘C. Drying Conditions: Osmotic dehydrationwithout ultrasound for 120 min and with ultrasound for 45 min	Hardness and chewiness of mushrooms with osmotic dehydration for 120 min without ultrasound was lower as compared to osmotic dehydration for 45 min with ultrasound due to loss of cell turgor and resultant rapturing due to higher steeping time	[116]
Beet snacks (*B. vulgaris* var. rubra)	Ultrasound Device: Ultrasound probe & bath Medium of Propagation: Osmotic solution (40-60∘Brix) Ultrasound Characteristics& Treatment Time for Probe System: Frequency: 24 kHz, Time: 5, 10 & 15 min Ultrasound Characteristics & Time for Bath System: Frequency: 40 kHz, Time: 10, 20 &30 min Drying Conditions: Drying temperature 55 ± 5 ∘C.	Ultrasound treatment exerted no effect on the hardness of the osmotically dried beetroot	[117]
Melon	Ultrasound Device: Ultrasound Bath Medium of Propagation: Sucrose solution (50 g sucrose/100 g water) Ultrasound Characteristics: Frequency: 25 kHz,	Ultrasound treatment reduced the hardness of the samples	[108]
	Intensity: 4870 W/m2 Time & Temperature of Ultrasound treatment: 10, 20 & 30 min at 30 ∘C. Processing conditions: Samples were given different treatments viz. ultrasound, vacuum (0.02–0.03 MPa) and combination of ultrasound and vacuum Drying Conditions: Drying temperature 60 ∘C & 2 m/s air velocity		
Apple (*Malus domestica* cv. Granny Smith)	Ultrasound Device: Ultrasound Convective Air Drier that transmits ultrasounds from the walls of drying chamber Medium of Propagation: Air Ultrasound Characteristics: Frequency: 21.9 kHz, Power:25, 50 & 75 W Drying Conditions: Drying temperature 10 & −10 ∘C, 2 m/s air velocity	No significant effect of ultrasound was observed on the hardness of the dried apples	[118]
Guava	Ultrasound Device: Ultrasound probe & bath Medium of Propagation: Osmotic solution (0, 35, & 70∘Brix) Ultrasound Characteristics & Treatment Time for Probe System: Frequency: 20 kHz, Power: 0, 15, 25, and 35 kW, Time: 6, 13 & 20 min Ultrasound Characteristics & Time for Bath System: Frequency: 25 kHz, Power: 0, 1, 1.75, and 2.5 kW, Time: 20, 40&60 min Drying Conditions: Drying temperature 70 ∘C (20 % $m.c._{wb}$)	Ultrasonication reduced the hardness and chewiness of the dried guava. The samples showed 71 % reduction in the hardness of ultrasound treated samples in 70∘Brix solution and had texture similar to that of fresh sample	[119]
Pear	Ultrasound Device: Ultrasound Probe Medium of Propagation: Distilled water Ultrasound Characteristics:	Hardness of the sample decreased linearly with the increase in amplitude whereas 25 % amplitude showed no effect on the hardness.	[120]

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Table 5 (*continued*)

Material	Processing parameters	Results	Reference
	Frequency: 24 kHz, Power: 400 kW, Amplitudes: 25, 50, 75 and 100 % Time & Temperature of Ultrasound treatment: 5 min at 25 ∘C. Drying Conditions: Infrared drying at70 ∘C.		
Cranberries	Ultrasound Device: Ultrasound Bath Medium of Propagation: Water Ultrasound Characteristics: Frequency: 35 and 130 kHz, Power Output: 100 % Time of Ultrasound treatment: 10, 20, 30, 40, 50, 60, 70 & 80 min. Drying Conditions: Osmotic solution of sucrose + salt (Concentration: 40, 50 & 60 % of sucrose and 0, 4 & 8 % of salt), osmotic dehydration times (, 4, 6, 8, 10 & 12 h), convective drying temperature 70 ∘C and 2.5 m/s air velocity, microwave assisted hot air drying at 300 & 180 W power levels	The hardness of the dried cranberries decreased with the higher frequency of ultrasound. However, lower frequency (35 kHz) was more effective in maintaining delicate texture instead of higher frequency (130 kHz) as it caused rapture and damage in the texture	[121]

5.3. Economic feasibility

Quite recently, the use of high-energy, high-intensity probe ultrasonication has gained traction due to its more efficient process and better energy utilization than low-intensity ultrasonic baths. However, its use in the industry is limited due to techno-economic constraints and a lack of equipment manufacturing specialists.

5.4. Production of free radicals

In high-moisture food products, ultrasound pre-treatments may induce some adverse physicochemical effects as a result of the free radicals generated during ultrasonication. It has been reported that hydroxyl radicals and hydrogen atoms may potentially be formed due to the high pressure and temperature associated with the implosion of bubbles during cavitation [109]. This may result in the development of off-flavors and odors, denaturation of proteins, reduction in biochemical attributes like phenols, flavonoids, ascorbic acid etc. Production of free radicals necessitates the optimal selection of processing variables to minimize these adverse effects.

5.5. Non-optimization and non-standardization of processes

The most important challenge that ultrasound as a pre-treatment

Table 6
Recent selected studies about the effect of ultrasound assisted drying on the sensory properties.

Material	Processing parameters	Results	Reference
Kiwi	Ultrasound Device: Ultrasound Bath Medium of Propagation: distilled water and sucrose solution, grape syrup, and mulberry syrup (50∘Brix) Ultrasound Characteristics: Frequency: 27 kHz Time & Temperature of Ultrasound treatment: 20, 30 & 40 min at 30 ∘C. Drying Conditions: Drying temperature 50 ∘C (20 % m.c)	Ultrasonication resulted decrease in the score of sensory characteristics (particularly appearance and texture) . However, less decline was found in samples steeped in grape and mulberry syrup.	[85106]
	Ultrasound Device: Ultrasound Bath Medium of Propagation: Distilled water Ultrasound Characteristics: Frequency: 35 kHz, Intensity: $8.4 \cdot 10^{-2}$,$9.7 \cdot 10^{-2}$& $10.2 \cdot 10^{-2}$W/g Time & Temperature of Ultrasound treatment: 10, 20 & 30 & 40 min at 25 ∘C. Drying Conditions: Osmotic dehydration in 61.5 % sucrose solution for 120 min.	Ultrasound exhibited effect on the sensory appeal and all the samples that were ultrasound treated showed alike sensorial behaviour when evaluated by electronic tongue	
Sweet Potato	Ultrasound Device: Ultrasound Bath Medium of Propagation: Distilled water &Sucrose solution (35∘Brix) Ultrasound Characteristics: Frequency: 40 kHz, Intensity: 25 KW/m^3 Time & Temperature of Ultrasound treatment: 30 min at 25 ∘C. Drying Conditions: Drying temperature 65∘C& 1.5 m/s air velocity (m.c.30/ 100 g $_{w.b.}$), followed by microwave puffing (power intensity: 22.0 W/g and vacuum: 90 kPa)	Ultrasound treatment enhanced the appearance scores of the sweet Ultrasound mediated osmotic dehydration resulted in improvement of sensorial attributes	[86]
Melon	Ultrasound Device: Ultrasound Bath Medium of Propagation: Sucrose solution		

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Table 6 (*continued*)

Material	Processing parameters	Results	Reference
	(50 g sucrose/100 g water) Ultrasound Characteristics: Frequency: 25 kHz, Intensity: 4870 W/m2 Time & Temperature of Ultrasound treatment: 10, 20 & 30 min at 30 ∘C. Processing conditions: Samples were given different treatments viz. ultrasound, vacuum (0.02–0.03 MPa) and combination of ultrasound and vacuum Drying Conditions: Drying temperature 60 ∘C & 2 m/s air velocity	No significant effect was observed in the sensory characteristics of melon with ultrasound treatment	[108]
Carrot	Ultrasound Device: Ultrasound disruptor horn Medium of Propagation: Distilled Water Ultrasound Characteristics: Frequency: 20 kHz, Intensity: 0.26 W/cm3. Time & Temperature of Ultrasound treatment: 10 min up to 60 ∘C & 15 min up to 70 ∘C. Drying Conditions: Drying temperature 60 ∘C &4.9 m/s air velocity	Ultrasound treatment resulted in no detrimental effect on the sensory characteristics of the carrot and the scores were as par the carrot that have undergone blanching pre-treatment	[122]

technology is facing prior to widespread adoption is the non-standardization and non-optimization of reported processes. Several researchers have reported negative results on the product quality possibly because of an improper configuration of system parameters for specific products {87]. Consequently, a proper selection of variables including, energy flux, exposure time, type of sonication (bath/probe), probe type, depth of probe immersion, and sample volume would minimize the adverse effects on the treated product, maximize energy use efficiency and thus result in an effective process.

6. Conclusions

The use of ultrasound as a pre-treatment in the drying process significantly improves the efficiency of the process. A wide variety of recently published studies on the utilization of ultrasound technology in the food drying process were reviewed. The effect of processing variables like ultrasonic power, sonication treatment time, ultrasound frequency, method of application (probe or bath), and ultrasound amplitude on the drying kinetics and food quality, including bioactive components, color, texture, and sensory qualities, was also discussed.

The use of ultrasound as a pre-treatment has been shown to increase the rate of drying, decrease the amount of energy required, and improve the quality of the food by exposing it to less heat. There is a growing interest in the use of ultrasound technology, both for the characterization and quality assessment of food and ingredients as well as for stabilizing various types of food, as a result of the expansion of research into this field and the development of equipment for use in industrial settings. In the design of industrial ultrasound equipment and control systems for process variables, there are certain difficulties that must be overcome before the technology may advance in its applications. However, the use of high-frequency ultrasound is ideally suited for application in the characterization of food composition or the presence of foreign material, as well as the evaluation of quality characteristics for various types of food. There is still a great need for additional research into the impacts of ultrasonication on the drying and quality aspects of food components since the drying parameters for various food commodities would differ from one another. Also, more research should be done to improve ultrasound-assisted drying. The goal should be to reduce the amount of power and energy needed for drying while keeping the quality of the food as high as possible. Low-frequency ultrasound is also being utilized to enhance the freezing, thawing, drying, emulsification, filtration, extraction, and inactivation of microorganisms and enzymes. As this technology is integrated with other preservation techniques to reach the objectives of less process time and better efficiency, applications at the industry level are anticipated to rise. High-pressure ultrasound (manosonication) and the combination of temperature and ultrasound (thermosonication) will undoubtedly be very important in the near future. The effects of ultrasound on the extraction and synthesis of functional compounds and nutraceuticals that could be employed for the creation of new functional goods are related to future applications of major importance.

CRediT authorship contribution statement

R. Pandiselvam: Conceptualization, Methodology, Investigation, Writing – original draft, Writing – review & editing, Supervision, Funding acquisition. **Alev Yüksel Aydar:** Conceptualization, Investigation, Writing – original draft, Writing – review & editing. **Naciye Kutlu:** Writing – original draft, Writing – review & editing. **Raouf Aslam:** Writing – original draft. **Prashant Sahni:** Writing – original draft. **Swati Mitharwal:** Writing – original draft. **Mohsen Gavahian:** Writing – original draft. **Manoj Kumar:** Writing – original draft. **António Raposo:** Writing – original draft. **Sunghoon Yoo:** Writing – original draft, Writing – review & editing, Supervision. **Heesup Han:** Writing – original draft, Writing – review & editing, Supervision. **Anjineyulu Kothakota:** Writing – original draft.

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.

Data availability

Data will be made available on request.

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