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Drying of mushrooms by alternative technologies

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Abstract: This review addresses alternative technologies in edible mushroom drying. Principles of application and the literature are highlighted. The objective is to identify and discuss the potential advantages and drawbacks and to elaborate future applications of electrohydrodynamic, freeze, infrared, and microwave technologies in mushroom drying. The advantages of these alternative technologies can be listed as better quality, improved energy efficiency, and reduced processing time. Each method is promising in adding value to dried mushroom products. On the other hand, replacement of the conventional drying technique requires process optimization practices and feasibility analysis, especially for combined applications.

Key words: Edible mushrooms, electrohydrodynamic drying, microwave drying, freeze drying, infrared drying

1. Introduction

Edible mushrooms are nonpoisonous species of macrofungi that account for less than 1% of discovered species of mushrooms. Along with their organoleptic properties, mushrooms have some unique nutraceutical and functional properties; hence, they have gained economic and nutritional significance over time (Valverde et al., 2015). Worldwide production of mushrooms is steadily increasing in direct relationship with empirical data highlighting their medical and nutritional benefits (Chang, 2006). Their production, processing, retailing, and storage have created a huge industry with accelerating growth. In addition to their economic significance, mushrooms are rich in proteins, carbohydrates, dietary fiber, unsaturated fatty acids, vitamins, and minerals; hence, they are considered to be an ideal source of healthy nutrients in the modern diet (Sinha et al., 2021). For example, fresh button mushrooms (*Agaricus bisporus*) contain 90% to 95% moisture, 1.8% to 2.1% protein, 1.5% to 3.3% fiber, 0.41% to 0.78% ash, 4.5% to 5.8% carbohydrates, and 0.31% to 0.35% fat on a wet basis (Das and Arora, 2018). According to reference patterns of the Food and Agriculture Organization (FAO) on the amino acids present in foods, edible mushroom amino acid scores are equal to or higher than those of eggs, cow milk, soy protein, and beef (Xue et al., 2017). Mushrooms also contain essential or functional compounds such as glycoproteins, chitinous substances, sterols, terpenes, enzymes, enzyme inhibitors, phenolic compounds, natural antibiotics, and fundamental amino acids with significant health benefits and potential medical utilization (Rezaeian and Pourianfar, 2016; Bach et al., 2017). This makes them a prominent focus for nutrition. In addition to their nutritional quality, mushrooms are generally considered to be a food delicacy since they contain many desirable aroma, odor, and color compounds and have appealing taste and texture in both raw and processed forms (Luo et al., 2021).

Freshly harvested mushrooms are highly susceptible to enzymatic browning, microbial deterioration, and physiological and morphological changes due to high moisture content, high enzyme activity, high respiration rate, and the presence of microorganisms (Xue et al., 2017; Mutukwa et al., 2019). To prevent postharvest changes, mushrooms are washed to remove the attached soil, and they are generally blanched to inactivate the enzymes. Immediate chilling is then required to prevent further deterioration (Kratika, 2018). After postharvest treatments, mushrooms are either packed for fresh consumption or further processed. Since fresh mushrooms are high in moisture and nutrients, they have a maximum shelf life of 10 days under refrigerated conditions and 3 days under ambient conditions. Many effective methods have been developed, reaching back from the past few centuries to more recent decades, involving drying, freezing, canning, salting, modified atmosphere packaging, and pickling to increase the shelf life of mushrooms. All of these processes aim to prevent biochemical and structural changes and increase the shelf life up to months or years while maintaining food safety and quality and preserving the nutritional and functional properties

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of the mushrooms at a feasible cost (Xue et al., 2017). In that regard, each processing technique has its advantages and drawbacks due to issues of food safety, product quality, and operational cost.

Among the preservation methods listed above, drying is the most common practice on a global scale due to its broad theoretical, practical, and traditional background as well as low cost and simplicity (Xue et al., 2017). In addition to direct consumption, dried mushrooms are utilized in various food formulations, such as meat seasonings, snacks, instant soups, stuffings, pasta and pasta sauces, ready-to-eat pizza, salads, and microwave dishes (Dehkordi, 2010). This indicates that once the shelf life is extended while successfully maintaining the quality, safety, and nutritive properties of the mushrooms with a cost-effective process, successful commercialization of the product is achievable.

There are various ways to dry foods. However, even though the application of the drying process varies, all drying methods have the same basic principle of dehydrating the material by simultaneous heat and mass transfer (Dinani et al., 2014a). As water is removed from the system, microbial activity and biochemical reactions will be hindered, and in that case, handling would be expected to be facilitated, long-term storage will be energy and cost-effective, and the product will be value-added. Conventional drying processes involve solar drying, hot air drying, vacuum drying, and spray drying. Conventional drying methods entail passing hot air through the food material to evaporate the moisture. Water tends to move from food materials containing higher moisture to the surrounding air with lower equilibrium relative humidity. Process conditions such as air temperature, velocity, humidity, application time, and food material geometry have critical importance for the quality of the product and the effectiveness of the process (Xue et al., 2017). Even though the listed conventional techniques have a robust practical background and provide valuable outcomes, many researchers have made strong claims that the limitations of these processes lead to quality and nutritional losses in the final product. Application of heat for long durations utilized in conventional techniques causes deficiencies in flavor, color, and volatile concentration and results in the loss of nutrients. It is also indicated that high temperatures trigger structural metamorphosis, especially in the presence of pores. Accordingly, to increase the shelf life without compromising the product quality, structure, nutrition, vitamins and minerals, bioactive content, and other functional properties, the development of novel and energy-efficient drying technologies has emerged as an essential need in the edible mushroom industry (Puig et al., 2012; Das and Arora, 2018). All of these novel technologies keep the basic mechanism of moisture removal and aim to improve product quality and process efficiency. In that regard, recent alternative technologies can be listed as microwave (MW) applications applied alone and in combination with vacuum or hot air applications or infrared technology (IR), freeze drying (FD) applications applied alone or in combination with IR or ultrasound applications, IR technology in combination with conventional techniques, and electrohydrodynamic (ED) applications with hot air drying (Giri et al., 2014; Kantrong et al., 2014; Dinani et al., 2015a, 2015b; Vallespir et al., 2019). In the case of mushroom processing, alternative technologies are promising for providing shorter processing times, reductions in energy consumption, and improved nutritional and textural properties.

This review considers these novel technologies as alternatives in edible mushroom drying by first accounting for the principles and the basis of applications related to each technique and then investigates the present studies in the literature by highlighting the critical points and outcomes to deeply elaborate on these techniques. Accordingly, the objective is to present an overall summary of alternative technologies in edible mushroom drying and discuss the potential advantages and disadvantages and future applications of MW, ED, FD, and IR technologies in edible mushroom drying processes.

2. Electrohydrodynamic (ED) drying

2.1. Principles

ED drying is a method that applies high voltage to an electrode of a very small radius of curvature to create corona wind (Singh et al., 2015). It is a nonthermal processing technique applied using either alternating current (AC) or direct current (DC) high voltages. AC is a type of electrical current in which the direction of the flow of electrons switches back and forth at regular intervals or cycles. DC is an electric current that is unidirectional, so the flow of charge is always in the same direction.

Under the influence of a high-voltage electric field, ionized forms of air constituents are generated. These charged ions collide with noncharged molecules and transfer their momentum, which creates ionic wind. The degradation of the saturated air layer by the produced corona wind causes an increase in the rate of evaporation. During this process, the required drying temperature drops because the water molecules in the material orient themselves in the direction of the electric field, causing the entropy to decrease. The thermodynamic reasons behind the decrease in entropy are the rapid rate of evaporation and exothermic interactions between the electric fields and dielectric materials (Bajgai et al., 2006; Singh et al., 2012). ED applications are performed in the range between the inception voltage, i.e., the minimum voltage required for ionization, and the breakdown voltage, i.e., the maximum voltage causing arc discharge. Reactive species referred to as low-density cold plasma are created as a result of the intense ionization of air. Ionization can be induced by single or multiple needles or wire electrodes with direct or alternating currents. The simultaneous effect of cold plasma, high electric field, and ionic wind on the food samples gives ED drying its distinctive characteristics, although they do not cause a significant loss in moisture when applied alone (Paul and Martynenko, 2021).

The reduction of energy usage and preferences for food products of superior quality are gaining popularity among consumers. Compared to hot air drying systems, ED systems decrease food production costs because they consume less energy with a simpler design. In addition, ED drying provides products of superior quality in terms of physiochemical properties such as color, shrinkage, flavor, and nutrient contents. Since it is a nonthermal process, it is also suitable for drying heat-sensitive materials (Martynenko et al., 2021). Moreover, there are ongoing studies focusing on the commercialization of ED processes; for instance, a prototype has been designed and constructed to demonstrate that this technology can be potentially scaled up for industrial applications (Lai, 2010). Figure 1 presents a schematic diagram of ED drying, in which basic elements of ED drying such as the voltage supply, transformer, pointed needle electrodes, and ground electrode are shown.

ED drying systems consist of a vertically moveable electrode with a needle that helps to adjust the gap between the high-voltage electrodes and grounded electrode, a fixed horizontal grounded plate upon which a sample can be placed, a voltage regulator, and a transformer. The sharp point electrode is connected to the transformer. The transformer is connected to the voltage regulator to adjust the high-voltage parameters (Elmizadeh et al., 2017). The drying rate is affected by voltage level, the gap between the electrodes, and the sharpness of the corona-generating needles. Until sparkover occurs, if the voltage increases, the drying rate will increase. It is also important to find the optimum electrode gap and needle sharpness (Bajgai et al., 2006).

2.2. Studies

There are several studies in the literature related to the ED drying of mushrooms. In the earlier studies of Dinani et al. (2014a), mushroom drying was mathematically modeled. More specifically, drying kinetics, time to reach constant weight, effective moisture diffusion coefficient, and the energy consumption of ED, pure hot air, and hot air-combined ED drying systems were investigated for different voltages (17, 19, and 21 kV) and electrode gap values (5, 6, and 7 cm). As the electrode gap decreased and the voltage increased, the time required to reach the final moisture content in the mushroom slices decreased and so energy consumption decreased. Furthermore, increasing the voltage increased the effective moisture diffusion coefficient in drying mushroom slices. As a result, drying kinetics, time, effective moisture diffusion coefficient, and energy consumption were significantly affected by the applied voltage and electrode gap. In addition, the combination of ED with hot air significantly reduced the drying time with increasingly effective water diffusion coefficients and drying rates and less energy consumption. Compared to the hot air-dried samples without electric field treatment, the effective moisture diffusion coefficient of the hot air-combined ED-dried samples were more than doubled ($5.34 \pm 1.09 \times 10^{-10}$ m^2/s for control samples and $12.24 \pm 3.99 \times 10^{-10}$ m^2/s for ED-dried samples with 5-cm electrode gap and 21-kV applied voltage treatments) (Dinani et al., 2014b). The time necessary for achieving constant weight for mushroom slices ranged from 229.2 ± 17.7 min

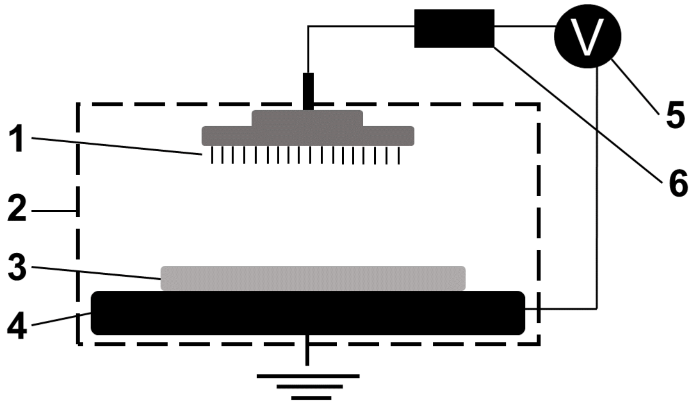

Figure 1. Schematic diagram of ED drying. 1- Needle electrodes, 2- chamber, 3- product, 4- ground electrode, 5- voltage supply, 6- transformer.

with the 5-cm electrode gap and 21-kV treatment to 360.0 ± 9.8 min for the control.

In the later studies of Dinani et al. (2015a), the effects of varying parameters of hot air-combined ED drying on mushroom quality were elaborated. Solid and bulk densities, porosity, shear strength, water absorption capacity, and total color difference of button mushroom (*Agaricus bisporus*) slices were investigated by comparing them with the oven drying technique. The independent variables of this study were voltage (17, 19, and 21 kV) and electrode gap (5, 6, and 7 cm). Compared to oven-dried samples, there was no significant difference in terms of total color difference. Increases in porosity and water absorption capacity and decreases in apparent density and shear strength were observed in hot air-combined ED drying. Shear strength and the hardness of the dried mushrooms decreased due to the highly porous structure of the hot air-combined ED-dried mushrooms. Furthermore, increases in porosity caused the internal stress to increase, leading to a reduced drying time and higher drying rate. As a consequence, higher rehydration capacity was obtained. According to their results, increasing the voltage level or decreasing the electrode gap decreased the apparent density and thus increased porosity. They also increased water absorption capacity and decreased shear strength. Differential scanning calorimetry studies showed that the enthalpy of protein denaturation of ED-dried mushroom slices was reduced with a decrease in electrode gap and increase in voltage (Dinani et al., 2015b).

More recently, Martynenko et al. (2021) examined the effects of voltage, electrode geometry, air flow, humidity, and material thickness on the drying rate of white mushroom slices for ED drying with and without forced air flow. According to their results, the drying rate was proportional to moisture content, increasing with electric field strength and decreasing with the emitters' density, air humidity, and material thickness. Decreasing the relative humidity of air from 70% to 30% or using forced air flow with a velocity of 1.0 m/s in ED drying was found to improve efficiency significantly. While color degradation mostly occurred in 40 °C thermal drying combined with forced air flow at 1 m/s, there was no significant color change such as browning or yellowness in ED drying. Additionally, the specific energy consumption of the nonthermal cases (forced air, ED, and ED combined with forced air) for the first hour of drying was approximately the same and was nearly 1600 kJ/kg. This was almost 160 times lower than the specific energy consumption in thermal drying. In addition, the specific energy consumption of thermally dried mushrooms for the entire drying period was 165 times higher than that of the drying performed by combining ED with forced air flow, considered the most energy-efficient drying in that study.

In contrast to the studies described above, Dutta et al. (2012) compared ED and MW pretreatments prior to FD of mushroom samples. As a pretreatment, ED provided impressive results in terms of improved quality and less shrinkage. However, it did not affect the drying rate.

3. Freeze drying (FD)

3.1. Principles

FD, also called lyophilization or cryodesiccation, is a process in which water in the form of ice under extremely low pressure is removed from a product by sublimation. Sublimation allows ice to transform directly from a solid to a vapor state without passing through a liquid phase (Franks, 1998). The FD process typically involves three steps, which are freezing, sublimation (primary drying), and desorption (secondary drying) (Nowak and Jakubczyk, 2020). Primary drying is generally the longest of these three phases, so optimizing it is the major focus in the industry (James, 2001; Depaz et al., 2016).

The first step is freezing, which transforms most of the water into ice, leaving the solute in a glassy and/or crystalline phase (Ratti, 2013). A small percentage of water is closely bound to the food matrix and does not freeze; the volume of water that persists in the liquid state is determined by the initial composition of the food and temperature (Castro and García, 2002). At this stage, solid food should be quickly frozen to create tiny ice crystals that reduce the damage to the cell structure of the food. Slow freezing is used to form a lattice of large ice crystals in liquid foods that lack a cellular structure. The sublimed ice creates channels that allow vapor to exit more quickly than from solid foods (Magnussen et al., 2009; Fellows, 2017).

Primary drying is the second step of the FD process and it mostly takes place as the sublimation of ice at low pressure. Sublimation of water can occur at pressures and temperatures below the triple point (611.7 Pa and 0.01 °C) (Berk, 2009). The pressure surrounding food is decreased under 611.7 Pa and heat is slowly applied to the frozen food to induce the ice to sublime to water vapor. The sublimation front moves towards the frozen food as drying progresses, leaving behind partially dried food. Because the pressure of the freeze-dryer is lower than the vapor pressure at the ice's surface, a water vapor pressure gradient is formed. As a result, the water vapor moves through the dried food to the drying medium and is condensed on the cooling coils (Fellows, 2017). Basic elements of the equipment and design are presented in Figure 2.

Sublimation of ice crystals creates porous structures, resulting in a powdered substance with excellent rehydration properties (Ishwarya et al., 2015). Primary drying should always be performed at 2–3 °C below the maximum allowable product temperature, which for an amorphous matrix is the glass transition temperature of

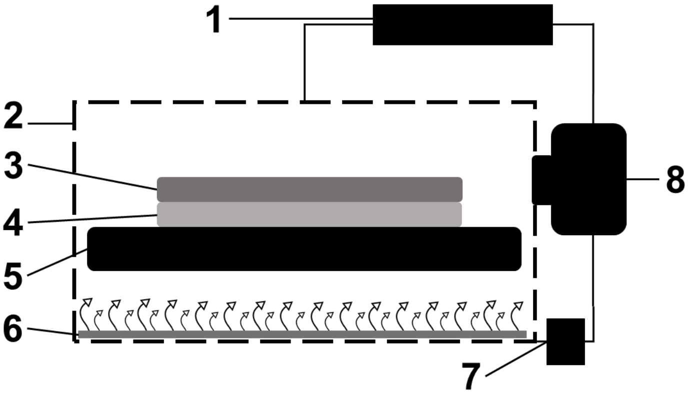

Figure 2. Schematic diagram of FD equipment. 1- Refrigeration system, 2- chamber, 3- product: dry layer, 4- product: frozen layer, 5- tray, 6- radiant heat source, 7- vacuum pump, 8- condenser unit.

the maximally freeze-concentrated solution (T_g) or the collapse temperature (T_c) (Passot et al., 2007; Depaz et al., 2016). If the glass transition temperature is exceeded during the primary drying process, the structure can collapse, lowering the rate of water sublimation/desorption, causing physicochemical changes in the product, and resulting in an undesirable product. As a result, the second drying stage takes longer, the product's rehydration capability deteriorates, and the final moisture content of the product rises. This may lead to a decrease in product stability during storage (Horn and Friess, 2018). The amorphous phase occurs as a glasslike material below T_g, preventing large-scale molecular movement. Drying just below T_g improves the efficiency of the primary drying step, as well as preventing material collapses and resulting in a more uniform distribution of bound water at the end of the lyophilization process (James, 2001; Severo et al., 2017).

The residual moisture content may be as high as 7%–8% at the end of the primary drying stage, although the product appears to be dry. Continued drying at a warmer temperature is required to reduce the residual moisture content to optimal levels (Severo et al., 2017). The last step is desorption (secondary) drying of the material to the final humidity. Desorption of water from the material usually occurs at an elevated temperature and low pressure after primary FD is complete and all ice has sublimed in the region (Tang and Pikal, 2004). When the water pressure of the associated solid equals the water pressure of the condenser, the water tightly bound to the matrix is removed (Castro and García, 2002).

FD is applied to labile products, resulting in a high-quality final product; owing to the unavailability of liquid water and the low process temperatures, most chemical reactions and microbiological modifications are prevented (Waghmare et al., 2021). FD is performed at low temperatures to preserve the flavor, color, and quality of the food while preventing thermal damage to heat-sensitive nutrients (Berk, 2009). In other words, the nutritional and organoleptic properties of freeze-dried products are preserved during the process. FD is utilized to dry high-value foods that have valued aromas or textures such as coffee, herbs, spices, strawberries, meat, and mushrooms (Fellows, 2017).

FD is a high-cost technology with a high initial expense, high energy usage, and a long processing time, although it has several advantages over conventional drying methods in terms of product quality (James, 2001; Fang and Bhandari, 2012). Spray FD, adsorption FD, fluid-bed FD, tunnel FD, and MW-assisted FD are some of the modified FD techniques that have arisen to minimize costs (Wang et al., 2011; Fang and Bhandari, 2012; Jiang et al., 2013; Ratti, 2013).

Spray FD is an unconventional FD process that creates special powdered products while preserving the benefits of standard FD. Because of its advantages over other drying methods in terms of product composition, homogeneity, and the preservation of volatiles and bioactive compounds, spray FD has the ability to produce high-value materials (Haseley and Oetjen, 2018; Luy and Stamato, 2020). Spray FD involves the atomization, solidification, and sublimation of a solvent at low temperature and pressure. Due to the low process temperatures, spray FD has been used to manufacture highly viable encapsulated probiotic cells, beverage powders, and skim milk powder. It allows the preservation of highly volatile flavor compounds and superior product quality (Fang and Bhandari, 2012; Ishwarya et al., 2015; Vishali et al., 2019).

3.2. Studies

In a study conducted by Piskov et al. (2020) with oyster mushrooms (*Pleurotus ostreatus*), the color intensity of freeze-dried mushrooms was found to be lower than that of sun-dried mushrooms. It was reported that the enzyme activities of freeze-dried mushrooms were lower, resulting in the lighter color. Moreover, the whiteness/darkness value (L*) of oyster mushrooms increased after FD, while decreasing after vacuum drying (Ucar and Karadag, 2019). In freeze-dried mushrooms, the value of redness/greenness (a*) decreased, yellowness/blueness (b*) remained unchanged, and redness and yellowness increased in vacuum-dried mushrooms. Freeze-dried mushrooms are whiter after drying than fresh mushrooms. The effect of FD on color may be positive due to the inhibition of browning reactions. Browning during drying can be caused by the acceleration of the reaction of the polyphenol oxidase enzyme at higher temperatures and water loss, as well as the nonenzymatic browning reaction that occurs during heating (Rajarathnam et al., 2003). On the other hand, Duan et al. (2015) reported that both enzymatic browning and nonenzymatic browning took place during MW-assisted FD of button mushrooms (*Agaricus bisporus*), but the effect of enzymatic browning was more significant. Enzymatic browning occurs due to two types of polyphenol oxidase, which are tyrosinase and laccase. While laccase activity is limited, enzymatic browning in button mushrooms is predominantly caused by tyrosinase (Lin and Sun, 2019).

Texture and morphology are the other important quality parameters for the consumer acceptance of dried mushroom products. Ucar and Karadag (2019) reported that the size reduction of vacuum-dried mushrooms was 60.13%, while it was 7.63% in freeze-dried mushrooms compared to fresh mushrooms. The effect of different drying methods on the shrinkage ratio of mushrooms also varies by drying method. Shrinkage ratio values for hot air, MW-assisted vacuum-dried, and freeze-dried mushrooms were found to be 0.41, 0.51–0.53, and 0.69, respectively (Giri and Prasad, 2009; Duan et al., 2015). The FD method provides a bright appearance and good internal microstructure. Information about the porosity of the structure, including the presence of open or closed pores, is crucial for determining the quality and texture of dehydrated food products and plays a key role in the thermal conductivity, heat, and mass transfer (Liu et al., 2017). The relationship between porosity (total, open-pore, and closed-pore porosity) and quality of MW-assisted freeze-dried mushrooms was investigated, and it was found that when the moisture content was below 25% on a dry basis, many open pores could turn into closed pores, and the closed-pore porosity was observed to be relatively stable at moisture contents below 17%. Total porosity and closed-pore porosity also had a significant effect on the texture of MW-assisted freeze-dried mushrooms, while open-pore porosity had a significant effect on the rehydration ratio. The MW-assisted FD process can be used to minimize drying time and maintain product quality during rehydration (Liu et al., 2017). Another application that provides lower drying times is ultrasound application. Ultrasound treatment during atmospheric FD has a considerable impact on the drying kinetics of button mushrooms, decreasing drying time by 74% and increasing effective diffusivity by 280%. In terms of quality parameters including color, texture, rehydration, and cell damage, ultrasonic treatment has no significant effect (Carrión et al., 2018).

While bioactive and aroma compounds are significantly affected by drying methods, FD helps the product keep those compounds (Chen et al., 2020; Zhao et al., 2020). The volatile composition and aroma compounds of shiitake mushrooms (*Lentinula edodes*) were preserved effectively by vacuum FD in contrast to hot air-dried mushrooms (Hou et al., 2021). The vacuum FD method also maintains the nutritional quality of button mushrooms (*Agaricus bisporus*). FD and the combination of FD with MW vacuum drying processes could effectively preserve the monosodium glutamate-like components of button mushrooms (Pei et al., 2014). Dried wine cap mushrooms (*Stropharia rugosoannulata*) treated with vacuum FD were found to have higher levels of soluble sugars, organic acids, free amino acids, and 5′-nucleotides compared to natural and hot air drying (Hu et al., 2020). The application of mid-IF drying with FD was reported to cause a substantial increase in sulfur compounds such as dimethyl, trisulfide, and 1,2,4-trithiolane, as well as aroma retention (Wang et al., 2015).

According to Wu et al. (2015), freeze-dried and vacuum-dried samples had higher hydroxyl radical scavenging effects as well as greater reducing power than hot air-dried samples. Using the fluorescence recovery after photobleaching method, freeze-dried mushrooms exhibited higher antioxidant capacity than vacuum-dried or hot air-dried samples (Wu et al., 2015). In another study, FD was the method that preserved organic acid compounds and flavor the most, with values that were comparable to fresh samples. Vacuum drying and FD are two important drying methods for achieving better nonvolatile flavor retention (Fan et al., 2012).

In addition to the dehydration method, the parameters of the applied method also have important effects on the composition and quality of mushrooms. Process parameters in the FD of button mushrooms (*Agaricus bisporus* L.) were optimized by Tarafdar et al. (2017) according to thickness (2 mm, 5 mm, and 8 mm), pressure (0.04, 0.07, and 0.10 mbar), and primary (–2, –5, and –8 °C), and secondary (25, 28, and 31 °C) drying temperatures. The contents of protein, ascorbic acid, and antioxidants were used to evaluate the quality of freeze-dried mushrooms. The optimum values for process variables were determined for pressure, sample thickness, and primary and secondary drying temperatures as 0.09 mbar, 0.36 cm, and –7.53 °C and 25.03 °C, respectively. The secondary drying temperature had a significant impact on protein and antioxidant content while all three FD parameters had a significant impact on ascorbic acid content, with temperature having a greater impact. The antioxidant content was obtained as 8.60 ± 0.44 mg/g for freeze-dried products and 9.10 ± 0.10 mg/g for fresh button mushrooms. The optimized values for protein and ascorbic acid were 7.28 mg/g and 26.92 g/100 g compared to 8.43 mg/g and 28.00 mg/100 g, respectively, for fresh button mushrooms (Tarafdar et al., 2017). The storage conditions of freeze-dried products are also critical for maintaining product quality and minimizing the degradation of components. Freeze-dried mushrooms were stored under different typical conditions (RT: 25 °C, 55% RH; HT: 37 °C, 85% RH; AT: ambient temperature) and resultant odor changes and bacterial composition were evaluated. The bacterial diversity in freeze-dried mushrooms increased across the whole of storage, and HT samples exhibited the greatest diversity index among the three groups. Variation of dominating species was induced by differences in storage conditions. As a result, the volatile compounds formed during storage differed from one product to another (Yang et al., 2019).

4. Infrared (IF) drying

4.1. Principles

IR radiation is defined as part of the electromagnetic spectrum between visible light and microwaves and is subdivided into the three categories of near-IR (NIR) with wavelengths between 0.75 to 1.4 µm, mid-IR (MIR) with wavelengths ranging from 1.4 and 3 µm, and far-IR (FIR) with wavelengths between 3 and 1000 µm (Pan and Atungulu, 2010). Water has high energy absorption around 3, 6, 12, and 15 µm. The IR radiation band that is important in food heating and drying is given in Table 1. When IR radiation is absorbed by the O-H bonds in water, the bonds start to rotate with the same frequency as the incident radiation. As a result of the transition of IR radiation to rotational energy, water evaporates (Rosenthal, 1992; Pan and Atungulu, 2010).

The vibrational, rotational, and electronic states of the atoms and molecules are changed when the emitted electromagnetic energy reaches a food surface. The movements and rotations of the molecules are modified as the waves penetrate the material. Stretching and bending are the two basic vibrations that exist. Stretching is the contraction or extension of the space between atoms while bending is the displacement of the atoms (Riadh et al., 2015; Yadav et al., 2020). As a food surface is exposed to IR radiation, a fraction of the incident energy is reflected and absorbed and the remainder is transmitted. As a result of absorption by the medium as well as scattering, electromagnetic radiation is weakened. Due to the combined effect of reflection, refraction, and deviation, the radiated energy is directed to another destination from the original direction of propagation. The absorbed waves are converted to heat and raise the temperature of the material (Pan and Atungulu, 2010; Aboud et al., 2019).

In IR radiation drying, also known as thermal radiation drying, heat is transferred to the food material in the form of radiant energy. The IR heating process is faster since energy is transmitted simultaneously from the heating source to the food. The surface of the IR-treated material is heated by the IR source and the interior of the material is heated by conduction through food molecules. The temperature varies from the surface to the core. The air in contact with the food surface is heated indirectly, but not as hot as it is in convection and conduction heating. IR wavelengths between 2.5 and 200 µm are the most widely used wavelengths for drying. Wavelengths between 1.4 and 5 µm are considered more effective in cooking food because of their ability to penetrate a few millimeters in depth into the steam layer covering the food as well as inside the food. The amount of radiation that falls on any surface depends on both the spectrum and the direction.

Table 1. Infrared absorption band characteristics of chemical groups relevant to heating of food (Rosenthal, 1992).

Chemical group	Absorption wavelength (µm)	Relevant food components
Aliphatic carbon–hydrogen	3.25–3.7	Fats, carbohydrates, protein
Carbonyl group (C=O) (ester)	5.71–5.76	Fats
Carbonyl group (C=O) (amyl)	5.92	Proteins
Carbon–carbon double bond (C=C)	4.44–4.76	Unsaturated fats
Hydroxyl group (O-H)	2.7–3.3	Water, carbohydrates
Nitrogen–hydrogen group (-NH-)	2.83–3.33	Proteins

With respect to protein, sugar, carbohydrates, and water, IR absorption of food is unique. The absorption of IR radiation is determined by the position of incident radiation, the properties of the food surface, and the spectral structure. The temperature of the IR heating elements determines the wavelength at which the maximum radiation occurs (Riadh et al., 2015; Aboud et al., 2019). The basics of IR equipment are illustrated in Figure 3.

IR radiation heating has numerous advantages, such as highly energy-efficient drying, water-savings, and environmental sustainability, and it is characterized by heating homogeneity, heat transfer efficiency, shorter heating times, low energy usage, and improved product quality. Furthermore, IR heating preserves vitamins and causes minimal flavor loss (Pan and Atungulu, 2010; Aboud et al., 2019). In addition to many advantages of this technology, there are also some disadvantages. IR technology can cause burns due to high amounts of heat or tissue rupture due to long-term exposure to IR radiation. In addition, it is not susceptible to the reflection properties of coatings. The extent of penetration into food is limited and energy impinging on the food material is different from place to place due to complex shapes and sizes (Riadh et al., 2015; Salehi, 2020).

4.2. Studies

The application of IR heating for food material is a robust technique that is gaining popularity in various industries (Sakare et al., 2020). Doymaz (2014) investigated the effect of different IR power levels on the drying kinetics of button mushrooms. Mushroom slices were dried at four different IR power levels (83, 125, 167, and 209 W). As the IR power level increased from 83 to 209 W, drying time was reduced from 300 to 40 min. The dehydration and rehydration behaviors of the mushroom slices were influenced by the power level. It was stated that the moisture diffusivity values increased significantly as the IR power level increased. This was most likely because higher power levels caused a rapid increase in sample temperature, increased the vapor pressure, and resulted in faster drying. The water status change mechanism of shiitake mushrooms during FIR drying was studied using the LF-NMR transverse relaxation method (Younas et al., 2021). The use of FIR drying was considered to be an efficient way to reduce water. After a 240-min FIR drying operation at 70 °C, total water was reduced by decreased by 87.36% to 17.18%. In the production of mushroom chewing tablets, intermediate-wave IR (IWIR) drying was also found to increase the drying rate and reduce the drying time. Under the same power density, there was considerable variation in overall product quality between IWIR and hot air drying. It was stated that the flavor and texture of IWIR-dried mushrooms were superior (Wang L et al., 2014).

In another study, the IR drying characteristics of mushroom slices were investigated in the temperature range of 50–90 °C. At varying temperatures, drying processes were completed in 60–168 min. Only a falling drying rate cycle was seen and the logarithmic model was the most suitable model for the IR drying activity of thin-layer mushroom slices. The average effective moisture diffusivity increased with increasing temperature and decreased with the moisture content of mushroom slices (Darvishi et al., 2013). The level of IR drying power and temperature play significant roles in determining the drying time. Rachmat and Adiandri (2015) studied the effect of FIR (25–1000 μm) heating on the quality of sliced-straw mushrooms. Conveyor type-FIR irradiation drying was found to be effective in reducing drying time while minimizing color changes. Drying shiitake mushrooms by conveyor-style FIR with temperatures below 70 °C and air velocity of 0.6 m/s resulted in dried mushrooms with relatively higher antioxidant capacity (Sugawara and Nikaido, 2014). In another experiment, shiitake mushrooms were dried using hot air and IR. The IR-dried products had higher polysaccharide contents than the hot air-dried products despite a decreased rehy-

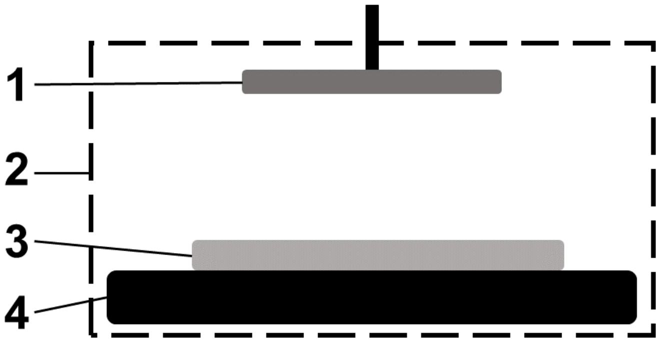

Figure 3. Schematic diagram of IR drying. 1- Infrared lamp, 2- chamber, 3- product, 4- tray.

dration rate. Polysaccharide concentration was closest to that of fresh mushrooms after IR drying combined with MW treatment (Wang et al., 2019). When MW-assisted drying was used, the maximum polysaccharide retention was attained. In dried shitake mushrooms treated with intermittent microwaving coupled with air drying, the types and amounts of nitric aroma were most prevalent.

Combining IR with other drying methods (e.g., hot air, vacuum, MW, or FD methods) can create synergistic effects (Sakare et al., 2020). In the IR-vacuum drying of button mushroom (*Agaricus bisporus*) slices, the effects of IR radiation power (150–375 W), system pressure (5–15 kPa), and time (0–160 min) on the drying kinetics and characteristics of the mushrooms were studied (Salehi et al., 2017). The drying time of the button mushroom slices was affected by both the IR lamp power and the vacuum pressure. The rate constants of nine different kinetic models for thin-layer drying were calculated using nonlinear regression analysis of the experimental data, which showed that the IR power level had the main impact on the moisture ratios, while pressure had a slight impact. As demonstrated in another study (Doymaz, 2014), the effective moisture diffusivity increased with increasing power and changed between 0.83 and 2.33 × 10^{-9} m^2/s. Color change (ΔE) values increased with increasing IR power. Products with better color can be obtained by using a combination of different drying methods. In another study in which a combination of different drying methods was used, shiitake mushrooms were dehydrated by MW-vacuum drying (MVD) and MW-vacuum combined with IF drying (MVD+IR). MVD was applied at four different MW powers (56, 143, 209, and 267 W) under various absolute pressures (18.66, 29.32, 39.99, and 50.65 kPa), whereas two different IR radiation powers (100 and 200 W) were used for MVD+IR (Kantrong et al., 2014). Lower absolute pressure, higher MW power, and higher IR power were found to improve the drying rate. The researchers also suggested that drying using MVD+IR could improve the color of dried shiitake mushrooms, as well as the rehydration ratio and texture of rehydrated samples.

5. Microwave (MW) drying

5.1. Principles

Microwaves are electromagnetic waves in the range of 300 MHz to 30 GHz (Regier et al., 2017). In MW heating, alternating electromagnetic field energy is converted into thermal energy (Vadivambal and Jayas, 2007). Its mechanism is based on dipole rotation and ionic conduction. Dipole rotation is the continuous rotation of polar molecules to orient themselves with the changing electric field, whereas ionic conduction is due to the forward and backward movement of the dissociative ions in an alternating electrical field. These rotations result in collisions between molecules, which increases the kinetic energy in the system and creates heat (Regier et al., 2017). In addition, MW heating is a type of volumetric heating, where MW energy is absorbed by the materials directly and internally and converted into heat. Unlike conventional heating, in which heat is transferred from the surface to the center of the materials, faster heating rates are achieved with MW methods as heat is generated throughout the material. A sample MW oven used for drying purposes is pictured in Figure 4. MW drying accomplishes moisture transfer with the driving force provided by the water vapor pressure difference between the interior parts and the surface of the material. It provides higher thermal efficiency and shorter drying time compared to conventional hot air drying. In addition, there are improvements in the properties of the products, such as color, flavor, nutritional value, microbial stability, enzyme inactivation, rehydration capacity, texture, and fresh-like appearance. Operational costs are lower with MW drying because heating occurs in the product directly rather than

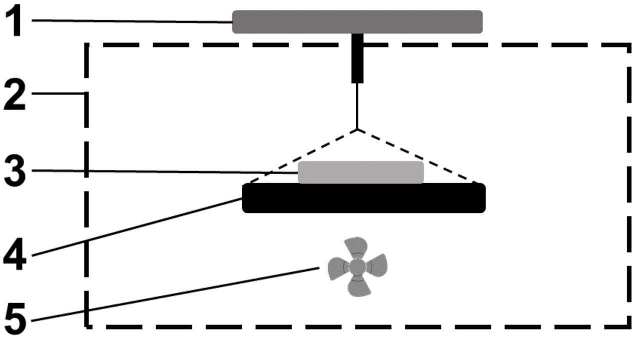

Figure 4. Schematic diagram of MW drying. 1- Digital balance, 2- drying chamber, 3- product, 4- tray, 5- fan.

from the oven walls or through the surrounding air. For this reason, the heat loss from the oven to the environment is very low and energy is not consumed to heat the walls of the oven or the atmosphere. MW heating enables fast startup and shutdown and precise process control (Vadivambal and Jayas, 2007). In addition, since the processing rate is faster in MW drying, it requires smaller floor space compared to conventional dryers. On the other hand, due to the high penetration power of MW energy, overheating problems may be observed depending on the structure, geometry, and dielectric properties of the material and oven design. To overcome these difficulties, the usage of the hybrid/combination mode concept or MW-assisted food processing technologies is a solution. With this technology, with the integration of MW energy into the system, products with better quality are obtained that cannot easily be achieved with traditional techniques. In other words, conventional food processes are combined with MW energy to overcome the shortcomings of both conventional food processing technologies and MW methods, resulting in high-quality products while saving energy, time, and operating costs (Chizoba Ekezie et al., 2017). The first example is the combination of MW energy with hot air drying. Although the hot air drying process has some limitations, such as poor energy efficiency, long drying time, and lower quality, it also has benefits, such as excellent surface water removal. Compared to conventional hot air drying, MW drying has a variety of features for use in food drying processes, including volumetric heating, high thermal efficiency, rapid drying, and improved product quality. As a result, it is preferable to combine these two sources of energy for drying in order to take advantage of their combined benefits (Omari et al., 2018).

Intermittent drying can be used to prevent overheating. This process requires the application of microwaves in pulsed proportions with convective drying. The intermittent MW-convective drying process is often preferred as the heating rate can be maneuvered at appropriate intervals, allowing the temperature and moisture profiles within the product to be redistributed during the off-period and maximizing energy efficiency and product quality (Chizoba Ekezie et al., 2017).

MW-assisted IR drying combines MW heating and IR heating. When MW energy is applied to food, heat is generated that rapidly raises the temperature of the food. Moisture diffuses from the center to the surface of the food due to a pressure gradient. However, surface moisture cannot be removed easily since the surrounding air is cold. Therefore, sogginess is observed on the surface of MW-dried products. IR energy, on the other hand, creates changes in the vibrational states of atoms and molecules. Due to its lower penetration depth, IR heating is localized on the product surface, which reduces surface moisture and prevents the dried product from becoming soggy. Reducing drying time, saving energy, and achieving high energy efficiency and high product quality are the key advantages of IR drying (Kantrong et al., 2014). Sogginess on the product surface is eliminated when IR is combined with MW.

FD is a suitable method for heat-sensitive foods as it prevents chemical decomposition and encourages easy rehydration. To reduce the limitations of FD, such as long drying time, low productivity, and high energy costs, MW-assisted FD may be preferred.

Another method is MVD. The combination of MW energy and vacuum drying has gained popularity due to its volumetric heat absorption and reduced pressure. This technique results in rapid evaporation of moisture with minimum alterations in the dried product quality.

The final example is MW-assisted ultrasound drying. This method allows drying to be carried out at lower temperatures, which reduces the likelihood of oxidation or degradation (Chizoba Ekezie et al., 2017).

5.2. Studies

Several studies have used MW energy to dry mushrooms. In the study conducted by Das and Arora (2018), sliced button mushrooms of different thicknesses were dried by applying MW and hot air alternatively. The constant parameters of this study were MW power level of 120 W, drying air temperature of 60 °C, and drying air velocity of 1 m/s. The convective air drying of mushroom (slice thickness: 2.5 mm) at 60 °C took about 10 times longer than the integrated drying system to reach to the desired final moisture content of 10% (wet basis). Products with lower water activity, lighter color, and higher rehydration rate could be obtained in the application of MW and hot air drying alternatively. The drying of mushrooms using a MW hot air drying system with variable MW power was studied by Omari et al. (2018). During the drying process with different power densities (1.5, 2.0, and 2.5 W/g), statuses (constant and variable microwave power), and hot air temperatures (23, 50, and 70 °C), the variation of moisture content with drying time was evaluated. As the power density and air temperature increased, drying time decreased. One of the reasons for this was that the amount of MW energy absorbed by the product and the temperature gradient in the product increased and intensified the flow of moisture to the surface with the rising intensity of MW power. The other reason was that as air temperature increased, surface mass transfer resistance decreased, allowing moisture to escape more easily. Furthermore, by switching the power density state from variable to fixed, the drying time was increased. Increasing the intensity of power during the application was beneficial in terms of time reduction, but then there were some drawbacks, such as deterioration of the quality of the dried food product. Another study investigated the MVD of button mushrooms. The effects of MW power between 115 W and 285 W, system pressure between 6.5 kPa and 23.5 kPa, and product thickness between 6 mm and 14 mm on energy use and drying efficiency were investigated. Up to a certain point, the drying efficiency was constant, and then it decreased with decreasing moisture content. Drying efficiency was significantly affected by MW power and product thickness while the effect of system pressure was less important. It was found that there was an inverse relationship between MW power and drying efficiency. The effect of product thickness on efficiency was more distinct at a given pressure and low MW power levels (Giri et al., 2014). Another investigation was carried out to observe the effect of two different drying methods, MVD and MVD+IR, on drying characteristics, qualities, and specific energy consumption of shiitake mushrooms (Kantrong et al., 2014). Increasing the MW and IR power and decreasing the pressure caused a decrease in drying time and energy consumption and an increase in drying speed. The rehydration rate increased with increasing IR power compared to samples dried with MVD, from 1% to 10% at IR power of 100 W and from 2% to 20% at IR power of 200 W. In addition, the color and texture of the MVD-IR-dried shiitake mushrooms were better than those of mushrooms dried with MVD only. It was found that the optimum drying conditions for this research entailed the combination of 267 W of MW and 200 W of IR at 18.66 kPa resulting in minimum energy consumption of 28.21 kWh/kg. In another study reported by Wang HC et al. (2014), the effects of the MIR-assisted convection drying (MIRCD), hot air coupled with radio frequency drying (HCRFD), and hot air coupled with MW drying (HCMD) on the drying characteristics and quality parameters of shiitake mushrooms were compared. Each drying technique was carried out at a fixed air temperature and power level. Results obtained under the same power density conditions showed that drying method is an important factor for the drying properties and quality characteristics of dried shiitake mushrooms. The fastest drying was achieved with HCMD, followed by MIRCD. The highest surface temperature was reached in mushrooms dried with HCMD. In terms of uniform heating, MIRCD and hot air drying methods were better than HCRFD and HCMD. Products with better color and nutrient retention were obtained by MIRCD and HCRFD. In addition, MIRCD-dried products had less shrinkage and lower hardness values. According to these results, MIRCD was found to be the most suitable method for the industrial drying of shiitake mushrooms. In another study, the drying of shiitake mushrooms under four different drying methods, namely hot air drying, MVD, MVD after ultrasonic pretreatment, and MVD combined with airborne ultrasonic treatment, was investigated to compare the total sugar, total phenol, ergosterol, sulfur, and free amino acid values and microstructures of dried samples (Lei et al., 2021). The drying temperature did not exceed 60 °C in any of the processes. Two different ultrasonic power levels (120 W and 280 W) were used for MVD after ultrasonic pretreatment and MVD combined with airborne ultrasonic treatment. According to scanning electron micrographs of the dried samples, fresh samples had high water contents and irregular cell structures. For all treatments, drying made the pores of the mushrooms larger. Hot air-dried and MVD samples showed shrinkage and fractures, but the cellular structure of MVD samples was clearly observed due to the shorter drying time. Ultrasound application increased the microscopic cavities due to the alternating expansion and contraction. The combination of airborne ultrasound and MVD treatment processes generated greater vapor pressure differences between the inside and outside of the materials, and rapid sublimation of moisture in a short time and the expansion of structural openings led to an increase in microporosity compared to the ultrasonic pretreated MVD samples. In addition, the amino acid contents of dried samples were higher compared to fresh ones due to the breakdown of the proteins during drying. The highest amino acid content of 30.52 mg/g dry weight was obtained with 280-W ultrasound power airborne ultrasonic treatment combined with MVD followed by ultrasonic pretreatment (ultrasound power of 280 W; 24.02 mg/g dry weight), while the lowest amino acid content was observed with hot air drying (21.51 mg/g dry weight). Overall, airborne ultrasonic treatment combined with MVD was found to be better for maintaining product quality and volatile sulfur-based substances at levels similar to those of fresh samples (Lei et al., 2021).

6. Comparison of drying methods

Conventional hot air drying is one the most common methods used to dry mushrooms. In air drying, the drying is generally performed between 50 and 70 °C with or without pretreatments. However, there are inferior food quality characteristics, such as dark color, flavor loss, and low rehydration capacity, due to the long drying time and overheating of the product surface (Giri and Prasad, 2009).

There are many studies on mushroom drying by conventional methods in the literature. In these studies, the effects of air temperature, air velocity, slice thickness, and pretreatments on drying behavior and product quality have typically been investigated. Celen et al. (2010) investigated the effects of different slice thicknesses (2, 4, and 6 mm) and drying air temperatures (40, 45, 50, and 60 °C) at a fixed air velocity of 2 m/s on the drying behavior of cultured mushrooms. It was observed that increases in slice thickness slowed the drying rate while increases in drying temperature increased the rate of moisture removal from mushrooms significantly. However, increasing the temperature above a certain value for large values of slice thickness did not have a significant effect on the drying rate. The most suitable model in defining the drying behavior of mushrooms was the diffusion approach model. Lidhoo and Agrawal (2008) studied the effect of hot air temperature on the quality of dried mushroom. Mushroom slices after blanching were dried using hot air at different temperatures (45, 55, 65, 75, 85, and 95 °C). Hot air drying at 65 °C was found to produce a product of desirable quality in terms of browning index and rehydration quality. Thin-layer drying of the "Oyster Pleurotus" variety of mushroom at air temperatures of 45, 50, and 60 °C with air velocities of 0.9 and 1.6 m/s was performed by Pal and Chakraverty (1997). The effect of pretreatment (steam blanching followed by sulfiting and citric acid pretreatment) before drying was also studied. Taking the drying time and quality of the dehydrated product into account, a combination of a drying air temperature of 50 °C and an air velocity of 0.9 m/s was found to be suitable for the drying of both untreated and treated mushrooms.

Aroma profile is an important quality parameter for mushrooms, which is expected to be changed by drying. The effects of different hot air drying temperatures (40, 50, 60, 70, and 80 °C) on the umami taste and aroma profile of *Suillus granulatus* mushrooms were recently studied (Hou et al., 2022). The results showed that the drying temperature changed the aroma profile of *S. granulatus*. Mushrooms dried at 60 °C exhibited significantly higher equivalent umami concentrations and more desirable mushroom-like and almond odors.

The duration of drying was reduced by approximately four times in forced convection compared to natural convection (Rubina and Aboltins, 2021). However, it was recommended to interrupt the air flow after 7 h of drying, which allows optimizing the power consumption since forced convection has a significant impact on moisture removal only during the first 7-h period.

The outcomes of drying of oyster mushrooms by natural convection and solar drying with different controlled flow rates and ventilations area were compared (Sukkanta et al., 2023). Naturally dried mushrooms were darker than the standard. With a value of 37.69% in terms of thermal efficiency, solar drying with a flow rate of 87.83 m^3/h and ventilation area of 0.12 m^2 was discovered to be the best.

Fluidized bed drying of sliced mushrooms in two batch sizes (0.5 kg and 1.0 kg) was studied at different drying air temperatures (50, 70, and 90 °C) and air velocities (1.71 and 2.13 m/s) (Kulshreshtha et al., 2009). The results indicated that the drying time decreased only marginally with an increase in air velocity. A drying air temperature of 50 °C was better as it resulted in a dried product having better rehydration characteristics, less shrinkage, and lighter color. The highest energy efficiency (79.74%) was observed while drying a batch size of 1 kg at a drying air temperature of 50 °C using air velocity of 1.7 m/s.

Liu et al. (2021) analyzed the drying of mushrooms in terms of energy efficiency and showed that the moisturizing strategy can be considered as a promising method to enhance energy and exergy efficiency of the hot air dryer with the improvement of product quality and sustainability of drying systems.

Since mushrooms are very sensitive to high temperatures and high drying times, it is critical to find the most suitable drying method to minimize quality loss during drying. Alternative techniques are introduced into the drying processes of mushrooms to eliminate the weaknesses of conventional drying techniques, which can be summarized as quality and nutritional losses appearing in the final product due to the use of relatively higher temperatures and long processing times. Improving the energy efficiency, which is about 50% in conventional drying, and reducing the energy consumption are other goals (Elmizadeh et al., 2017). In addition, addressing the environmental concerns that arise from the utilization of fossil fuels in conventional cases is also critical (Lingayat et al., 2017). The application of alternative techniques alone or in simultaneous or consecutive combination with other techniques surely provides advantages. However, the feasibility of introducing an alternative technique into the industry depends on cost and energy considerations. It is essential to compare and contrast the utilities and expenses related to these techniques.

ED drying technology is usually advised to be used in combination with conventional hot air drying systems in mushroom processing to accelerate the drying by involving electrical energy in the process. This is considered to be highly advantageous since electricity can be produced from clean energy sources and provides energy efficiency and relatively low cost compared to other nonthermal drying techniques (Paul and Martynenko, 2021). The mechanism of action theoretically depends on utilizing high electric field applications to increase the momentum of air molecules inside the food material and enhance mass transfer during the drying process (Elmizadeh et al., 2017). In this way, a mechanical boost is achieved in water removal, and so the process is accelerated and the processing time is decreased. In the application of high electric fields, the effects of processing conditions such as voltage, electrode gap, product and electrode geometry, pretreatments, relative humidity, and processing temperature are highly material-specific and require optimization for each product (Paul and Martynenko, 2021).

Specifically in the case of mushrooms, ED drying remarkably accelerated the drying process, especially when combined with forced air. Mass reduction in the first hour of drying was found to decrease to a third. It was also found that ED drying required less energy than thermal drying and had the potential to decrease energy consumption on an industrial scale (Martynenko et al., 2021). Dinani et al. (2014b) indicated that mushroom slices dried by hot air drying assisted by ED fields were dried in a significantly shorter time. Besides improvements in energy consumption and time, end-product quality was also assessed for mushrooms under ED-assisted air drying methods. The results showed that a significant increase in porosity and hence better-protected shape and water rehydration properties were obtained compared to oven-dried samples (Dinani et al., 2015a). The application of ED drying prevented the color formation usually observed in convection drying due to extended drying times and the need for high temperatures. In addition, the nutritional contents of the mushrooms were better protected in ED systems (Martynenko et al., 2021). All in all, ED drying was evaluated to be a promising alternative technology with the advantages of providing better quality and improved nutritional properties. Compared with conventional methods alone, energy consumption and processing time are decreased. On the other hand, the disadvantages of the ED drying technique include its novelty and lack of industrialization. Its applicability to industry in terms of scale-up, equipment design, energy dissipation, workplace safety, and fixed and variable cost analysis still needs further clarification. In addition, postprocessed sample characteristics, food safety achievements, and effects of pretreatments are also unknown. Optimization of the application is also required for each food material to be studied (Paul and Martynenko, 2021). ED drying is a promising technique to be applied in industry; however, the intense research, engineering, and comparative analysis required to bring it to the application stage are still in the process of development.

MW technology is utilized in mushroom drying solely or in combination with various other technologies such as hot air drying or IR drying technology (Chizoba Ekezie et al., 2017; Regier et al., 2017; Wang et al., 2019).

In a study conducted by Priyadarsini et al. (2022), various drying techniques such as hot air drying, MW drying, and FD were used to improve the shelf life of oyster mushrooms. The rehydration ratio was significantly higher in freeze-dried samples followed by hot air-dried samples at 40 °C. The highest color change was obtained for MW-dried samples and the value was lowest in the case of FD samples. The highest amount of protein was observed in hot air-dried samples at 40 °C (30.81%) followed by freeze-dried samples (29.53%). No significant difference in ascorbic acid content, antioxidant activity, or phenolic content was found between hot air drying at 40 °C and FD. Keeping economical points in mind and considering quality aspects such as hardness, microstructure, minerals, and physicochemical properties, hot air drying at 40 °C resulted in an acceptable product.

The major advantage of MW technology is the achievement of very fast heating. However, when it is used alone in drying, due to the uneven absorption of microwaves, the temperature distribution is most generally nonuniform and temperature control is very hard to achieve. This may result in some problems such as uncontrolled heating along the corners or edges of food products that may result in burning, occurrence of localized hot spots, and emergence of off-flavors or nutritional losses (Bashir et al., 2020; Luo et al., 2021). On the other hand, this property could be utilized as a selective heating mechanism to heat the moisture-rich interior parts of certain samples without burning the exterior parts (Chandrasekaran et al., 2013). Furthermore, MW drying is highly successful in the falling rate drying period, in which the diffusion of water from interior to exterior parts is the rate-determining step. This mechanism involves the achievement of volumetric heating under MW applications, allowing microwaves to heat the interior water, cause vaporization, and create a pressure gradient to accelerate the diffusion of water from the center to the surface of the material. Thus, water is capable of being removed from the inside without burning the surface and preventing shrinkage (Das and Arora, 2018). However, this process has to be carefully optimized as internal heating may result in an excessive increase in pressure and hence puffing and deterioration of the integrity of the structure (Chandrasekaran et al., 2013; Tian et al., 2016). All in all, MW processes require controllability. One of the strategies applied to increase the controllability of MW processes is the use of an on/off method, in which the MW oven is periodically turned on and off to prevent excessive heating and decrease energy consumption (Das and Arora, 2018). However, compliance with this strategy has to be considered along with product properties and drying characteristics, especially in drying processes for foods with high moisture contents such as mushrooms. In the end, MW applications alone may not be the best solution, but the utilization of various strategies or the combination of MW processing with other technologies in drying processes is highly promising.

MW technology is commonly combined with conventional hot air drying to provide improved results. The contribution of MW drying to convection drying systems may take place at constant or falling rates. At the beginning of the drying process, where the constant rate period dominates for most foodstuffs, the purpose of involving MW energy in a conventional hot air drying system is to obtain a rapid temperature rise and stimulate a puffing effect to maintain the porous structure. In the falling rate period, i.e., the later stage of drying where interior water loss is important, the purpose is to accelerate the diffusion of water. In conventional drying of fruits and vegetables with high moisture contents and fibrous structures, the constant rate drying period is performed well with conventional methods. However, the falling rate period is very slow. Utilizing MW technology especially in this period reduces the processing time and energy consumption, increases the drying rate and enhances rehydration capacity, and eases shrinkage caused by excessive exposure to hot air (Chandrasekaran et al., 2013). A combination of the on/off strategy, hot air drying, and low-power MW application resulted in a decrease in processing time, improved product quality, and improved processing parameters such as color, rehydration ratio, and effective moisture diffusivity (Das and Arora, 2018). MW and hot air drying strengthen each other when considered in combination. Even though it is not highly common, this combination is readily utilized in industrial drying processes. Its advantages include improved product quality, higher processing efficiency, decreased energy consumption, and, therefore, decreased variable costs. On the other hand, processing conditions are highly specific to the product and have to be carefully determined for the desired qualities. Thus, kinetic studies and product quality analysis are required before application. Another application to increase the controllability and effectiveness of MW drying systems involves the incorporation of vacuum into the system. The basic principle of vacuum applications is to decrease the surrounding pressure to achieve evaporation at a lower temperature. Hence, the temperature becomes controllable, product quality is better preserved, processing time may be decreased, and energy efficiency is achieved (Das and Arora, 2018). Studies have shown that MW vacuum offered a better drying performance than hot air MW drying in terms of the mass of water evaporated per unit amount of energy supplied into the system. Furthermore, drying time decreased by 70% to 90% in the drying process of mushrooms compared to hot air drying (Chandrasekaran et al., 2013). In addition, in terms of product quality, it also provided superiority compared to the sole use of MW processing. For instance, in the drying process of shiitake mushrooms, in terms of nutritional quality MW vacuum was better at retaining the structure of polysaccharides and proteins due to fast drying and low temperature. The absence of air in vacuum applications inhibits the oxidation of uronic acid and certain vitamins such as B12 and D2. Uncontrollably high temperatures in applications involving MW alone result in greater changes in physical properties of the product such as hard crust formation, lower rehydration ratio, and darker color, but under vacuum these phenomena are largely prevented (Tian et al., 2016). The advantages of introducing vacuum into MW systems can be summarized as increased efficiency and product quality and reduced energy consumption. Vacuum drying is a common technique in industry, especially for heat-sensitive foods, and the incorporation of MW energy brings concrete advantages in terms of product quality. However, combining vacuum and MW technology together in a system increases both the fixed and variable costs, and in that regard, critical requirements have to be carefully analyzed.

The conditions of combined MW and hot air drying for *Termitomyces albuminosus* were investigated and optimized using drying rate, protein content, color L*, DPPH scavenging ability, rehydration ratio, texture, sensory score, and overall score as responses (Li et al., 2021). There were significant differences between the flavor compounds in dried and fresh edible mushrooms. The impact of different drying methods (MW, hot air, freeze-vacuum drying, and MVD) on product flavor was also recently studied (Zhang et al., 2021). It was observed that vacuum FD was conducive to retaining the original flavor; in contrast, hot air-dried edible mushrooms generated new flavor compounds, causing the loss of some characteristic flavor compounds.

Another novel method in mushroom drying is the application of IR technology. In these applications, an IR lamp is used to provide radiation. It emits energy to be absorbed by the food material and moisture is removed by inducing changes in the vibrational states of atoms. The main advantage of utilizing radiation is the ability to work without heating the medium, heating just the food material (Wang et al., 2019). IR technology is applied for various fruits and vegetables and has provided reductions in drying time, color change, and energy consumption and increased product quality (Aboud et al., 2019). IR heating can be applied alone or in combination with other techniques such as hot air, MW, or vacuum to create a synergistic effect (Wang et al., 2019). IR drying, when used alone, is a perfect fit for thin slices of products since heating is achieved from the surface. Structural, nutritional, and biological quality characteristics are better preserved without the risk of burning, and energy loss is minimized since energy is focused only on the material when compared with conventional techniques (Salehi, 2020). Various combinations of IR technology were previously studied. IR and vacuum were combined, and the results showed that the system required precise optimization for the adjustment of excessive color formation in button mushrooms caused by increasing IR power (Salehi et al., 2017). Furthermore, the consecutive application of IR and FD provided remarkable improvements in the energy consumption and quality of shiitake mushrooms (Wang et al., 2015). In the study of Kantrong et al. (2014), IR technology was introduced into a MW vacuum system to dry shiitake mushrooms. Drying time decreased with increasing IR power due to increased radiative heat and surface temperature; hence, energy consumption was reduced. Quality parameters such as color, hardness, and rehydration ratio were also improved. A synergistic effect of increased internal temperature by MW and increased surface temperature by IR was obtained. Hence, enhanced migration of water from the interior by MW heating was supported by enhanced surface moisture loss by IR. However, applications of IR are limited since they require predictive simulation models for the optimization of the process variables for each of the materials to be used, especially for food materials that are highly sensitive to color and textural changes, such as mushrooms. Accordingly, equipment size, product capacity, and variable costs arise as the main concerns while discussing the compatibility of IR to the industrial scale (Chizoba Ekezie et al., 2017).

Finally, FD is another method that offers advantages in mushroom drying. High-quality dried products with low bulk density, high porosity, better rehydration characteristics, improved rehydration ratios, and minimal nutritional loss are achieved due to low temperatures and the lack of oxygen in FD (Ucar and Karadag, 2019; Piskov et al., 2020). It was reported that freeze-dried shiitake mushroom had better physical quality in terms of color, less shrinkage, and a homogeneous structure. However, the drying time was comparably long and the desired browning aroma formation did not occur (Zhang et al., 2021). Even though FD provides good results alone, they occur at a high cost in terms of energy and time, and palatability may also emerge as a problem. The equipment is quite costly, vacuum applications make a significant contribution to the variable cost, process conditions have to be carefully adjusted to keep the triple point of water, and it is not possible to increase the drying rate while maintaining the quality. In this case, FD alone is not an energy-efficient system; hence, its utilization is only feasible for high-value products (Tarafdar et al., 2017). In the application of FD technology to mushroom processing, deficiencies were eased by combining it sequentially with other methods such as IR, hot air drying, or MW. For instance, FD in consecutive application with IR was effective in decreasing the drying time compared to FD alone while maintaining the quality parameters of dried mushrooms (Wang et al., 2015). Even though the energy consumption could be decreased according to the decreased processing time in FD, capital cost and the continuous system adaptability of the process are still obstacles for its feasibility.

Several drying techniques involving alternative technologies have been introduced, investigated, and discussed. The concern is to ease the challenges of conventional methods causing shrinkage, browning, and oxidation of vitamins or lipids in mushrooms (Xue et al., 2017). All of these methods have aimed at providing a higher quality of dried mushrooms in terms of nutritional value, taste, texture, and visuality compared to the conventional hot air drying technique when utilized under optimal working conditions (Chizoba Ekezie et al., 2017; Wang et

Table 2. Studies on drying of shiitake mushrooms using different methods.

Process details	Time (min)	Final moisture content (w/w)	Color change (ΔE)	Reference
Hot air (60 °C, 2 m/s air flow)	960	<8% (db)	14.8	(Zhang et al., 2021)
IR (225 W) + hot air (60 °C)	600		5.21	
FD (50 °C)	2880		5.05	
Hot air (60 °C, 1 m/s air flow)	550	13% (db)	12.5	(Wang et al., 2019)
IR (60 °C)	350		15	
Intermittent MW + hot air (60 °C)	200		16.6	
Vacuum drying (60 °C, –90 kPa)	900	13% (db)	5	(Tian et al., 2016)
MW (539 W)	18		14.9	
MW (15 W/g) + vacuum (–80 kPa)	11		5.5	
IR (50 °C) + FD (4 h, 50 °C)	410	<12% (db)	8.4	(Wang et al., 2015)
MW (4.0 W/g) + hot air (60 °C)	90	12% (db)	15.45	(Wang HC et al., 2014)
IR + hot air (60 °C, 1 m/s air flow)	200		6.32	

db: Dry basis.

al., 2019; Martynenko et al., 2021). Nutritional, textural, and visual properties were observed to be highest in applications involving vacuum. Incorporation of vacuum allows water to boil and evaporate easily at much lower temperatures. Complications arising from exposure to high temperatures for longer times were eased by the presence of a vacuum (Martynenko et al., 2021). Details of processing conditions for different drying techniques and changes in color attributes (ΔE values) indicating the differences in colors of dried products from that of fresh shiitake mushroom are presented in Table 2. This comparison of various drying techniques for the same material briefly summarizes the details described above. For instance, the least color change indicating the best color attributes was obtained in the case of FD since both the heat and oxygen exposures of the system were minimal (Wu et al., 2015). This was followed by vacuum involving other treatments, such as MW vacuum or air drying vacuum applications, and then materials of the lowest quality and poorest nutritional value may be expected to be obtained by hot air-combined and MW or IR-only systems due to exposure to high temperatures. It can be concluded that low-temperature applications have the potential to improve the quality attributes of dried mushrooms. On the other hand, MW and IR applications have the significant advantage of decreasing the processing time to a considerable extent with virtually no degradation of nutritional, textural, or color attributes compared to the conventional method (Tian et al., 2016; Wang et al., 2019). Considering the time advantages of MW and IR methods and the quality improvements of FD and vacuum applications, optimal protocols can be generated. For instance, an appropriate combination of FD and vacuum was found to be advantageous in terms of both processing time and color attributes (Wang et al., 2015). Together with processing time and product color, the energy consumption of several methods was also evaluated by Motevali et al. (2011) and the overall findings are summarized in Table 3. All mushroom samples were dried until 6%–7% moisture content on a wet basis. When the processing times and energy consumption levels of each system were compared, it was obvious that hybrid technologies provided better outcomes than solo applications. Even though IR technology is advantageous in terms of processing time, its energy consumption is almost equal to that of hot air drying. Combining these two technologies results in a drastic decrease in both drying time and energy consumption. The same phenomenon was also observed for MW and vacuum applications separately. MW applications provided low energy consumption and reduced drying time and quality issues, while in the case of vacuum drying relatively high energy consumption and drying time were observed. These two technologies, when combined, provide excellent outcomes in terms of energy consumption, processing time, and product quality (Motevali et al., 2011; Wang HC et al., 2014).

Among the methods present in the literature discussed here, ED applications seem to be particularly promising since they provide perfect outcomes in terms of color and texture (Paul and Martynenko, 2021). However, energy consumption, efficiency, product quality during and after processing, and scale-up attributes have to be carefully examined before drawing conclusions about its feasibility in the mushroom industry. Various studies have explained this method, combining it with other techniques and offering parameters specific for mushrooms. However, further comparisons with other mushroom drying methods in terms of quality and energy consumption are required for its dissemination (Elmizadeh et al., 2017; Martynenko et al., 2021; Paul and Martynenko, 2021). MW applications when applied alone do not offer high-quality products due

Table 3. Specific energy consumption for drying of mushroom with different methods and process conditions (Motevali et al., 2011).

Name of the process	Process conditions	Drying time (min)	Specific energy consumption (kWh/kg)
Hot air drying	Air velocity (m/s): 0.5–1.0 Temperature (°C): 40–60	165–379	50.84 ± 2.48 to 93.45 ± 2.86
IR drying	Radiation intensity (W/cm^2): 22–49 Air velocity (m/s): 0.5–1.0	74–172	50.84 ± 1.59 to 93.45 ± 1.69
Hot air + IR drying	Radiation intensity (W/cm^2): 22–49 Temperature (°C): 40–60 Air velocity (m/s): 0.5–1.0	42–113	15.04 ± 1.65 to 71.10 ± 2.09
MW drying	MW power (W): 130–450	40–58	2.51 ± 0.17 to 6.00 ± 0.24
Vacuum drying	Absolute pressure (mbar): 200–800 Temperature (°C): 40–90	135–520	41.97 ± 3.31 to 24.34 ± 3.66
MW + vacuum drying	Absolute pressure (mbar): 200–800 MW power (W): 130–450	11–45	3.20 ± 0.24 to 9.60 ± 0.35

to localized and accelerated heating even if they significantly decrease the processing time. Hence, it is more promising to combine MW methods with other processes such as hot air, vacuum, or IR. Hybrid MW systems seem highly advantageous in terms of energy consumption, processing time, and product quality. Furthermore, in terms of specific energy consumption, the cost of a MW-vacuum system was found to be lowest among MW, MW-vacuum, hot air, and vacuum drying systems (Tian et al., 2016). In addition, even if they are not traditional, MW vacuum processes are already industrialized and utilized in the mass production of certain goods. Hence, their adaptability to the mushroom drying industry is better facilitated compared to other novel techniques discussed here. IR technologies alone may not be strong enough contenders to spark the motivation for industrialization since they do not provide huge advantages over conventional approaches. However, together with other methods, they can make valuable contributions. The present study has shown that IR techniques shorten the time, increase the efficiency, and reduce the quality loss compared to hot air drying (Doymaz, 2014; Salehi, 2020). Finally, FD was found to provide superior quality in terms of color, porosity, nutrients, and valuable compounds, but the use of FD alone may not be feasible for commercialized mushroom products since the variable cost is a huge problem. However, in combination with IR or in consecutive use with hot air drying or application of effective pretreatment techniques, it provides promising results in terms of color, nutritional value, taste, and the industrial adaptability of the process (Wang et al., 2015; Zhang et al., 2021).

Alternative techniques are being introduced for the drying process of mushrooms in order to compensate for the weaknesses of conventional hot air drying such as the quality and nutritional losses that appear in the final product due to the use of higher temperatures and long processing times. Alternative methods to assist or replace hot air drying have been described in detail in this review. Among the discussed methods, ED drying seems promising in terms of quality and drying rate; however, for industrialization, further research about both product quality and scale-up attributes is required. In solo applications, MW drying has low controllability and causes quality loss, but when used in combination with other technologies such as vacuum or hot air drying, it is a time- and energy-efficient technology. Additionally, the nutritional and textural quality of the product is preserved during MW drying. Its affordability and the existence of readily industrialized applications for various foods make it a good choice. IR drying can be considered as a valuable contribution to the conventional methods in terms of time and energy savings. However, it may not provide short-time applications or high-quality products when utilized alone. The consecutive use of IR with FD or hot air applications would be promising in terms of energy, time, and nutritional quality. Finally, the best product quality in terms of color, nutrients, texture, and porosity can be obtained by FD, but it is slow, highly energy-consuming, and costly in solo applications. FD-combined methods have a bright future in the mushroom industry.

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Author Contributions

Zinnur Yağmur Buğday: Conceptualization, investigation, writing; Kübra Ertan: Conceptualization, investigation, writing; Sema Zeren: Conceptualization, investigation, writing; Serpil Şahin: Conceptualization, supervision, reviewing, editing; Servet Gülüm Şümnü: Conceptualization, supervision, reviewing, editing.

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