Chapter

Drying Technology Evolution and Global Concerns Related to Food Security and Sustainability

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Abstract

Undoubtedly, rapid population growth has sharply increased global food demand. Although the green revolution, accompanied by food industrialization practices, helped a lot in meeting this demand, the food gap is still huge. Regardless of COVID-19, due to that 14% of the world's food is lost before even reaching the market, and thus the food insecurity prevalence by rate (9.7%), where the food losses are valued at $400 billion annually according to FAO. In the face of such issues related to food insecurity and food losses, drying technology since its inception has been known as the most common operation in food processing and preservation. However, the excessive use of the drying process and exposure to heat for long periods led to a severe deterioration in the physicochemical quality characteristics of these products. At the same time, growing attention on human health through monitoring the quality and safety of food to avoid chronic diseases led to increasing awareness of the consumer to obtaining products with high nutritional value. Therefore, there has been a great and rapid evolution in drying technology to preserve food with high quality. Hence, this chapter aims to shed light on the drying technology evolution in food processing and preservation as one of the most important post-harvest treatments in the agriculture field.

Keywords: drying technology, drying methods, food processing, quality, food security

1. Introduction

Nobody denies that the world is inclining toward alternative sources of energy: a world where human habitats are safe, resilient, and sustainable and where there is universal access to affordable, clean, reliable, and sustainable energy. One of the most important applications of energy is food preservation using drying technology. Preserving food by drying is the oldest method used at home and by food transformation industry. Dried food became an important result, allowing humans to be independent from food supply in any environmental conditions [1]. Food drying techniques have long been applied since ancient times in conventional ways, such as drying in the sun.

From the traditional to the most innovative, there are several drying solutions. Depending on the drying method used, the processing time, the product's final quality, or the efficiency of the process can vary considerably. Currently, drying methods have been developed with the latest technology to reduce the damages caused by biochemical changes, which decrease nutritional value during the drying process. Conserving energy and achieving the best quality of dried products have become the most important factors that determine the usefulness and success of operating any drying unit, where heat is transmitted through the drying unit in three forms conduction, convection, and radiation. In this regard, when the temperature of the fresh material increases, the molecular motion gains more energy; as a result, it causes changes in the structure of the material as well as its chemical properties to increase the shelf life and improve the quality [2]. As indicated by [3], literature data reported more than 400 different types of plants. Among them, only 100 different types are applied in practice, design, heat input, operating temperature and pressure, and quality specifications of the final dried product are the main variables considered for building dryers. However, such technologies are expensive, high-energy demanding, and greenhouse gases producing. In the past, food products were dried, exploiting sun energy. In several countries, sun drying is still used for domestic food transformation. At the industry level, the spoilage reduction, in order to improve the stability of dried products during their storage, is an important input to stimulate a great and rapid evolution in drying technology [4]. A lot of published literature in the areas of drying of food products is already available, but often each paper has been focalized on selected types of drying plants. Furthermore, this chapter will shed light more on the most common industrial drying techniques applied in the food processing process, independently from the basic principles on which they are based to build them. In this way, the reader could choose the methodology most adequate to his objective in an easy and fast manner.

2. Solar drying methods

In the past, the first method used to dry food was sun. Solar energy directly hit the food, left exposed to the air or placed on the ground. It should be considered that this type of drying is influenced by external contamination, the presence of insects and other small animals, the available area, the poor standardization of the process, and the potential development of bad smells [5]. Therefore, this methodology is a most economical solution. Fruits and vegetables that grow and are cultivated in remote areas lend themselves well to conservation by solar drying, while losing some of their peculiarities and nutritional value. But in the past, this method required large space and time and offered poor process control. This natural method takes place when materials are dried with unheated forced air, taking advantage of its natural drying potential. A natural evolution of sun drying has been realized by planning the use of solar dryers, as an efficient system for solar energy use [6]. Countries that enjoy large amount of natural sun exposure have, as the obvious option for drying, the solar dryers based on natural convection [7]. In this way, is possible to save costs and energy. However, uncontrollable climate changes are the main negatively influenced factors [8]. On the basis of climate and environment conditions or if a better quality is needed, the use of mechanical air drying can be the best solution. In any case, sun drying is the cheapest method to dry food. Nowadays, both sun drying and mechanical air driers are available on the market.

More than 250,000,000 tons of horticultural products and cereals are dried every year using natural drying [8]. Especially in developing countries, the products are placed on the ground and turned periodically until completely dry. The newly developed solar drying allows the use of renewable energy sources, minimizing the defects of traditional techniques.. The drying process influences the amount and the organization of water molecules in the food cells producing changes in the product matrix [9]. Modern solar drying techniques try to combine aspects of the natural process with industrial needs, applying the concept of drying for maintenance of the characteristics of the raw materials and the environment in which they are grown (developing countries). The devices designed to effectively carry out this type of drying use mainly the energy of the sun for their functioning, shielding their deleterious effects and creating a hygienically suitable treatment environment, in tune with the microclimatic conditions of the environment. In African countries, for example, during the last 10 years, a great effort has been made to improve the horticultural drying process, with the introduction of more efficient solar drying systems [10–14].

The management of the production cycle is influenced both by intrinsic factors linked to the nature of the material to be transformed and by external factors, therefore determined by the context in which the production takes place. The final quality of the product strongly depends on the choices of technological parameters regarding processing and packaging. These choices can favor the conservation of compounds with high nutritional value present in raw materials that can still be found in final products, improving their nutritional quality. Important, especially in this pandemic era [15–17]. Solar drying has been proven to be adequate to be applied to several crops [18]. It allows the production of products with desirable quality together with minimal environmental impact. Since the process is slow and weather-dependent, so a wise strategy "fan off-fan on" must be devised considering the following conditions: air temperature, relative humidity, moisture content, and temperature of the material being dried. Solar dryers are systems capable of exploiting solar radiant energy to heat a flow of air used to dry products. There are types with natural ventilation (which exploit the "chimney" effect) or with forced ventilation, which can be powered by a photovoltaic system or other electrical source [6]. Recently, a very comprehensive review of several types of natural convective and direct-type (NCDT) solar dryers has been brought [19] with the aim of collecting the most interesting practices of solar drying technology for the benefit of one and all. Authors have classified in a precise way the different types of dryers. They explain the main characteristics of the "direct types" (i.e., (i) direct solar cabinet dryer, (ii) modified solar cabinet dryer with natural convection, (iii) direct solar drying using the chimney, (iv) foldable solar crop dryer; and the "natural convection type," then particular attention has been made at modeling the process and the evaluation of the performances. Furthermore, regarding indirect solar drying technologies, the most exhaustive review has been reported in Ref. [20] and has been written some years ago. Efforts have been made all over the world around to increase efficiency and drying time; thus, modern dryers are equipped with fans, efficient collectors, different thermal storage materials, reflectors, auxiliary heat sources, and sun-tracking systems. A recent paper [21] has reported an interesting development of closed, indirect heating, forced convection solar dehydrator with desiccant, which is economical, hygienic, and works off the grid. The whole experimental design has been discussed, paying attention to (i) energy balance, (ii) quantity of air required, (iii) flow of air required, (iv) area of the solar heater/collector, and (v) rates of dehydration.

3. Industrial drying techniques

Generally, drying involves the coexistence of complex processes, which may be operated simultaneously. Initially, the energy is transferred from hot drying agent to fresh product. Then, the unbounded moisture evaporation (free water) occurs, and eventually, water particles bound inside the cellular structure. These particles exposed to diffusion and thus migration, and transferred to the product surface, where the water is lastly evaporated [22]. The attributes of dried products can be effectively influenced by the parameters of process, such as pressure, temperature, gas feed rate, and relative humidity. In addition to protein formulations characteristics, such as composition and excipients type, and solutes concentration, viscosity as well as solvent type [23]. A large assortment of dryers has been developed to dehydrate and preserve these products to meet different quality and cost requirements. As indicated by [3], over 400 dryer kinds have been described in the reviews, although only about 100 types are commonly use. Differences in dryer design are due to the product physical characteristics, modes of heat input, temperatures and pressure operating, dried product qualifications, etc. Conventionally, food stuffs are dried by open sun drying system. Though this system is still common in many places for non-commercial use, there have been several efforts to improve advanced drying systems for products on a commercial scale. It is obligatory to enhance the drying systems to reduce waste [4]. Regarding this concern, this section will shed light more on the most common industrial drying techniques applied in the food processing process.

3.1 Rotary drying

Rotary drying is also known as tumbling dryer. It is considered the oldest continuous and the most common high-volume dryer used in industry. It has developed more adaptations of the technology than any other dryer classification. Rotary dryers stand out for their flexibility and applicability to a large number of materials, as well as their high processing capacity [24]. Large amounts of granular substantial with particles of 10 mm or larger that are not too fragile or heat-sensitive or cause any other solids handling problems are dried in rotary dryers [25]. Conventional rotary dryers have flights, which lift solids and make them cascade across the dryer section (active phase) when there is effective fluid-particle contact [26]. It is one of the many drying methods existing in unit operations of chemical engineering. The drying takes place in rotary dryers, which consist of a cylindrical casing usually made of steel plates rotating on bearings, lightly inclined horizontally. Usually, its length is 5–90 m, while its diameter is 0.3–5 m, and rotates at 1–5 [25]. It is regularly worked at a negative interior pressure to stop dust get-away. Wet feedstuff is presented into the system upper edge and the feed proceeds through it by force of rotation, head influences and shell inclines. Then the dried stuff is withdrawn at lower edge. The direct heat rotary dryer diagram is illustrated in **Figure 1**. Gas flow direction throughout the cylinder in the case of the solids is dictated by the processed substance characteristics. Current flow is utilized for heat-susceptible substances even with high entrance gas temperature because of the gas's fast cooling through initial surface moisture evaporation. While for other substances, the countercurrent flow is desired for higher thermal efficiency. In the first status, the solid flow rate is boosted by gas flow, whereas it retarded in the second status [27–30].

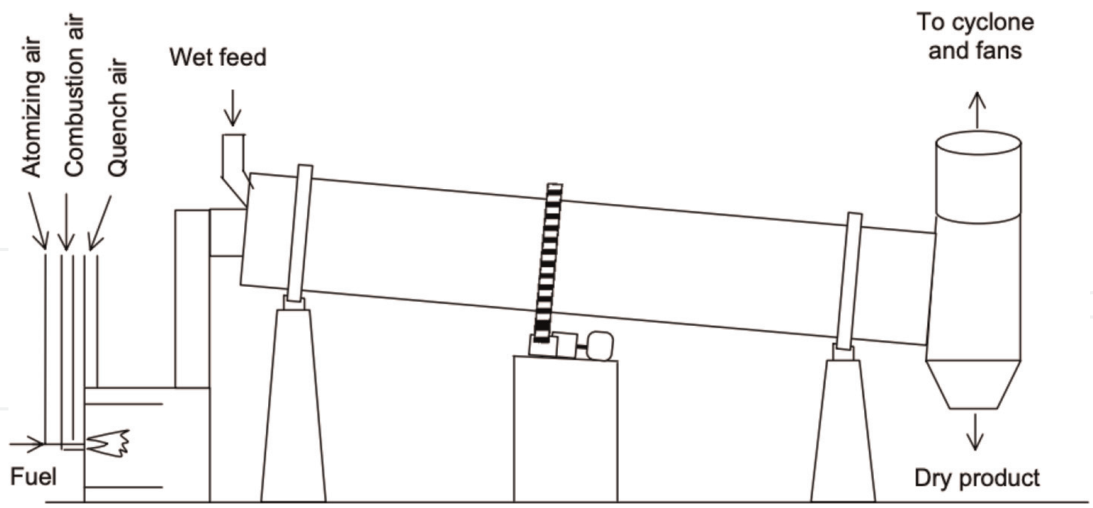

Figure 1.
Diagram of direct-heat rotary dryer.

3.1.1 Types of rotary dryers

A. Direct rotary dryer; it comprises a nude metal cylinder attached with or without flights. It is appropriate for low or medium-temperature processes, which is limited by the of metal characteristics strength;

B. Direct rotary kiln; it comprises a metal cylinder padded in the inner with isolate bulk or refractory brick, to be appropriate for process under maximum temperatures;

C. Indirect steam tube dryer; it comprises a bare metal cylindrical shell together with one or more rows of metal tubes composite longitudinally within it. It is appropriate for the process up to the obtainable steam temperature or in processes that required cooling for the water tubes;

D. Indirect rotary calciner; it comprises a nude metal cylinder encompassed by an electrically or fired heated furnace. It is suitable for procedure at temperatures up to the highest, which could be tolerated by the cylinder metal that being generally from 800 to1025 K for stainless steel, when from 650 to700 K for carbon steel; and

E. Direct Roto-Louvre dryer; it is the most important type, as the product proceeds in a crosscurrent movement to the gas. It is appropriate for medium and low - temperature processes.

However, the period that molecules spend in the active step is low, consequently affecting the process energy efficiency. The prospect of the rotary and crossflow for the wood chips drying was acheived by Cairo et al. [31] when they reported that the best execution was pointed out by the crossflow dryer.

3.1.2 Combined conduction-convection heating rotary dryer

For drying the high-moisture paddy in the field conditions, a combined conduction and convection heating rotary dryer for 0.5 t/h capacity was designed and developed

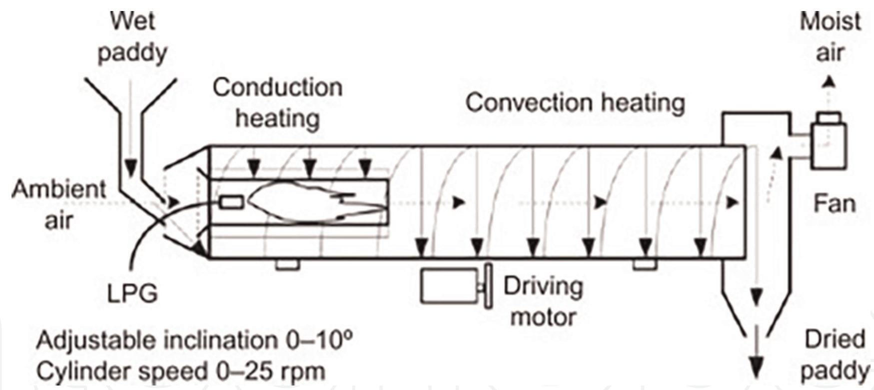

Figure 2.
A schematic drawing of combined conduction and convection-type rotary dryer.

by Likitrattanaporn et al. [32] by using liquefied petroleum gas (LPG) as the heat source. Moreover, a trial rotary dryer proposed with a system of concurrent flow comprising two main parts, a discharge cover, and a double cylinder is illustrated in **Figure 2**. The forward motion of the paddy happens by rotary motion of the cylinder and inclination angle. The air is inflated within the cylinder by a suction fan positioned on the discharge cover top. A 1-hp motor with a 1–60 reduction gear was utilized for driving the rotary dryer. LPG bulb on the entry edge heats the air. The heated air stirs to another end by the suction fan. Through the forward movement, the paddy contacts the external surface for the interior cylinder. Where, the conduction heating occurs followed by a cascading activity over the interior of the outer cylinder, which causes a convection heating. After this, paddy is placed into the emptying cover and got out of the dryer. When the suction fan absorbs the humid air, comparatively less humidity is taken away through the last or third pass at 100°C and 110°C, meaning 1.5% and 1.7%, respectively. At 120°C, the humidity content of 2.1% could be extracted. Clearly, this is because there was less free water available at the third pass of drying [33].

3.2 Fluidized-bed dryers

Fluidized-bed dryers (FBDs) are used extensively for the drying of wet particulate and granular materials with sizes ranging from 50 μm to 5 mm that can be fluidized, and even slurries, pastes, and suspensions that can be fluidized in beds of inert solids [34]. Here, the product is held aloft in a high-velocity hot air stream, thus promoting good mixing and heat transfer for uniform and rapid drying (**Figure 3**). FBDs are commonly used in processing many products such as chemicals, carbohydrates, foodstuff, biomaterials, beverage products, ceramics, medicines in agglomerated or powder form, healthcare stuffs, fertilizers, agrochemicals and pesticides, detergents, pigments, and surface-active agents, tannins, polymer and resins, as well as products for combustion, calcination, incineration, waste management, and environmental protection processes. Fluidized-bed operation offers imperative benefits such as good materials mixing, high amounts of heat and mass transfer, as well as easy material moving [34].

The air passages across a cribriform tray from below the foodstuff in addition to check it. The fragments are consumed in one end and from above. This support pushing along pieces formerly in a dryer, which they leave at the other termination. This is fortified by the lower-humidity fragments having lesser density and mass. This

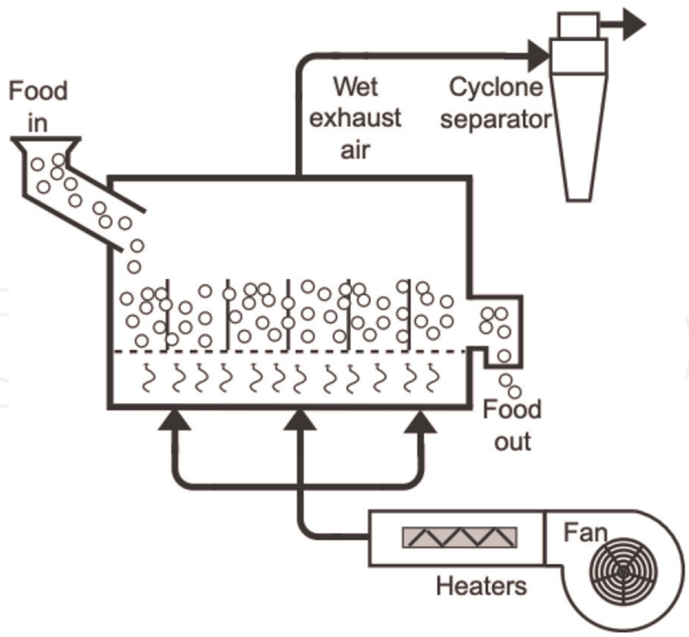

Figure 3.
Fluidized-bed dryer.

system has a suitable thermal efficiency and reduces individual fragments over warming [35].

The traditional fluidized bed is made by passaging a gas stream from bottom of bed for special materials. With little gas speeds, the bed of units is packed, which rests on a gas distributor plate. The passages of fluidizing gas is done over wholesaler, which regularly spread crossways bed [35]. The pressure droplet through the expansion of bed as the velocity of fluidizing gas is improved. At a particular gas speed, a fluidized bed is formed when the whole bed weight is completely supported by gas stream. This state is identified as minimum fluidization,and the corresponding gas velocity is named minimum fluidization velocity. Pressure drop through the bed remains near the same as pressure drop at minimum fluidization even if the gas velocity is increased further. **Figure 4** demonstrates numerous particulate bed regimes from filled to bubbly bed when the gas velocity is boosted. The graphs express the bed pressure drops and bed void age under many regimes [35].

By superficial gas velocities greater than the lowest fluidization velocity, typically from 2 to 4 umf, the fluidized bed is controlled. The minimum fluidization velocity could be assessed experimentally and using numerous correlations [36]. It should be noted that these correlations have limitations such as particle size, column dimensions, and operating parameters. Thus, they are valid in a certain range of criteria and operating conditions.

3.2.1 Fluidized-bed dryer's benefits and limitations

Commonly fluidized-bed drying advantages included a removal of moisture high rate, easy material transport inside the dryer, high thermal efficiency, control easing, as well as low cost of maintenance. The fluidized-bed dryer's limitations comprise high electrical power consumption, high pressure drop, poor quality of some particulate stuffs, unsimilarity product quality for certain categories of such dryers, pipes and vessels erosion, fine particles entrainment, and particle pulverization or attrition, as well as fine particle agglomeration, etc. For detailed discussion, see [37].

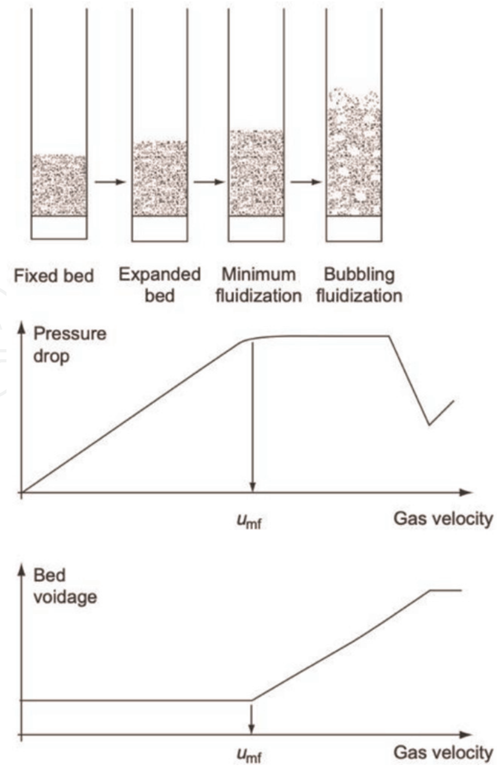

Figure 4.
Various regimes of a bed of particles at different gas velocities.

Similar to drying, the fluidized bed has located a varied range of industrial purposes in many industries for dedusting, granulation, mixing, coating, agglomeration, incineration, chemical reactions, gasification, combustion as well as cooling, etc. Many procedures could be combined to fluidized bed drying in the same processor for achieving more than two procedures in one unit. Practices that could be favorably integrated to fluidized-bed drying are explained briefly in the following. The mixing influence in a fluidized bed is commonly suitable for particles size within 50 and 2000 mm. In the case of fine particles, which are less than 50 mm, or for the case of particles that are hard to fluidize when moistened, vibration is generally applied to enhance the mixing effect and fluidization characteristic [35–37]. For large particles, the supplement of internals or the usage of the spouting mode can assist to develop the operation. Good particle mixing is essential for fluidized-bed drying. So, the awareness of particle characteristics and properties is required to ensure good fluidized-bed dryer performance. Moreover, the particles bed can be fluidized by an energetic flow or by bed fluidizing sections regularly such as the entire bed is fluidized in order once over a cycle. Evidently, this process results in saving drying air and therefore electrical power, but it leads to an elongated operating time due to the intermittent heat input mode. In addition, intermittent fluidization can decrease the mechanical damage problem to particles because of continual vigorous particles clash and corrosion-induced dusting [35–37].

Spray drying, coating, agglomeration, and granulation share similar basic operative standard. The fine spray of the solution paste slurry suspension is sprayed in a fluidized bed of inert particles or the drying substance oneself, which is already overloaded in the room drying. Solid particle development and formation take place in the room as evaporation and drying enthuse moisture [35]. In granulation, the growth of solid particles is acheived by succeeding wetting and liquid feed coating onto the solid particles and coated layer solidification by hot drying air. In the coating, a layer of the priceless active agent could be coated on a less expensive substrate or adding a surface agent on solid particles, which is necessary for downstream processing. Through spraying a proper binder onto the solid particles bed, granulated or agglomerated solid big-size particles are formed [35–37]. During most situations, sole spray drying is not power efficient to remove the whole wet content in solids. It is because a significant amount of heat and time are necessary for the elimination of internal water, which is stuck in the solids internally. The drying system of the fluidized bed could be combined as the second phase of drying for removing interior moisture. This could be followed by the third phase of fluidized bed cooling for preventing condensation troubles during the packaging in various applications [35–37].

3.3 Drum dryers

The drum dryer is normally used to dry slurries, pastes, concentrated solutions, or viscous on rotating steam-heated drums [38, 39]. This is because of the moisture boiling off and flashing or of irreversible thermochemical transformations of their content, which take place on their first interaction with the hot drum surface [40–42]. The viscous slurry or paste is automatically spread by spreading action of both counter rotating drums into a fine sheet, which follows to warmer drum within single-drum dryers or splitting sheets on both hot cylinders in double-drum dryers. The adhering fine paste sheet is then speedily dried conductively by excessive heat flux of steam condensation in the drum. In the case of humid slurries, which generate wet slabs, the wet thin slab drying could be improved by blowing heated dry air on the sheet outward. The fine slab has heat-sensible supplies, which could be dried also at a minor temperature in the vacuum [43].

It can be used in the irreversible thermochemical transformations during the slurry's first contact with the hot drum. This is to impart the certain required qualities together of the dried product [44]. In the case of starch slurries, to produce pregelatinized starch, the starch can be gelatinized before the sheet is dried. When the thin sheet is exposed to the high heat flux and high temperature for a short period, the pored structure is imparted to the dried slab, because of the speedy formation of vapor bubbles in the slab during drying. The pored goods are premium in immediate food constructions because they are more readily wetted and can be simply rehydrated. For this, a drum dryer is broadly utilized over the universe in pregelatinized starch fabrication for immediate food construction.

3.3.1 Types of drum dryers

The drum dryer was first patented for use in the manufacture of pregelatinized starch in Germany [45]. Number and configuration of drums, heating systems, and product removal have been considered in many experiments. The drum diameter varies from 0.45 to 1.5 m, and its length varies from 1 to 3 m. The drum wall thickness is between 2 and 4 cm. The drum dryer is classified according to the steam-heated drums number and configuration as well as the atmosphere pressure around the drying sheet.

3.3.1.1 Atmospheric double-drum dryer

This dryer type has a higher rate of production, it can handle a wide range of goods as well as it is more efficient [38–40, 46]. Across the pendulum nozzle or a header, there are several nozzles, the paste or slurry is nourished onto the tweak of two

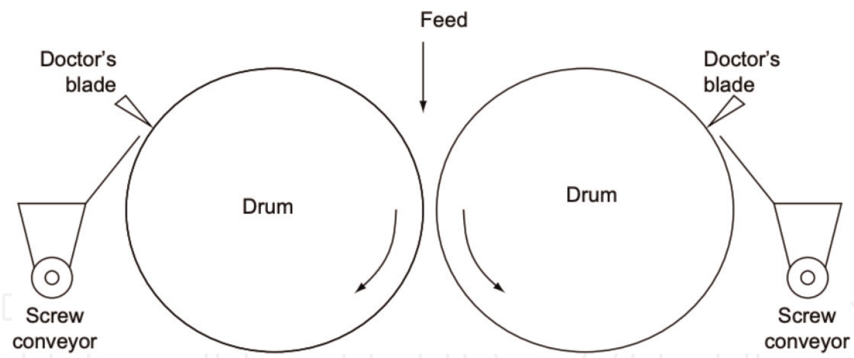

Figure 5.
Double-drum dryer with nip feed.

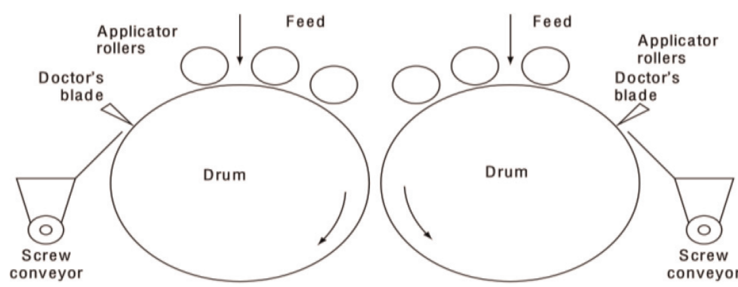

Figure 6.
Twin-drum dryer with applicator roller feeds.

steam-heated drums counter-rotating toward each other, making a boiling pool at the tweak as illustrated in **Figure 5**. The feedstuff could be nourished in the drum tweaks and applicator cylinder as shown in **Figure 6**. Starch slurries turn into gelatine in boiling pool to form pastes, which be extra sticky. The counter-rotation of the drums spread the slurry or paste into two soft slabs on both drums that subsequently dry conductively.

3.3.1.2 Atmospheric single-drum dryers

The paste or slurry is nourished throughout a header that has various nozzles or across a pendulum nozzle onto the tweak of a steam-heated drum and highly cooler applicator cylinder counter-rotating toward each other, then making a boiling pool at the tweak (**Figure 7**) [38–40, 46]. Starch slurries turn into gelatine in boiling pool, making pastes extra sticky. The drum counter rotation and applicator cylinder diffuse the paste/slurry into a soft slab on the warm drum, which subsequently dries

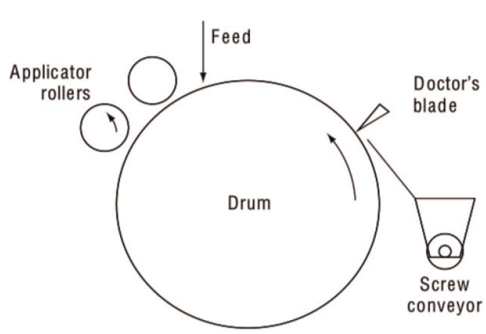

Figure 7.
Single-drum dryer with applicator roller feed.

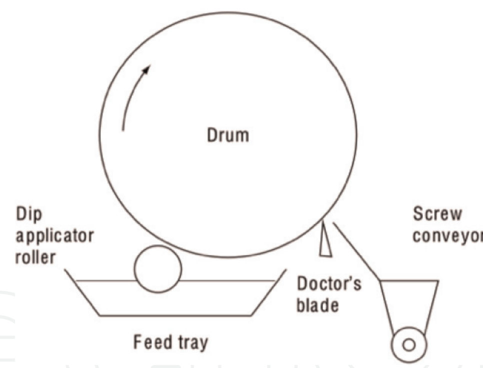

Figure 8.
Single-drum dryer with dip roller feed.

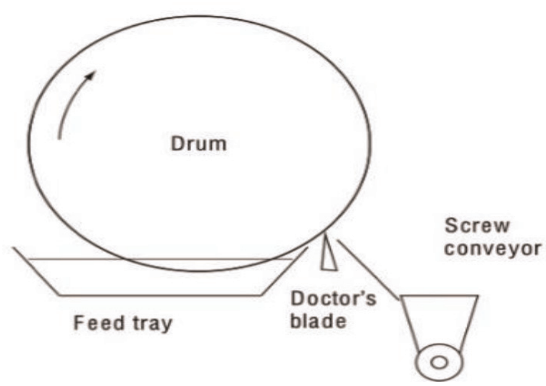

Figure 9.
Single-drum dryer with dip feed.

conductively. Otherwise, the slurry could be nourished by dip coating a dip or applicator cylinder in a feed plate at the dryer bottommost, then cylinder coated on the drum as illustrated in **Figure 8**. Also, the slurry could be nourished by dip coating the drum directly in the feed tray (see **Figure 9**) or scattered or marked from a feed plate as illustrated in **Figure 10**.

3.3.1.3 Atmospheric twin-drum dryers

The applied of slurry is by direct dip coating of the twin drums in the feed tray at the dryer bottom (**Figure 11**), or by splash, or spray feeders from a feed tank at the

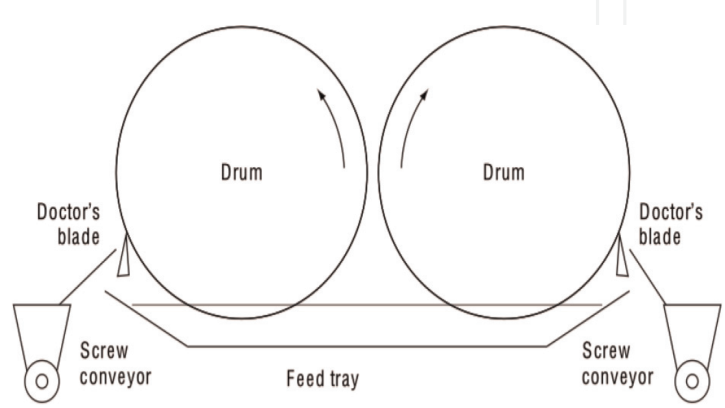

Figure 10.
Twin-drum dryer with dip feed.

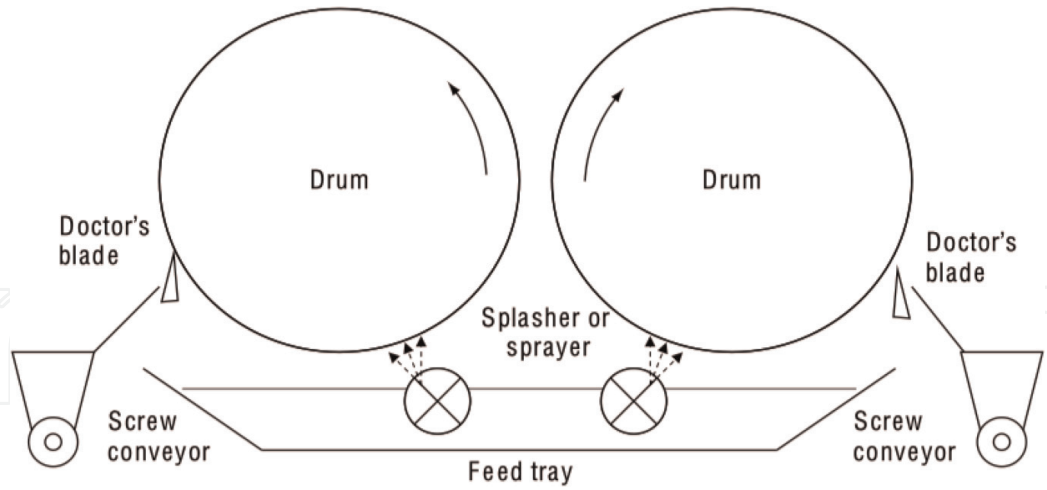

Figure 11.
Twin-drum dryer with splasher or sprayer feed.

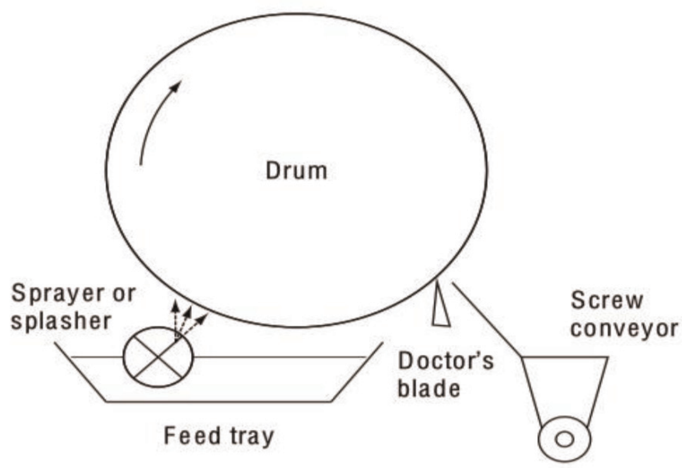

Figure 12.
Single-drum dryer with splasher or sprayer feed.

dryer bottommost (**Figure 12**) onto the top of the both steam-heated drums, which are counter-rotating faraway from each other [38–40, 46]. Sheets are made by cohesion onto the drum top and are held up versus gravity by their surface tension, then dry conductively. This kind of dryer is appropriate for mixtures that produce dusty stuffs.

3.3.1.4 Enclosed drum dryers

If the solvent steam other than humid discharged in the course of the drying by the drum requires to be improved, or if dried foodstuffs produce much powder, the atmospheric twin-drum dryers could be bounded in vapor or in dust-tight enclosure [38–40, 46]. The steam vapor could be retrieved by an appropriate condenser, and the dust could be eliminated using a wet scrubber.

3.3.1.5 Vacuum double-drum dryer

Heat-sensitive materials can be dried in a vacuum double-drum dryer where the dryer is enclosed in an airtight enclosure under a vacuum (**Figure 13**) [38–40, 46].

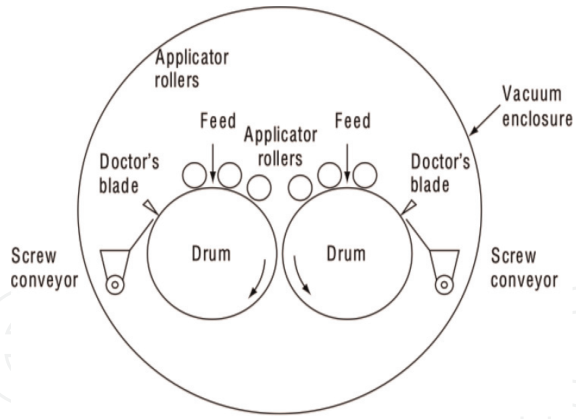

Figure 13.
Vacuum double drum dryer.

This dryer type is also attached to a vacuum pump, a scrubber, and a condenser. Dryer operation is like its atmospheric version excluding that there are two product basins: one is for vacuum breaking and the other is for product discharge.

3.4 Industrial spray drying systems

The development of spray drying equipment and techniques evolved over several decades. With the sudden need to minimize the food materials transport weight, spray drying was established during World War II. This method enables feed transformation from a fluid state into a dried particulate shape by feed spraying into hot drying media. It is a continual particle processing drying operation. The feed could be an emulsion, suspension, solution, or dispersion. The dried product could be in the shape of granules, agglomerates, or powders dependent on feed's chemical and physical characteristics, and the dryer scheme, as well as the final powder properties, desired [47]. Spray drying is a suspended particle processing (SPP) operation. This method uses fluid atomization for creating droplets. The droplets are dried into single particles when transferred to a hot gaseous drying media, generally it is air. It is considered a one-step continual unit processing procedure. Nowadays, over 25,000 spray dryers are used commercially to dry products such as fine and heavy chemicals, dyestuffs, dairy products, agrochemicals, and biotechnology products as well as mineral concentrates used in pharmaceuticals for preparing with evaporation capacities ranging from a few kg/h to over 50 tons/h.

Spray drying advantages:

- Biological products, pharmaceuticals, and heat-sensitive foods could be dried at atmospheric pressure with minimum temperatures. Sometimes the inactive atmosphere is used.

- Product characteristics are considerably further effectively controlled.

- Spray drying authorizes high-capacity production within the continual process and comparatively modest tools.

- Goodstuff links into contact together with the equipment surfaces in an anhydrous condition.

- A comparatively regular, spherical particle with about the same attribution of nonvolatile compounds as in the liquid feed is produced by spray drying.

- The efficiency could be compared with that of other types of direct dryers because the operative gas temperature might range from 150 to 600°C.

Spray drying disadvantages:

- If the product has a high bulk density, spray drying fails.

- Generally, the system is not elastic. If the unit is designed for fine atomization, it might not be able to make a coarse product and vice versa.

- The feed has to be pumpable.

- Has a high initial investment compared with other continuous dryer types.

- Increasing the drying cost when the product is recovered and dust collection.

Spray drying involves of three process phases: (1) atomizing, (2) moisture evaporation and spray-air mixing, and (3) separation of dry product from the exit air. Every phase is conducted according to the operation of the dryer as well as the design or chemical and physical properties of the feed, determining the features of the final product. A spray drying procedure model is illustrated in **Figure 14**.

3.4.1 New developments in spray drying

Numerous innovative designs and operational modifications have been proposed in the literature [48–51] although very few are readily available commercially due to incomplete knowledge about the new systems.

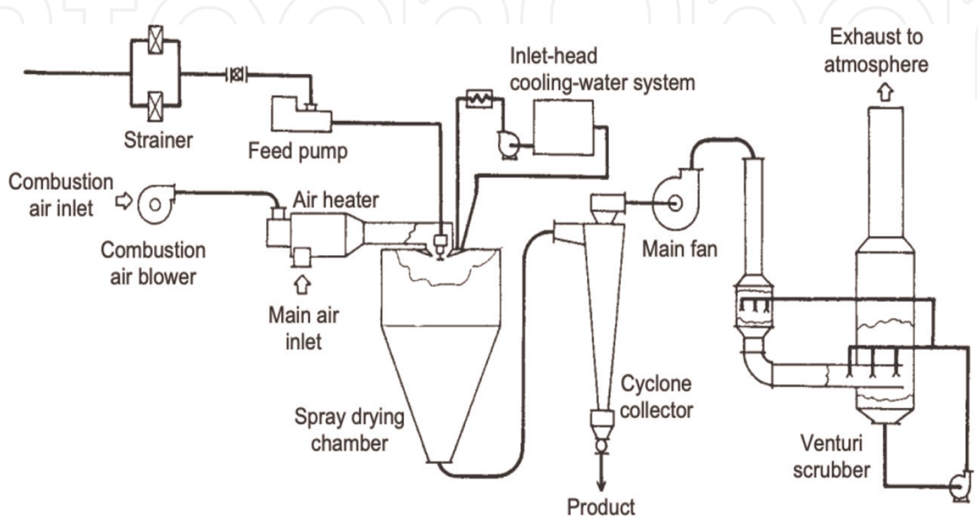

Figure 14.
Spray drying process and plant.

3.4.1.1 Superheated steam spray drying

Although superheated steam drying was proposed one century ago, the potential of superheated steam like a drying medium was not exploited industrially for half a century. The advantages of this type of drying are reviewed by [52] as follows:

- No oxidative damage
- No explosion hazards
- Recovery of potential heat supplied for evaporation
- Ability to operate at vacuum and high operating pressure conditions
- Minimizing air pollution by closed-system operation
- Producing a product with better quality under appointed conditions

When the constraints could brief to the following:

- The higher temperature of product
- The capital costs is higher than the hot-air drying
- The possibility of air infiltration making recovery of heat from exhaust steam is difficult using compression or condensation

The initial scheme of a superheated steam spray dryer was made by Gauvin [53, 54]. The patent on superheated steam spray drying was issued by Raehse and Bauer [55]. This drying has been examined using the CFD system by Frydman et al. [56].

3.4.1.2 Two-stage horizontal spray dryer

A horizontal spray dryer has been suggested as an alternative to the conventional vertical types [57, 58] for pharmaceutical materials and heat-sensitive food [59, 60]. The low temperatures of drying permit flavor reservation, controlled porosity and density, high solubility, as well as fine goodness agglomerated products. Essential energy provisions relative to the conventional vertical spray dryer with a lower electrical loading for a specific capacity.

A suggested design is described in **Figure 15**. The high-pressure pump is used for feed pushing to the spray nozzles. These nozzles are organized in several configurations. Then, the spray travels horizontally from the nozzles, and due to gravity, it goes down. After that, transporting of the dried powders using a conveying strap in the bottom and carried to bag filters or cyclones. A model for the horizontal spray dryer (6.0 m × 3.0 m × 3.0 m) has been presented by Cakaloz et al. [61].

In the single-stage horizontal spray dryer process (**Figure 16**), it has been shown that the dwell period might be overly short for allowing the droplets for drying completely. Therefore, to overcome this constraint, a new two-stage, two-dimensional horizontal spray dryer idea is suggested by Mujumdar [58] and shown in **Figure 15**,

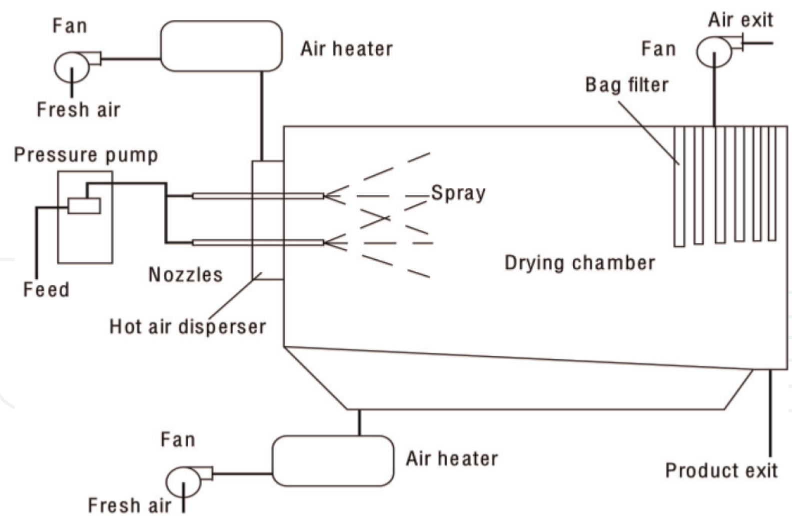

Figure 15.
Proposed layout of a two-stage horizontal spray dryer.

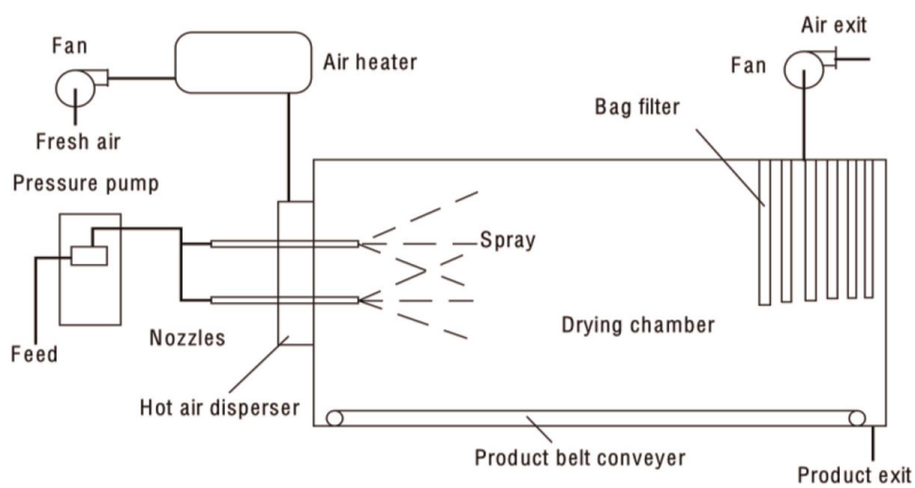

Figure 16.
Schematic layout of the horizontal spray dryer.

which is prepared for permitting long drying periods. This is necessary for big droplet sizes and heat-sensitive products. The variance between single and two-stage horizontal spray driers is that in the single spray drier, there is a fluid-bed dryer, which is installed at the horizontal chamber bottom. Whereas, the two-stage horizontal spray drier is not commercialized yet. The CFD process could be utilized to emulate the horizontal spray dryer, which should be connected to a fluid-bed drying system. The droplet's surface moisture is taken away rapidly from the chamber of spraying. While the inner water occupies longer, which could be extracted in a thin layer, out of a deliberation dryer in the bottom of the room.

3.4.1.3 Low-humidity spray drying

On occasion, it has to choose freeze dryers instead of spray dryers, particularly for pharmaceuticals and biochemicals drying. This is because spray drying utilizes high-temperature gas like the medium of drying and the sediments on the wall cannot be averted in feasible spray dryers. The products are subject to degradation by

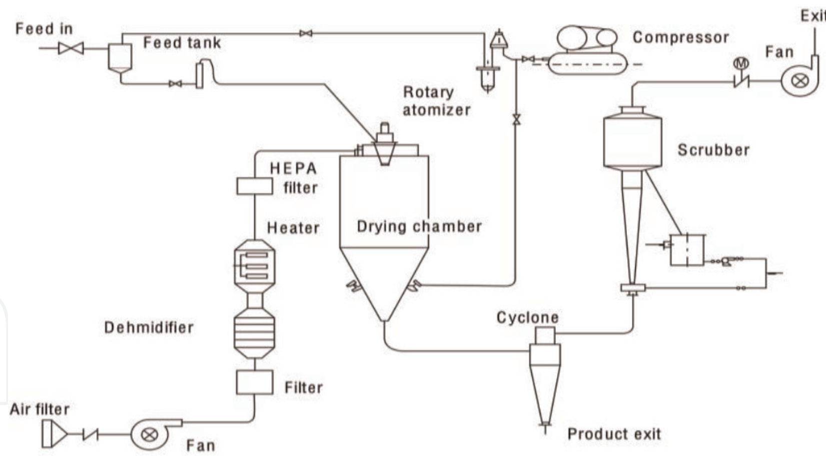

Figure 17.
Schematic layout of the low-dew-point spray dryer.

overheating [48]. Yet, the freeze dryer has high operating, and capital costs, as well as high energy consumption, compared with the spray dryer [62, 63].

To decrease the active compound degradation in the dried powders, a novel kind of spray dryer was proposed, such as low dew point (LDP) spray dryer. This type utilizes air at a nearby surrounding temperature of 80°C and quite minimum humidity (**Figure 17**). It comprises four units: the preprocessing system of drying air including heating and dehumidification; the preparation system of feed; the drying system and feed atomization including drying chamber, air disperser, and atomizer, etc., in addition to the system of product collection.

3.4.1.4 Spray freeze drying

The freeze drying (FD) is a significant drying machinery for pharmaceuticals, foods, and biochemicals, which could preserve the biological activity, aroma or flavor, etc. Freeze drying is a drying method, in which the solvent in the material is solidified at low temperatures, then sublimates directly from the solid into the vapor state under vacuum. The freeze-drying process of an aqueous solution contains three phases: product freezing, ice sublimation, and removal of solvent vapor. Nevertheless, compared with spray drying, the freeze drying is an order-of-magnitude costlier drying method because of its need for vacuum, refrigeration, and long operating times [64]. In a recent combination of both drying processes, called spray freeze drying (SFD), this process was carried out as a batch method as follows: The liquid nitrogen is atomized in a cryogenic medium to spray the droplets to freeze. Frozen droplets are scuttled in a cryogenic medium and processed out and dried in the freeze-dryer under a vacuum. A model flow slab is illustrated in **Figure 18**. This method is conducted in batches instead of continuously, because of the required long freeze-drying time. In addition, it is appropriate for high-significant products with low tonnages [65].

A new method called a combined atmospheric spray and fluidized-bed freeze drying (ASFBFD) process was examined. The planned schematic flow graph is described in **Figure 19**. It mainly comprises internal fluidized bed, drying or freezing room, liquid nitrogen cooler, internal bag filter, fan, nozzles, valves, pipes, pump, etc. [65].

The process is briefly explained as follows: The feed is transported into the nozzle from the top through a pump, where it is atomized using a nozzle. The fine spray is

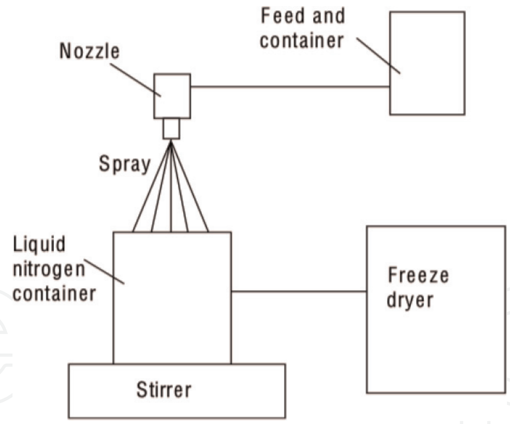

Figure 18.
A schematic flowchart of the conventional spray freeze drying.

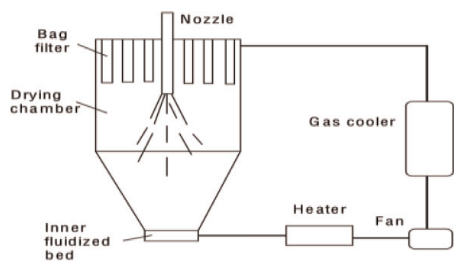

Figure 19.
Batch-type atmospheric pressure combined with spray and fluidized-bed dryer.

connected with freeze nitrogen or air immediately. Upon the material of feed, the drying medium is frozen to about −90°C using liquid nitrogen and inflated by a fan within the fluidized-bed cribriform tray. The fluidized bed is placed at the bottom of the chamber. As the temperature of the cool air is lower enough for spray freezing, the frozen atoms conserve their main conditions and go to the bottom or to the fluidized bed through gravity. Nearly a few frozen atoms might be restricted by air or nitrogen; nonetheless, they are detached from the air using the interior bag filter. Throughout the phase, the spray freezing drying is investigated continuously until the exhaustion of feed in the batch procedure. After this phase is completed, suitable drying terms are chosen, such as liquid nitrogen, which is regulated to meet freeze-drying terms. Drying actual operation and its time terms should be specified. Many investigators have already investigated many studies on atmospheric freeze drying [66–72]. These reviews showed that the atmospheric spray and fluidized-bed freeze drying grouping is a viable new procedure that needs additional R&D. Lastly, a summary of the comparison between the four drying processes, such as SD, FD, SFD, and ASFBFD, is assumed in **Table 1**.

3.4.1.5 Encapsulation

Spray drying and fluid-bed drying lead to another common food application of these technologies, that is, microencapsulation. It is defined as a process by which one material or more is entrapped within alternative material [73]. This method is generally used to prevent the core material from degradation and to control releasing or separate reactive constituents in a formulation. Because the spray dryer is generally fast, available, economical and produces good-quality products [74], it enhances the

Drying method	**Spray drying (SD)**	**Freeze drying (FD)**	**Spray freeze drying (SFD)**	**Atmospheric spray and fluidized-bed freeze drying (ASFBFD)**
Drying period	Short	Long	Long	Medium
Final shape	Irregular or agglomerated	Cake	Porous and spherical, mono	Porous and spherical
Power requirments	Low	High	Highest	Medium
Quality dried product	Medium	Good	Good	Good
Operation	Continuous	Batch	Batch	Semicontinuous
Productivity	High	Medium	Low	Medium
Cost	Low	High	High	High

Table 1.
Drying method properties [65].

most public means of encapsulation process. This procedure is simple and comparable with the one-phase spray drying technique. The coated substance is named active or core substance, and the coating substance is entitled a shell, while the wall substance is called a carrier or encapsulant [75]. The encapsulated active substance is scattered in the hydrocolloid transporter, such as maltodextrin, dextrin, Arabic gum, gelatin, and modified starch. Subsequently, the emulsifier is supplemented, and the mix should be homogenized to compose an oil-in-water emulsion, then it's consumed by the atomizer for the spray dry. In the drying room, the aqueous stage dries, and the active substance is captured as atoms through the protein film or hydrocolloid, discharging of the active substance from capsules under specific terms. The temperature, moisture, and pressure are the main controlling factors of its release [76].

3.4.2 Energy efficiency enhancement

Spray drying is an energy-intensive procedure. With the increased energy costs with overall production stage changes, spray dryer consumers have to look for techniques to enhance the spray dryer system's thermal efficiency. For typical single-stage drying, the best method to control energy practice is to raise the inlet temperature and keep the outlet temperature low, as well as take full benefit of the energy introduced. Nevertheless, the weakness of this procedure is the potential product degradation in food spray drying [52, 77, 78].

3.5 Freeze drying

Freeze drying is used for high-quality foodstuffs stabilization, certain biological materials, and pharmaceuticals such as proteins, vaccines, bacteria, and mammal cells. These substances are freeze-dried; thus, the quality of the dried product is retained [63, 79]. Freeze drying is a process in which the water or another solvent is sublimated by the direct transition of water from solid (ice) to vapor, thus omitting the liquid state, and then desorbing water from the "dry" layer [80–84].

As a rule, freeze drying produces the highest-quality food product obtainable by any drying method. This is due to the fact that freezing water in the material prior to lyophilization inhibits chemical and biochemical such as non-enzymatic browning, protein denaturation,, microbiological, and enzymatic reactions processes. Consequently, the content of various nutrients, smell, and taste do not change. Raw materials comprise water, ranging from 80% to 95%. The water is removed by sublimation resulting in extremely porous structure creation of the freeze-dried products, and the finalized rehydration or lyophilizing happens immediately when water is added to the substance at a later time [85, 86]. However, the water in foodstuffs could be free or bound to the solution using different powers. The free water is freezed, but the bound does not. In the freeze-drying method, the iced and some bound water should be detached. Consequently, lyophilization is an extremely complex and multistep procedure that comprises (a) freezing under atmospheric pressure phase, (b) main drying; appropriate freeze drying; ice sublimation, at decreased pressure. For example, iced water is managed, then sublimation at 0°C and absolute pressure of 4.58 mmHg could happen. Nevertheless, subsequently the water usually exists in a solution or a joint state, the substance should be cooled below 0°C to preserve water in a frozen phase. So, during the main drying step, the frozen layer temperature as showed in **Figure 20** is at −10°C or lower at absolute pressures of about 2 mmHg or less. As the ice sublimes, the sublimation interface, which began at the external surface (**Figure 20**), dried material retreats and porous shell residues. The latent heat (2840 kJ/kg ice) could be operated using the dried substance and frozen layers, as illustrated in **Figure 20**. The vaporized water is conveyed within the dried substance porous sheet. Through the main drying step, in the dried layer, a large amount of nonfrozen water might be desorbed. The desorption method might affect the amount of heat that reaches the sublimation interface, and subsequently, it might affect the velocity of the sublimation front moving. The period when there are no frozen sheets is possessed to perform the end of the primary drying phase. (c) Secondary drying phase; desorption drying; drying the product to the required final humidity, this stage starts at the end of the primary drying stage, and the desorbed water vapor is transported through the pores of the material that is dried [63, 80, 87]. During the above three phases, six main physical phenomena could be distinct, which have a significant impact on the process path, the quality of the obtained substance, and

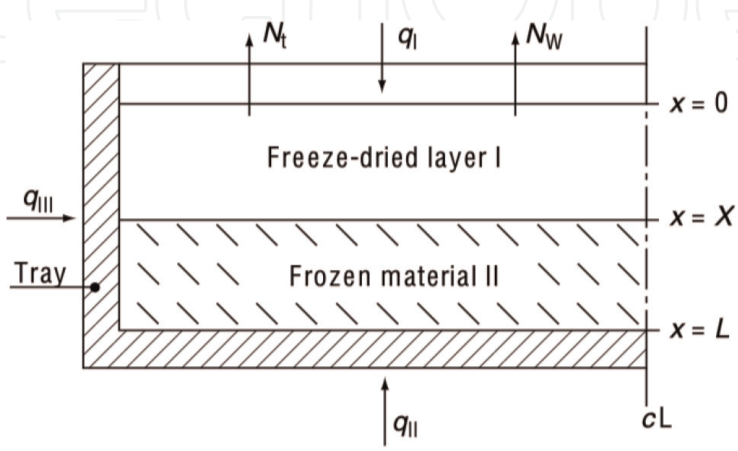

Figure 20.
Diagram of a material on a tray during freeze drying. The variable X denotes the position of the sublimation interface (front) between the freeze-dried layer (layer I) and the frozen material (layer II).

its overall costs [88]. Those phenomena are as follows: the water is transitioned into ice, then the ice to a vapor phase, the water particles are desorpted from substance structures, the obtainment of sufficiently low pressure, the re-sublimation of water vapor removed from the substance on the condenser surface, and the removal of a layer of ice from the capacitor surface.

In this context, the conditions of the freeze-drying process should be selected in a way that does not melt the water. The presence of water during freeze drying may result in many changes in the composition, morphology, and physical properties of foods (e.g., shrinkage), then reducing product quality during storage [89]. The effect of freeze-drying conditions on the nutritional properties, antioxidant activities, and glass transition characteristics of different food materials can be found in the literature [90–95]. Despite the long processing time and high cost, it is preferred for extreme-quality products. Though some damages in bio compounds could be set after freeze drying, this method is preferable to maintain nutritional qualities, particularly when operated under a vacuum. Moreover, the quality parameters such as freeze-dried products' rehydration and porosity are favorable for manufacturing foods. Newly, the freeze-drying process condensation with innovative technologies or pretreatments permit overcoming some of these drying processing challenges [96].

3.5.1 Microwave freeze drying

The limitations on heat transfer amounts in conventionally managed freeze-drying operations have led to providing internal heat generation with the use of microwave energy [97, 98]. Hypothetically, the use of microwaves must result in an instant drying rate, because the transferring of heat does not need internal temperature slopes and the temperature of ice could be preserved near to the maximum allowable temperature for the frozen layer exclusive of the need for extreme surface temperatures. For example, if it is allowable to keep the iced layer at −12°C, after that it has been assessed that the drying time for an ideal process using microwaves for a hypothetical 1-in. slab would be 1.37 h [99]. It should be notable that this drying time compares very approvingly with 8.75 h needed for the heat input within the dry layer, while 13.5 h for heat input within the iced layer without the removal of dry layer, and even with relatively short time of 4 h of drying for continuous removal of dry layer. Examining the freeze drying of a 1-in.-thick slab beef, the actual drying time of slightly over was 2 h, compared with 15 h for traditionally dried slabs [100]. Despite these benefits, the microwave application has not been successful [99, 101–105]. Because of the following reasons: (A) Supplied energy in the microwave form is too expensive [101]. (B) The tendency to glow discharge, which could cause gases ionization in the room and food deleterious changes, and losses of useful energy. The tendency to glow discharge is larger in the pressure ranged from 0.1 to 5 mmHg and could be decreased by operating the freeze dryers at pressures under 50 mm. The operation at low pressures has a double drawback: (1) it is much expensive, because of the demand for condensers operating at a very low temperature and (2) At these low pressures, the drying rate is much slower. (C) The process control is very difficult. Meanwhile, water has an inherently greater dielectric loss factor than ice, any localized melting produces a rapid chain reaction, which results in runaway overheating. (D) The economical equipment suitable for a large continuous scale is not yet available. In spite of these constraints, microwave freeze drying is considered a potential development [101].

3.5.2 Industrial freeze dryers

The main types of industrial freeze dryers include the following:

3.5.2.1 Tray and pharmaceutical freeze dryers

The hugest amount of industrial freeze dryers in process are of the vacuum batch style with freeze drying of the food stuff in trays. There are two main styles, depending on the type of condenser used. The first style showed the condenser plates in the same chamber and near the tray-heater assembly. The second style is representing the condenser in a separate chamber linked to the first by a wide, in over-all, butterfly valve. This latter type of the factory is permanently used in pharmacological industries, but it can also be used for freeze-drying foods. To reduce product contamination risk, especially in the pharmaceutical industries, a new freeze-dryer plant concept has been developed. The system, as illustrated in **Figure 21,** has two doors: a little one is for charging the stuff before drying, when the full door, which is opposed to the little door, is for discharging the stuff after drying. The condenser is positioned on the floor, which is under the first floor, where the drying chamber is placed. The freeze dryer shelves are lowered to the drying chamber bottom and then lifted one by one to a location in line with the filling machine. The charging of foodstuff is prepared under a laminar flow of sterilized air; the little door is unlocked only for each plate filling and then is directly closed [87].

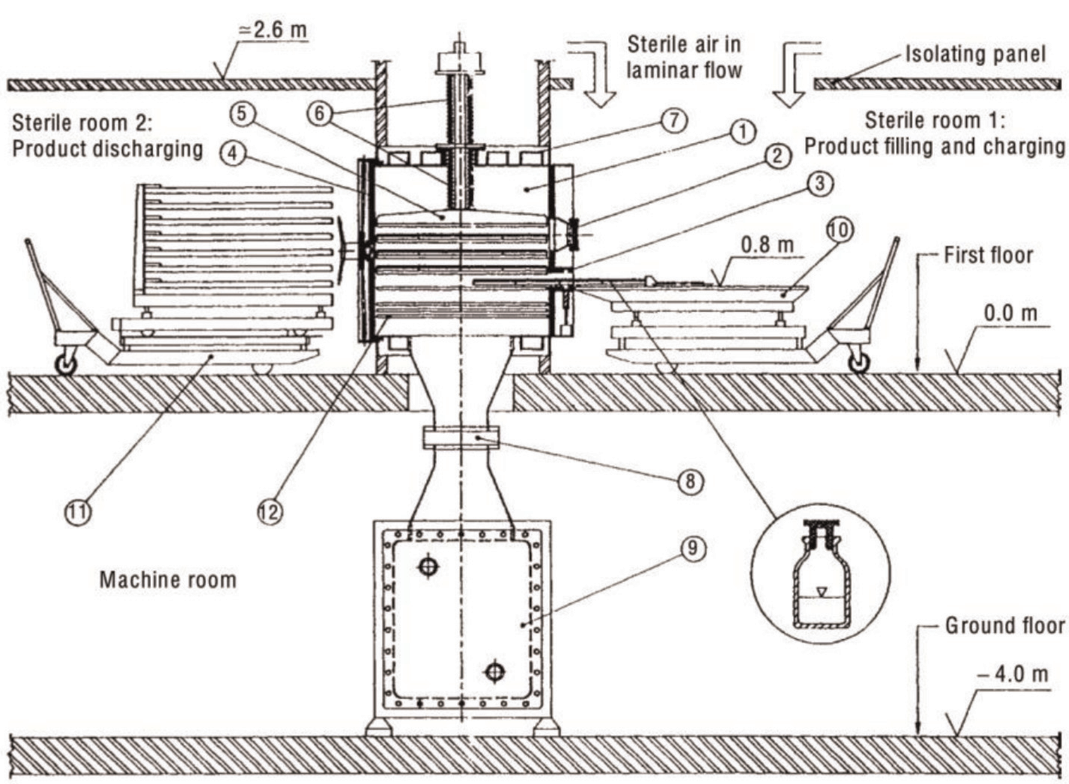

Figure 21.
Industrial freeze dryer design with stoppering device (Criofarma model C300-7): 1, drying chamber; 2, inspection window; 3, automatic small door opening; 4, full door; 5, hydraulic press for stoppering the bottles after drying; 6, PTFE elbows for double sterile condition inside the stoppering plug; 7, reenforcing member and cooling coils after steam sterilization; 8, isolation butterfly valve; 9, ice condenser chamber; 10, loading device; 11, discharging device; 12, unloaded shelves.

3.5.2.2 Multi-batch freeze dryers

The freeze-drying system in a batch factory is usually programmed and organized to minimalize the drying time and enlarge the factory production. With a single-batch factory, the load on the several systems will be very variable during the drying rotation. The product flow and handling operations will be alternating because of the batch process specifically. This means that optimum use of supplies will not be probable in a sole-cabinet batch system. To extent this weakness, an industrial freeze-drying factory is built with numerous batch cabinets instructed to operate with staggered and overlying drying rotations. Each cabinet can be filled with materials from the same system, and they are assisted by the similar central system for vacuum pumping, tray heating, and condenser refrigeration. Although, the procedure is individually organized in each cabinet from a unattached control panel. This builds probably the simultaneous different foodstuffs production, which rises the operation flexibility of the factory. With only two cabinets in operation, an important part of the batch weakness may be excluded; for example, with four cabinets, an excellent leveling of loads will be accomplished. A huge amount of industrial freeze-drying factories operate today in this style as multi-cabinet batch factories [81, 99, 106].

3.5.2.3 Tunnel freeze dryers

The process in the tunnel freeze dryer (**Figure 22**) takes place in a large vacuum cabinet into which the tray-carrying trolleys are loaded at intervals through a large vacuum lock at one end of the tunnel and discharged similarly at the other end. The drying conditions are carefully controlled in a number of sections of the tunnel by temperature-pneumatic controllers [81]. The plates of vapor constriction fit closely inside the channel walls yet permitting the trolleys to passage through two locations in the tunnel main unit, and gate valves turn off the locks from the main unit. Thus, the tunnel is divided into five autonomous process zones. When trolley is not moving during the period, a tray-lifting scheme causes all trays to sit in each trolley on heaters below the top. The heaters consume flat-top surfaces and ribs under which vacuum

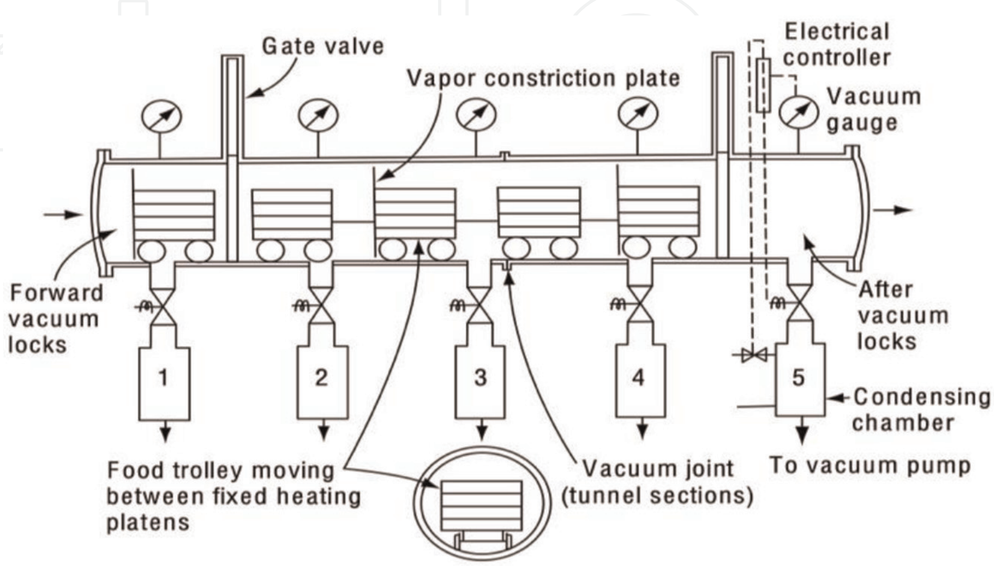

Figure 22.
Typical tunnel freeze dryer schematic diagram.

steam passes. They are cantilevered in couples from both sides of the tunnel. Vacuum steam heating has numerous benefits, including high latent heat of condensation and temperature control operating pressure. The cooling system comprises a great aqua ammonia absorption freezer instead of a compression factory. Because of easiness with the refrigeration, load can be diverse by controlling the feed of oil to the boiler that heats the absorber.

The whole capacity of the tunnel freeze dryer can be boosted as it increases volume of business. Large business factories for cottage cheese and coffee processing have been set up in this way. The tunnel freeze dryers have the same benefits of factory capacity operation that can be attained as in multi-batch factories. On the other hand, the flexibility for simultaneous production of materials or in swapping between products is missing.

3.5.2.4 Vacuum spray freeze dryers

The vacuum spray freeze dryer system is illustrated in **Figure 23**. It has been industrialized for tea infusion, coffee extract, or milk. The product is applied by spraying from a sole jet upward or downward in a cylindrical tower of about 3.7-m diameter by about 5.5-m high [81, 107]. The solutions are solidified into little particles by evaporative freezing. In the tower, a frozen helical condenser is coiled between the internal wall and central hopper, the latter accumulating the partially dry powder as it drops freely to the tower bottommost. This is in turn associated with a tunnel where the drying technique is accomplished on a stainless-steel belt migrant among radiant heaters. The dried material passes into a hopper that feeds a vacuum padlock, allowing alternating product removal for packing. The whole system operates under a vacuum of about 67 Pa. In the initial evaporation, the diameter of frozen particles obtained by spraying into a vacuum is about 150 mm and loses about 15% moisture, and there is no sticking of these particles.

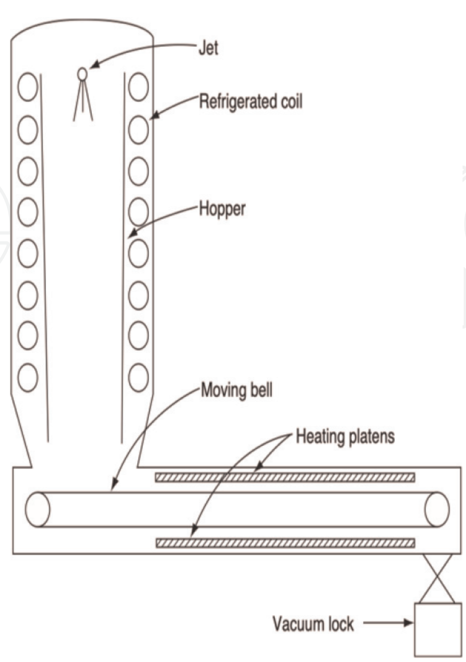

Figure 23.
Vacuum spray freeze dryer layout.

3.5.2.5 Continuous freeze dryers

Continuous freeze dryers are used for products drying in trays and for agitating bulk material drying. When the product is handled in trays, then the most delicate treatment of the product is attained. The food material is placed in the tray. Hence, it is not exposed to scratch, and it falls in contact with surfaces only that completely meet required hygiene values. While agitating a crushed product, more efficient heat transfer to sole product particles can be realized. Thus, a significant decrease in the heating surface is achievable. Although, scratch of the product by agitation increased the production of water vapor per unit, the heating surface tends to bring little product particles with vapor stream away from the bulk bed of product and cause product loss. Any system problems for water vapor elimination to retrieve the product loss may more than counterbalance the advantage of the higher heater surface load [108]. The heat transfer to the product and the trays is by radiation, which is the easiest mode to safeguard a correct as well as consistently distributed heat transfer to the material during the practice. The radiant heat is formed by horizontal heater saucers that are gathered within temperature zones. Each tray remains for a fixed time in each temperature zone for drying time minimized [108].

4. Electromagnetic waves dryers

Electromagnetic spectrum ((EMS) is the range of all wave types of EM radiation represented in Radio, Microwave, Infrared, Visible light, Ultraviolet, X-ray, and Gamma-ray. It is known that the Sun is a source of energy across the full spectrum, and its electromagnetic radiation covers the atmosphere constantly. The EM waves already have several applications in the agriculture field such as imaging, remote sensing, quality sensing, and dielectric heating in both pre-harvest and post-harvest treatments as shown in **Figure 24**. Agricultural products are considered dielectric materials and thus can store electric energy and convert it into heat. The converted heat is different from one plant to other according to its permittivity (ε) in general. This value of permittivity (ε) is noticeably frequency-dependent. Therefore, the dielectric constant parameter for agricultural products varies with frequency. For instance, the permittivity (ε) of water has an absorption peak in 24 GHz frequency. As a result, the temperature of the water stored in the agricultural products rises and evaporates, its moisture content decreases, and the drying process takes place. As a result, the drying processes of agricultural products using electromagnetic waves took a great place compared with traditional methods of drying, especially for agricultural products that are highly sensitive to heat, as one of the best modern technological solutions to maintain the quality of agricultural products and the production of dried products. Therefore, in the following, the most famous electromagnetic spectrum bands used in the drying process will be presented, which are both infrared and microwaves.

4.1 Infrared dryers

Conserving energy and achieving the best quality of dried products have become the most important factors that determine the usefulness and success of operating any drying unit. Where heat is transmitted through the drying unit in three forms

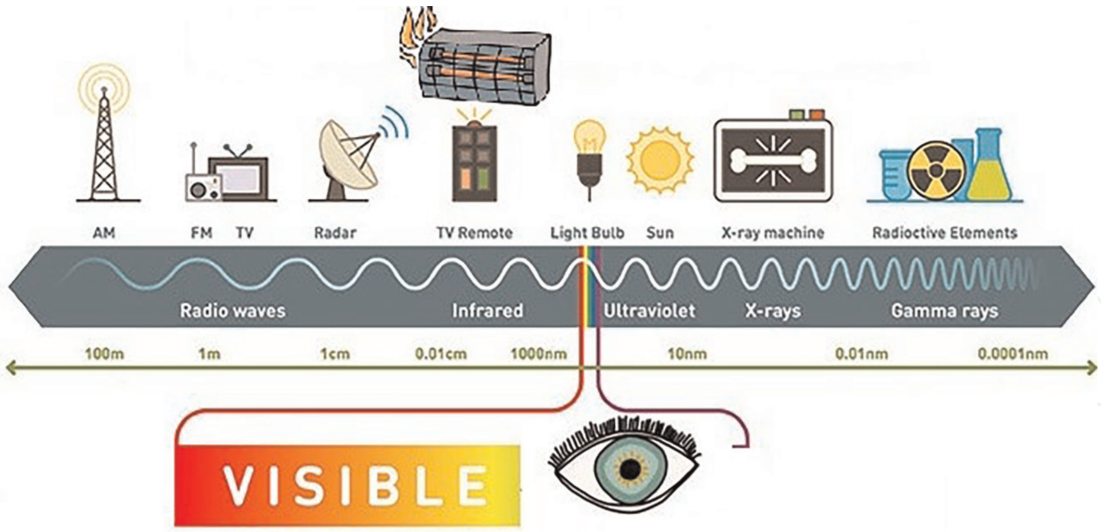

Figure 24.
Shows some applications of the EM spectrum.

conduction, convection, and radiation. In this regard, when the temperature of the fresh material increases, the molecular motion gains more energy; as a result, it causes changes in the structure of the material as well as its chemical properties to increase the shelf life and improve the quality [2]. Drying agricultural products, one of the most important processes of food processing and preservation, is a high priority in achieving food security. Where, drying process aims to improve the stability of food products, by reducing water activity, which leads to a decrease in microbial activity and thus limits physical and chemical changes during the storage of dried products [109]. The common conventional approach to the drying process is using convection heat transfer by transferring heat from hot air to the target product by convection, and as a result, the water evaporates into the air also by convection. However, this conventional drying method was characterized by many related disadvantages such as time consumption, low efficiency, unfair exposure to high temperatures, quality variation, in addition to high energy consumption [110]. These disadvantages of traditional drying by convective led to the innovation of other drying technologies to overcome these drawbacks such as drying by microwave, infrared (IR), osmotic drying, fluidized bed, and hybrid drying methods (integrating two or more drying methods). IR drying technique is one of the most important modern drying technologies compared with traditional drying because it is characterized by short process time, uniform temperature, high heat transfer coefficient, good quality of final products, improved energy efficiency, and safe as mentioned [111–113]. Therefore, [114–119] concluded that drying by IR heating is a promising method to achieve high-quality dried products and is suitable for fruits, vegetables, grains, and other high-value products. IR heat derives from the IR radiation that lies between the visible light (Vis) spectrum and the microwave band along the electromagnetic spectrum as depicted in **Figure 25**. IR drying technology idea is based on making changes in the electronic, rotational, and vibrational states of the atoms and molecules of the fresh material when exposed to IR radiation within the wavelength range of 780–106 nm.

IR band is divided into three regions, near-IR (NIR) is the first region whose wavelength ranges from 750 to 2500 nm to 0.75–1.4 μm at temperatures between 400 and 1000°C, the second region called mid-IR (MIR) with wavelength ranges from 2500 to 25,000 nm to 1.4–3 μm at temperatures between 400 and 1000°C.

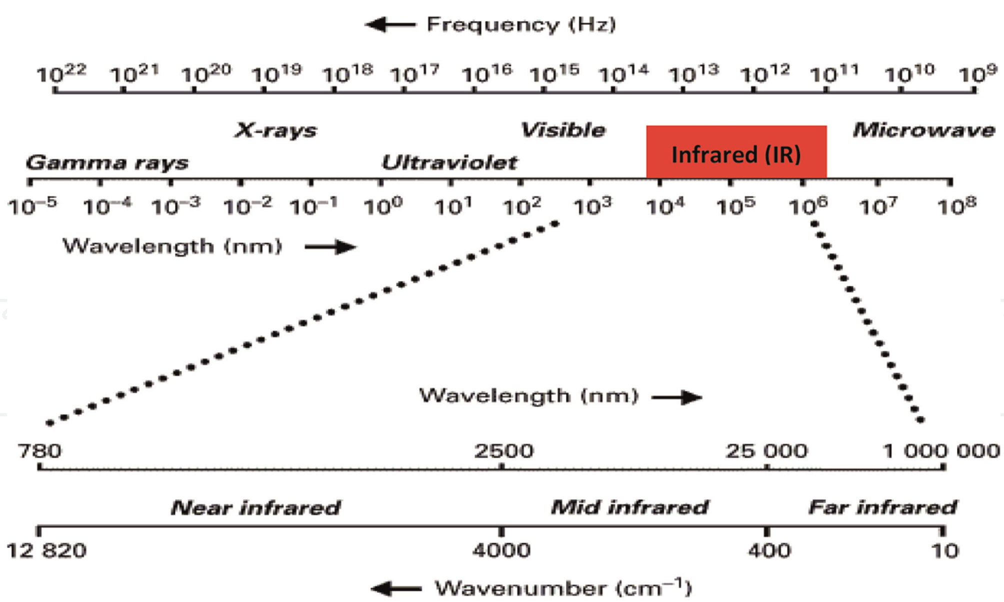

Figure 25.
Depict highlighting infrared (IR) radiation region.

While the wavelength of the third region (far-IR, FIR) ranged from 25 × 103 to 106 nm ≃3–1000 μm at temperatures above 1000°C [120, 121]. After IR radiation penetrates the fresh material surface, IR rays move and vibrate the constituent molecules of the fresh material through the frequency of the IR band within a frequency of 60 × 103–150 × 103 MHz, which results in friction between the molecules and leads to rapid internal heating [114, 122–124]. There are many sources of IR radiation according to their operational power, whether they are electrically heated or gas-fired generators to generate IR energy. The most common electrical heated sources are reflector-type IR incandescent lamps (incandescent vacuum lamp, gas-filled lamp, and tungsten halogen lamp), IR emitter-type quartz tubes, ceramic, and radiant panels as shown in **Figure 26**. While the traditional IR sources used for heating are electric heaters that produce infrared radiation in a range of 1100–2200°C and gas-fired generators, which consist of a perforated metal plate heated by gas flames until the temperature of the metal plate rises and infrared energy is radiated at a temperature range of 343–1100°C [110, 125, 126]. IR radiation sources can provide different wavelengths ranging from short to long wavelengths according to the voltage value applied to the IR emitters. The efficiency is another significant factor in the evaluation of both electric IR heaters and IR gas heaters, where the efficiency of electric IR heaters ranges from 40 to 70%, more than the efficiency of IR gas heaters, which ranges from 30 to 50%, and emit medium to long IR. In addition, Sheridan and Shilton, 1999, mentioned that the appropriate IR wavelength for industrial heating ranges from 1.17 to 5.4 μm, which corresponds to temperature values from 260 to 2200°C, and found that the best efficiency of heat transfer by IR radiation source occurs when the heater turns red. The idea of electric infrared emitters is based on passing an electric current to an electric heater through a high-resistance wire such as nichrome wire, iron chromium wire, and tungsten filament. When the metal wire is heated to the glowing stage and the temperature rises to 2200 K, it will emit NIR with a wavelength between 0.7 and 1.4 μm. Accordingly, the Incandescent lamp type for producing IR radiation is classified as a short-wave IR emitter, while the quartz tube type is classified as a medium-IR wave emitter [126].

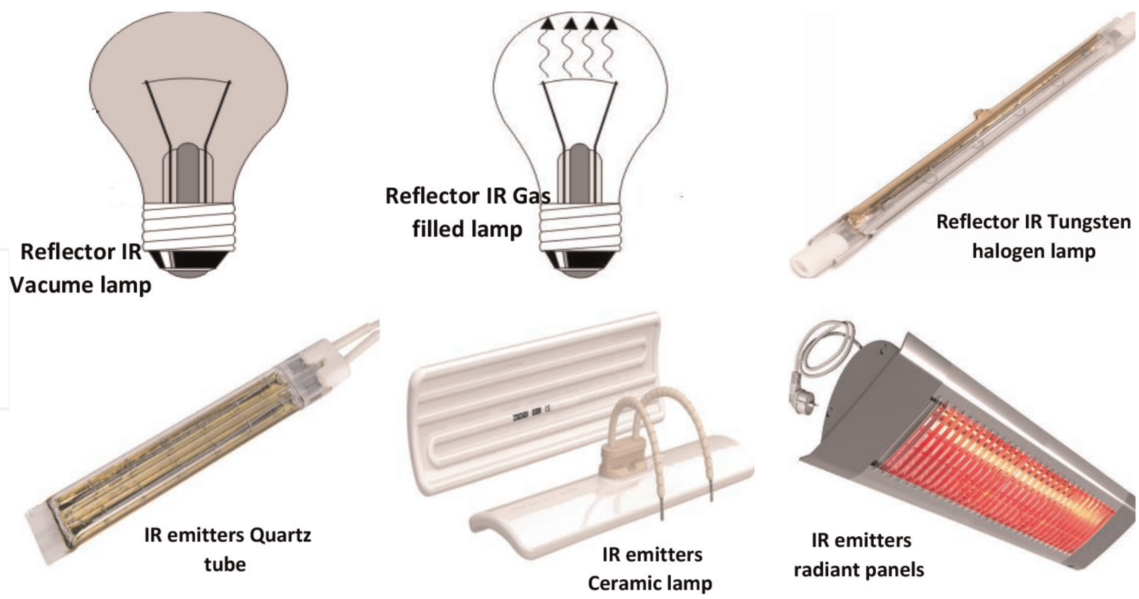

Figure 26.
Shows the types of infrared sources.

Many studies have reported that organic matter and water are the main constituents of fresh material or foodstuffs, which is based on the absorption of IR radiation significantly, especially at Mid and Far IR [113, 127, 128]. Where, the water absorption spectral coefficient was noted at 3 (MIR) and 6 (FIR) μm different wavelengths as shown in **Figure 27** and concluded that these wavelengths are considered suitable to be fixed in large-scale IR dryers for food products that generally contain 90% water. Confirming this, both [129, 130] mentioned that food efficiently absorbs IR radiation at wavelengths greater than 2.5 μm through a change in the state of vibration of the vibrating mechanism, which leads to a high temperature of the product being dried.

Several studies have proved that IR heating as a non-traditional drying method has many advantages and benefits such as uniform heating, short processing time, high heat transfer rate, high efficiency (80–90%), low energy consumption, low cost

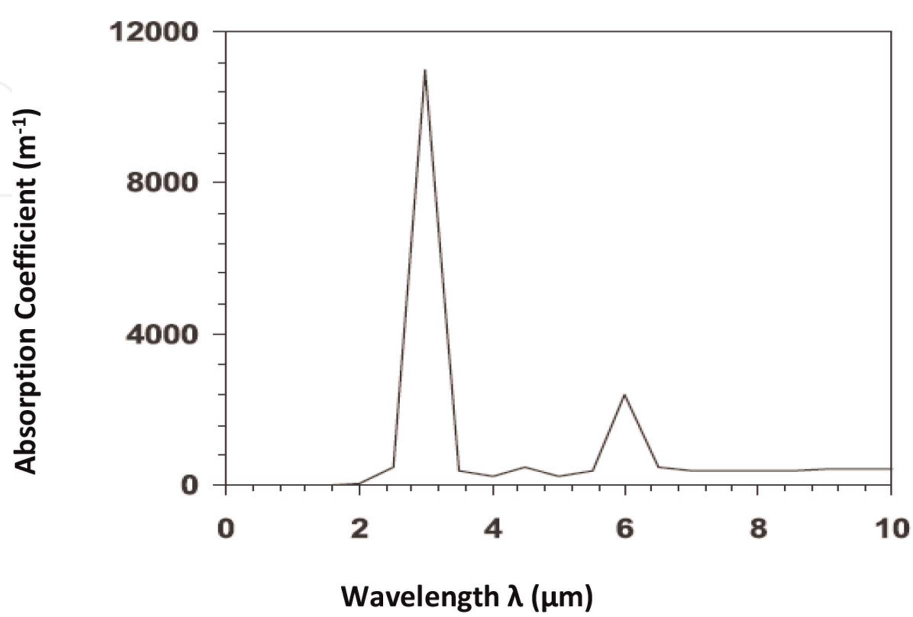

Figure 27.
Depicts the water absorption coefficient at different IR wavelength.

characterized, and improving final product quality in addition to it could be used as an application to measure water content in food products. Nowak et al. [113, 131–133] observed that far-infrared drying helps retain sensory quality in products such as sweet potatoes, grapes, Cordyceps militaris, and mangoes. Also, [134] investigated the effects of both hot air temperature and the IR drying method on the kinetics of persimmon slices, and the results found that the logarithmic model was the best model fitted to the experimental IR drying. In this regard, [135] studied the combined hot air at temperature levels (of 55, 65, and 75°C) and the IR drying method at radiation lamp power levels of 150, 250, and 375 W, on the persimmon fruits' moisture loss kinetics. The study finds that the drying time was reduced by 36% when increasing the drying hot air temperature from 55 to 75°C, while the drying time was reduced by 68.4% with increasing IR radiation power from 150 to 375 W. Nowak and Lewicki [113] dried the apple slices with IR radiation and by convection under equivalent conditions and reported that the heat-irradiated apple slices evaporated much more water than that not heated by IR energy until 80% of water is removed. Sun et al. [136] mentioned that the IR drying method combined with hot air as a pre-drying method can save 20% of drying time as compared with the IR drying alone throughout the drying of a thin layer of apple pomace. Chen et al. [117] conducted a comparative study between traditional hot-air (HA) and innovative drying methods of short- and medium-wave infrared radiation (SMIR) for drying jujube slices. The results find that the jujube slices dried by SMIR were of better color, higher retentions of vitamin C, total flavonoids content (TFC), and cyclic adenosine monophosphate (cAMP) content than the HA drying method, in addition to shorter drying time and higher drying efficiency. Also, the effects of the IR drying method on carrots were studied by [137]; the results pointed out that increasing IR drying time caused dramatic changes in the water state in dried carrots. Moreover, [138] used a combined drying method of IR and freeze drying to produce high-quality dried bananas at reduced cost, and the results showed that the dried banana samples were of a better color, higher crispness, and higher shrinkage compared with those produced by using regular freeze drying. As well, [139] achieved a considerable moisture reduction and higher drying rates in drying bananas with IR drying compared with hot air drying in the early stage.

4.2 Microwaves dryers

Microwaves (MW) are a form of electromagnetic beam, as are radio waves, ultraviolet radiation, X-rays, and gamma-rays. MV is located in the electromagnetic beam range between radio and infrared bands as shown in **Figure 28**. MW has wavelengths of about 30 cm to 1 mm, and frequencies ranging from about 1 GHz to nearly 300 GHz [140]. Microwaves have many applications such as communications, radar, astronomy, and remote sensing, and the most famous application for most people is cooking. Where the MV rays are absorbed by water at certain frequencies.

This property of MV is useful in cooking. Water in the food absorbs microwaves, which cause the water to heat up, then cook the food. Therefore, MV was used as a heating system in several industrial applications such as food, chemical, and materials processing, for example, cooking food and drying fruits and vegetables in both batch and continuous operations. MW radiation as a drying technique is based on the passage of microwaves through the material causing a molecule oscillation [114, 141], which leads to the volumetric heating of the material. MW volumetric heating (MWVH) is a way of using MW to penetrate uniformly throughout the volume of the product, thus delivering energy evenly into the body of the material. Hence, equally

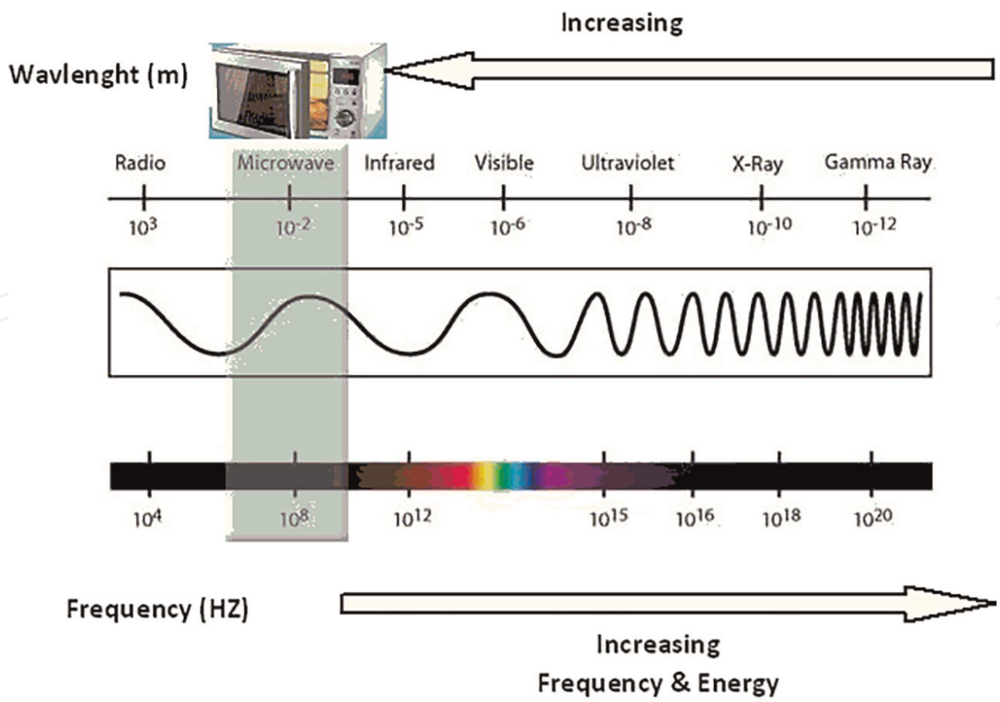

Figure 28.
Shows microwave band on electromagnetic beam.

heated the entire volume of a flowing liquid, suspension, or semisolid. Conversely, the traditional thermal processing methods rely on conduction and convection from hot surfaces to deliver energy into the product. A comparison study between MW and convective drying methods is shown in **Figure 29**. Alibas and Yilmaz [142] studied the effects of both these two drying methods on the drying kinetics, thermal properties, and quality parameters of orange slices. The results show that the MW drying

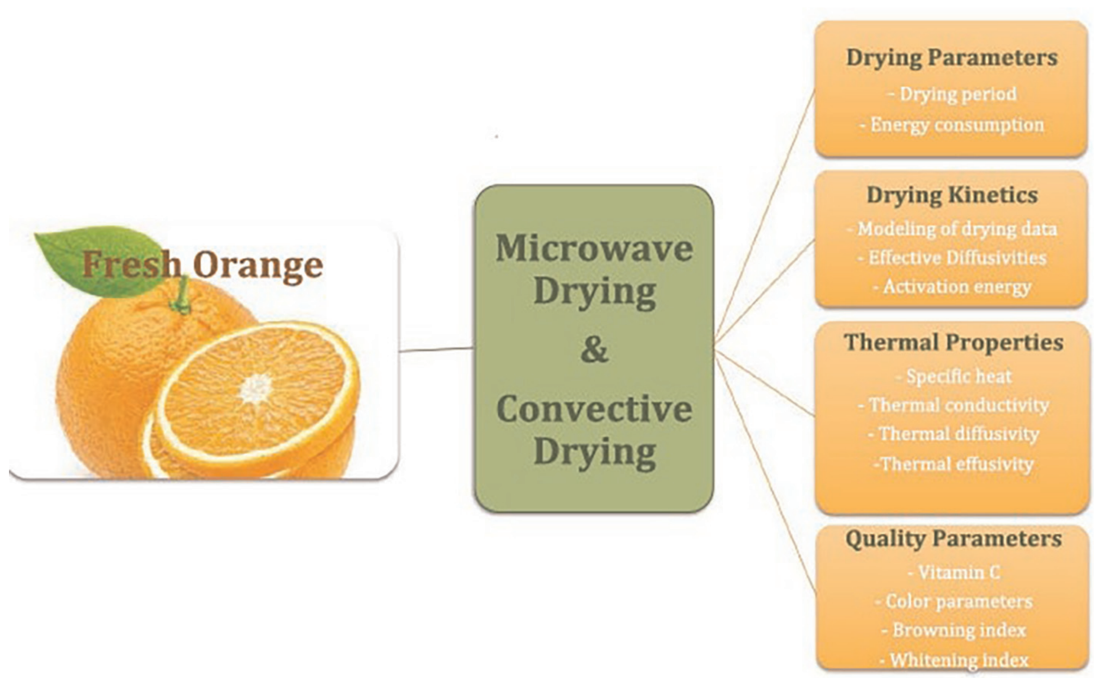

Figure 29.
Graphical comparison steps of the MW and convective drying methods.

processes were completed between 16 and 136 min depending on eight different microwave output power levels between 90 and 1000 W. On the other hand, in convective drying processes completed within the range 460–3120 min, at four different drying temperatures of 50, 75, 100, and 125°C. As well, the energy consumption was measured, and it observed that the MW drying method's energy consumption was very low at high and low powers. Finally, it is concluded that the most suitable drying method is MW drying at medium powers of 350 and 500 W by considering both drying and quality parameters.

Microwave drying technology is characterized by low energy consumption and short processing time, more uniform and energy efficient, making it an attractive source of thermal energy. However, some results indicated that microwave radiation alone is not sufficient to complete a drying process with high quality. Therefore, it is recommended to combine techniques, such as forced air or vacuum, to further improve the efficiency of the MW process [114, 141, 143–148]. Accordingly, several studies on drying using MW of various fruits and vegetables attached with an auxiliary system such as convective and vacuum methods reported that is more efficient than both MW and conventional drying techniques individually. As well, both [141, 148–153] mentioned that the MW drying technique is widely used in incorporation with hot air-drying systems. Where, the hot air removes water in a free state from the product surface, while the MW radiation removes water from the inner of the product. Furthermore, it is concluded that the MW-hot air combination drying systems not only increase the drying rates but also better retain the quality of the final products. In this regard, Sharma and Prasad [154], modified and developed a 600 W, 2450 MHz MW oven into an MW-hot air drier as shown in **Figure 30**. In order to explore the possibility of using a combined microwave-convective drying technique for processing garlic and assessment of the quality of the finished product. The results showed that the combined MW-hot air drying resulted in a reduction in the drying time and an extent of 80–90% in comparison to conventional hot air drying and a superior-quality final product. Alibas [155] studied the chard leaves quality characteristics during drying by MW, convective, and combined MW-convective. The results showed that the drying periods lasted 5–9.5, 22–195, and 1.5–7.5 min for MW,

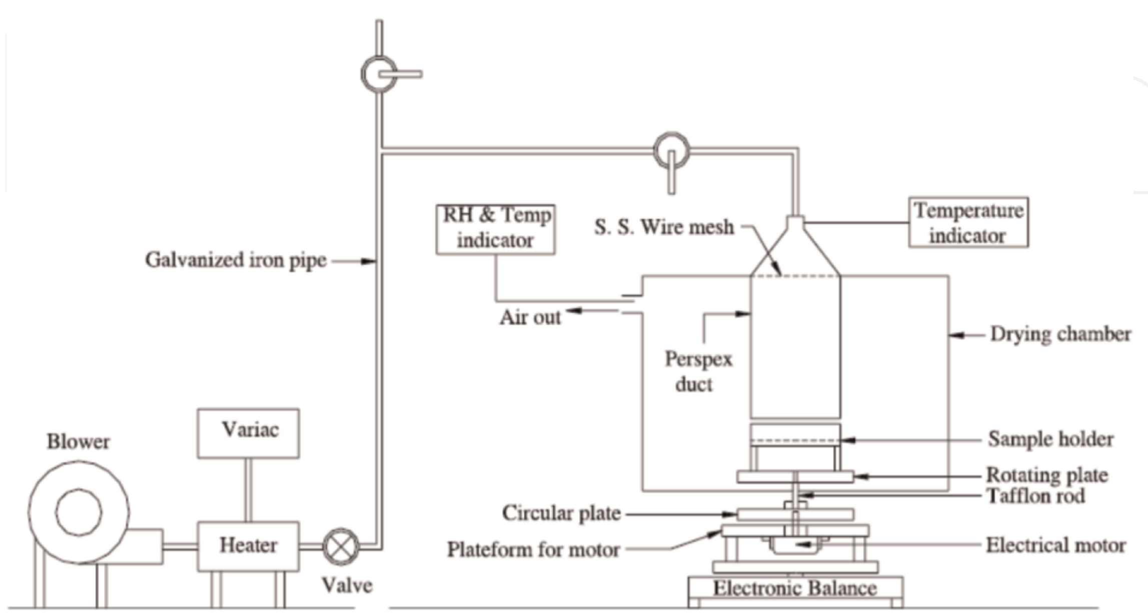

Figure 30.
Shows the microwave dryer attached to hot air.

convective, and combined MW-convective drying methods, respectively. Furthermore, the optimum drying period, color, and energy consumption were obtained for the combined MW-convective drying method. The optimum combination level was 500 W MW applications at 75°C.

Also, [156] studied the influence of MW-convective drying on chlorophyll and the color of herbs. The findings proved that the MW with auxiliary convective is a promising technique permitting the obtainment of dried material of high quality, additionally processing short time that can be an economic factor and incentive for the application of that method of drying on an industrial scale. In this regard [157] used different drying methods for Pistacia Atlantica seeds to study the impact on drying kinetics and quality properties. The results indicated that the MW drying method has afforded higher moisture removal in a shorter period compared with the traditional drying methods. Moreover, it was found that the essential oil composition was not considerably influenced by the MW drying method, and the texture quality is appropriate. Furthermore, [153] studied the effect of convective and vacuum MW drying on the bioactive compounds, color, and antioxidant capacity of sour cherries. It is found that in case of an increase in air temperature during convective drying as well as the increase in material temperature during VMWD deteriorated all the quality parameters of dried product. However, VMWD turned out to be much better than convective drying and competitive with a freeze-drying method. As it turned out that the best quality of the dried product and its more attractive color were found at VMWD at 480 W, followed by drying at MW power reduced to 120 W, which corresponds to anthocyanins content. As well, [158] dried pumpkin slices using convective and vacuum-MW drying methods to determine the drying kinetics, drying shrinkage, and bulk density, as well as to measure the color and carotenoid content of pumpkin slices dehydrated. They find that the vacuum-MW method has approximately tenfold shortened the time of pumpkin slice drying as compared with the convective method. Considering the viewpoint of color and carotene content, the vacuum-MW drying method was more effective than the convective method. Moreover, when use was made of vacuum-MW method, the dried products had a more attractive color. Sutar and Prasad [159], used microwave vacuum drying as shown in **Figure 31** to study the effect of vacuum in microwave drying operation and track the kinetics and moisture diffusivity of carrot slices. The results find that with the

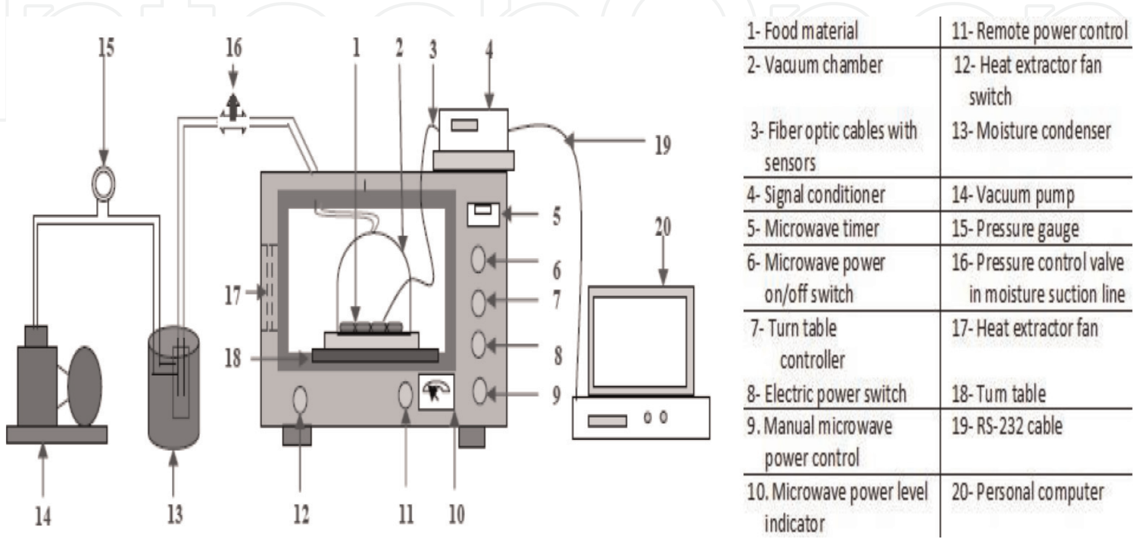

Figure 31.
Schematic diagram of the laboratory microwave vacuum dryer.

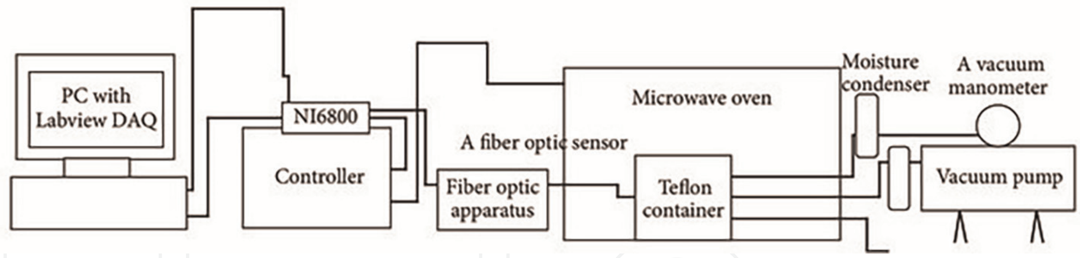

Figure 32.
Schematic diagram of the microwave vacuum drying system.

increase in microwave power density, the drying rates were increased and proved that the optimum model to predict the drying behavior of carrot slices' overall process conditions was the Page model. The combination of convective and vacuum-microwave (VMW) methods for drying kinetics and quality of beetroots was investigated by Figiel [160]. Where, convective drying with 60°C hot air and integration between convective pre-drying (CPD) and VMW drying method at 240, 360, and 480 W were used to dehydrate the Beetroot cubes.

The results showed that the VMFD method significantly reduced the total time of drying and decreased drying shrinkage in comparison with the convective method. Furthermore, the VMM-treated samples exhibited lower compressive strength, better rehydration potential, and higher antioxidant activity than those dehydrated in convection. Also, it is found that increasing the MW wattage and decreasing the time of CPD improved the quality of beetroot cubes dried by the combined method. Additionally, [161] optimized the drying process of Polygonum cuspidatum by using MW-vacuum drying and pretreatment methods as shown in **Figure 32**.

Where, a microwave vacuum drying system is designed and built that consists of a microwave drying unit, a power and temperature control unit, a moisture condenser, a vacuum pump, a vacuum manometer, and a PC-based data acquisition unit. The pretreatment methods were blanching for 30 s at 100°C, drying at 60°C, microwave pretreatment methods, and followed by microwave vacuum for 200 mbar at 50°C. Finally, it is concluded that it can be used to scale up the microwave vacuum drying system to a commercial scale.

5. Advanced and original drying methods

5.1 Instant controlled pressure drop method (détente instantanée controlee, DIC)

Major technical innovations in fruit and vegetable dehydration include pre or post-treatment under high or low pressure. At present, the instant controlled pressure drop method known by its French abbreviation DIC (détente instantanée contrôlée) was innovated as a solution to overcome the issues of drying shrinkage/collapse, to obtain a better quality of the dried plants. The DIC is characterized by its ability to handle a broad range of food products and is considered one of the newest innovative drying methods, regardless of its sensitivity to heat. The DIC processing method was developed, defined, and studied by [162]. DIC as a drying method is focused on exposing the product to high-pressure saturated steam for a few seconds and then followed by an abrupt pressure drop toward a vacuum. Then hot air-drying processing took place after DIC treatment as a conventional drying method. As well, [163] mentioned that

DIC processing is based on fundamental studies concerning the thermodynamics of instantaneity. Where, DIC system consists of six main parts processing vessel, vacuum tank, pneumatic valve, steam generator, air compressor, and vacuum pump as shown in **Figure 33**. The DIC work idea depends on exposing a partially dried product (usually the humidity is close to 30% db) to a high temperature/short time (HTST) such as a vapor pressure (P < 1.0 MPa) at high temperature (below 180°C) for a short time (less than a minute). Then this HTST stage was treated with a sharp pressure drop to a vacuum (within the pressure range of 3–5 kPa, and Δt from 10 to 60 ms). This leads to a mechanical influence represented in a severe pressure drop in a very short time. As a result, automatic evaporation of a part of water inside the product and at the same time a cooling operation were stimulated, which stopped their thermal degradation and gives a controlled expansion of the product [164–168].

Hence, **Figure 34** accurately describes the different stages of the work idea of the DIC processing unit as follows:

A. An elementary vacuum is implemented to minimize air resistance and simplify the steam diffusion within the product, then rapid heating is happen.

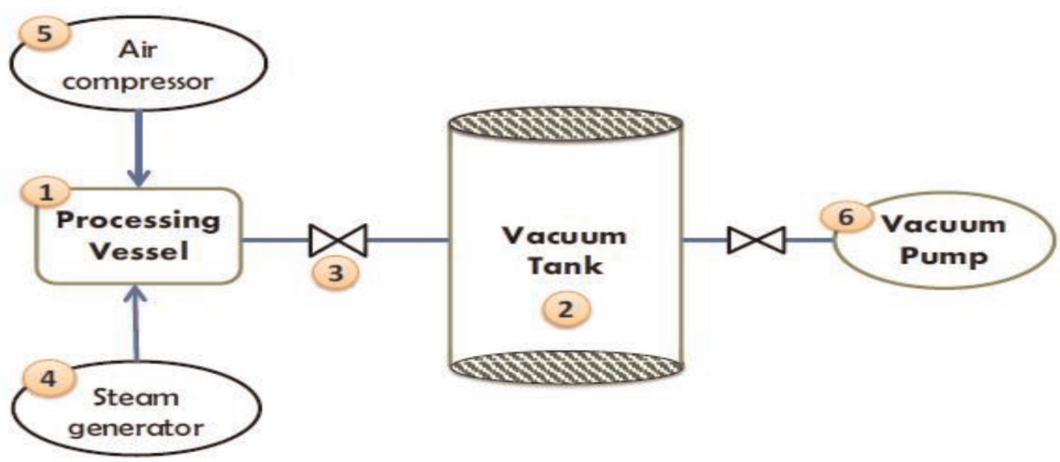

Figure 33.
Schematic of the DIC technology.

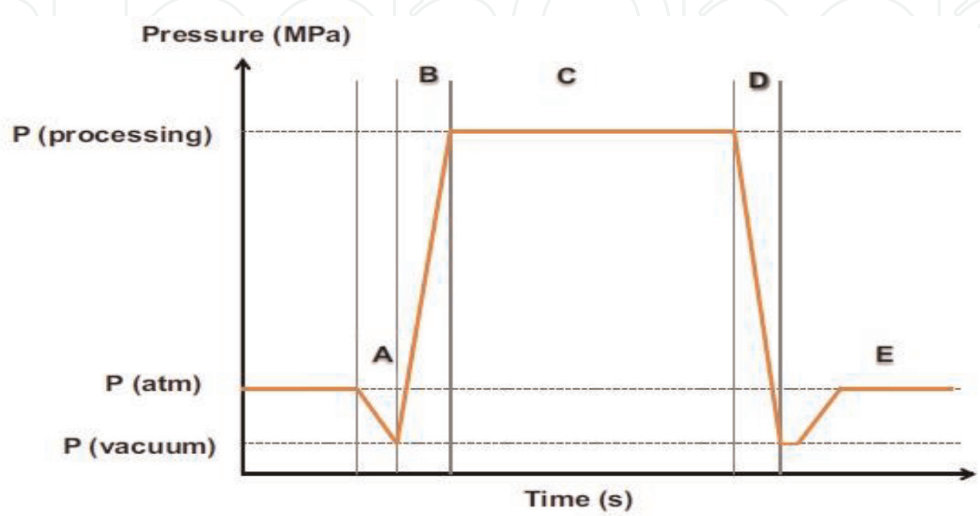

Figure 34.
Describes the work steps of the DIC system.

B. Secondly, injected saturated steam into the vessel until it reaches the highest pressure, then it is fixed.

C. Pressure and time parameters are given depending on the product treatment.

D. The pressurization needs to be followed by a sharp decompression till reached the vacuum.

E. Atmospheric air is injected to come again to atmospheric pressure, after the vacuum point, for sample recovery.

According to, [169], over the past 33 years, this technology has continued to expand its food applications and improve its characteristics on an industrial scale. DIC technology has continued over the past 33 years, to expand its food applications and improve its characteristics on an industrial scale. Since the DIC implementation has shown a quantum leap in quality enhancement and reducing the cost in the food industry generally, this is achieved by reducing the drying time of fruits and vegetables and enhancing the essential oils extraction, vegetable oils, and antioxidant elements. Additionally, it eliminates plant microorganisms and germs, which cause contamination, and reduces non-food ingredients and allergens. As well as it provides strong decontamination eliminating vegetative microorganisms and spores and reducing non-nutritional and allergenic components. It is known that convective air drying is one of the most industrial food drying operations applied. However, it has some disadvantages such as shrinkage and collapse of the product structure, low kinetics, nutritional losses, long drying periods, and microbial contamination. To overcome these disadvantages, the convection drying method has been enhanced by combining it with the instant controlled pressure drop technology (DIC), which has obtained excellent results, to improve the drying process and the total quality of dried products [170]. This integration has been termed "Swell-drying," which involves a hot airflow for the pre-drying stage coupled with a DIC texturing stage. A swell-drying operation generally consists of a first hot airflow pre-drying stage until a specific water content (between 0.20 g and 0.50 g H2O/g of solid material), then followed by a DIC texturing stage (100–900 kPa during a few seconds, followed by an abrupt controlled pressure drop), and a final air-drying stage until the weight is stable. In this regard, [171] applied the DIC technology to the quality characteristics of cell wall polysaccharides of apple slices and studied their relationship to the texture. The results showed that it is possible to get apple chips with a crisp texture and excellent honeycomb-like structure by coupling convective air drying with the DIC technology (swell-drying). Also, the samples showed an excellent rehydration ratio to a homogeneous porous structure and a large specific surface area. As well, [172] applied the swell-drying technology on fresh banana pieces and studied the effect of dehydration kinetics, water and oil holding capacity, and nutritional characteristics. Drying kinetics showed that DIC technology increased the effective water diffusivity by 23%. Moreover, the water holding capacity increased by 290% under high-pressure conditions under DIC treatments, reaching 7.8 against 2.0 g H2O/g db, while the oil holding capacity was 0.60 against 1.30 g oil/g db for non-textured samples. Finally, it is noted that the DIC treatment inhibited the transformation of banana starch to reduced sugar. Additionally, concerning the strawberry fruits, the swell-drying technology is an excellent processing method to produce strawberry snacks with a high crispness behavior and a high rehydration capacity in less time than convect air-drying conventional method [173]. As pointed out by [174, 175], the DIC treatment has a significant impact on strawberries' drying and rehydration kinetics, increasing the effective diffusivity, as well obtain the highest levels of phenols, flavonoids, and anthocyanins and antioxidant activities were achieved at 350 kPa for 10 s.

6. Conclusions

Human habitats are safe, resilient, sustainable, and a universal access to affordable, reliable, and sustainable energy, It's a world everyone dreams about. The world's eyes are turning toward alternative sources of traditional energy. Although wind and hydro power are also making progress, solar energy is becoming preferred due to its increasing affordability. Food preservation by drying is the time-honored and most common method used by humans. Food dehydration is one of the most important achievements in human history, it has achieved food security for humans even under the adverse environmental conditions that make it difficult to supply fresh food daily. Food drying techniques have long been applied since ancient times in conventional ways, such as drying in the sun. From the traditional to the most innovative, there are several drying solutions. Successive technological developments that have been going on for a long time had a significant impact on the growing consumer desire to obtain high-quality and safe agricultural products, whether the quality of the external appearance or the quality of the nutritional value of these products, whether fresh or dried. Therefore, a huge development has been achieved in drying technology for agricultural products. Starting with solar drying, traditional methods by convection, and drying using electromagnetic spectra such as microwave drying and infrared dryers, and newly invented methods. This continuous, renewable, and accelerated innovation in the field of food drying technology is to fulfill the consumer's increasing desire to achieve food security not only by providing food but with high quality, healthy and safe food. So far, no comprehensive research on industrial solar drying has been performed, and hopefully, further development in solar dryers based on the three "A" principles will take the shape in future, that is, Affordability, Availability, and Accessibility.

Food for all, no poverty, renewable energy, and employment generation are some of the key features. The future scope of solar dehydrators is mostly to increase usability for small-scale farmers and users by decreasing costs, increasing reliability and versatility, and making it easier to obtain. This in turn will increase production and lower the crisis of food for the human population.

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Conflict of interest

The authors declare no conflict of interest.

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References

[1] Guiné RPF. Food Drying and Dehydration – Technology and Effect on Food Properties. Saarsbruken: LAP LAMBERT Academic Publishing; 2015. ISBN: 978-3-659-75392-3

[2] Lee SC, Jeong SM, Kim SY, Park HR, Nam KC, Ahn DU. Effect of far-infrared radiation and heat treatment on the antioxidant activity of water extracts from peanut hulls. Food Chemistry. 2006;**94**(4):489-493

[3] Hii CL, Law CL. Product quality evolution during drying of foods, vegetables and fruits. In: Jangam SV, Law CL, Mujumdar AS, editors. Drying of Foods, Vegetables and Fruits. Vol. 1. 2010. pp. 125-144. ISBN: 978-981-08-6759-1

[4] Mujumdar AS, editor. Principles, Classification, and Selection of Dryers in Handbook of Industrial Drying. 3rd ed. CRC Press; 2006

[5] Araya-Farias M, Ratti C. Dehydration of foods: General concepts advances in food dehydration. In: Ratti C, editor. Advances in Food Dehydration. Boca Raton: CRC Press Taylor & Francis Group LLC; 2009. pp. 1-36. ISBN: 9780367386368

[6] Bala BK, Debnath N. Solar drying technology: Potentials and developments. Journal of Fundamentals of Renewable Energy and Applications. 2012;**2**. Article ID R120302. DOI: 10.4303/jfrea/R120302

[7] Udomkun P, Romuli S, Schock S, Mahayothee B, Sartas M, Wossen T, et al. Review of solar dryers for agricultural products in Asia and Africa: An innovation landscape approach. Journal of Environmental Management. 2020;**268**:110730. DOI: 10.1016/j.jenvman.2020.110730

[8] Rossi I, Asyifaa AH, Adiningsih FCA, Aulia GA, Achmad SR. Conventional and advanced food-drying technology: A current review. International Journal of Scientific & Technology Research. 2021;**10**(01):99-107

[9] Muncan J, Tsenkova R. Review: Aquaphotomics—from innovative knowledge to integrative platform in science and technology. Molecules. Open Access. 2019;**24**:2742. DOI: 10.3390/molecules24152742

[10] Jalata MW. Solar drying of fruits and windows of opportunities in Ethiopia. African Journal of Food Science. 2010;**4**(13):790-802. Available from: http://www.academicjournals.org/ajfs

[11] Bennamoun L. Reviewing the experience of solar drying in Algeria with presentation of the different design aspects of solar dryers. Renewable and Sustainable Energy Reviews. 2011;**15**(7):3371-3379. DOI: 10.1016/j.rser.2011.04.027

[12] Ndukwu MC, Bennamoun L, Abam FI. Experience of solar drying in Africa: Presentation of designs, operations, and models. Food Engineering Reviews. 2018;**10**(4):211-244. DOI: 10.1007/s12393-018-9181-2

[13] Ssemwanga M, Makule EE, Kayondo SI. The effect of traditional and improved solar drying methods on the sensory quality and nutritional composition of fruits: A case of mangoes and pineapples. Heliyon. 2020;**6**(6):e04163. DOI: 10.1016/j.heliyon.2020.e04163

[14] Imre LL. Solar drying. In: Mujumdar AS, editor. Handbook of

Industrial Drying. New York: Marcel Dekker; 1987. p. 357. DOI: 10.1080/07373938808916399

[15] Galanakis CM, Aldawoud TMS, Rizou M, Rowan NJ, Ibrahim SA. Food ingredients and active compounds against the coronavirus disease (COVID-19) pandemic: A comprehensive review. Food. 2020;**9**:1701. DOI: 10.3390/foods 91117 01

[16] Galanakis CM, Rizou M, Aldawoud TMS, Ucak I, Rowan NJ. Innovations and technology disruptions in the food sector within the COVID-19 pandemic and post-lockdown era. Trends in Food Science and Technology. 2021;**110**:193-200. DOI: 10.1016/j.tifs.2021.02.002

[17] Galanakis CM. The food systems in the era of the coronavirus (COVID-19) pandemic crisis. Food. 2020;**9**:523. DOI: 10.3390/foods 9040523

[18] Mathlouthi M. In: Caballero B, Finglas P, Toldrá F editors. Encyclopedia of Food Sciences and Nutrition, 2nd ed. Academic Press, New York. DOI: 10.1016/B0-12-227055-X/ 00369-2.

[19] Chavan A, Vitankar V, Mujumdar A, Thorat B. Natural convection and direct type (NCDT) solar dryers: A review. Drying Technology. 2021;**39**(13):1-22. DOI: 10.1080/07373937.2020.1753065

[20] Shrivastava V, Kumar A, Baredar P. Developments in indirect solar dryer: A review. International Journal of Wind and Renewable Energy. 2014;**3**(4):67-74

[21] Siddiqui AM, Thange S, Thite R, Todkar A. Forced-convection indirect solar dryer. International Research Journal of Engineering and Technology. 2021;**8**(5):2872-2877. e-ISSN: 2395-0056, p-ISSN: 2395-0072

[22] Pydi Setty Y, Ramana Murthy JV. Development of a model for drying of solids in a continuous fluidized bed dryer. Indian Journal of Chemical Technology. 2003;**10**:477-482

[23] Guerrero M, Albet C, Palomer A, Guglietta A. Drying in pharmaceutical and biotechnological industries. Food Science and Technology International. 2003;**9**:237-243

[24] Barrozo MAS, Mujundar A, Freire JT. Air-drying of seeds: A review. Drying Technology. 2014;**32**:1127-1141. DOI: 10.1080/07373937.2014.915220

[25] Yliniemi L. Advanced control of a rotary dryer [Ph.D. thesis]. Oulu, Finland: University of Oulu; 1999

[26] Santos DA, Duarte CR, Barrozo MAS. Segregation phenomenon in a rotary drum: Experimental study and CFD simulation. Powder Technology. 2016;**294**:1-10. DOI: 10.1016/j.powtec.2016.02.015

[27] Baker CGJ. Drying Technology. 1988;**6**(4):631-653, 754

[28] Kelly JJ, Tech. Ireland. 1969;**1**(2):25

[29] Kelly JJ, O'Donnell JP. Dynamics of granular material in rotary dryers and coolers. ICE Symposium Series. 1968;**29**:38

[30] Poersch W. Verfahrenstechnik. 1971;**5**(5):186

[31] Cairo N, Colangelo G, Starace G. Performance analysis of two industrial dryers (cross flow and rotary) for ligno-cellulosic biomass desiccation. Renewable Energy & Power Quality Journal (RE&PQJ). 2012;**1**:274-280. DOI: 10.24084/repqj10.292

[32] Likitrattanaporn C, Ahmad I, Sirisoontaralak P, Noomhorm A, et al. Performance evaluation of a mobile rotary dryer for high moisture paddy. In: Proceedings of the Third Asia-Pacific Drying Conference, 1-3 September 2003; Asian Institute of Technology, Bangkok, Thailand. pp. 199-207

[33] Imran A, Noomhorm A. Grain process engineering. In: Kutz M, editor. Chapter 12 in Handbook of Farm, Dairy and Food Machinery Engineering. 3rd ed. Academic Press. ISBN 9780128148037; 2019. pp. 267-298. DOI: 10.1016/B978-0-e12-814803-7.00012-9

[34] Kerr WL. Food drying and evaporation processing operations. In: Handbook of Farm, Dairy and Food Machinery Engineering. 2019. pp. 353-387. DOI: 10.1016/b978-0-12-814803-7.00014-2

[35] Law CL, Mujumdar AS. Fluidized bed dryers. In: Handbook of Industrial Drying. 2006. p. 3

[36] Gupta CK, Sathiyamoorthy D. Fluid Bed Technology in Material Processing. New York: CRC Press; 1999. (Chap. 1)

[37] Mujumdar AS, Devahastin S. Applications for fluidized bed drying. In: Yang WC, editor. Handbook of Fluidization and Fluid Systems. New York: Marcel Dekker; 2003. (Chap. 18)

[38] Moore JG. Drum dryers. In: Mujumdar AS, editor. Handbook of Industrial Drying. 1st ed. New York: Marcel Dekker; 1987. p. 227

[39] Moore JG. Drum dryers. In: Mujumdar AS, editor. Handbook of Industrial Drying. 2nd ed. New York: Marcel Dekker; 1995. p. 249

[40] Okos MR, Narsimhan G, Singh RK, Weitnauer AC. Food dehydration. In: Heldman DR, Lund DB, editors. Handbook of Food Engineering. New York: Marcel Dekker; 1992. p. 437

[41] Baumann R. Efficiency of roller dryers. Chem. Ing. Technol. 1953;**25**:607

[42] Daud WRW, Armstrong WD. Pilot plant study of the drum dryer. In: Mujumdar AS, editor. Drying '87. New York: Hemisphere Publishing Corporation; 1987. p. 101

[43] Daud WRW. Drum dryers. In: Handbook of Industrial Drying. 4th ed. Boca Raton: CRC Press; 2006

[44] Fritze H. Dry gelatinized starch produced on different types of drum dryers. Die Strake. 1973;**25**:244

[45] Mahler S. Verfahren zur Verhinderung von Klumpenbildung bei der Aufloesung kalt quellender Staeund Staerkepraeparate. Germ. Pat. 1921; DE389023 C

[46] Tang J, Feng H, Shen GQ. Drum drying. In: Encyclopedia of Agricultural, Food, and Biological Engineering. New York: Marcel Dekker; 2003. p. 211

[47] Michael JK. Spray drying and spray congealing of pharmaceuticals. In: Encyclopedia of Pharmaceutical Technology. Vol. 14. NY: Marcel Dekker INC; 1993. pp. 207-221

[48] Abuaf N, Staub FW. Drying of liquid–solid slurry droplets. In: Mujumdar AS, editor. Drying '86. Vol. 1. New York: Hemisphere/McGraw-Hill; 1986. pp. 277-284

[49] Amelot MP, Gauvin WH. Spray drying with plasma-heated water vapor. In: Mujumdar AS, editor. Drying '86.

Vol. 1. New York: Hemisphere/McGraw-Hill; 1986. pp. 285-290

[50] Anderson BS. Low ox spray dryers. Chemical Age of India. 1979;**30**(11)

[51] Strumillo C, Markowski A, Kaminski W. Modern developments in drying of paste-like materials. In: Mujumdar AS, editor. Advances in Drying. Vol. 2. 1983. pp. 193-232

[52] Mujumdar AS. Superheated steam drying. In: Mujumdar AS, editor. Handbook of Industrial Drying. 2nd ed. New York: Marcel Dekker; 1995. pp. 1071-1086

[53] Gauvin WH, Costin MH. Spray drying in superheated steam. In: Mujumdar AS, editor. Drying '80. Vol. 1. New York: Hemisphere/McGraw-Hill; 1980. pp. 320-331

[54] Gauvin WH. Novel approach to spray drying using plasmas of water vapor. Canadian Journal of Chemical Engineering. 1981;**59**(6): 697-704

[55] Raehse W, Bauer V. Process for spray drying materisals and mixtures thereof using superheated steam, 1995; USA Patent 5431780

[56] Frydman A, Vasseur J, Ducept F, Moureh J. Simulation of spray drying in superheated steam using computational fluid dynamics. Drying Technology. 1999;**17**(7):1313-1326

[57] Kwamya, Mujumdar AS. M. Eg. Project Report. Canada: Dept. Chem. Eng., McGill University; 1984

[58] Mujumdar AS. Dryers for particulate solids, slurries and sheet form materials. In: Devahastion S, editor. Mujumdar Practical Guide to Industrial Drying. 2000. pp. 37-71

[59] Available from: http://www.cerogers.com/html/horizontal_dryer.html

[60] Available from: http://www.fesintl.com/htmfil.fld/sprydryh.html

[61] Cakaloz T, Akbaba H, Yesugey ET, Periz A. Drying model for a-amylase in a horizontal spray dryer. Journal of Food Engineering. 1997;**31**:499-510

[62] Flink JM. Energy analysis in dehydration processes. Food Technology. 1977;**31**(3):77-79

[63] Ratti C. Hot air and freeze drying of high-value foods: A review. Journal of Food Engineering. 2001;**49**: 311-319

[64] Bruttini, Ligus. Freeze drying. In: Mujumdar AS, editor. Handbook of Industrial Drying. 2nd ed. New York: Dekker; 1995. p. 1423

[65] Dunoyer JM, Larouse J. Experience nouvelles sur la lyophilization. In: Trans. of Eighth Vacuum Symposium and Second International Congress. Vol. 2. 1961. p. 1059

[66] Tadeusz K, Mujumdar AS. Advanced Drying Technologies. New York: Marcel Dekker; 2001

[67] Wolff E, Gibert H. Atmospheric freeze drying, part I: Design, experimental investigation and energy saving advantages; part II: Modeling drying kinetics using adsorption isotherms. Drying Technology. 1990;**8**(2):385-428

[68] Meryman HT. Sublimation freeze drying without vacuum. Science. 1959; **130**:628

[69] Woodard HT. Freeze-drying without vacuum. Food Engineering. 1963;**35**(6):9

[70] Boeh-Gcansey O. Freeze drying in a fluidized-bed atmospheric dryer and in a vacuum dryer: Evaluation of external transfer coefficients. Journal of Food Engineering. 1988;**7**:127-146

[71] Mumenthaler M, Leuenberger H. Atmospheric spray-freeze drying: A suitable alternative in freeze-drying technology. International Journal of Pharmaceutics. 1991;**72**:97-110

[72] Lombrana J, Villaran MC. The influence of pressure and temperature on freeze drying in an adsorbent medium and establishment of drying strategies. Food Research International. 1997;**30**(3–4):213-222

[73] Risch SJ. Encapsulation: Overview of uses and techniques, encapsulation and controlled release of food ingredients. In: Risch SJ, Reineccius GA, editors. ACS Symposium Series 590. Washington, DC: American Chemical Society; 1995. pp. 2-7

[74] King CJ. In: Toei R, Mujumdar AS, editors. Control of Food-Quality Factors in Spray Drying, Drying '85. Hemisphere, New York; 1985. pp. 59-66

[75] Dziezak JD. Micro-encapsulation and encapsulated ingredients. Food Technology. 1988;**42**(4):136-148, 151

[76] Arshady R, George MH. Suspension, dispersion, and interfacial polycondensation—A methodological survey. Polymer Engineering and Science. 1993;**33**:865-876

[77] Huang LX, Wang Z, Tang J. Recent progress of spray drying in China (in Chinese). Chemical Engineering. (China). 2001;**29**(2):51-55

[78] Filková I, Huang LX, Mujumdar AS. Industrial spray drying systems. In: Mujumdar AS, editor. Handbook of Industrial Drying. 3rd ed. Boca Raton, Fl: CRC Press Taylor and Francis Group; 2006. pp. 215-256

[79] Assegehegn G, Brito-de la Fuente E, Franco JM, Gallegos C. The importance of understanding the freezing step and its impact on freeze-drying process performance. Journal of Pharmaceutical Sciences. 2019;**108**:1378-1395

[80] Haseley P, Oetjen GW. Freeze-Drying. Veinheim, Germany: Wiley-VCH; 2018. p. 421

[81] Mellor JD. Fundamentals of Freeze-Drying. London, UK: Academic Press Inc.; 1978. p. 386

[82] Adams GDJ, Cook I, Ward KR. The principles of freeze-drying. In: Wolkers WF, Oldenhof H, editors. Cryopreservation and Freeze-Drying Protocols. 3rd ed. Vol. 1257. Totowa, NJ, USA: Humana Press Inc.; 2015. pp. 121-143

[83] Franks F, Auffret T. Freeze-Drying of Pharmaceuticals and Biopharmaceuticals. Cambridge, UK: RSC Publishing; 2008. p. 218

[84] Liu YZ, Zhao YF, Feng X. Exergy analysis for a freeze-drying process. Applied Thermal Engineering. 2008;**28**: 675-690

[85] Meda L, Ratti C. Rehydration of freeze-dried strawberries at varying temperatures. Journal of Food Process Engineering. 2005;**28**:233-246

[86] Jia Y, Khalifa I, Hu L, Zhu W, Li J, Li K, et al. Influence of three different drying techniques on persimmon chips' characteristics: A comparison study among hot-air, combined hot-air-microwave, and vacuum-freeze drying techniques. Food and Bioproducts Processing. 2019;**118**:67-76

[87] Liapis AI, Bruttini R. Freeze drying. In: Mujumdar AS, editor. Handbook of Industrial Drying. 4th ed. Boca Raton, FL, USA: CRC Press; 2014. pp. 259-282

[88] Nowak D, Jakubczyk E. The freeze-drying of foods—The characteristic of the process course and the effect of its parameters on the physical properties of food materials. Food. 2020;**9**:1488. DOI: 10.3390/foods9101488

[89] Oikonomopoulou VP, Krokida MK, Karathanos VT. The influence of freeze drying conditions on microstructural changes of food products. Procedia Food Science. 2011;**1**:647-654

[90] Krzykowski A, Dziki D, Rudy S, Gawlik-Dziki U, Polak R, Biernacka B. Effect of pre-treatment conditions and freeze-drying temperature on the process kinetics and physicochemical properties of pepper. LWT. 2018;**98**: 25-30

[91] Martinez-Navarrete N, Salvador A, Oliva C, Camacho MM. Influence of biopolymers and freeze-drying shelf temperature on the quality of a mandarin snack. LWT. 2019;**99**:57-61

[92] Wu XF, Zhang M, Bhandari B. A novel infrared freeze drying (IRFD) technology to lower the energy consumption and keep the quality of Cordyceps militaris. Innovative Food Science and Emerging Technologies. 2019;**54**:34-42

[93] Silva-Espinoza MA, Ayed C, Foster T, Camacho MDM, Martinez-Navarrete N. The impact of freeze-drying conditions on the physico-chemical properties and bioactive compounds of a freeze-dried orange puree. Foods. 2019;**9**:32

[94] Khalloufi S, Ratti C. Quality deterioration of freeze-dried foods as explained by their glass transition temperature and internal structure. Journal of Food Science. 2003;**68**: 892-903

[95] Egas-Astudillo LA, Martínez-Navarrete N, Camacho MM. Impact of biopolymers added to a grapefruit puree and freeze-drying shelf temperature on process time reduction and product quality. Food and Bioproducts Processing. 2020;**120**:143-150

[96] Bhatta S, Stevanovic Janezic T, Ratti C. Freeze-drying of plant-based foods. Foods. 2020;**9**(1):87. DOI: 10.3390/foods9010087

[97] Burke RF, Decareau RV. Advances in Food Research. 1964;**13**:1-88

[98] Copson DA. Microwave Heating. Westport, CN: AVI Publishing; 1962

[99] Goldblith SA, Rey L, Rothmayr WW. Freeze Drying and Advanced Food Technology. London: Academic Press; 1975

[100] Hoover MW, Markantonatos A, Parker WN. Food Technology. 1966;**20**: 107-110

[101] Bouldoires JP, LeViet T. Microwave freeze-drying of granulated coffee. In: Second International Symposium on Drying. Montreal, Canada: McGill University; 1980

[102] Sunderland JE. An economic study of microwave freeze- drying. Food Technology. 1982;**36**(2):50-56

[103] Rey L, May JC, editors. Freeze Drying/Lyophilization of Pharmaceutical and Biological Products. New York: Marcel Dekker; 1999

[104] Wang ZH, Shi MH. Numerical study on sublimation-condensation

phenomena during microwave freeze drying. Chemical Engineering Science. 1998;**53**:3189-3197

[105] Wang ZH, Shi MH. The effects of sublimation-condensation region on heat and mass transfer during microwave freeze drying. Journal of Heat Transfer. 1998;**120**:654-660

[106] Snowman JW. Lyophilization techniques, equipment, and practice. In: Downstream Processes: Equipment and Techniques. New York: Alan R. Liss; 1988. p. 315

[107] Thuse E, Ginnette LF, Derby R. U.S. Patent 1968;**3**:362,835

[108] Bruttini R, Liapis AI. Freeze Drying. Handbook of Industrial Drying: CRC Press; 2007

[109] Mayor L, Sereno AM. Modelling shrinkage during convective drying of food materials: A review. Journal of Food Engineering. 2004;**61**(3):373-386

[110] Mujumdar AS. Handbook of Industrial Drying. 3rd ed. CRC Press; 2006. DOI: 10.1201/9781420017618

[111] Rastogi NK. Recent trends and developments in infrared heating in food processing. Critical Reviews in Food Science and Nutrition. 2012;**52**(9): 737-760

[112] Kocabiyik H, Tezer D. Drying of carrot slices using infrared radiation. International Journal of Food Science and Technology. 2009;**44**(5):953-959

[113] Nowak D, Lewicki PP. Infrared drying of apple slices. Innovative Food Science and Emerging Technologies. 2004;**5**(3):353-360

[114] Sakare P, Prasad N, Thombare N, Singh R, Sharma SC. Infrared drying of food materials: Recent advances. Food Engineering Reviews. 2020;**12**:381-398

[115] Yan JK, Wu LX, Qiao ZR, Cai WD, Ma H. Effect of different drying methods on the product quality and bioactive polysaccharides of bitter gourd (*Momordica charantia* L.) slices. Food Chemistry. 2019;**271**:588-596

[116] Venkitasamy C, Zhu C, Brandl MT, Niederholzer FJ, Zhang R, McHugh TH, et al. Feasibility of using sequential infrared and hot air for almond drying and inactivation of enterococcus faecium NRRL B-2354. LWT—Food Science and Technology. 2018;**95**(11):123-128

[117] Chen Q, Bi J, Wu X, Yi J, Zhou L, Zhou Y. Drying kinetics and quality attributes of jujube (*Zizyphus jujuba* Miller) slices dried by hot-air and short- and medium-wave infrared radiation. LWT—Food Science and Technology. 2015;**64**(2):759-766

[118] Zare D, Naderi H, Ranjbaran M. Energy and quality attributes of combined hot-air/infrared drying of paddy. Drying Technology. 2015;**33**(5): 570-582

[119] Bualuang O, Tirawanichakul Y, Tirawanichakul S. Comparative study between hot air and infrared drying of parboiled rice: Kinetics and qualities aspects. Journal of Food Processing & Preservation. 2013;**37**(6):1119-1132

[120] Sakai N, Hanzawa T. Applications and advances in farinfrared heating in Japan. Trends in Food Science and Technology. 1994;**5**:357-362

[121] Skjöldebrand C. Infrared heating. In: Richardson P, editor. Thermal Technologies in Food Processing. New York, NY, USA: CRC Press; 2001

[122] Calín-Sánchez Á, Lipan L, Cano-Lamadrid M, Kharaghani A, Masztalerz K, Carbonell-Barrachina ÁA, et al. Comparison of traditional and novel drying techniques and its effect on quality of fruits, vegetables and aromatic herbs. Foods. 2020;**9**:1261. DOI: 10.3390/foods9091261

[123] Boudhrioua N, Bahloul N, Ben Slimen I, Kechaou N. Comparison on the total phenol contents and the color of fresh and infrared dried olive leaves. Industrial Crops and Products. 2009;**29** (2–3):412-419

[124] Fasina O, Tyler B, Pickard M, Zheng GH, Wang N. Effect of infrared heating on the properties of legume seeds. International Journal of Food Science and Technology. 2008;**36**(1): 79-90

[125] Pan Z, Atungulu GG. Infrared Heating for Food and Agricultural Processing. 1st ed. CRC Press; 2010. DOI: 10.1201/9781420090994

[126] Hung JY, Wimberger RJ, Mujumdar AS. Drying of coated webs. In: Mujumdar AS, editor. Handbook of Industrial Drying. 2nd ed. New York, NY, USA: Marcel Dekker Inc; 1995. pp. 1007-1038

[127] Pawar SB, Pratape VM. Fundamentals of infrared heating and itsapplication in drying of food materials: A review. Journal of Food Process Engineering. 2017;**40**:1745-4530. DOI: 10.1111/jfpe.12308

[128] Sayed-Yagoobi J, Wirtz JW. An experimental study of gas-fired infrared drying of paper. Drying Technology. 2001;**19**:1099-1112

[129] Sun DW. Thermal Food Processing: New Technologies and Quality Issues. 2nd ed. Boca Raton, FL, USA: CRC Press; 2012. pp. 618-620

[130] Richardson P. Thermal Technologies in Food Processing. 1st ed. Boca Raton, FL, USA: CRC Press; 2001. pp. 292-294

[131] Salehi F. Recent applications and potential of infrared dryer systems for drying various agricultural products: A review. International Journal of Fruit Science. 2020;**20**(3):586-602

[132] Zhu Y, Pan Z. Processing and quality characteristics of apple slices under simultaneous infrared dry-blanching and dehydration with continuous heating. Journal of Food Engineering. 2009;**90**: 441-452

[133] Zartha Sossa JW, Orozco GL, García Murillo LM, Peña Osorio M, Sánchez SN. Infrared drying trends applied to fruit. Frontiers in Sustainable Food Systems. 2021;**5**:650690

[134] Mosavi Baygi SF, Farahmand A, Taghi Zadeh M, Zia FA. Modeling on hot air and infrared thin layers drying of persimmon slices. Food Science & Technology. 2015;**13**(53):161-171

[135] Salehi F, Kashaninejad M, Siahmansouri P, Moradi E. Moisture loss kinetics of persimmon during combined hot air-infrared drying process. Journal of Food Technology & Nutrition Sciences. 2017;**14**(2):39-48

[136] Sun J, Hu X, Zhao G, Wu J, Wang Z, Chen F, et al. Characteristics of thin-layer infrared drying of apple pomace with and without hot air pre-drying. Food Science and Technology International. 2007;**13**(2):91-97

[137] Xu C, Li Y, Yu H. Effect of far-infrared drying on the water state and

glass transition temperature in carrots. Journal of Food Engineering. 2014;**136**: 42-47

[138] Pan Z, Shih C, McHugh TH, Hirschberg E. Study of banana dehydration using sequential infrared radiation heating and freeze-drying. LWT - Food Science and Technology. 2008;**41**(10): 1944-1951

[139] Pekke MA, Pan Z, Atungulu GG, Smith G, Thompson JF. Drying characteristics and quality of bananas under infrared radiation heating. International Journal of Agricultural and Biological Engineering. 2013;**6**(3):58-70

[140] Stuchly SS, Stuchly MA. Microwave drying: Potential and limitations. In: Mujumdar AS, editor. Advances in Drying. New York: Hemisphere Publishing Corporation; 1980

[141] Feng H, Yin Y, Tang J. Microwave drying of food and agricultural materials: Basics and heat and mass transfer modeling. Food Engineering Reviews. 2012;**4**(2):1-18

[142] Alibas I, Yilmaz A. Microwave and convective drying kinetics and thermal properties of orange slices and effect of drying on some phytochemical parameters. Journal of Thermal Analysis and Calorimetry. 2021;**147**:8301-8321

[143] Ramaswamy HS, Pillet-Will T. Distribution and equalization of temperature in a microwave heated food model. Journal of Food Quality. 1992; **15**(16):435-448

[144] Tulasidas TN, Raghavan GSV, Mujumdar AS. Microwave drying of grapes in a single mode cavity at 2450 MHz –II: Quality and energy aspects. Drying Technology. 1995;**13**(8/9): 1973-1992

[145] Ruız Dıaz G, Martınez-Monzo J, Chiralt PFA. Modelling of dehydration-rehydration of orange slices in combined microwave/air drying. Innovative Food Science and Emerging Technologies. 2003;**4**:203-209

[146] Soysal Y. Microwave drying characteristics of parsley. Biosystems Engineering. 2004;**89**:167-173

[147] Orsat V, Changrue V, Vijaya RGS. Microwave drying of fruits and vegetables. Stewart Postharvest Review. 2006;**6**(4):1-7

[148] Joardder MUH, Karim A, Kumar C. Effect of temperature distribution on predicting quality of microwave dehydrated food. Journal of Mechanical Engineering Science. 2013;**5**:562-568. DOI: 10.15282/jmes.5.2013.2.0053

[149] Maskan M. Drying, shrinkage and rehydration characteristics of kiwi fruits during hot air and microwave drying. Journal of Food Engineering. 2001;**48**: 177-182

[150] Sham PWY, Scaman CH, Durance TD. Texture of vacuum microwave dehydrated apple chips as affected by calcium pretreatment, vacuum level, and apple variety. Journal of Food Science. 2001;**66**(9): 1341-1347

[151] Andres A, Bilbao C, Fito P. Drying kinetics of apple cylinders under combined hot air–microwave dehydration. Journal of Food Engineering. 2004;**63**:71-78

[152] Sunjka PS, Rennie TJ, Beaudry C, Raghavan GSV. Microwave–convective and microwave–vacuum drying of cranberries: A comparative study. Drying Technology. 2004;**22**(5): 1217-1231

[153] Wojdyło A, Figiel A, Lech K, Nowicka P, Oszmiański J. Effect of convective and vacuum–microwave drying on the bioactive compounds, color, and antioxidant capacity of sour cherries. Food and Bioprocess Technology. 2014;**7**:829-841

[154] Sharma GP, Prasad S. Drying of garlic (Allium sativum) cloves by microwave-hot air combination. Journal of Food Engineering. 2001;**50**:99-105

[155] Alibas I. Characteristics of chard leaves during microwave, convective, and combined microwave-convective drying. Drying Technology. 2006;**24**:1425-1435

[156] Śledź M, Witrowa-Rajchert D. Influence of microwave-convective drying on chlorophyll content and colour of herbs. Acta Agrophysica. 2012;**19**(4):865-876

[157] Yarahmadi N, Hojjatoleslamy M, Boroujeni LS. Different drying methods of Pistacia Atlantica seeds: Impact on drying kinetics and selected quality properties. Food Science & Nutrition. 2019;**8**:3225-3233

[158] Nawirska A, Figiel A, Kucharska AZ, Sokół-Łetowska A, Biesiada A. Drying kinetics and quality parameters of pumpkin slices dehydrated using different methods. Journal of Food Engineering. 2009;**94**:14-20

[159] Sutar PP, Prasad S. Modeling microwave vacuum drying kinetics and moisture diffusivity of carrot slices. Drying Technology. 2007;**25**(10):1695-1702

[160] Figiel A. Drying kinetics and quality of beetroots dehydrated by combination of convective and vacuum-microwave methods. Journal of Food Engineering. 2010;**98**:461-470

[161] Wanxiu X, Guanyu Z, Chunfang S, Shaogang H, Zhenfeng L. Optimization of microwave vacuum drying and pretreatment methods for polygonum cuspidatum. Mathematical Problems in Engineering. 2018;**2018**:1-11

[162] Allaf K, Vidal P. Feasibility study of a new process of drying/swelling by instantaneous decompression toward vacuum of in pieces vegetables in view of a rapid re-hydration. Gradient activity plotting university of technology of compiegne UTC N° CR/89/103, industrial SILVA-LAON partner. 1989

[163] Allaf K, Allaf T. Instant Controlled Pressure Drop (D.I.C.) in Food Processing: From Fundamental to Industrial Applications. New York: Springer; 2013

[164] Albitar N, Mounir S, Besombes C, Allaf K. Improving the drying of onion using the instant controlled pressure drop technology. Drying Technology. 2011;**29**:993-1001

[165] Ben Amor B, Allaf K. Impact of texturing using instant pressure drop treatment prior to solvent extraction of anthocyanins from malaysian roselle (hibiscus sabdariffa). Food Chemistry. 2009;**115**:820-825

[166] Haddad J, Allaf KA. A study of the impact of instantaneous controlled pressure drop on the trypsin inhibitors of soybean. Journal of Food Engineering. 2007;**79**(1):353-357

[167] Haddad J, Greiner R, Allaf K. Effect of instantaneous controlled pressure drop on the phytate content of lupin. LWT—Food Science and Technology. 2007;**40**(3):448-453

[168] Louka N, Allaf K. Expansion ratio and color improvement of dried vegetables texturized by a new process “controlled sudden decompression to the vacuum”: Application to potatoes, carrots and onions. Journal of Food Engineering. 2004;**65**(2):233-243. DOI: 10.1016/j.jfoodeng.2004.01.020

[169] Pech-Almeida JL, Téllez-Pérez C, Alonzo-Macías M, Teresa-Martínez GD, Allaf K, Allaf T, et al. An overview on food applications of the instant controlled pressure-drop technology, an innovative high pressure-short time process. Molecules. 2021;**126**:6519, 1-37

[170] Mounir S, Allaf T, Mujumdar AS, Allaf K. Swell drying: Coupling instant controlled pressure drop DIC to standard convection drying processes to intensify transfer phenomena and improve quality—An overview. Drying Technology. 2012;**30**:1508-1531

[171] Xiao M, Yi J, Bi J, Zhao Y, Peng J, Hou C, et al. Modification of cell wall polysaccharides during drying process affects texture properties of apple chips. Journal of Food Quality. 2018;**2018**:1-11

[172] Setyopratomo P, Fatmawati A, Sutrisna PD, Savitri E, Allaf K. The dehydration kinetics, physical properties and nutritional content of banana textured by instantaneous controlled pressure drop. Asia-Pacific Journal of Chemical Engineering. 2012;**7**: 726-732

[173] Alonzo-Macías M, Montejano-Gaitán G, Allaf K. Impact of drying processes on strawberry (Fragaria var. Camarosa) texture: Identification of crispy and crunchy features by instrumental measurement. Journal of Texture Studies. 2014;**45**:246-259

[174] Alonzo-Macías M, Cardador-Martínez A, Mounir S, Montejano-Gaitán G, Allaf K. Comparative study of the effects of drying methods on antioxidant activity of dried strawberry (Fragaria Var. Camarosa). Journal of Food Research. 2013;**2**: 92-107

[175] Maritza AM, Sabah M, Anaberta CM, Montejano-Gaitán JG, Allaf K. Comparative study of various drying processes at physical and chemical properties of strawberries (Fragaria var camarosa). Procedia Engineering. 2012;**42**:297-312