FUNDAMENTAL DRYING TECHNIQUES APPLIED IN FOOD SCIENCE AND TECHNOLOGY[1]

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ABSTRACT

Fresh food and food products with high water activity are easily degradable. Drying is one of the most fundamental preservation techniques used to improve the shelf-life of food. However, drying techniques used for the removal of excess water from food need to be efficient, economic, and able to create dried food with high-quality. The drying process needs to protect nutrient compounds, aroma, texture, and appearance of products. However, due to the emission of hot exhaust gases from the conventional dryer to the environment, and according to the demand for the application of green energy, the use of non-conventional dryer with higher efficiency and faster drying is considered in a recent review. This paper reviews the mechanisms, advantages, and applications of some conventional and non-conventional drying techniques in the food industry. These include hot air drying, spray drying, electrohydrodynamic drying, infrared drying, radio frequency drying and microwave drying.

Keywords: *Spray drying, Radio frequency drying, Electrohydrodynamic drying, Infrared drying*

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INTRODUCTION

Drying is an ancient technique which is used for hundreds of years to protect food products from various microbial spoilage and chemical deterioration it is aimed to extend the shelf-life of foodstuff. Drying technology is an indispensable unit operation for the large-scale preservation of foodstuff. Also, it has a vast application to create new products with various shapes (such as powder, flake, granules, etc.) in the food manufacturing sector. The goal of drying is to decrease moisture content and water activity of food products to the desired level by thermal or non-thermal processes **[1, 2]**. Furthermore, drying decreases packaging, transportation, handling costs. The different benefits of the drying process were shown in Figure 1.

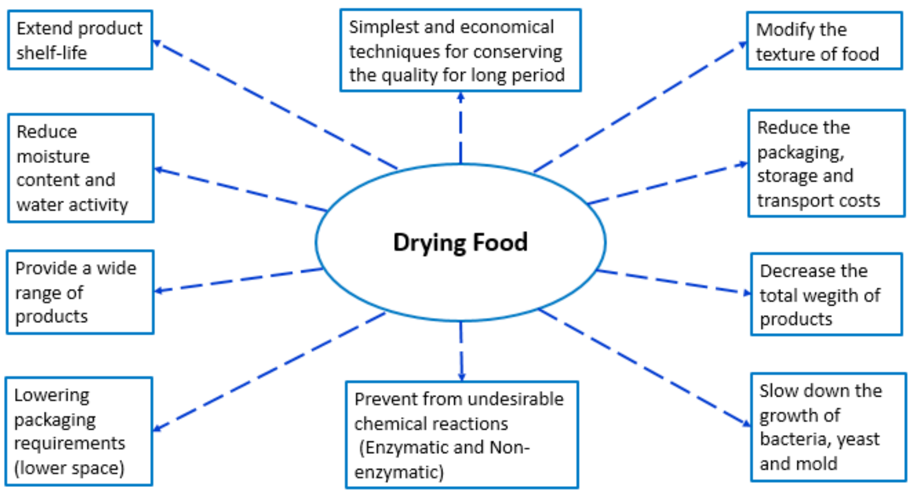

Figure 1. Application of drying technology in the food industry.

Water as the main component of foodstuff has a crucial role in the oxidation of fats and lipids and the growth of microorganisms in food with high moisture content and high-water activity. Also, the amount of water in dried products has an important effect on the texture and flavor of dried food. Exposing a foodstuff to the environment leads to the transfer of water between the food and environment due to the tendency of food to reach the most stable condition according to the equilibrium state **[3]**. Drying is the most simple and economical method and used to decrease the water activity and moisture content of the material to decrease physical and chemical changes of food **[4]**. The drying technology can be classified into conventional and non-conventional drying methods. Many conventional drying methods have lower operating costs, but they emit hot exhaust gases to the environment. Therefore, nowadays many non-conventional drying methods are taken into consideration.

Sun-drying is a conventional drying method that directly exposed food to open sunlight and wind. However, it depends on the weather condition and also has a high risk of contamination. The use of a solar dryer to change solar energy to heat to decrease the water content of food can be a good alternative for sun-drying **[5]**. Another traditional and commonly used drying technique is hot air drying (HAD) which can be done under natural or forced convection. More than 85% of industrial dryers use hot air for drying materials **[6]**. Hot air drying was used by many authors in the drying of different foodstuffs such as carrot, pumpkin, and apple at the air temperature of 50, 60, and 70°C **[7]**, mango slice at 60°C **[8]**, red carrots at 60°C, square, circle and triangle apple chips at 110, 115, and 120°C **[1]**, Lentil seed at 45, 50, 55, and 60°C **[9]**, and persimmon at 45, 50, 55, 60, and 65°C **[10]**.

Another conventional drying method is spray drying which is applied to drying liquid food. In this method, a liquid feed is injected into the atomizing units which convert it to the fine droplets, and then spray these fine droplets to the hot airflow. Consequently, the rapid evaporation of water produces dried particles and due to short drying time, it is suitable for drying the food with high heat sensitivity. Also, spray drying can use to encapsulate various bioactive compounds such as nutrients, vitamins, probiotics, antioxidants, enzymes, and aroma compounds. Many examples of utilization of spray dryer can be cited such as encapsulation of carotenoids **[11, 12, 13, 14]**, lycopene **[15]**, β-carotene **[16]**, guava extract **[17]**, curcumin **[18]**, fish oil **[19]**, *Bifidobacterium infantis* and *Lactobacillus plantarum* **[20]**, *L. rhamnosus* GG **[21]**.

Infrared (IR) drying is a non-conventional drying process that uses IR rays for drying food products. The penetration of IR rays into a depth of moist food can increase its temperature, moisture diffusion and water evaporation from samples. Many heat-sensitive materials such as fruits and vegetables successfully can dry with this method due to the short drying time **[22]**. The IR methods are used to dry some food products such as mushroom **[23]**, carrot **[24]**, rainbow trout **[25]**, orange peel **[26]** and tomato slice **[27]**.

Other non-conventional drying methods are microwave drying (MVD) and radiofrequency drying (RFD) which both use electromagnetic radiation. As electromagnetic rays penetrate to the interior of food, it converts by a various mechanism to thermal energy which rises the food temperature volumetrically and causes an increase in the diffusion of moisture and water evaporation. The MVD and RFD were used for drying of different food materials, carrot powders **[28]**, onion **[29]**, garlic puree **[30]**, nectarine slices **[31]**, kiwifruit [32], carrot cubes **[33]** and potato flour **[34]**.

Electrohydrodynamic (EHD) drying is a non-conventional method that worked based on the generation of ion flow from a discharged electrode. Drying happens under the influence of generated airflow and change of ion direction inside the food. It is used for drying carrot, apple slices, tomato slice, mango, mushroom and quince slices **[35, 36, 37, 38, 39, 40]**. This study aims to present an overview of the application of some conventional and non-conventional drying methods in the food industry (e.g., hot-air drying, spray drying, microwave drying, infrared drying, radio frequency drying and electrohydrodynamic drying) and highlight their working mechanisms, critical factors which control the drying, their advantage and their application in the food industry.

The fundamental drying techniques applied in the food science and technology can be classified into conventional and non-conventional drying methods.

Conventional Drying Technology

Hot air drying

Hot air drying (HAD) is a traditional technology widely used to preserve agricultural products and foodstuff in the food industry. In this process, the food is exposed to a continuous hot air stream to separate moisture from products. HAD is a non-toxic, harmless, and cost-effective drying process which extends the shelf life, protects the products from microbial spoilage and undesired deterioration reactions, decreases the packaging, storage and transport costs **[41]**. However, the various transport phenomena such as heat, mass and momentum transfer simultaneously are occurred in the samples which creates complexity in the theory behind HAD unit operation. Different heat transfer phenomena such as convection and conduction along with various mass transfer mechanisms like as capillary and diffusion are participating in the HAD process **[1]**. Slow drying at a low temperature produces a dense food product while, fast-drying at high temperature creates less dense foodstuff but produces a crust on the surface of food **[42]**. Also, the long drying time of HAD process generally leads to produce a product with a higher amount of shrinkage and less amount of rehydration capacity **[43]**. The hot drying of many food products has been addressed in several studies such as Lentil seed **[9]**, tomato concentrate droplets **[44]**, pear slice **[45]**, corn **[46]**, Indian gooseberry shreds **[47]**, cocoa bean **[48]**, square, circle and triangle shape apple chips **[1]**, bamboo slice **[49]**, peppermint leaves **[50]**, pin nut seeds **[51]**, carrot slice **[24]**, persimmon **[10]**, shiitake mushroom **[52]**, mango cubes **[53]** and red pepper **[54]**.

Farias et. al. **[55]** studied the kinetic drying of longitudinally sliced banana at a HAD system and they used airflow with temperature ranges of 40 to 70°C with the relative humidity from 7.30 to 29.60%. The temperature, mass, and dimensions of samples were measured, and the thermal measurement of samples was done according to the geometrical parameters of the banana (longitudinal slices). It was stated that at the beginning of the drying process volume of samples suddenly decreased due to the high rate of water loss at this stage and the linear relation was found between shrinkage and amount of moisture removed. Also, they reported that shrinkage was affected by the geometric shape of the samples due to various shrinkage rates at the different directions (radial and axial). It was stated that drying occurred at a falling rate period and increases in air temperature and decreases in relative humidity lead to an increase in both drying and shrinkage rate.

Kian-Pour & Karatas **[1]** studied the effect of the different geometrical shapes of apple chips such as square, circle, and triangle on the drying kinetics of samples dried by hot air (temperatures of 110, 115, and 120°C; velocity: 1.75 m/s). It was revealed that triangle shape samples exhibited the higher Reynolds and Nusselt numbers, lower drag force, maximum diffusion coefficient, and minimum heat and mass transfer coefficients, highest fracturability and crispness, and the lowest drying time which were related to the characteristic length and sharp edge of samples and also due to development of amorphous structure at the temperature over 100°C. Onwude et. al. **[56]** dried pumpkin with different thicknesses (3, 5 and 7 mm) by hot air (from 50 to 80°C, and air velocity of 1.16m/s). The results revealed that an increase in the sample thickness caused an increase in drying time due to the long distance between the internal and external part of the sample which is the main reason for the increase in the travel time of moisture from inside to the outside of samples. It was stated that due to the same reasons, the heat and mass transfer were higher at the samples with 3 mm thickness and the activation energy was lower. Also, the authors reported that simultaneously increase in drying temperature and decrease in pumpkin thickness lead to a decrease in drying time more than 30%.

Senadeera et. al. **[10]** investigated the effect of air temperature (from 45 to 65°C) on the kinetics of drying, color, and shrinkage of persimmon. The results revealed that the L* value (lightness) of the dried sample was close to the brightness of fresh persimmon. The results of the Huge angle and total color difference demonstrated that drying at 65°C could protect the natural color of fresh samples and lead to decreases browning reaction during the HAD method due to lower drying time. Papoutsis et. al. **[57]** compare the effect of different drying methods (HAD, vacuum, and freeze-drying) (70, 90, and 110°C) on some bioactive compounds of lemon peel. It was stated that the maximum total phenolic content belonged to the samples dried with hot air drying at 110°C while, it was minimum at the products dried by freeze dryer. The phenolic materials are bound in the food structure and high temperature can change the cell structure and release this bioactive material from the food matrix. Also, it was reported that the antioxidant capacity of lemon peel dried with a hot air dryer or vacuum dryer was higher than samples dried with a freeze dryer.

Spray drying

Spray-drying is a unique one-step continuous drying operation that converts the fluid food to solid or semi-solid materials by atomization of liquid as individual droplets into the stream of hot drying air **[58, 59]**. The liquid (emulsion, dispersion, solution) is injected by a pump to the atomizer section which converted the feed solution into a spray of relatively small droplets. Generally, three type atomizer is commercially available such as 1) centrifugal disc atomizer which is suitable for high-capacity drying because of its flexibility and low maintenance, 2) pneumatic nozzles (two-fluid nozzles) which used compressed air to atomize the liquid food and are suitable for small size drying operation due to its less efficiency and the high cost of compressed air, and 3) pressure nozzles which the liquid food enter the nozzle core and left the nozzle with different angle under pressure (range of 5–7 MPa).

The droplets immediately contact with the hot gas flow (generally air) and due to the large surface area of small droplets, evaporation takes place rapidly therefore, the droplets' temperature remains low so the high drying temperatures can be used without negatively or significant effect on the product quality. The short drying time of the spray dryer makes it suitable for drying heat-sensitive materials. The dried products are collected at the bottom of the chamber and they are separated from the airflow via a cyclone by the centrifugal force, after that the air is expelled outside of the cyclone by passing among a filter. Convectional spray dryers provide powder of different sizes from **[6, 58, 59]**. However, the agglomeration can be used to modify some properties of food powder such as decreasing caking and lump formation, improve product porosity and solubility, modify fluidity, change product density and improve the homogeneity of products **[60]**. A schematic of the spray dryer is shown in Figure 2. The factors which affected the spray drying process and physicochemical properties of the product mainly are inlet and outlet air temperatures, feed and air rates, initial solid content of the feed, and residence time during the drying chamber **[58]**.

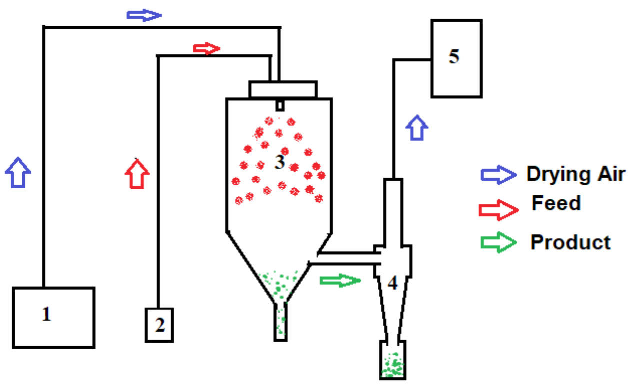

Figure 2. A schematic of spray dryer for drying of foodstuff. 1) Air compressor, 2) Feed, 3) Drying Chamber, 4) Cyclone, 5) Filter

Spray dryer can be used for encapsulation of active compounds in food such as essential oils, vitamins, probiotics, antioxidants, enzymes, color materials, and additives. The encapsulations are used for 1) protect sensitive food compounds against pH, temperature, oxidation, hydrolysis, etc., 2) maintain the nutrition, 3) permit adding nutrient, flavor, color pigment, taste-enhancer materials after processing, 4) prolonged-release of bioactive ingredients into the formulation, 5) preserving volatile materials, 6) masking unwanted flavors and aromas, 7) improve the antibacterial efficiency of compounds **[61]**. The encapsulation is used to entrap the target material (core) into a thin film (wall or carrier). The encapsulating agents (wall material) have an important effect on the storage stability, encapsulation efficiency, protection of core materials, controlled release, etc. Different type of wall materials such as carbohydrates (cellulose, carrageenan, maltodextrin, dextran, sodium alginate, starch, gum Arabic, alginate, guar gum, pectin), proteins (zeini gluten, whey protein, albumin, etc.), and lipids/waxes (phospholipids, beeswax, etc.) are used in encapsulation of bioactive compounds **[62]**. However, to obtain an encapsulated product with desired properties, both process conditions and the encapsulating materials (such as surface tension, viscosity, air, and feed temperature, atomizer conditions) need to be optimized **[61]**.

The encapsulation of different carotenoids compounds using carbohydrates as wall materials was reported such as encapsulation of total carotenoids by 15% -30% w/v maltodextrin **[14]**, lycopene by (10% and 20% w/v)) maltodextrin **[15]**, β-carotene by starch **[16]**. Also, various protein compounds used for encapsulation of carotenoids such as gelatin **[11]**, soy protein isolate **[12]**, whey protein **[13]**. Álvarez-Henao et. al. **[63]** used spray drying process to improve the stability of lutein and protect its functionality as an antioxidant. Maltodextrin, gum arabic, and modified starch were used at the different concentration as the core materials and mixture of core and wall materials was spray-dried (air: 50m^3/h, inlet temperature 185°C; feed:4 mL/min). The results of the study of Maroof et al. **[61]** shown that the yield of encapsulation ranged from 9.90 to 32.7%, the encapsulation efficiency was varied between 2.38% and 91.94%, the particle-sized changed from 1.64 to 14.20 μm. They reported that the mixture of Arabic gum: maltodextrin: modified starch with a ratio of 33.3:33.3:33.3%, exhibit the formulation to protect the lutein and increased its stability during the 2-day storage.

Osorio et. al. **[17]** used spray dryer for encapsulation of the guava extract and used maltodextrin and Arabic gum as the wall materials. The retention of volatile compounds due to encapsulation was reported. It was stated that Arabic gum modified fluidity during dehydration, but it caused a decrease in the thermal stability of the dried powder. Liu et. al. **[18]** used spray dryer to improve the solubility and bioavailability of curcumin. The inlet temperature of the drying medium was adjusted at 110 and 150°C and the whey protein isolate solution (5wt %) was used as a wall material for encapsulation of curcumin (59.5 mg/mL). The results revealed that encapsulation increased both the solubility and antioxidant properties of curcumin. Jansen-Alves et. al. **[64]** investigated the encapsulation of propolis extract with a spray dryer by using rice, pea, soybean, and ovalbumin proteins as the encapsulation agents. Encapsulation efficiency was between 70.2 and 90.20 % and the highest antioxidant activity belonged to the rice protein. Also, dried powder exhibited various shapes and sizes and they showed different physical attributes such as enthalpy, the glass transition temperatures, solubility %, water absorption %, and hygroscopicity %. Aquilani et. al. **[19]** used spray dryer for encapsulation of fish oil and added it to the Cinta Senese pork burgers. The comparison between burgers with added encapsulated fish oil (M) and burgers with add normal fish oil (N) demonstrated that after storage and cooking of burgers, the fatty acids of EPA and DHA were better protected in M burgers than in N burgers. It was stated that microencapsulation of fish oil was an efficient way to protect EPA and DHA from oxidation. Furthermore, sensory evaluation of products indicated that the chilled storage can be used for M products while frozen storage needs to use for N products. Pino et al**. [65]** used maltodextrin (5- 15% w/w) mixed with gum Arabic (10% w/w) to the encapsulation of cold-pressed winter squash seed oil by spray dryer (140-180°C). It was stated that encapsulated seed oil had higher antioxidant activity than raw oil due to the barrier properties of wall material against oxidation of the oil.

Also, the spray dryer has a vast application in the production of dried bacteria, as it can produce a huge amount of product with a lower energy cost compared with the freeze dryer. Bustamante et al. **[20]** used spray dryer for encapsulation of two probiotic bacteria: *Bifidobacterium infantis* and *Lactobacillus plantarum*.

The mucilage (M) and soluble protein (SP) extracted from chia seed and flaxseed were used as wall materials. It was stated that the use of ternary blends consists of maltodextrin, M, and SP as the wall material produced encapsulated *B. infantis* and *L. plantarum* with a high level of probiotics survival (more than 98%) during spray drying and viability during storage at 4°C. Also, encapsulation improved the resistance of *B. infantis* and *L. plantarum* to simulated gastric juice and bile solution. Furthermore, when the encapsulated probiotic powder was combined with the instant juice powder, after the long-term storage (45 days) at 4°C the high amount of probiotic viability (>9Log_{10}CFU/g) was observed. The different percent of survival (%) for various probiotics was reported by many authors. For instant 50% for *L. rhamnosus* GG encapsulated in micellar casein and whey protein solutions **[21]**, 69% for *L. plantarum* A17 encapsulated in whey protein isolate pH:7 and 39.3% at pH:4 **[66]**, 60% for *Lactobacillus casei* BL23 encapsulated in sweet whey fermented growth medium with inlet drying temperature of 140°C. Also, the survival (%) increased to 100% when the *L. casei* BL23 dried at 127°C however, *Propionibacterium freudenreichii* ITG P20 showed 100% survival at both 140 and 127°C **[67]**.

The major problems with conventional drying technology are long drying times and nutrition loss along with poor sensorial attributes of dried food (for hot air drying and sun drying), high energy consumption and operating cost (for vacuum and freeze-drying), unique demands for the form of dried food (for heat pump assisted drying methods and spray dryer), unsufficient reduction in the water content of food (for osmotic drying) **[68]**. To overcome these problems, non-conventional drying technologies can be used.

Non-Conventional Drying Technology

Infrared drying

In infrared (IR) dehydration the IR rays generated from the heating power can penetrate to a depth of a wet foodstuff and increase its temperature. Therefore, the increases in the diffusion rate of moisture in the sample lead to the evaporation of water. The advantages of IR drying compared to conventional drying includes superior energy efficiency, high heat transfer rate, and uniform heating of product **[2, 69].** The short drying time in this method makes it suitable for heat-sensitive materials such as fruits and vegetables **[2, 22, 69, 70].**

Infrared radiation (IR) is an electromagnetic wavelength in the range of 0.78 μm (visible light) and 1000 μm (microwave). IR radiation can be classified into three sub-groups. Near-infrared (NIR) with the wavelength between to , mid-infrared (MID) which appear in the wavelength of 1.40 μm to 3 μm and far-infrared (FIR) radiation in the wavelength of *3* μm to 1000 μm. The penetration depth (PD) demonstrates the length at which the intensity of IR inside the food is nearly 37% of IR value at the food surface **[69]**. The penetration depth of IR radiation is dependent on the composition and properties of food such as density, moisture content, and porosity, as well as properties of irradiated medium **[22]**. The NIR (short wavelength) seems to be better in the drying of food with higher thickness, in contrast, FIR (longer wavelength) showed better results in drying of foodstuff with a lower thickness **[69]**. Generally, the collision of electromagnetic radiation with food causes alters in the electronic, rotational and vibrational situation of atoms and molecules **[71]**. As the food molecules expose to the IR radiation they start to vibrate with the frequency of 60,000–150,000MHz. Therefore, the creation of intermolecular friction due to this vibration leads to the rapid increase of internal temperature and heats the food which increases the water vapor pressure inside the food **[72]**.

When a food product is exposed to IR radiation, three situations may happen such as the reflected, absorbed, and transmitted radiation. Absorption wavelength (μm) of chemical groups such as Hydroxyl group (OH) in water and sugars, carbonyl group in lipids and proteins are different from each other **[69]**. The absorption spectrum of IR wavelength for different compositions in food is 3, 4.7, 6, and 15.3 μm, for water, 3–4 μm and 6–9 μm for proteins **[73]**, and 3 μm and 7–10 μm for sugar, 3–4 μm, 6 μm, and 9–10 μm for lipids **[22]**. Pawar & Pratape **[74]** reported the usage of different infrared wavelength in the drying of various food product such as NIR drying for apple, tomato, parboiled rice, pomegranate arils, hazelnut, and carrot; MIR drying for meat, vegetables, seedless grapes, shredded squid; FIR drying for Barley, citrus press cake, tiger prawns, onion, potato, barely, cashew, brown rice. The main parameters which need to consider during IR drying are IR intensity and IR time, the distance among food surface with IR producing element, and finally the thickness of foodstuff. Therefore, with the correct selection of these variables, it is possible to control the drying time, energy consumption, and quality attributes of dried food. It was stated that an increase in drying rate and moisture diffusion and decrease in drying time can achieve by an increase in IR temperature and IR intensity. In contrast, an increase in the distance between the IR radiation source and the surface of the foodstuff causes an increase in drying time. Furthermore, food materials with higher thickness exhibit higher drying time compare with thin material **[23, 26, 27, 75]**. Doymaz **[24]** studied on the drying of carrots at different IR power (62, 74, 88, 104, 125W) and they observed that at all IR intensity, increase the temperature from 20 to 50°C, improved the rehydration ability of dried carrot due to change in the cell wall. Also, an increase of IR decreased the *L**value of products and produced carrots with a darker color. Ismail & Kocabay **[25]** compared the infrared drying (at power levels of 83, 104, and 125 W) and microwave drying (at power levels of 90, 180, 270 and 360 W) of Rainbow trout (*Oncorhynchus mykiss*) fillets. They demonstrated that drying caused an increase in the "*L*" and "*b*" values and at the same time it decreased the "*a*" value of sample. Furthermore, increased in the IR power, decreased the "*L*" value and changed in the color parameters in IR drying was more than microwave drying. Also, microwave drying exhibited higher activation energy compare with IR drying.

Bejar et al. **[26]** studied the impact of IR drying at different temperatures (40, 50, 60 and 70 °C) on the total phenols, water (WHC), and oil holding capacity (OHC) of orange peel. They reported that infrared drying significantly increased the WHC while decreased OHC. IR drying at higher temperatures reduced the WHC, but it has not influenced the OHC of samples. Besides, total phenolic compounds were found to be higher in the samples dried at higher IR temperatures (60 and 70 °C). Wang et al. **[23]** compared IR drying and hot air drying of mushroom chewing tablets. Both experiments were conducted at 60, 70 and 80 °C. They reported that IR dying improved the drying rate and decreased the drying time of samples compare with hot air drying. Also, the texture properties of samples showed that samples dried with IR had lower hardness and chewiness values which may be related to the faster evaporation of water compare with hot air dryers. As IR can easily penetrate the inside parts of the materials, make the facility in the transfer of heat, therefore, IR drying is much more rapid than hot air drying and the rapid evaporation of moisture from interior tissue of mushroom chewing tablets has a puffing effect and produce softer structure compare with hot air drying. Also, sensory evaluation demonstrated that the overall acceptance of samples dried with the IR method was higher than those dried by hot air techniques and the highest acceptance score belonged to the samples dried with IR at 70°C.

Abano et al. **[27]** used three different levels of distance between IR source and tomato slices (38 to 50 cm), and various thicknesses of the sample (7 to 11 mm) in catalytic infrared drying of fresh tomato slices. The results revealed that when the distance decreased, drying time and ascorbic acid content of tomato slice were significantly decreased, while lycopene content of dried tomato slice and the color parameters such as the ratio of redness to yellowness increased. Furthermore, samples with higher levels of thickness had a longer drying time and a higher amount of lycopene but a lower amount of ascorbic acid. Also, the non-enzymatic browning index, a^*, b^* *and* L^* values of dried tomato decreased with increasing the thickness of samples. Li et al. **[75]** reported that moisture diffusivity of mid-infrared dried beef jerky was 158.1% higher than that of hot air-dried samples. Also, the time and energy consumption of IR drying was lower than hot air drying. The authors demonstrated that mid-infrared drying can boost protein denaturation in myofibril structures of beef jerky, lead to more immobile water inside the myofibrillar matrix migrated to the outside of it which increased the levels of free water inside the samples and subsequently accelerating the diffusion of free water to the surface.

Microwave drying

Microwave is electromagnetic radiation that can spread through space by both electric and magnetic fields **[76]**. Microwave drying is another drying method that has many advantages compared to hot air drying such as:1) decrease hardening of the food product by volumetric heating from the center to the surface of the sample, 2) significantly decrease drying time via increase heat and mass transfer, 3) increasing drying rate and moisture diffusion 4) make a facility to separate bound water molecule which removing of them are difficult in the hot air drying **[76]**. Microwave heating is done by change of energy from electromagnetic radiation type to thermal type. It penetrates the food and increases the temperature of the material volumetrically which leads to an increasing in the rate of diffusion and pressure gradients inside the food materials. Heating at microwave methods takes place by two methods: dipolar reorientation and ionic conduction.

Dipolar reorientation

In the dipolar reorientation mechanism, the water molecule of foods due to their dipolar nature, try to align themselves with the electric fields, therefore, rotated in direction of electric fields **[77]**. But as the number of change in direction of electric fields is very huge (2.45 billion times a second), the rapid rotation of water molecules creates friction and generate heat in the food samples which exposed to this electric field and produce volumetric heating. The efficiency of microwave heating on food with high water content (such as fruit and vegetables with near 80% of dipolar water molecules) is higher compare with foods contain a high amount of fats and sugar (with lower molecular dipole rotation) **[76]**.

Ionic conduction

Ionic conduction which in this mechanism electric fields produced inside of foods by microwave rays cause migration in the ions presented in food (for example ions in salty foods) and the movement of these ions generate heat in food products **[76]**.

The effect of microwave drying on the different properties of various food products has been investigated such as drying kinetics, color and structure of Trabzon persimmon **[78]**, aroma and phenolic compound of carrot powders **[28]**, bioactive compound and antioxidant activity of green peas **[79]**, kinetic drying of onion **[29]**, water activity, color, optic index and volatile oil of garlic puree **[30]**, drying kinetics and texture of nectarine slices **[31]**. However, to increase the performance of drying, microwave drying uses simultaneously with other drying methods mainly hot-air dryers for fast drying of foodstuff **[43]**.

The effect of microwave vacuum drying (MVD), pulse-spouted vacuum microwave drying (PSMVD), pulse-spouted microwave drying (PSMD), and microwave freeze-drying (MFD) on the drying kinetics, color, apparent density, texture, and microstructure of green soybean have been investigated **[80]**. According to the results, green soybean dried with MFD methods showed good bright color and preserved the original shape of samples. However, in terms of the quality of dried soybean, PSMVD/PSMD exhibited a better effect than MVD. Çelen **[78]** studied the effect of microwave drying (120, 350, 460, and 600 W and 2450 MHz) on the drying kinetics, color, and microstructure of Trabzon persimmon (5, 7, and 9 mm). The results reveal that as the microwave power increased, drying time and energy consumption decreased, while the diffusion coefficient and drying rate increased. However, drying at higher microwave power, create higher temperature with non-uniform distribution of microwave energy inside the sample which leads to burns in some regions. Furthermore, long drying duration also can create burned region at the lower microwave power. The authors recommended that supported microwave drying with conventional drying can produce a dried sample with better color. In terms of microstructure, it was stated that increasing in microwave power level leads to an increase in the pores number and pore growths **[78].** Keser et al. **[28]** investigated the effect of different microwave power levels of 150 W to 450 Won the aroma and phenolic compound of powdered carrot. It was stated that an increase in the level of furan, alcohol, aldehyde, acids, and pyrazine in dried carrot powders were related to the microwave power. Also, the amount of some terpenes such as elemicin and myristicin were higher at the samples dried at lower microwave power (150W). Furthermore, the phenolic and antioxidant capacity of samples dried at microwave with lower power (150 W) were preserved better in comparison with other samples. Besides, their results revealed that dried powdered carrots with higher L^* values had lighter color than fresh carrots and as microwave powered increased, products became darker which may be related to the generation of higher temperature at a higher level of microwave power. The similar results relation between microwave power levels with the color of products were reported by different authors **[81, 82]**. Therefore, the authors recommended using low microwave power in the drying of carrots.

Radio frequency drying

The principle of drying by radio frequency (RFD) wave is the same as microwave drying (MVD). Both of them are known as dielectric heating due to their electromagnetic energy which can penetrate to food interior, convert to thermal energy, and rise the center temperature of food **[3]**. However, the main parameter which separates RFD from MVD is the frequency range. The electromagnetic waves in the range of 10 to 300 MHz are used for drying food products. When a food material with dielectric property (involves polarized molecules, positive and negative charged ions) is exposed to an electrical field, each positive and negative ion inside food moves toward oppositely charged regions known as "ionic migration." Besides, the movement of dipolar molecules is named "dipole rotation." Therefore, both ionic migration and dipole rotation mechanisms create friction between molecules, which generate heat inside the sample. The main factor that has an impact in the RFD of foodstuff are dielectric and thermal attributes of food and also distributions of electromagnetic field **[68]**. However, non-uniform heating of the material in RFD leads to overheating in corners, and edges of food **[83]**.

Wang et al. **[84]** used radio frequency drying (electrode gap:14, 15 and 16 cm) combined with hot air drying (temperatures 30, 40, and 50°C) to drying in-shell hazelnuts. They demonstrated that at the electrode gap of 14 cm and temperature of 40°C hot-air assisted radiofrequency (HARF) decreased drying time to 22 minutes compared with hot air drying (420 min). Also, the drying rate and mass transfer coefficient were higher compare with hot air drying, while energy consumption was lower. Furthermore, the total phenolic content of in-shell hazelnuts dried with HARF was higher than hot air dries samples while their peroxide value and polyphenol oxidase activity were lower than hot air-dried products. RFD is used by different authors for various foodstuff such as carrot cubes **[33]**, chicken powder **[85]**, kiwifruit **[32]**, potato flour **[34]**, apple slices **[86]**.

Electrohydrodynamic (EHD) drying

In the EHD drying, a discharge electrode (such as a sharp needle or thin wire) is exposed to high voltage, therefore an ion flow generates and collisions between charged ions with non-charged molecules produced an ionic or corona wind. The movement of corona wind to the collecting electrode speeds up under the influence of electric fields and the speed of wind can be reached to 200 m/s. Also, the collision of ionic wind with air molecules creates an airflow from 0.1 to 10 m/s. The contact of ionic wind with the material disturbs the saturated layer of air on the food surface and enhance the evaporation phenomena. Besides, water molecule inside the food change their direction according to the electric field and cause a reduction in the entropy which leads to decreasing the temperature of the food being dried. Therefore, heat-sensitive foods can be successfully dry by this method **[87, 88]**. A schematic of EHD drying was shown in Figure 3.

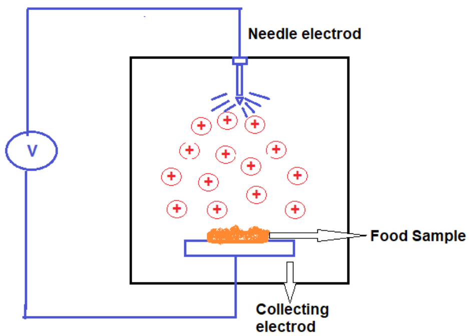

Figure 3. A schematic of electrohydrodynamic drying of food **[36, 87]**.

Martynenko & Zheng **[36]** studied the electrohydrodynamic drying of apple slices. Voltage adjusted between 0 and 15 kV and distance between needle and plate electrode fixed at 22 mm. It is stated that EHD drying had not a significant effect on apple browning at 5 and 10 kV and they showed that as air velocity increased, quality degradation decreased. Ding et al. **[35]** exposed carrot slice with 5 mm thickness on EDH drying with the voltage of 10 -30 kV and electrode gap of 100 mm. The results revealed that carrots dried by EHD had higher carotene content than sample dried with oven dryer and the EDH drying cause improvement in rehydration ratio. Different authors used EHD for drying of food products such as tomato slice **[37]**, mango **[38]**, mushroom slices **[39]** and quince slices **[40]**.

Multi-stage combined drying

Nowadays, many combinations of drying techniques are used to overcome the deficiency of a single drying process which involved parallel and tandem drying. In parallel drying methods products are dried simultaneously by two or more drying techniques while, tandem drying refers to the use of one drying technique followed by one or more other dehydration processes **[3]**. Some combined parallel drying systems were shown in Table 1.

Table 1. Multi-stage combined drying system in the food industry

Technique	Results	References
RFD + HAD	This method produced uniform dehydration and products with higher quality compare with HAD	**[89]**
RFD + HP	It reduced the color loss of dried food samples. The produced cracking (due to shrinkage) can be eliminated	**[89]**
MVD + SBD	More uniform drying compares with MVD due to the fluidization of particles which make the facility in the heat and mass transfer	**[90]**

MVD + PSBD	The main disadvantage of MVD is non-uniform drying, however, combined a pulse spouted bed drying to MVD can produce more uniform and faster drying compare with MVD	**[91]**
MVD + PSBFD	The combination of MVD with pulsed-fluidized bed freeze dryer enhanced the uniformity of drying by pulse agitation. This method can protect stem lettuce slices from colour loss, it can increase rehydration capacity and produce a higher level of hardness after rehydration	**[92]**
HP + FIR	A combination of heat pump drying with far-infrared drying can decrease the drying time and can improve some quality parameter such as nutritional level, sensorial properties, and functional attributes of food products	**[93]**
FIR + LPSSD	According to the use of low drying temperature at low pressure, the combination of far infrared drying with low-pressure superheated steam drying can be suitable for heat-sensitive foodstuff	**[94]**
IR + FD	Decrease drying time and it can produce crispy texture in food	**[95]**
EHD + VFD	By a combination of EHD drying and vacuum freeze-drying, the advantage of low energy consumption of EHD dryer and production a high-quality dried food by vacuum freeze dryer can merges	**[96]**
EHD +SD	In this method, a low-voltage nozzle is used which give a moderate charge to droplets and the charged particles are collected by an EHD field	**[97]**

CONCLUSION

This review investigated various conventional and non-conventional drying methods for drying of food materials. These technologies could be used to decrease moisture content and water activity of food products to protect them from chemical, and microbiological deterioration. Among the conventional drying technology, hot air drying, and spray drying were reviewed according to their vast application in the food industry. However, the main concern about conventional drying is low energy efficiency and the emission of hot exhaust gases to the environment. Therefore, non-conventional drying methods were reviewed, and their mechanisms, advantage, and applications were studied. Among the non-conventional drying techniques microwave drying, infrared drying, radio frequency drying, and electro hydrodynamic drying were investigated. These data could be useful for food industries to make enlightened decisions on the selection of proper drying methods for food products.

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