# Literature review: use of ultrasound and ethanol as pre-treatment in the drying of vegetable products with bioactive compounds

# Revisión bibliográfica: uso de ultrasonido y etanol como pretratamiento en el secado de productos vegetales con compuestos bioactivos

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## ABSTRACT

Despite the broad therapeutic action of plant species with bioactive compounds and drying being the most recommended operation for maintaining the quality of various plant materials, the fact that these materials differ in terms of moisture content, chemical composition, and morphology makes the optimization of drying methods and parameters for each species essential tools for obtaining dried plant biomass of high commercial value. The use of ethanol as a pre-treatment for drying, through immersion, allows for the modification of the product's natural structure and improves moisture transfer, consequently increasing the drying rate (KOMPANY *et al*., 1990). Ultrasonic waves can increase the availability of energy and accelerate mass transfer processes in the product, preserving its main qualitative attributes without significantly raising the drying air temperature (O'DONNEL *et al*., 2010). Therefore, this review aimed to elucidate the use of ultrasound and/or ethanol pre-treatment in the drying of various medicinal plant species, exploring their mechanisms of action and addressing their main effects on the desorption process and the chemical composition of these materials.

**Keywords:** medicinal plants, drying, pre-treatment, ultrasound, ethanol.

## RESUMO

Apesar da ampla ação terapêutica de espécies vegetais com compostos bioativos e secagem ser a operação mais recomendada para manter a qualidade de vários materiais vegetais, o fato de que esses materiais diferem em termos de teor de umidade, composição química e morfologia torna a otimização de métodos e parâmetros de secagem para cada espécie ferramentas essenciais para a obtenção de biomassa vegetal seca de alto valor comercial. O uso do etanol como pré-tratamento para secagem, por imersão, permite a modificação da estrutura natural do produto e melhora a transferência de umidade, consequentemente aumentando a taxa de secagem (KOMPANY *et al*., 1990). As ondas ultrassônicas podem aumentar a disponibilidade de energia e acelerar os processos de transferência de massa no produto, preservando seus principais atributos qualitativos sem aumentar significativamente a temperatura do ar de secagem (O'DONNEL *et al*., 2010). Portanto, esta revisão teve como objetivo elucidar o uso de ultrassom e/ou pré-tratamento do etanol na secagem de várias espécies de plantas medicinais, explorando seus mecanismos de ação e abordando seus principais efeitos no processo de dessorção e na composição química desses materiais.

**Palavras-chave:** plantas medicinais, secagem, pré-tratamento, ultrassom, etanol.

## RESUMEN

A pesar de la amplia acción terapéutica de las especies vegetales con compuestos bioactivos y el secado, siendo la operación más recomendada para mantener la calidad de diversos materiales vegetales, el hecho de que estos materiales difieran en cuanto a contenido de humedad, composición química y morfología hace que la optimización de los métodos y parámetros de secado para cada especie sean herramientas esenciales para obtener biomasa vegetal seca de alto valor comercial. El uso de etanol como tratamiento previo para el secado, a través de la inmersión, permite la modificación de la estructura natural del producto y mejora la transferencia de humedad, aumentando en consecuencia la tasa de secado (KOMPANY *et al*., 1990). Las ondas ultrasónicas pueden aumentar la disponibilidad de energía y acelerar los procesos de transferencia de masa en el producto, preservando sus principales atributos cualitativos sin aumentar significativamente la temperatura del aire de secado (O'DONNEL *et al*., 2010). Por lo tanto, esta revisión tuvo como objetivo dilucidar el uso de ultrasonido y/o pretratamiento de etanol en el secado de diversas especies de plantas medicinales, explorando sus mecanismos de acción y abordando sus principales efectos en el proceso de desorción y la composición química de estos materiales.

**Palabras clave:** plantas medicinales, secado, pretratamiento, ultrasonido, etanol.

## 1 INTRODUCTION

Drying consists of a simultaneous process of heat and mass transfer between the drying air and the wet product. The objective of this process in plant species with bioactive compounds is to promote, through the reduction of water content, the maintenance of the quality of bioactive compounds and the preparation of these species for safe and prolonged storage, with the aim of meeting the needs of the phytotherapeutic, food, and cosmetic industries (PIMENTEL *et al*., 2012).

However, during drying, continuous exposure to drying air can cause physical modifications to the product, alter organoleptic characteristics (color, taste, and aroma), promote the loss of volatile compounds, alter the chemical composition, and directly interfere with the quality standard for consumer acceptance (ARGYROPOULOS; MÜLLER, 2014; CHIN; LAW, 2011; JIN *et al*., 2017; ORPHANIDES; GOULAS; GEKAS, 2015). In addition, a prolonged drying period leads to higher consumption of thermal and electrical energy (KUMAR; KARIM; JOARDDER, 2014). Therefore, the optimization of drying methods and the quality of the dried product are two indispensable variables in the drying of plant materials.

The use of ultrasound and/or ethanol as pretreatment for the drying of plant products is a promising alternative. The application of ultrasonic waves to the cells of the product causes a series of compressions and expansions. The forces involved in this process can be greater than the surface tension that holds the water content within the cell, creating microscopic channels that facilitate water removal (FUENTE-BLANCO; BLANCO, 2006). In this way, it is possible to reduce the water content without significantly increasing the product's temperature. This is one of the main reasons for the use of ultrasonic energy in food technology applications, such as drying (AMANI *et al*., 2017).

The use of ethanol as a pre-treatment for drying is justified because it facilitates the dissolution of cell wall components and mass transfer during the immersion process and later during drying. Consequently, the use of ultrasound and/or ethanol pre-treatment in the drying of plant products has been investigated with the aim of optimizing drying since not all drying technologies operate under optimal conditions in terms of energy consumption, safety, low environmental impact, and maintenance of the quality of the final product (KOWALSKI; SZADZIŃSKA, 2014; KUMAR; KARIM; JOARDDER, 2014; ORPHANIDES; GOULAS; GEKAS, 2015).

## 2 MECHANISM OF ULTRASOUND ACTION

Discovered by Pierre and Marie Curie in 1880, ultrasound is considered a versatile technology that can be defined as sound at frequencies above 16 kHz, inaudible when transmitted through the air (SORIA; VILLAMIEL, 2010). Regarding the drying process of plant products, the primary justification for using ultrasound as a pre-treatment is due to the direct and indirect effects of ultrasound on the applied product.

The direct effects are related to the "sponge effect" (SCHÖSSLER; JÄGER; KNORR, 2012a). In other words, ultrasonic waves traveling through the product can cause a series of compressions and expansions, similar to sponges being squeezed and quickly released. Since the forces generated by this movement (compression and expansion) are greater than the surface tension that holds the water inside the product, microscopic channels and cavities are created, increasing porosity and mass transfer, i.e., the removal of water that is strongly bound to the plant matrix of the product. With each compression and expansion, there is greater mobility and migration of water from the interior to the surface of the product, which, upon contact with the drying air, is evaporated (DE LA FUENTE *et al*., 2006; YAO, 2016; MIANO; IBARZ; AUGUSTO, 2016). This phenomenon reduces both the time and cost of drying without affecting the main chemical and physical characteristics of the product (YAO, 2016).

The indirect effects are related to the formation of microchannels due to acoustic cavitation (CHEMAT; ZILL-E-HUMA; KHAN, 2011). Ultrasound waves traveling through the product induce the cavitation phenomenon (formation of bubbles) in the water present inside or outside the cells of the product. When the bubbles collapse, shear forces are released, which, in turn, are associated with pressure shockwaves, micro liquid jets, and acoustic transmission (LEONG; MARTIN; ASHOKKUMAR, 2017).

Shockwaves are defined as waves that propagate radially outward from the point of collapse in the surrounding fluid. These shockwaves can be used to increase mass transfer rates (LEONG; MARTIN; ASHOKKUMAR, 2017). Micro liquid jets are high-speed jets that form when the bubbles collapse due to unidirectional expulsion.

Acoustic transmission is the propagation of disturbances in the fluid caused by induced oscillations due to the cavitation phenomenon, resulting in the formation of localized shear forces in the vicinity of bubbles.

Acoustic cavitation in aqueous media can lead to the formation of free radicals H+ and OH- due to the breakdown of water molecules, and these can recombine to form other molecular products, as shown below (KENTISH; ASHOKKUMAR, 2011):

$H_2O \rightarrow H + OH$

$H + H \rightarrow H_2$

$OH + OH \rightarrow H_2O_2$

$H + OH \rightarrow H_2O$.

These produced radicals can affect the quality of certain substances and can be used to enhance the functionality of selected food ingredients (ASHOKKUMAR *et al*., 2008). The activity of antioxidants in food and biological systems depends on the degree of hydroxylation (SORIA; VILLAMIEL, 2010). In ultrasound technology, the formation of radicals is considered a disadvantage for preserving the bioactivity of various bioactive compounds, such as phenols and flavonoids, for example (SORIA; VILLAMIEL, 2010).

For applications where OH- radicals adversely affect the integrity of the constituents of interest, the use of low-frequency ultrasound is recommended. This is because both stable cavitation and an increase in the number of active bubbles can increase the quantity of radicals generated at high ultrasound frequencies (ASHOKKUMAR *et al*., 2008).

## 3 ETHANOL MECHANISM OF ACTION

Different mechanisms are associated with the effect of using ethanol as a pre-treatment on the drying kinetics and the quality of dried plant products. According to Llavata *et al*. (2020), the primary justification is the "Marangoni effect," which is the mass transfer (water) that occurs due to the difference in surface tension between the two fluids, which in this case are ethanol (organic solvent) and the water present in the plant product.

Ethanol, with a molecular formula of $CH_3$-$CH_2$-OH, is a colorless liquid with a molecular weight of 46.07, described as one of the most distinctive oxygen-containing organic compounds. Its physical and chemical properties primarily depend on the hydroxyl group, -OH, which imparts polarity to the molecule and promotes intermolecular interactions through hydrogen bonds. These two characteristics account for the differences observed between low-molecular-weight alcohols (including methanol and ethanol) and their respective hydrocarbons. In the liquid state, hydrogen bonds are formed by the attraction of the hydrogen from the hydroxyl group of one molecule to the oxygen of the hydroxyl group of another molecule.

"When an ethanol molecule bonds with a hydroxyl group of a water molecule, this bond makes it completely miscible with water, meaning the two substances together result in a homogeneous mixture in any proportion. Thus, when in contact with the plant product, ethanol (whose surface tension is lower than that of the water present on the product's surface) is capable of entering the plant matrix, mixing with water. Meanwhile, differences in osmotic pressure cause a displacement of water from the sample's surface to the surrounding ethanol. Consequently, the outer layer of the product contains both water and ethanol. When subjected to drying, ethanol evaporates rapidly, resulting in a concentration gradient of water/ethanol. As a result, more water than ethanol remains on the product's surface. This region with a higher concentration of water than ethanol has greater surface tension, causing the water inside the product to be strongly "pulled" toward its surface. This water migration process occurs successively until an equilibrium in surface tension is reached. As a result, there is greater mass transfer (water), higher drying speed, and drying rate (ROJAS; AUGUSTO, 2018a; KOMPANY *et al*., 1990). This increased water migration from the interior to the surface of the product due to the presence of ethanol is referred to as the Maragogi Effect.

## 4 EFFECTS ON THE PROCESS AND CHEMICAL COMPOSITION

### 4.1 ULTRASOUND

Zotti-Sperotto *et al*. (2020) evaluated the influence of ultrasound pre-treatment combined with heat pump drying on drying time, yield, and the chemical composition of essential oil from Varronia curassavica Jacq., Ocimum gratissimum Linn, and Lippia origanoides. Leaves from the three species were subjected to ultrasonic pre-treatment for 0, 3, 5, 10, 15, 20, and 30 minutes at 37 kHz and dried at 40 °C in a fixed-bed dryer equipped with a heat pump, with an airflow of 0.8 m $s^{-1}$. As a result, the authors found that ultrasound reduced drying time, did not cause qualitative changes in the chemical constituents of the essential oils extracted from the leaves of the studied species, and maximized the yield of V. curassavica essential oil. However, the yield of O. gratissimum essential oil showed a significant reduction. Additionally, the authors concluded that the mechanical effects of ultrasound waves can effectively enhance the essential oil extraction process by increasing solvent penetration into the cellular material, facilitating content release. The recommended ultrasound pre-treatment time for reducing drying time and preserving the green color of Varronia curassavica and Ocimum gratissimum leaves should be 5 minutes, and for Lippia origanoides, it should be 15 minutes.

Sledz *et al*. (2016) studied the effect of ultrasound pre-treatment at different frequencies (21 and 35 kHz) for 20 and 30 minutes on the drying kinetics and qualitative parameters of microwave-convective dried parsley leaves (with 200 W power and 30°C temperature). The application of ultrasound at 35 kHz contributed to a reduction in drying time of 56% and 11% for 20 and 30-minute durations, respectively. The authors concluded that the 21 kHz frequency for 20 minutes was recommended as a pre-drying treatment for parsley leaves due to the reduction in drying time (52%), preservation of phenolic content, and color retention.

In a complementary study, Sledz *et al*. (2015a) assessed the influence of ultrasound pre-treatment (21 kHz) during microwave drying at different powers (100 and 300 W) and drying temperatures (20, 30, and 40 °C) on drying time, energy consumption, and parsley leaf quality. Ultrasound significantly reduced drying time by up to 29.8% and energy costs by up to 33.6%, compared to untreated material. Furthermore, ultrasound provided better color retention and did not affect lutein content. In both studies, the authors attributed the reduction in drying time to the formation of microscopic channels caused by ultrasonic cavitation, reducing water transfer resistance and increasing evaporation.

Pei *et al*. (2021) studied the influence of ultrasound pre-treatment (42 kHz at 25°C) followed by infrared drying on drying rate, color difference, and microstructure of saffron. The effect of pre-treatment duration (30 and 60 seconds) and drying temperature (50, 60, 70, and 80 °C) on the main chemical composition, total flavonoid content, antioxidant activity, and volatile compounds in saffron was also assessed. The results showed that drying temperatures and ultrasound pre-treatment durations significantly affected drying rate, color, microstructure, as well as the chemical properties and volatile compounds of saffron. Ultrasound pre-treatment significantly reduced drying time and improved color quality at 50°C. The authors reported that this could be explained by the creation of microchannels on the saffron's surface, reducing water migration resistance. Based on gas chromatography (GC-MS) analysis, it was found that aldehydes and ketones are the major aroma compounds in dried saffron, and the ratio of these two compounds exceeded 85% of the volatile content in all drying methods. The best result was obtained with the combination of 30-second ultrasonic pre-treatment and drying at 50°C, where chemical properties, especially color and aroma characteristics, as well as antioxidant activity and flavonoid contents, were at their highest values. Therefore, the authors concluded that ultrasound pre-treatment before infrared drying can reduce the process time without altering saffron quality.

## 4.2 ETHANOL

Wang *et al*. (2019) evaluated the effect of vacuum, ethanol pre-treatment, and hot air infrared drying methods on the characteristics and quality of green onion slices (Allium fistulosum). The pre-treatment of green onions included four conditions: 1) Control: immersion in distilled water under normal pressure, 2) Ethanol: immersion in 75% ethanol under normal pressure, 3) Water + vacuum: immersion in distilled water under a vacuum of 0.6 bar, 4) Ethanol + vacuum: immersion in 75% ethanol under a vacuum of 0.6 bar. Pre-treatment times were 5, 10, 20, and 30 minutes. The drying process was carried out in a hot air infrared drying oven at 60°C. Higher retention of ascorbic acid was observed in dried samples pre-treated with ethanol and ethanol + vacuum. According to the author, the higher retention of this compound in the plant matrix is due to ethanol minimizing water contact with ascorbic acid (since when it penetrates the product's internal structures, intercellular air is expelled, leading to oxidative reactions, primarily those caused by enzymes that require oxygen to interact with the environment). This provides protection to the vitamin against oxidation and water solubility. Additionally, green onion slices pre-treated with ethanol and ethanol + vacuum showed better water loss than the control and water + vacuum samples, which, in turn, shortened the drying time and increased the retention rate of ascorbic acid in the samples.

Junqueira *et al*. (2021) assessed the effect of ethanol pre-treatment on the phenolic compound content during vacuum drying of taioba leaves. In the study, taioba leaves were sprayed with ethanol (4.0 × 10-4 L), and drying experiments were conducted at two different temperatures (40 and 50°C) with a vacuum pressure of 10 kPa. The results demonstrated a shorter drying time for samples dried at 50°C. According to the author, the shorter drying time associated with the higher evaluated temperature is due to ethanol increasing the vapor pressure in the sample, which intensifies the movement of water from the interior to the surface of the leaves (Maragogi Effect). Moreover, the different treatments reduced the content of phenolic compounds and antioxidant activity. According to the author, irreversible changes in cell structure are observed during drying, and decompartmentalization occurs, favoring degradative reactions (as these damages trigger the release of enzymes, primarily polyphenol oxidase and peroxidase), which lead to the loss of these compounds.

Lima (2015) studied the influence of ethanol pre-treatment on the drying kinetics of guaco leaves (Mikania glomerata Sprengel/Mikania laevigata Sch. Bip. ex Baker). The pre-treatment involved immersing guaco leaves in ethanol (40%, 70%, and absolute ethanol) for different times (5, 45, and 85 seconds) at room temperature. Drying experiments were conducted in an oven at 50°C. The shortest drying times were observed for treatments with absolute ethanol at immersion times of 45 and 85 seconds, with a 4% reduction in drying time compared to the control. According to the author, the shorter drying time provided by the use of absolute ethanol can be explained by ethanol's contribution to the diffusion and release of water content into the environment, reducing drying time. Additionally, the mixing of the solvent with the sample's aqueous solution results in an ethanol-water mixture with higher vapor pressure than one containing only water, contributing to increased water evaporation and reduced drying time. The authors also observed more pronounced shrinkage in leaves treated with absolute ethanol at all immersion times compared to 40% and 70% ethanol solutions. As for coumarin content, according to the authors, treatment with 70% ethanol and an immersion time of 45 seconds showed the highest coumarin content (4.10 mg $g^{-1}$), while treatment using absolute alcohol with an immersion time of 85 seconds showed the lowest yield (1.12 mg $g^{-1}$). The reduction in coumarin content can be justified by the longer contact time of ethanol with the product, favoring greater "extraction" of coumarin.

## 4.3 ULTRASONICATION + ETHANOL

Rojas, Silveira, and Augusto (2020) assessed the effect of pre-treatments (ethanol and ethanol+ultrasonication) on the drying of pumpkin cylinders. Effects on drying kinetics, energy consumption, and carotenoid preservation were studied. In the study, pumpkin cylinders were dried at a temperature of 50°C and an air velocity of 0.8 ± 0.1 m $s^{-1}$. Ethanol pre-treatment was carried out by immersing the samples in absolute ethanol for 15 and 30 minutes, while ultrasonication pre-treatment was performed at a frequency of 25 kHz, at room temperature, for 15 and 30 minutes. According to the authors, all pre-treatments, when compared to the control, reduced drying time by 49%, 52%, 48%, and 59% for samples pre-treated with ethanol (15 minutes), ethanol (30 minutes), ethanol+ultrasonication (15 minutes), and ethanol+ultrasonication (30 minutes), respectively. The combination of ethanol+ultrasonication (30 minutes) showed the highest reduction in both drying time (approximately 59%) and energy consumption (44%). Regarding carotenoid content, the evaluated pre-treatments did not show significant differences after drying, meaning that the pre-treated samples preserved approximately 100% of the carotenoid content. However, control samples (without pre-treatment) exhibited partial degradation of 23% in carotenoid content after drying.

Da Cunha *et al*. (2020) evaluated the influence of pre-treatment (ethanol, vacuum pulse, and/or ultrasonication) on the drying of melons (Cucumis melo). Effects on water activity, ascorbic acid content, total phenolic compound content, total carotenoid content, color, and antioxidant activity were studied. According to the authors, eight types of pre-treatments were evaluated, where samples were immersed in ethanol solution for 10 minutes with different concentrations (100% and 50% ethanol/water ratio). Four treatment conditions were used: control, only ultrasonication at a frequency of 25 kHz, vacuum at a pressure of -650 to -700 mmHg, and the combination of ultrasonication with vacuum. For all conditions, a processing time of 10 minutes was applied at a temperature of 30 °C.

Drying was conducted in a fixed bed dryer with a drying air temperature of 60 °C and an air velocity of 2 m $s^{-1}$. The condition that achieved the shortest drying time was the one using ultrasonication pre-treatment for 10 minutes in

100% ethanol solution. However, drying resulted in a considerable reduction in melon's bioactive compounds and antioxidant activity. Regarding phenolic compounds, samples immersed in 100% ethanol had values of 0.44 and 0.38 mg GAE $g^{-1}$ DW for ethanol and ethanol+ultrasonication treatments, respectively, while samples immersed in 50% ethanol had contents of 0.50 and 0.42 mg GAE. $G^{-1}$ DW (ethanol and ethanol+ultrasonication, respectively).

For carotenoid content, samples immersed in 100% ethanol had values of 35 and 28 µg $g^{-1}$ DW for ethanol and ethanol+ultrasonication treatments, respectively, while samples immersed in 50% ethanol had contents of 64 and 37 µg $g^{-1}$ DW (ethanol and ethanol+ultrasonication, respectively). As for ascorbic acid content, samples immersed in 100% ethanol had values of 116 and 121 mg $100g^{-1}$ DW for ethanol and ethanol+ultrasonication treatments, respectively, while samples immersed in 50% ethanol had contents of 184 and 133 mg $100g^{-1}$ DW for ethanol and ethanol+ultrasonication treatments.

The authors concluded that, in general, pre-treatment conditions using 50% ethanol immersion resulted in lower losses for total phenolic compounds, total carotenoids, and ascorbic acid. The reduction in phenolic compounds, according to the authors, can be attributed to the fact that these compounds are hydrophilic, meaning they have an affinity for water, which in turn has an affinity for ethanol. Another explanation is that ethanol intensifies the effects of ultrasonication on the sample's structure. These factors may justify the higher loss of compounds observed in samples that used 100% ethanol solution compared to those with 50% ethanol. Additionally, phenolic compounds are sensitive to high temperatures and oxidation, making them more susceptible to degradation in the presence of heat and oxygen. The loss of carotenoids is associated with the fact that these molecules are liposoluble, meaning they dissolve in organic solvents like ethanol. Regarding water activity, all dried samples had values below 0.62, making them safe for storage. For color parameters, after the drying process, a decrease in brightness (L*) and yellow color (b*) was observed in all samples, while the red color parameter (a*) was intensified.

Feng *et al*. (2019) assessed the effects of different pre-treatments (ethanol, ethanol+ultrasonication, water+ultrasonication, and control) on the microstructure of garlic during infrared drying. In the study, garlic samples were gently immersed in a 75% (v/v) ethanol solution at 25±1°C for 30 minutes. Ultrasonication pre-treatment was conducted using tri-frequency ultrasonication modes (20, 40, and 60 kHz) with a power density of 50 W $L^{-1}$ with 10 seconds of pulsation on and off for 30 minutes. The authors reported that, except for allicin content (the main bioactive substance in garlic), the quality characteristics of shrinkage, surface roughness, flavor, color, and microbial content of garlic samples pre-treated with ethanol+ultrasonication were predominantly better than control samples, as well as those pre-treated with ethanol and water+ultrasonication. According to the authors, the lower allicin content in samples pre-treated with ethanol+ultrasonication, compared to water+ultrasonication, can possibly be attributed to the adverse effects of ethanol in promoting protein denaturation, which can result in the inactivation of alliinase, the enzyme responsible for catalyzing alliin into allicin in garlic. Another explanation is the greater solubility of allicin in ethanol compared to water. It's also highlighted that the allicin content in garlic samples pre-treated with ethanol+ultrasonication was significantly lower than those pre-treated with ethanol alone. This occurred because the application of ultrasonication destroyed the cellular structure of garlic and promoted the release of allicin from the cells, which was subsequently dissolved in ethanol. Additionally, a greater number of holes with higher density were observed in samples pre-treated with ethanol+ultrasonication. According to the authors, the higher hole density in samples pre-treated with ethanol+ultrasonication, compared to other treatments, can be explained by the strengthening of the acoustic cavitation effect generated by ultrasonication when ethanol is used as the propagation medium, given that water and ethanol have different properties (viscosity, vapor pressure, and surface tension). (Miano, Ibarz, and Augusto, 2016; Tao *et al*., 2018). Furthermore, the fact that the components of cell walls and membranes can be dissolved by ethanol during the pre-treatment makes them more vulnerable to damage caused by ultrasonic cavitation.

Regarding infrared drying of pre-treated garlic, Feng *et al*. (2019) reported that, when compared to the control, pre-treatments with ethanol+ultrasonication, ethanol, and water+ultrasonication promoted a reduction in drying time of 27.27%, 13.64%, and 9.09%, respectively. According to the authors, the greater reduction in drying time provided by the application of ethanol+ultrasonication pre-treatment can be explained by a higher mass transfer rate (of water) and a greater incidence of ruptures in the membranes and cell walls of garlic slices resulting from the treatment. As a consequence, a greater release of gases present in the intercellular spaces of garlic slices and increased migration of water from the interior to the surface of the product were observed.

Santos *et al*. (2021) evaluated the effect of pre-treatments (ethanol, ethanol+ultrasonication, water+ultrasonication, and control) on the structure, quality, and energy consumption of carrots subjected to convective drying at 40°C. In the study, carrot slices were immersed in either water or absolute ethanol for 30 minutes, and ultrasonication was applied at a frequency of 25 kHz at 20 °C for 30 minutes. The results demonstrated that pre-treatments with ethanol and ethanol+ultrasonication were the most efficient. According to the authors, ethanol and ethanol+ultrasonication pre-treatments reduced drying time by 51% and 50%, respectively, while the water+ultrasonication treatment reduced it by 33% compared to the control. In terms of energy consumption, all pre-treatments reduced energy consumption by 53% and 62% (ethanol and ethanol+ultrasonication, respectively) when compared to the control, while the water+ultrasonication treatment reduced it by 41%. Regarding the structure, the authors reported that the cortical parenchyma of carrots exhibited greater shrinkage of the cell wall when pre-treated with ethanol and ethanol+ultrasonication. This shrinkage, according to the authors, is due to ethanol intensifying the effect of ultrasonication and favoring the Marangoni effect, which promoted mass transfer of the product during drying. As for carotenoid content, there was no degradation of these compounds during drying for all treatments. According to the authors, the preservation of carotenoids may be related to the drying temperature (40°C).

Freitas *et al*. (2021) evaluated the effect of pre-treatments with ethanol and ultrasound on the convective drying of pineapple in terms of product color, water activity, ascorbic acid, and total carotenoid content. For the pre-treatment stage, samples were immersed in ethanol solutions of different volumetric fractions (50% and 100%), and experiments were conducted for 10 minutes with and without the use of ultrasound (frequency of 25 kHz and temperature of 30°C). The fruit samples were dried in a fixed-bed dryer at 60°C with a drying air velocity of 2 m $s^{-1}$. The results showed that the drying time was 146 minutes for the control, 97 minutes for ethanol (50%), 95 minutes for ethanol (100%), 85 minutes for ethanol+ultrasound (50%), and 60 minutes for samples treated with ethanol+ultrasound (100%). Furthermore, higher effective moisture diffusivities were obtained when ethanol+ultrasound was applied before drying. The two-term exponential model provided the best fit for the experimental drying data. According to the authors, the shorter drying time in the ethanol+ultrasound (100%) treatment was due to the presence of ruptures in the cell tissue and the formation of microchannels resulting from acoustic cavitation (ultrasound sponge effect), which facilitated capillary flow, along with the Marangoni effect induced by ethanol.

As for water activity, although Freitas *et al*. (2021) did not observe significant differences between the pineapple samples dried with and without pre-treatment, pineapple immersed in 100% ethanol had the lowest water activity values, contributing to greater microbiological stability of the dried fruit. Regarding carotenoid content, despite the loss of these compounds in all dried samples (approximately 5; 1.23; 2.1; 2; 1.3; and 1.4 µg $g^{-1}$ for fresh samples, control, ethanol (50%), ethanol (100%), ethanol+ultrasound (50%), and ethanol+ultrasound (100%), respectively), the pre-treatment with ethanol without ultrasound preserved a higher amount of carotenoids. Despite carotenoids being sensitive to factors such as heat and processing time, the reason for the higher retention of these compounds in the product, according to the authors, is that ethanol, when entering the plant matrix, replaces the air in the tissue, forming an ethanol-water mixture, which improved the drying effect, avoiding oxidation reactions (due to the lower presence of oxygen inside the tissues), and accelerating the drying process (Marangoni effect). Wu *et al*. (2019) claim that fast drying can inactivate oxidative enzymes and better preserve bioactive compounds.

Amanor-atiemoh *et al*. (2020), in their study on vacuum pulse drying of apples with ethanol pre-treatment (30% v $v^{-1}$) + ultrasound (power of 300 W $L^{-1}$, frequency of 20 kHz, for a period of 10, 20, and 30 minutes at temperatures of 60, 70, and 80 °C), observed that the application of ethanol+ultrasound for 30 minutes reduced the drying time by 27% (at 60 °C), 31% (at 70 °C), and 22% (at 80 °C) compared to the control treatment. Additionally, the authors reported that the total free amino acid content significantly increased with ethanol+ultrasound for 30 minutes when dried at 60 °C. This treatment also showed a higher content of carbohydrates, phenolics, total free amino acids, and carboxylic acid.

## 5 FINAL CONSIDERATIONS

Although the application of pre-treatments with ultrasound and/or ethanol in drying processes can optimize the process by reducing time and energy consumption, their effects on the retention of chemical compounds in various dried plant species are still uncertain. This is because each specific matrix responds differently to each pre-treatment and process, emphasizing the need for further studies. Furthermore, various variables can influence the content of chemical compounds in the final dried product, such as drying air temperature, ultrasound exposure time, ethanol concentration, as well as the microstructure, chemical composition, and other characteristics of the sample. Therefore, applying ultrasound and/or ethanol pre-treatment to other products or under different drying conditions is still necessary to better understand their effects on drying and the quality of dried products (BITENCOURT *et al*., 2022).

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## REFERENCES

AHMAD-QASEM, M. H.; BARRAJON-CATALAN, E.; MICOL, V.; MULET, A.; GARCIA-PEREZ, J.V. Kinetic and compositional study of phenolic extraction from olive leaves (var.Serrana) by using power ultrasound. Innovative *Food Science & Emerging Technologies*, v. 17, p. 120-129, 2013.

AMAMI, E.; KHEZAMI, W.; MEZRIGUI, S.; BADWAIK, L.S.; BEJAR, A.K.; PEREZ, C.T.; KECHAOU, N. Effect of ultrasound-assisted osmotic dehydration pretreatment on the convective drying of strawberry. Ultrasonics Sonochemistry, v. 36, p. 286–300, 2017.

AMANOR-ATIEMOH, R.; MUSTAPHA, A.T.; SARPONG, F.; ZHOU, C. Effect of ethanol with ultrasound pretreatment on the drying kinetics, quality parameters, functional group, and amino acid profile of apple slices using pulsed vacuum drying. Journal of Food Process Engineering, 2020.

ARGYROPOULOS, D.; MÜLLER, J. Changes in the content and composition of essential oil during convective drying of lemon balm (Melissa officinalis L.). Crops and Products, v. 52, p. 118-124, 2014.

ASHOKKUMAR, M.; SUNARTIO, D.; KENTISH, S.; MAWSON, R.; SIMONS, L.; VILKHU, K.; VERSTEEG, C. Modification of food ingredients by ultrasound to improve functionality: A preliminary study on a model system. Innovative Food Science & Emerging Technologies, v. 9, n. 2, p. 155- 160, 2008.

BITENCOURT, B.S.; CÔRREA, J.; CARVALHO, G.R.; AUGUSTO, P.E.D. Valorization of Pineapple Peel for Food or Feed: Effects of Ethanol Pretreatment on Convective Drying and Quality Properties. Valorization of Residues and Biomass, v. 13, p. 1-14, 2022.

BRANDTS, J.F.; HUNT, L. The thermodynamics of protein denaturation. III. The denaturation of ribonuclease in water and in aqueous urea and aqueous ethanol mixtures. Journal of the American Chemical Society, v. 89, p. 4826-4838, 1967.

CHEMAT, F.; ZILL-E-HUMA.; KHAN, M. K. Applications of ultrasound in food technology: processing, preservation, and extraction. Ultrasonics Sonochemistry, v. 18, n. 4, p. 813-835, 2011.

CHIN, S.K., LAW, C.L. Drying of medicinal plants, in: Jangam, S. V., Law, C. L., Mujumdar, A.S. (Eds.). Drying of Foods, Vegetables and Fruits, Singapore, pp. 105–136, 2011.

DA CUNHA, R.M.C.; BRANDÃO, S.C.R.; MEDEIROS, R.A.B.; SILVA, JÚNIOR E.V.; SILVA, J.H.F.; AZOUBEL, P.M. Effect of ethanol pretreatment on melon convective drying. Food Chemistry, 2020.

DE LA FUENTE-BLANCO, S.; RIERA, E.; APARICIO, V.M.A.; BLANCO, A. Food drying process by power ultrasound. Ultrasonics, v. 44, p. e523-e527, 2006.

FENG, Y.; ZHOU, C.; YAGOUB, A.E.A.; SUN, Y.; OWUSU-ANSAH, P.; YU, X.; WANG, X.; XU, X.; ZHANG, J.; REN, Z. Improvement of the catalytic infrared drying process and quality characteristics of dried garlic slices by ultrasound-assisted alcohol pretreatment. LWT, v. 116, p. 108577, 2019.

FREITAS, L.D.C.; BRANDÃO, S.C.R.; SILVA, J.H.F.; ROCHA, O.R.S.; AZOUBEL, P.M. Effect of Ethanol and Ultrasound Pretreatments on Pineapple Convective Drying. Food Technology and Biotechnology, v. 59, 2021.

FUENTE-BLANCO, S; BLANCO, A. Food drying process by power ultrasound. Ultrasonics Sonochemistry, v. 44, p. 523-527. 2006.

JIN, W.; MUJUMDAR, A.S.; ZHANG, M.; SHI, W. Novel Drying Techniques for Spices and Herbs: a Review, 2017.

JUNQUEIRA, J.R.J.; CÔRREA, J.L.G.; RESENDE, N.S.; BALBINO, T.C.V.; GATTI, I.P.; MENDONÇA, K. S. Ethanol pretreatment on taioba leaves during vacuum drying. Ciência e Agrotecnologia, 2021.

KENTISH, S.; ASHOKKUMAR, M. The physical and chemical effects of ultrasound. In: Ultrasound technologies for food and bioprocessing. Springer, New York, p. 1-12, 2011.

KOMPANY, E.; ALLAF, K.; BOUVIER, J. M.; GUIGON, P.; MAUREAUX, A. New process for the dehydration of fruits and vegetables with instant rehydration. Industries Alimentaires et Agricoles, p. 1243–1248, 1990.

KOWALSKI, S.J.; SZADZIŃSKA, J. Convective-intermittent drying of cherries preceded by ultrasonic assisted osmotic dehydration. Chemical Engineering and Processing, v. 82, p. 65–70, 2014.

KUMAR, C.; KARIM, M.A.; JOARDDER, M.U.H. Intermittent drying of food products: A critical review. Journal of Food Engineering, v. 121, p. 48–57, 2014.

LEONG, T.S.H.; MARTIN, G.J.O; ASHOKKUMAR, M. Ultrasonic encapsulation– a review. Ultrasonics Sonochemistry, v. 35, p. 605-614, 2017.

LLAVATA, B.; GARCÍA-PÉREZ, J.V.; SIMAL, S.; CÁRCEL, J.A. Innovative pre-treatments to enhance food drying: a current review. Current Opinion in Food Science, v. 35, p. 20–26, 2020.

MIANO, A.C.; IBARZ, A.; AUGUSTO, P.E.D. Mechanisms to improve mass transfer in foods with ultrasound technology: Describing phenomena in two model cases. Ultrasonics Sonochemistry, v. 29, p. 413-419, 2016.

ORPHANIDES, A.; GOULAS, V.; GEKAS, V. Drying Technologies: Vehicle to High-Quality Herbs. Food Engineering Reviews, 2015.

PEI, Y.; XU, W.; SONG, C.; LI, Z. Effects of ultrasound pretreatment followed by far-infrared drying on physicochemical properties, antioxidant activity, and aroma compounds of saffron (Crocus sativus L.). Food Bioscience, p. 101186, 2021.

PIMENTEL, F. A.; CARDOSO, M. G.; ANDRADE, M. A.; ZACARONI, L. M.; GUIMARAES, L. G. M.; Influence of drying on yield and chemical composition of volatile compounds of Piper piscatorum trel. & yunck. (Piperaceae) roots. Química Nova, São Paulo, Vol. 35, n. 4, p. 715-718, 2012.

ROJAS, M. L.; AUGUSTO, P. E. D. Microstructure elements affect mass transfer in foods: The case of convective drying and rehydration of pumpkin. LWT, v. 93, p. 102–108, 2018a.

ROJAS, M. L.; SILVEIRA, I.; AUGUSTO, P. E. D. Ultrasound and ethanol pre-treatments to improve convective drying: Drying, rehydration, and carotenoid content of pumpkin. Food and Bioproducts Processing, v. 119, p. 20–30, 2020.

SANTOS, K.C.; GUEDES, J.S.; ROJAS, M.L.; CARVALHO, G.R.; AUGUSTO, P.E.D. Enhancing carrot convective drying by combining ethanol and ultrasound as pre-treatments: Effect on product structure, quality, energy consumption, drying, and rehydration kinetics. Ultrasonics Sonochemistry, v.70, 2021.

SCHÖSSLER, K.; JÄGER, H.; KNORR, D. Effect of continuous and intermittent ultrasound on drying time and effective diffusivity during convective drying of apple and red bell pepper. Journal of Food Engineering, v.108, p.103-110, 2012a.

SLEDZ, M.; WIKTOR, A.; NOWACKA, M.; WITROWA-RAJCHERT, D. Drying kinetics, microstructure, and antioxidant properties of basil treated by ultrasound. Journal of Food Process Engineering, 2015a.

SLEDZ, M.; WIKTOR, A.; RYBAK, K.; NOWACKA, M.; WITROWA-RAJCHERT, D. The impact of ultrasound and steam blanching pre-treatments on the drying kinetics, energy consumption, and selected properties of parsley leaves. Applied Acoustics, v. 103, p. 148-156, 2016.

SORIA, A.C.; VILLAMIEL, M. Effect of ultrasound on the technological properties and bioactivity of food: a review. Trends in Food Science & Technology, v. 21, n. 7, p. 323-331, 2010.

TAO, Y.; ZHANG, J.; JIANG, S.; XU, Y.; SHOW, P.L.; HAN, Y. Contacting ultrasound enhanced hot-air convective drying of garlic slices: Mass transfer modeling and quality evaluation. Journal of Food Engineering, v. 235, 2018.

VILLELA, F.A.; SILVA, W.R. Drying curves of corn seeds using the intermittent method. Scientia Agricola, Piracicaba, v. 49, n. 1, p. 145-153, 1992.

WANG, X.; FENG Y.; ZHOU, C.; SUN, Y.; WU, B.; YAGOUB, A.E.G.A.; ABOAGARIB, E.A. Effect of vacuum and ethanol pretreatment on infrared-hot air drying of scallion (Allium fistulosum). Food Chemistry, v. 295, p. 432-440, 2019.
WU, XIAO-FEI.; ZHANG, MIN.; LI, ZHONGQIN. Influence of infrared drying on drying kinetics, bioactive compounds, and flavor of Cordyceps militaris. LWT, v. 111, p. 790-798, 2019.

YAO, Y. Enhancement of mass transfer by ultrasound: Application to adsorbent regeneration and food drying/dehydration. Ultrasonics Sonochemistry, v. 31, p. 512–531, 2016.

ZOTTI-SPEROTTO, N.C.; MELO, E.C.; SOUZA, M.I.L.; FONSECA, M.C.M.; GONZAGA, D.A.; ÁVILA, M.B.R.; DEMUNER, A.J.; VENTRELLA, M.C.; LELIS, A.C.V. Effect of drying with ultrasonic pretreatment on the yield and quality of the essential oil of Varronia curassavica Jacq. and Ocimum gratissimum Linn. Industrial Crops and Products, v. 147, p. 112-211, 2020.