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Review

Technological advancements in the drying of fruits and vegetables: A review

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The aim of the review was to look into technological advances and methods for dehydrating fruits and vegetables, as well as the shortcomings of these methods and potential ways to improve them. All fruits and vegetables can be dried in various forms, including cuts, juice, paste, slurry, and even whole, using various dryers. Recent research on drying has focused on improving energy consumption/ efficiency, product recovery, and nutrient preservation. Technological advancements in drying methods involve development and optimization of novel drying techniques, including their combination to obtain quality products. As the demand for new and healthier ready-to-eat goods with lengthy shelf lives and greater rehydration capability expands, advancements in the drying of fruits and vegetables are crucial. The drying process has a tremendous impact on the product's quality and cost. New drying procedures may provide advantages such as enhanced energy efficiency, higher product quality, lower costs, and decreased environmental impact. Dehydration of agricultural products is a critical process that must be carried out with caution.

Key words: Dehydration, drying, fruits, technological advances, vegetables.

INTRODUCTION

Fruits and vegetables are the most commonly consumed super or functional foods (Rwubatse et al., 2014), yet their high moisture content (over 80%) makes them especially susceptible to bacteria that cause spoiling (Maisnam et al., 2017; Valarmathi et al., 2017). Keeping fresh is the best way to preserve the nutritional value of fruits and vegetables, but most storage methods necessitate low temperatures, which are difficult to maintain throughout the distribution chain. In contract, drying is an effective post-harvest management strategy, particularly in Nigeria and other Sub-Saharan African countries where power outages and rising fuel prices make low-temperature storage, handling, and distribution facilities scarce (Dereje and Abera, 2020). To improve

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their shelf life and increase food security, approximately one-fifth of the world's fresh produce are dried (Pragati and Preeti, 2014; Betoret et al., 2016; Feng et al., 2021). Dried fruits and vegetables make healthy eating more practical and can help close the gap between recommended and actual fruit consumption. By lowering water activity, dehydration keeps fruits and vegetables healthy and safe, prolonging their shelf life much beyond that of fresh produce. Drying processes also affects enzymatic behavior, sensory properties, and microbial growth (Özbek et al., 2007; Dereje and Abera, 2020).

Fruit and vegetable storage through drying has a long history and is based on sun and solar drying processes (Sagar and Kumar, 2010). Drying used to be as simple as lying the product out on mats, rooftops, or drying floors in the sun (Ahmed et al., 2013), using solar radiation and convective air. Other options include drying the harvest beneath a cover, on treetops, or even on field shelves (Rwubatse et al., 2014). Heat is transferred to the fruit or vegetable raw material through convection from the ambient air and radiation from the sun on its surface during sun drying. Since foods to be dried are exposed and climatic changes can occur, the method is highly unsanitary and volatile. Mechanized solar dryers such as tray, carbinet and tunnel dryers have been designed to overcome the challenges of damage, dust, pest infestation and unexpected rainfall encountered in open air drying (Pragati and Preeti, 2014; Rwubatse et al., 2014; Karam et al 2016; Ajuebor et al., 2017). Application of mechanized drying to conserve agricultural produce has grown significantly, necessitating the development of fast drying methods and approach that decrease the amount of fuel dispelled in these operations. It has been noticed that the aim of drying agricultural products has shifted. Previously, the goal was to lengthen the life span of dried fruits and vegetables, but now the goal is to produce high-quality dried vegetables and fruit (Rwubatse et al., 2014; Babu et al., 2018).

Presently, various drying methods are being utilized in equipment which may run on combustible fuels and/or electricity (Maisnam et al., 2017; Norhadi et al., 2020; Feng et al., 2021; Radojčin, et al., 2021). Convective drying within built-in structures is applicable to cabinet, tray and tunnel dryers (Mercer, 2014; Misha et al., 2013), with advances seen in fluidized bed drying (Law and Mujumdar, 2006). Drum dryers use conductive drying on heated surface in drying (Kerr, 2013). Fruit and vegetable juices have been dried and concentrated using atomization (Cal and Solohub, 2009; Mercer, 2014). Lyophilization, or the direct sublimation of ice to vapor, as well as the use of lower pressure in fruit and vegetable drying, result in products with improved rehydration, sensory properties, and drying times (Falade and Igbeka, 2007; Cenkowski et al., 2008). In explosion puff drying and low pressure super-heated steam drying, the concept of drying with steam and decreased vapor pressure is used. Not only is the drying time reduced, but the thermal efficiency is also improved (Calín-Sánchez et al., 2020). Due to the need to reduce energy losses during traditional hot air drying, heat pump drying systems were developed, which increase energy efficiency and reduce fossil fuel consumption (Fayose and Huan, 2016). Prior to drying, osmotic pretreatment of fruits and vegetables has been widely used to reduce processsing time and increase the overall consistency of the dried food product (Mehta et al., 2013). In addition, the use of electromagnetic waves in the drying of fruits and vegetables is rapidly increasing. The process involves the use of indirect electro heating (Marra et al., 2009) and vegetal products are dried in less time and at lower temperatures (Kahyaoglu et al., 2012; Nindo and Tang, 2007; Calín-Sánchez et al., 2020). However, technological advancements in the drying of vegetables and fruits, the process shortcomings, as well as potential ways to improve the process are reviewed.

ADVANCEMENTS IN THE DRYING OF FRUITS AND VEGETABLES

Drying fruits and vegetables has been practiced for ages and is dependent on sun and solar drying processes (Sontakke and Salve, 2015). The development of advanced drying technologies was prompted by low product quality and product contamination. Freeze, vacuum, osmotic, cabinet or tray, fluidized bed, spouted bed, Ohmic, micro wave, and combined and osmotic dehydration are the most frequently utilized drying methods (Pragati and Preeti, 2014; Maisnam et al., 2017; Tontul, and Topuz, 2017; Sakif et al., 2018). With the exception of freeze-drying and osmotic dehydration, the fundamental strategies for forcing water to vaporization during drying include conduction, convection, and radiation, with forced air being utilized to encourage vapor removal (Sagar and Kumar, 2010; Pragati and Preeti, 2014; Kumar and Belorkar, 2015). Drying methods can be broadly classified into traditional, mechanized and advanced methods of drying (Pragati and Preeti, 2014; Maisnam et al., 2017; Hasan et al., 2019).

Traditional methods of drying of fruits and vegetables

Sun drying is the oldest method of fruit and vegetable preservation (Misha et al., 2013). Solar energy, air, and a smokey flame have all been used to evaporate moisture from fruits, meats, cereals, and plants throughout history (Ahmed et al., 2013). Fruits are safe to dry in the sun because of their high sugar and acid content, but vegetables are poor in sugar and acid, rendering them unsuitable for sun drying. Fruits are placed whole or sliced in trays on elevated slabs and exposed to the open air until desired dryness is achieved. The best screens are stainless steel, teflon coated fiber glass or plastic. The optimum conditions for dying to occur are a minimum temperature of 86°F and a relative humidity of less than 60% (Ahmed et al., 2013). Low capital and operating costs, as well as the fact that little skill is required, are the key advantages of sun drying (Ahmed et al., 2013). One major drawback is that when the specific fruit ripens, optimal conditions for sun drying might not be sufficient. Insect infestation, dust and debris contaminants, longer drying time, direct exposure warming, quality degradation, and low rate of heat transmission owing to condensation of the evaporated moisture are only a few of the key concerns experienced when drying in the open air (Sontakke and Salve, 2015). This method can be used to dry raisins and plums.

Mechanized methods of drying of fruits and vegetables

Mechanical or electrical equipment is used to assist with artificial drying. Significant amounts of moisture may be extracted via artificial methods (Babu et al., 2018). Moreover, various parameters such as temperature, drying air flow, and drying time may all be controlled (Okoro and Madueme, 2004; Babu et al., 2018; Xiao et al., 2018).

Solar drying

Food is dried using solar dryers in the solar drying process. Solar dryers such as tray, cabinet, tunnel, spray and fluidized dryers are a form of convectional dryer in which the food is dried by air heated with sunlight energy and/or radiant energy absorbed by the food through a refractive medium, typically glass or polyethylene (Weiss, 2001; Alamu et al., 2010). While solar drying produces better product quality than sun drying, most solar dryers have a smaller capacity compared to open air drying. The process challenges include moisture condensation within the dryer and increased humidity as a result. There two types of solar drying such as direct and indirect solar drying (Figure 1). Food products such as berries, bananas, mangoes, and rosemary can be dried with solar dryers (Abhay et al., 2017).

Cabinet dryer

Fruit and/or vegetables to be treated are laid on shelves/racks within the drying chamber of the cabinet and blasted with hot dry air (Mercer, 2014). Although the equipment is inexpensive, the process is a batch operation with a high operating (labor) cost and low performance. Vital components of the dryer are depicted in Figure 2. Different models for potatoes chip, grapes, apricot and beans have been designed. A cabinet dryer designed for treating okra, chili pepper and plantain was fabricated and the performance evaluated by Ajuebor et al. (2017). The cabinet dryer performed optimally at the 70°C, relative humidity of 60%, and air speed of 3.0 m/s. At these values of the process parameters, drying time was shorter and of all the analysis carried out, the result obtained was better at this point.

Tray drying

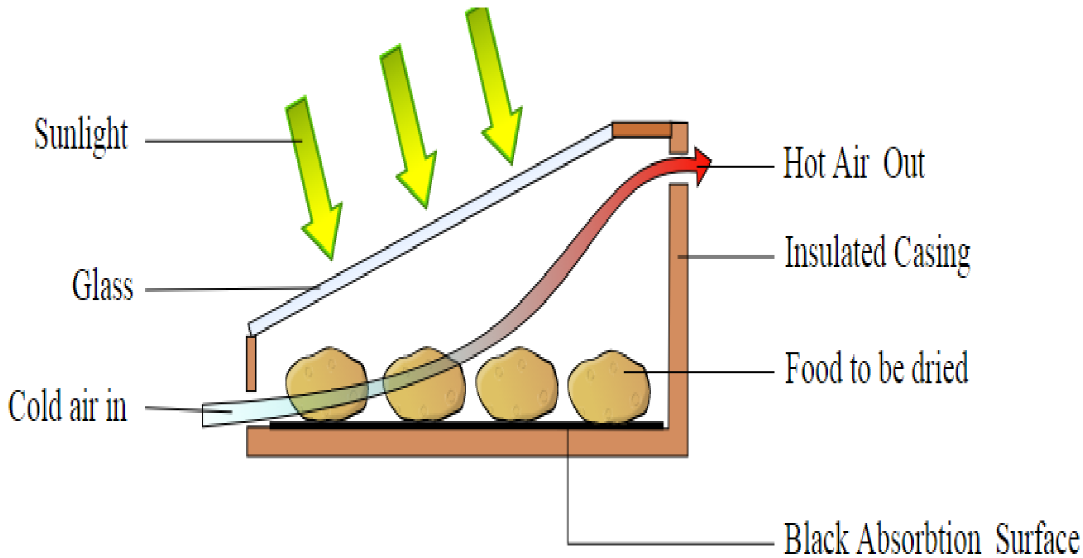
It is a batch dryer with a drying mechanism that is similar to a cabinet dryer. To optimize the amount of open space for air circulation, dried fruits and vegetables are arranged on large wire mesh trays (Figure 3). Once the trays have been loaded, they are placed on supports within a drying cabinet or compartment. After that, the drying chamber is sealed, and air is blown into it (Mercer, 2014). Uniform airflow distribution over the trays is critical to the tray dryer's performance (Misha et al., 2013). The tray dryer's major problem is uneven drying, which is caused by insufficient airflow circulation in the drying chamber. Solar energy is used in most of the dryer systems that have been built to lower operating cost (Misha et al., 2013). Colak and Hepbasli (2007) developed a model to dry green olives. This process can be used to dry apple, banana, and apricot slices. Because of the increased drying rate , improved product quality and appearance, the tray dryer was determined to be more effective than the oven dryer (Norhadi et al., 2020).

Tunnel dryers

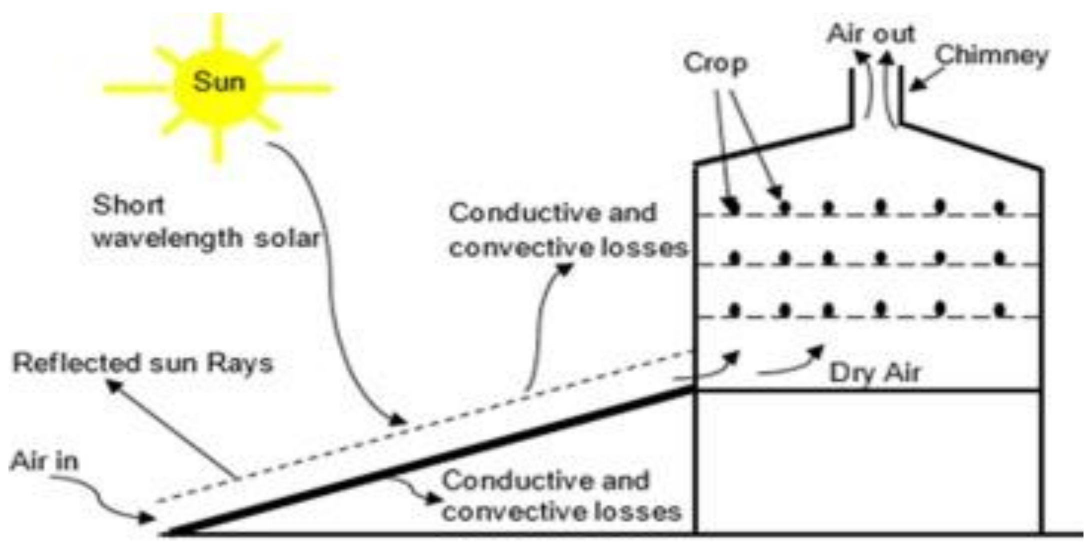
Considered an advancement of the tray and cabinet dryers, it was designed to replace sun drying of prunes with heated forced air dryer (Brennan, 2006). Tunnel dryers are long tunnels through which trucks transporting trays pass with or against a stream of drying air (co-current, counter current or mixed current). A truck carrying wet food enters one end of the tunnel, while another with dehydrated products exits the other end. The trucks are driven manually or mechanically (e.g., with the help of chains), depending on the scale of the trucks and the tunnel. Despite the flexibility of the drying method, tunnel dryers need significant amount of labor to run than a continuous belt dryer thus making it less widely utilised (Mercer, 2014). Apricots, peaches, pears, apples, figs, dates, and other fruits and vegetables have been dried using this process in the form of fragments, purees, and liquids.

Drum drying

A set of metal drums are heated with steam or hot water



A: Direct solar drying



B: Indirect solar drying

Figure 1. A schematic of a direct and indirect solar drying. Source: Adapted from: Abhay et al. (2017).

to the desired temperature. The food to be dried is introduced into the thin gap, or nip, between the drums as they rotate in opposite directions (Figure 4). This fruit or vegetable raw material must be in the form of a slurry or viscous liquid. The food sticks to the spinning heated drum's surface after passing through the nip, and moisture evaporates. Baked food is from the drum surface while rotation continues; using a doctor blade/ knife that continually skims the drum surface, extracting the dried materials (Mercer, 2014). The food can be applied to the drum surface in a number of ways (Kerr, 2013). The viscosity of the feed determines the feeding process. Drying parameters such as drying temperature, feed rate, rotation speed, feed concentration, and surrounding air condition influence the characteristics of drum-dried food such as particle size, bulk density,

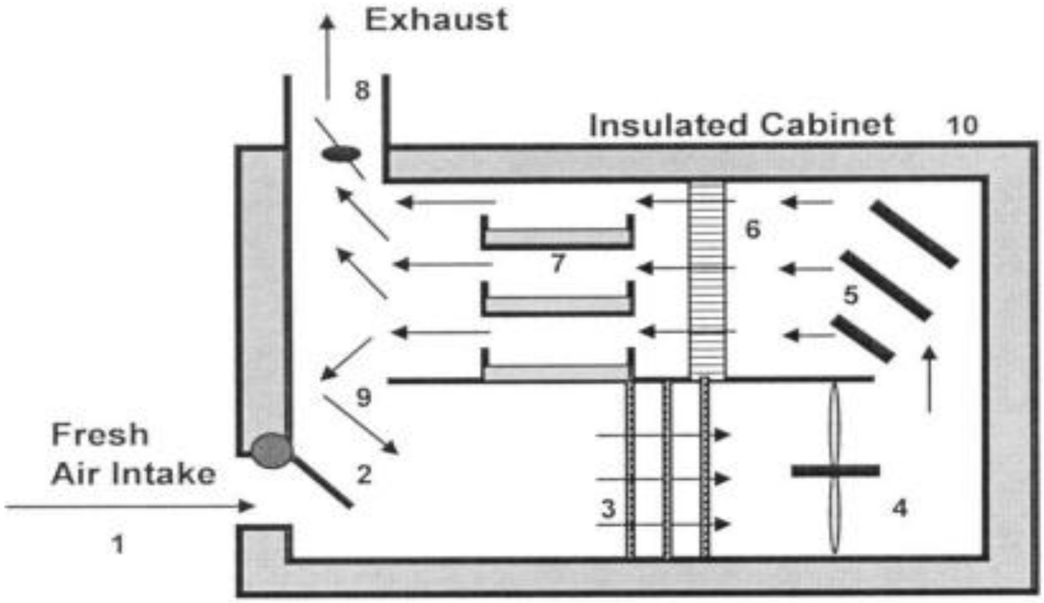


Figure 2. The components of a cabinet dryer. Source: Mercer (2014).
1 = Fresh air enters cabinet dryer, 2 = Adjustable damper allows fresh air and recirculation to be balanced, 3 = Heaters warm the air stream to the desired temperature, 4 = Adjustable fan conveys air and controls volumetric air flow-rate, 5 = Air distribution plates even out flow pattern of air, 6 = Screens filter particles from air and create back pressure, 7 = Product is contained in trays with heated air passing over them, 8 = Air is exhausted from cabinet dryer after removing moisture from products, 9 = Heated air with some drying capacity may be re-circulated, 10 = Cabinet is insulated to prevent excessive heat loss. The arrows indicate air flow.

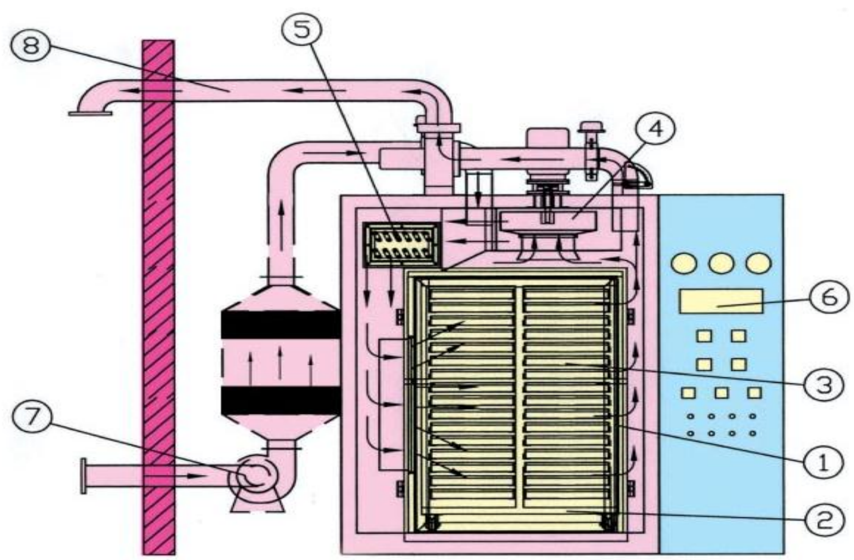
moisture content, and solubility (Nastaj, 2000; Pua et al., 2010). Cooked food flavor and non-enzymatic browning can result from heated surface drying. Heated surface drying may result in cooked flavor of the food and non-enzymatic browning. There is also difficulty in scraping-off sugar rich foods, high energy consumption of the process and hydration in the processing area due to condensation. The method has been used to transform mashed potatoes into dried flakes which can be used as instant mashed potatoes.

Spray drying

Cal and Solohub (2009), claim that the device was created to boost the drying and concentration of liquid substances by atomizing. Fruit or vegetable juice is blasted via an atomizing valve, resulting in small droplets that are equally spread throughout a vast drying chamber and allowed to fall into hot air flowing upwards (Mercer, 2014; Tontul and Topuz, 2017). Changes in parameters such as particle diameter, air temperature, and air speed, among others, can be used to accomplish the required degree of drying, so that when the droplets touch the bottom of the drier, they have devolved into small powder particles (Mercer, 2014). The technique may not be suitable for foods sensitive to mechanical damage, due to the strong shear action during atomization. Some drawbacks include the loss of bioactive compounds in the food and the stickiness of sugar-rich foods to drying equipment. In addition, the scale of the equipment and the cost of installation are also substantial. Tomato juice has been dried into powder using this method (Phisut, 2012; Verma and Singh, 2015).

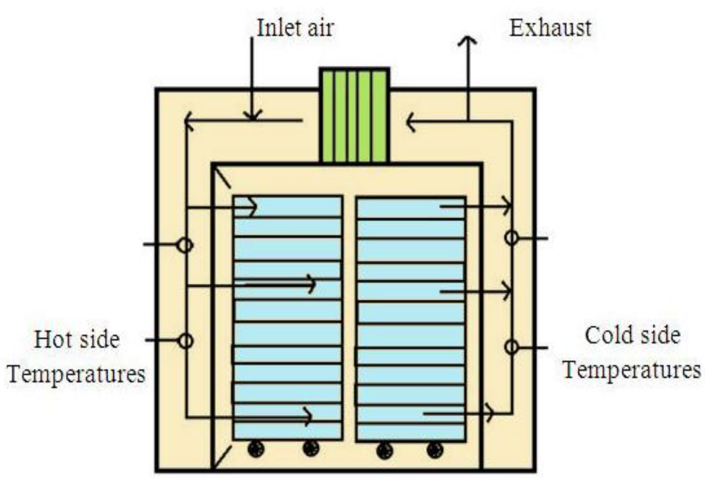
Fluidized bed dryers

The fact that the drying medium, which is usually warm air, comes into contact with all surfaces of the product being dried is recognized by fluidized bed dryers (Mercer, 2014). This drying method reduces the possibility of soluble material migrating by lifting the food particles and transporting them outside using heated air blown from beneath the bed. Through openings in the bottom, heated air is blown into the drying chamber. A linear velocity can be achieved by using a sufficient volumetric flow rate of air to lift the wet fruit or vegetable and keep it suspended in the air that is drying it (Mercer, 2014). The method is widely used to dry wet granular and particle food products that can be fluidized in beds of inert solids, such as slurries, pastes, and suspensions (Law and Mujumdar, 2006). The down sides of this method are particle size restrictions and poor thermal efficiency. Vegetables such as peas, green beans, carrots, and onion slices are commonly dried using this process (Kumar and Belorkar, 2015).



A: Tray dryer

1 = drying chamber, 2 = drying trolley, 3 = drying tray, 4 = circulation fan, 5 = Heat exchanger, 6 = control panel, 7 = fresh air inlet, 8 = exhaust damper.



B: Tray dryer working principle

Figure 3. Tray dryer and its working principle.
Source: Misha et al. (2013).

Advance methods of drying of fruits and vegetables

Various sophisticated drying techniques, including as solar, microwave, vacuum, infrared, freeze, oven drying, and various combination drying technologies, have been developed across the world and are effectively utilized for various fruits and vegetables (Hasan et al., 2019).

Freeze drying

Freezing the food, sublimating the ice, and extracting bound water molecules are all steps in the process. During freezing and low temperatures, the lack of liquid water causes the production of a higher-quality end product and completely stops most microbe-mediated

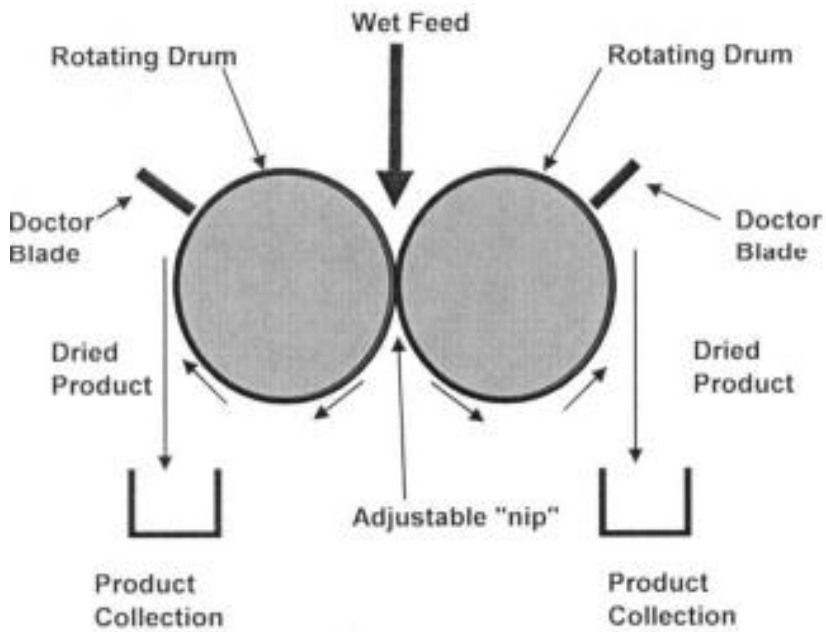


Figure 4. Functional parts of a drum dryer. Source: Adapted from: Mercer (2014).

reactions (Falade and Igbeka, 2007). The food is first frozen (at - 20°C), after which a controlled quantity of heat is supplied under vacuum to induce sublimation, in which ice is converted straight to vapor and subsequently condenses as ice on a refrigeration coil, which is generally kept at -55°C (Claussen et al., 2007; Oetjen and Haseley, 2004). One of the most significant characteristics of freeze dried fruits is their rehydration capacity. The immense expense and quantity of energy used throughout the freezing, drying, and condensing processes are disadvantages of freeze drying products. Because of the long freeze drying period, the product can collapse, resulting in a rough product with minimal rehydration ability and a loss of aroma. Exotic fruits and vegetables, soup ingredients, mushrooms, orange juice, mango pulp, and other industrial applications of the technique have all been effective. Though using a microwavewas able to optimize the freeze drying of onions (Abbasi and Azari, 2009; Schossler et al. (2012) developed an integrated ultrasound freeze drying device to dry bell pepper. The use of ultra sound technology was found to minimize rate of drying by 11.5%.

Vacuum drying

For the drying of fruits and vegetables, vacuum technology is used in conjunction with other drying methods such as freeze drying and microwave. In vacuum drying, pressure-driven flow is the most common mode of moisture migration (Cenkowski et al., 2008; Parikh, 2015). It is carried out below 101 kPa but above 0.6 kPa, with heat transfer normally taking place through conduction. Drying time is shortened since water boils at a low temperature under vacuum due to the pressure. Additionally, the product's water circulation improves, resulting in increased mass transfer. High pressure, on the other hand, can cause product darkening.

Osmo-dehydration

Osmotic dehydration is the process of partially drawing the moisture out of fruits and vegetables by immersing them in a hypertonic solution containing sorbitol, glycerol (sugars of high osmotic pressure) or salt. When food is placed in a hypertonic solution, solutes from the solution diffuse into the tissue of the fruits and vegetables (Mehta et al., 2013). The pretreatment preserves the food color, taste, and nutritional qualities, and it can be done with mild heat treatments. As a result, the energy needs for the overall dehydration process are effectively reduced. Difficulty predicting the final chemical composition of the product and it's taste, unnecessary wastage of osmotic solution, and leaching out of pigment, acids, carbohydrates, minerals, and vitamins are only a few of the issues that must be overcome. According to Kumar and Sagar (2014), fruit drying is more successful when osmotic treatment and vacuum drying are combined.

Heat pump dryer

Hot air drying is inefficient and wastes a lot of energy. As

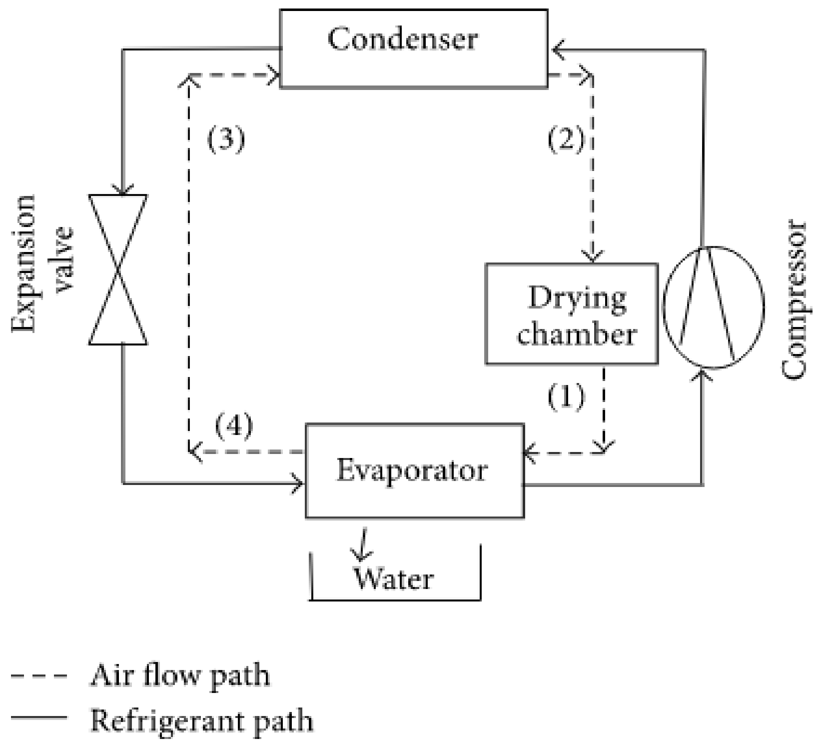


Figure 5. Component arrangements of a heat pump dryer.
Source: Fayose and Huan (2016).

a result, numerous approaches focusing on recovering exhaust air during the manufacturing process have been developed. The heat pump drier was created with this objective in mind (Calín-Sánchez et al., 2013). In this type of dryer, a refrigerator is employed to recover latent heat by water condensation (Figure 5). Dry heated air is provided to the product as a result of the process, resulting in the release of humid air. In the heat pump evaporator, the air is condensed, allowing the latent heat of vaporization to be utilized for warming the drying air. Heat pump dryers improve energy efficiency while reducing fossil fuel consumption (Fayose and Huan, 2016). The advantage of this drying procedure over a standard hot air dryer is the reduction of time and temperature due to the lower relative humidity (Moses et al., 2014; Rahman, 2020). Heat pump drying also takes less time to dry than other drying technologies and is easy to design, making it ideal for low-tech countries in the Sub-Saharan region (Fayose and Huan, 2016). Heat pump drying technology has been combined with other drying processes to overcome some of its flaws and generate improved product quality, cheaper energy consumption, and increased thermal efficiency. Heat pump assisted sun drying, microwave drying, infrared drying, fluidized bed drying, air freeze drying, radio frequency drying, and chemical heat pump assisted drying are all examples of heat pump assisted drying. This is especially necessary for heat-sensitive materials like fruits and vegetables, which require only a low temperature (Fayose and Huan, 2016).

Explosion puff drying

The puffing chamber, vacuum chamber, vacuum pump, decompression valve, steam generator, and air compressor are all components of explosion puff drying equipment (Calín-Sánchez et al., 2013). The decompression valve is closed after the food is put in the puffing chamber (Figure 6). Fruits or vegetables sample are heated to 95°C using steam from the steam generator and retained for 5 min while the air compressor raises the pressure inside the equipment to 0.2 mPa. By opening the decompression valve, the pressure is decreased; allowing puff samples to be vacuum dried (Feng et al., 2021). This process incorporates hot air drying and vacuum freeze drying to provide a less expensive alternative to freeze-dried products (Zou et al., 2013; Chen et al., 2017). Inadequate knowledge of the hygroscopic properties of fruit or vegetable to be dried leads to poor product. Furthermore, nutrient losses due to high temperatures during vacuum drying are a significant disadvantage of the method (Feng et al., 2021). Puff drying works well with diced carrots, resulting in a product that browns minimally and rehydrates well when put in water (Kerr, 2013).

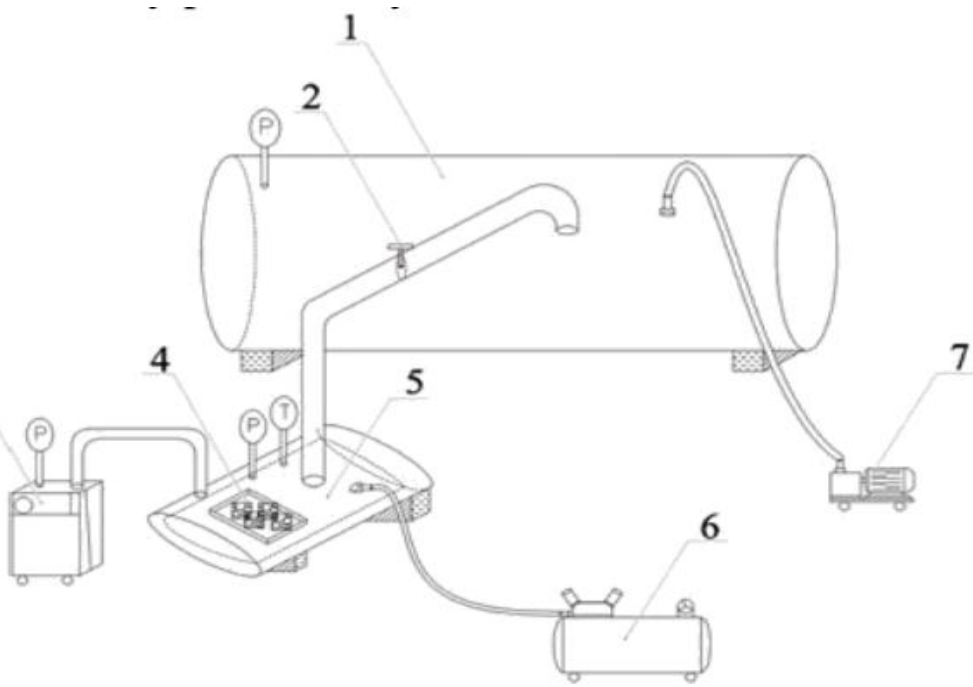


Figure 6. Schematic diagram of explosion puff drying device and accessories. Source: Fan et al. (2018). 1 = Vacuum chamber, 2 = Decompression valve, 3 = Steam generator, 4 = Food samples, 5 = Puffing chamber. 6 = Air compressor, 7 = Vacuum pump.

Low-pressure superheated steam drying

The dehydration process takes place in a sealed drying chamber with a low pressure maintained by a vacuum pump. To prevent excess steam condensation, a steam trap is installed in the reservoir that receives the drying agent from the boiler. The use of a heater with a temperature control device considerably reduces the first steam condensation during the start-up cycle. Calín-Sánchez et al. (2020) suggested the use of a variable-speed electric fan to distribute steam in the drying chamber (Figure 7). According to Sehrawat et al. (2016), the process results in better retention of bioactive components with reduced oxidative changes. However, during drying, the steam collects dust, particles and solids from the raw material. This process has been used to successfully dry onions (Sehrawat and Nema, 2018).

Electromagnetic radiation techniques

Many traditional drying methods rely on hot air provided by an electric heater or gas to assure heat transmission, typically by convection, between the hot air and the food. The electromagnetic wavelength spectrum, on the other hand, is used as a source of energy in several other approaches. A precise wavelength of electromagnetic waves reaches out to the product, producing heat and speeds up the drying process (Rahman, 2020). The method works by indirect electro heating because electrical energy is first converted to electromagnetic radiation before being translated into heat in the food product (Marra et al., 2009). Some of the drying procedures that make use of this principle are as follows:

Refractance window technology: Refractance window drying is a new method of drying that uses circulating water at atmospheric pressure to deliver heat energy to dehydrated food (Pragati and Preeti, 2014; Niakousari, 2018; Kigozi et al., 2021). Any heat that is not used is recycled, and liquid forms of fruits or vegetables to be dried are spread out on a clear plastic conveyer belt. Food on the moving belt dries in a couple of minutes, as opposed to hot air tray or tunnel dryers, which take several hours, or freeze dryers, which take even longer. Convection, conduction, and radiation are the three forms of heat transfer pathways used in this drying technique. All of these heat transfer modes worked together to produce an energy-efficient drying process. Food to be treated must be liquid or semi-liquid. The substance is usually an infrared translucent plastic material floating on the heated circulating water area, and it is applied to the surface of a conveyer belt. When infrared energy passes through the water surface, the refractive principle of the water surface provides a window. When moist food and transparent plastic come into touch, an infrared window is formed, allowing infrared energy to be transferred directly to the material (Figure 8). The drying time for this method

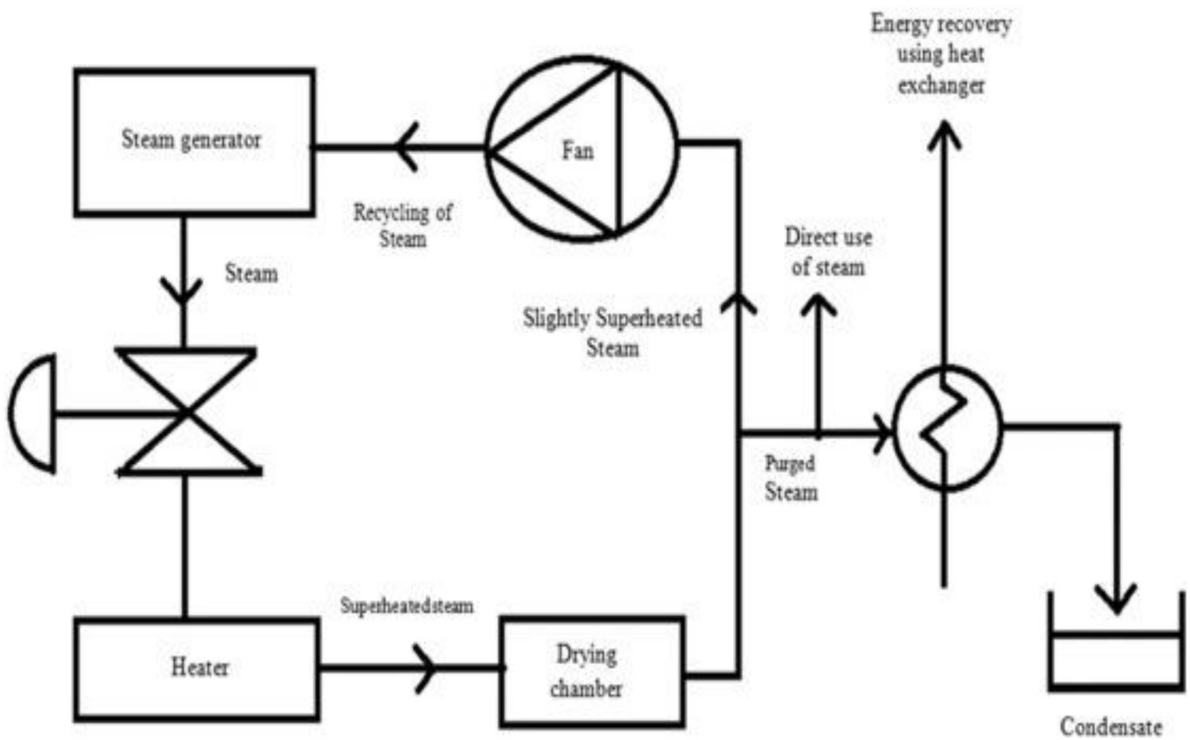


Figure 7. Low-pressure superheated steam drying setup. Source: Adapted from; Sehrawat et al. (2016).

is very limited, according to studies on pure pumpkin (Sabarez, 2016), dehydration through the refractance window takes place at ambient pressure and at lowered temperatures (-30°C), making it a good choice for heat-sensitive foods. According to Nindo and Tang (2007), this method has emerged as a novel cheaper option for dehydrating fruits and vegetables. The sample thickness and drying temperature, however, have an impact on the process. This method can be used to dry berry slices and puree into powder, flake, or sheet form.

Microwave drying: Microwaves are propagated through space using electronic and magnetic fields. Microwave heating is advantageous because it takes less time and heat to reduce the moisture content in foods (Kahyaoglu et al., 2012). The volumetric heating that occurs when electromagnetic waves move through a substance, causing its molecules to oscillate, is the basis for microwave drying. Thermal energy is produced by this oscillation, which is then used to extract water from the wet food. 915 and 2450 MHz are the most used frequencies in the food drying industry. When compared to traditional methods, this drying technology is able to produce high-quality dried products with lower costs and more energy efficiency due to the volumetric heating that is dispersed across the entire food sample. However, according to Joardder et al. (2013), the process causes product harm as a result of insufficient heat control and mass transfer. Microwave dried fruits and vegetables are prone to scorching because of reduced moisture content towards the end of the drying process. As a result, it has been suggested that it should be used in conjunction with other methods, such as the use of microwaves in conjunction with vacuum. Giri and Prasad (2007) used microwave-vacuum drying to prepare button mushrooms As opposed to convective air drying, they discovered that microwave drying takes 70 to 90% less time and retain better rehydrating properties.

Infra-red heating: Infrared drying occurs when a fresh fruit or vegetable is subjected to electromagnetic radiation with a wavelength range of 0.8-1000 µm, which causes infrared drying. Infrared has a wavelength range of 0.75 to 1000 µm (Askari et al., 2013). The heat from the heating source is delivered to the food surface via infrared radiation. The surrounding air, on the other hand, is unaffected by the procedure. This approach is one of the finest for combining with traditional drying processes because of the equipment simplicity and energy savings. Furthermore, rapid and effective heat transfer is recommended, resulting in increased organoleptic and nutritional value of the item, uniform heating, and cheaper final expenses (Boudhrioua et al., 2009). At the atomic and molecular levels, infrared exposure causes charge to accumulate in the electronic state, as well as in the vibrational and rotational states. This causes the food to increase in temperature while the temperature of the air around it remains constant. Agricultural commodities

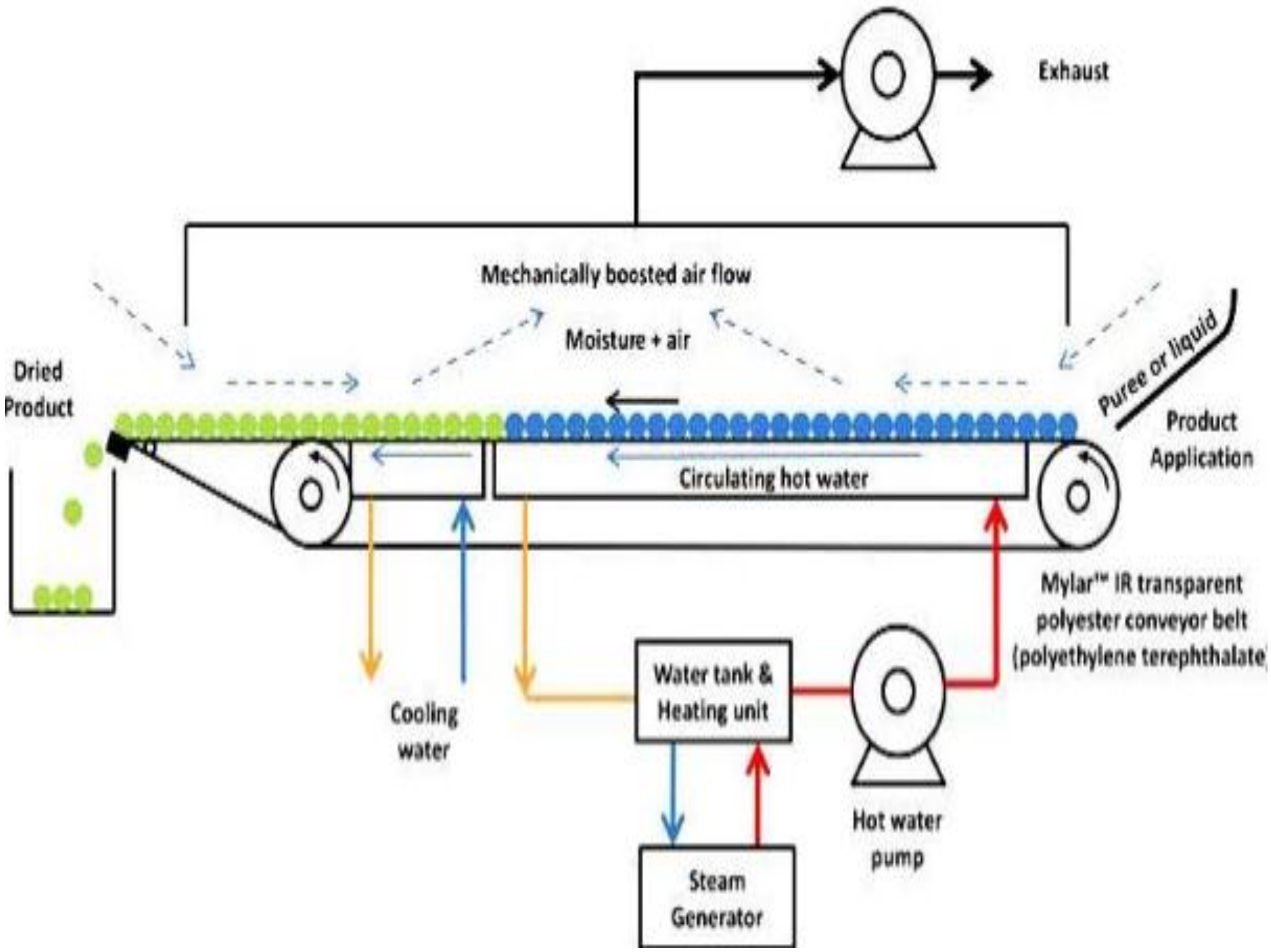


Figure 8. Refractance window drying. Source: Adapted from: Moses et al. (2014).

such as carrots, sweet potatoes, and tomatoes have been dried using infrared drying (Boudhrioua et al., 2009).

Radio frequency drying: This technology can be used not only for wireless communication, but also for food processing. Radio frequency heating is the interaction of an electromagnetic field created by a radio frequency generator with the molecular species in a substance (Caln-Sánchez et al., 2020). As a result, the food sample is sandwiched between two electrodes that are subjected to a 40,000,000 times per second changing electric field. The electric fields, like the polar molecules in the meal, alternate, generating friction and heating the entire product. Because water is bipolar by nature, it heats up and evaporates (Babu et al., 2018). Larger equipment and high operating costs are a considerable disadvantage. Radio frequency has been extensively explored as an alternative to the typical hot air drying procedure in horticulture produce such as apple slices and snack meals (Marra et al., 2009).

Combined drying methods

Combination of drying methods overcome the drawbacks of traditional drying by incorporating the benefits of many methods while reducing the harmful effects that arise when only one technique is used (Chua and Chou, 2014).

Microwave- assisted convective drying

Hot air drying is unsuccessful in drying fruits and vegetables due to the long drying period and use of extremely high temperatures. Microwave-assisted convective drying, according to Calin-Sánchez et al. (2020), can alleviate these issues. As a result, the heated air reduces unbound moisture on the food's surface, while the microwave energy uses volumetric heating to eliminate bound moisture from the product's insides. Nonetheless, according to Kumar and Karim (2017), more research is needed to establish when microwaves should be optimally integrated into the process, such as when the drying rate begins to fall, when the drying rate is already declining, when the drying rate is already falling or when moisture content is reduced.

Convective drying followed by vacuum microwave drying

Calin-Sánchez et al. (2020), describe a two-stage process that begins with convective pre-drying of the fresh food and ends with vacuum microwave drying of the product. Convective pre-drying reduces unbound moisture without altering bioactive components in fruits and vegetables, and vacuum-microwave finishing drying reduces moisture content to the appropriate level. These two combined drying techniques, it has been claimed, are more efficient than either of the methods employed independently. Sour cherries, jujube, orange peel, beetroot, blackcurrant, pumpkin, plums, and hemp, among other fruits and herbs, have proved that the method improves food quality (Calin-Sánchez et al., 2020).

Fluidized bed drying - assisted by microwaves, far infrared rays, and ultrasounds

In a similar way to convective drying, microwave energy can help in fluidized bed drying. This procedure, however, requires numerous drying phases and, in particular, more investigation into its applicability to different products; additionally, the initial device costs are substantial (Calin-Sánchez et al., 2020). It was able to monitor the influence of allicin (the organosulfur component found in garlic) in the drying phase because far infrared rays assisted fluidized bed was employed in the first stage of drying (Calin-Sánchez et al., 2020). When high-powered ultrasound is used on heat-sensitive horticulture commodities, the mass transfer process is accelerated, resulting in a higher-quality dried product. Fruit and vegetable ultrasound procedures have been proven to reduce adverse effects such as shrinking, discoloration, breaking, and nutritional alterations. It is also recognized as a low-cost and energy-efficient system, in addition to having an easy user interface (Singh and Kingsly, 2008).

Intermittent drying of food products assisted by temperature, pressure, humidity, convection, radiation, and microwave

Drying necessitates a significant amount of energy (Calin-Sánchez et al., 2020), discovered intermittent drying as an energy-efficient and successful strategy for enhancing drying kinetics, boosting product quality, and lowering drying process energy consumption. Intermittent drying is when the drying conditions alter over time. Adjusting the drying air temperature, humidity, pressure, and even the heat input mode can help accomplish this (Kumar and Karim, 2017). Intermittent drying was found to be possible by modifying the airflow rate, air temperature, humidity, or operating pressure, all of which can be accomplished by varying the thermal energy source. Intermittent drying can aid to decrease browning impacts and chemical reactions that help to preserve the product's bioactive ingredients in terms of food quality (Pham et al., 2017).

CONFLICT OF INTERESTS

The authors have not declared any conflict of interests.

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