Chapter

Role of Food Microwave Drying in Hybrid Drying Technology

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Abstract

Dehydration is the key to food preservation reducing volume and increasing shelf life. Dehydration technology has witnessed renaissance with the development of advanced technology such as microwave drying, freeze drying, fluidized bed drying, and refractance window drying. Combination of drying methods has increased the versatility of dehydration process of which field-based drying methods have always been hyped and microwave drying being the most adorned of all, considering its ease of fabrication and drying efficiency. Synergizing it with methods such as hot air drying, freeze drying, fluidized bed drying, or vacuum drying enhances its performance and the quality of the dried product. The merits and functionality of each method in hybrid drying with microwave have been discussed in the chapter.

Keywords: drying, moisture, microwave, hybrid, efficiency

1. Introduction

Dehydration is proclaimed as the key to increased shelf life of perishable food, pertaining to the reduction of available moisture for microbial growth. It has been one of the most ancient apt techniques for food preservation, the conventional methods being air drying, solar drying, etc. Dehydration has not only contributed to the extended life of fresh food and throughout the year availability of seasonal products [1] but also has minimized the hassle of voluminous handling of raw and processed products, thus paving its way to reach end consumers like space researchers in spaceships, marine staff, war zones, and needy ones in far flung inaccessible areas.

Researchers and scientists have experimented with dehydration methods such as fluidized bed drying, freeze drying, osmotic dehydration, drying by natural radiation, spray drying, to understand the compatibility of the methods with the different kinds of food in terms of nutrient retention, operation cost, efficiency, shelf life, and final quality of the dehydrated product. Each method or device projected for dehydration has evolved with time. The relentless efforts to attain maximum efficiency have paved way for the advanced dehydration methods and gradually have ignited the concept of combining the individual methods, hence introducing the hybrid drying technology. The amalgamation of two to more drying techniques has also added to the versatility of the methods. The demand to adhere to the norms and policies in relation to environment, government regulation, increased throughput, quality, etc., has necessitated enumeration of methodologies such as hybrid drying technique for achieving optimum results. The conventional convective hot air drying has been improvised many times by researchers with combination of nonthermal drying techniques such as ultrasound, ultraviolet radiation, or pulse electric field [2], which proved to produce better quality dried products in lesser drying time compared to single-operation system of hot air drying. Subsequently, the prospects of combining the nonthermal technologies with other kinds of drying techniques have been explored by thinkers. Of all methods, field-based drying methods have received ample attention by researchers due to the profound advantages of these techniques such as improved drying kinetics, efficient rehydration ratio, and high-quality end product. The promising scope of synergized drying methods using field-based methods has encouraged experimentation with different combination sets of which microwave drying has been popular, due to the ease of fabrication, nutrient retention of food, and cost effectivity. Hybrid dehydration processes with microwave treatment envisage to minimize loss of heat-sensitive food components. This chapter focusses on microwave drying hybridization with other drying methods, thus compounding an insight herein on the breaches attended and the lags yet to be addressed through further research.

2. Advancement in dehydration technology

The ardent efforts on improvisation of dehydration technique and application to different kinds of foods have been relentless, thus nearing perfection from all aspects inch by inch. The traditional sun-drying method inspired designing of solar dryers by intervention of science and technology. Conventional air drying method accentuated with the introduction of hot air dryers and oven dryers to reduce dependency on natural sources. However, the process being energy-driven involved huge amount of recurring cost due to the immense consumption of high-priced electric energy, thus subsequently bringing in novel technologies such as vacuum drying, freeze drying, spray drying, and ample of advanced methods, which enhanced the drying behavior further with comparatively lesser energy need [1]. Energy efficiency of the drying method has always been the focus point to optimize the operation cost without compromising on product quality. The heat pump dehumidifiers and superheated steam drying proved to be energy-efficient methods, resulting in dried products with better rehydration properties and nutritional content. The heat pump dehumidifiers enabled recycling of air by adding and rejecting heat during the process through heat pumps and condensers resulting in minimization of energy consumption. Superheated steam drying has shown promising results in terms of retention of heat-sensitive compounds of food such as vitamin C, thus encouraging its implementation in the food industry [3–5]. Microwave drying is known for its deep penetration characteristic within food layers and plays an important role in food drying, especially when in combination with other drying methods. Microwave vacuum drying is reported to be efficient at 26–52°C. When subjected at 640–710 W to orange juice concentrates for the production of fruit gel, the color of the gel has been attractive and lighter as compared to the ones prepared by air drying [6]. Plate-transducer power ultrasonic generators aided the generation of high-intensity ultrasound waves, which added new dimension to dehydration of vegetables. Several techniques on application of high-intensity ultrasound waves directly to vegetable surfaces have been explored by scientists as ultrasounds increase the evaporation rate of moisture substantially reducing the duration of drying [7]. Refractance window drying system has gained popularity over the years because of its efficiency in terms of quality retention and inexpensive equipment setup. It has shown impressive performance in the conversion of liquid products such as juice, puree, to flakes, leather, sheets, etc., having attractive color, aroma, and antioxidant activity. It is used for the production of egg powder, fruit powder, herbal extract, etc. [8]. Nonthermal drying technologies like osmotic drying have been effective for fruits like apricot with an initial pretreatment of drying material. Dielectric drying through radio frequency (RF) and microwave systems has been extensively used in food industry, wherein electrical energy is converted to heat energy by polarizing the electric dipoles in the food material with electric fields. The techniques are apt enough to be successfully replicated for other kinds of high-value fruits as studied in apricot drying [9].

3. Advancement in hybrid dehydration methods

Hybrid methods of drying are prevalent to envisage the merits at the maximum extent and have a versatile approach toward efficient drying. Combination of two or three drying methods not only reduces the sole dependency on hot air drying but also increases energy efficiency and better nutritional retention in comparison with the hot air-dried products that are more susceptible to nutritional loss, shrinkage, color change, flavor change, and texture hardness [10]. The approach of hybrid drying thrives to conglomerate the merits of individual drying techniques, minimizing the demerits of each. Coupling of convective drying with field-based drying methods has been reported to be effective to retain nutritional and functional components of fruits and vegetables. Application of ultrasounds is a nonthermal method of dehydration. Subjecting apple slices to ultrasonication after convective air drying has shown reduced processing time and better quality retention [11]. Infrared radiation is also implemented to heat-sensitive food products for drying in a synergistic way with freeze drying and vacuum drying. It is being used for drying of high-value herbs such as *Ginkgo biloba* and *Cordyceps militaris* [12]. Microwave drying has been the most sought after dehydration method to synergize with other methods. Electromagnetic waves penetrate food, causing oscillation of molecules which in turn generate heat inside the food. The technology coupled with other drying methods increase drying efficiency manifold. For drying of spices, microwave drying has proved to be effective when conjugated with drying methods such as infrared drying or fluidized bed drying [13].

4. Hybrid drying with field-based drying methods

The field-based drying methods are the ones that employ electromagnetic energy and acoustic energy such as microwave, infrared radiation, radio frequency (RF), and ultrasound for nonthermal drying. These kinds of drying techniques exhibit better food quality in terms of appearance and nutrition value. In addition, the techniques have rapid drying kinetics and improved thermal efficiency in comparison with the conventional hot air drying. Individually, each technique has its own set of advantages. Introduction of field-based drying methods to the conventional techniques imbibes its own benefits such as increased drying efficiency and low energy consumption.

4.1 Benefits of field-based drying technology

4.1.1 Microwave drying

i. Generates internal vapor

ii. Heating is volumetric

iii. Drying rate is high

4.1.2 Drying with radio frequency

i. Wavelength employed is longer than microwave

ii. Penetrates the food deep

4.1.3 Infrared drying

i. Transfer medium is not required for energy deliver

ii. Specific areas on food surface can be targeted

4.1.4 Ultrasonic drying

i. Strongly adhered moisture can be removed [10]

5. Hybrid drying with microwaves

Fabrication of field-based drying models calls for considerable technical inputs and high costs. Sophisticated equipment setups are required to run the drying system [14]. Maintenance and running of the hybrid setups with field-based drying requires technical knowledge and expertise. Considering the ease of modeling and feasibility of hybrid drying with field-based methods, microwave drying is best suited for miniature setups as well as extensive layouts. However, microwave drying if employed solely lacks energy efficiency, because removal of water using microwaves is costly considering the high rates of electric energy. Moreover, useful heat is not generated from all the emitted microwaves [15]. Microwave drying shows best result when combined with other formats of drying.

5.1 Heat features of microwave

The operating frequency of microwave is 300 MHz to 300 GHz. The domestic microwave oven induces microwaves of frequency 2450 MHz, whereas in commercial large-scale level microwaves of range 900 MHz are deployed.

The heating mechanism involves absorption of microwave energy by the water present in the food cavities, resulting in evaporation of water due to temperature rise. Microwave heating is a dielectric heating system, wherein the molecules carrying negative and positive charge (such as sugar, fat, and water molecules) align themselves to the alternating electric field subjected by the microwaves. The process in turn generates heat as the rotating molecules strike other molecules and set them in motion causing difference in vapor pressure between the central and surface layers of food. This causes moisture in the food to travel out of it fast making microwave drying a rapid, uniform, and energy complacent method in comparison with hot air drying. Penetration of microwaves into food depends on the composition of food and also the frequency of microwave. The microwaves with lower frequency penetrate deeper into the food in comparison with the ones of higher frequencies.

The electromagnetic energy is converted to heat energy for temperature rise. Hence, the heat generation rate per unit volume Q determines the rate of temperature increase. The Q value can be enumerated as follows [16]:

$$Q = 2\pi f \mathcal{E}_0 \mathcal{E}'' {E^2}_{rms} \tag{1}$$

where Q = heat generated per unit volume.

f = frequency

$\mathcal{E}_0$ = 8.854 x 10–12 F/m (free space permittivity)

$\mathcal{E}''$ = material's dielectric loss factor

E_{rms} = root mean square of electric field intensity at the location

The temperature increases as time increases for any given location in the food which is expressed as follows [16]:

$$Q = \rho C_p \frac{\Delta T}{\Delta t} \tag{2}$$

where ρ = material density

Cp = specific heat capacity

T = temperature

t = time

Replacing Eq. (1) with Eqs. (2) and (3) is obtained [16]:

$$\rho C_p \frac{\Delta T}{\Delta t} = 2\pi f \varepsilon_0 \varepsilon'' {E^2}_{rms} \tag{3}$$

From Eq. 3, the change in temperature with respect to time can be calculated for any location of food subjected to microwave heating [16, 17].

5.2 Microwave with hot air drying

Hot air drying in itself is a time-consuming and energy-demanding process. The extensive exposure to high temperature causes loss of nutrients and heat-sensitive compounds of the food. Migration of solutes to food surface occurs resulting into case hardening. Rehydration of the dehydrated food becomes a challenge due to shrinkage of the food during drying. Microwaves in conjunction with hot air drying minimize the drawbacks of both kinds of method. Application of this hybrid format of drying is gaining popularity in the industries and factories. The drying time is considerably reduced with accelerated energy flow to the evaporating point of the food structure even when in moving state within the product. The microwave drying drives moisture from the center to the surface from where it is deliberately removed by the airflow from hot air dryer. The moisture carrying capacity of the airflow is determined by its velocity and temperature that need to be controlled keeping in consideration the heat sensitivity of the volatile components and phytochemicals present in the product. Herein, optimization of airflow, temperature, and microwave power density is crucial for success of the process [15].

Apart from continuous microwave drying, intermittent microwave drying is also gaining popularity for its efficient performance with convective hot air drying. It overcomes the drawbacks of continuous microwave drying such as humidity and uneven temperature distribution, through the power-off phases in the working cycles during which there is a chance of even distribution of moisture and heat by the continuous hot airflow. This subsequently enhances the drying characteristic of intermittent microwave heating in comparison with continuous microwave in terms of nutrient retention and quality standards, though the time involved is longer in intermittent microwave heating when coupled with hot air drying [14]. Food quality might be susceptible to constant microwave heating for long duration which is, however, not so as in case of subjection to intermittent microwaves. Studies on osmotic dehydrated strawberries showed that intermittent microwave drying with magnetron at switched off condition for almost 74% of the time enumerated high-quality strawberries in terms of retention of phenolics, antioxidants, and anthocyanins [18]. Similarly in case of parsley subjected to hybrid drying conditions such as convective hot air microwave drying and intermittent microwave drying showed that retention of vitamin C, color, and rehydration property was the best for the ones with intermittent microwave drying [19].

5.3 Microwave with freeze drying

Freeze drying is the freezing of moisture in food to ice and subsequent conversion of ice to vapor on lowering the pressure. Freeze drying by itself is an energy consuming method, hence subjected to high-value products such as cocoa, coffee beans, and nutraceutical herbs. The dehydration rate is low, and cost incurred is high. In spite of being cost-intensive, it is the most sought after drying method for heat-sensitive products because of its acclaimed capacity to conserve the macronutrients, micronutrients, color, antioxidative properties, and functional properties of the food. The advantage of the method is the sublimation stage of the ice crystals without involvement of oxygen, which enables successful retention of the quality attributes of a product such as structure, color, flavor, and aroma and help easy rehydration [10].

Combining freeze drying with microwave drying process accentuates its efficacy by minimizing its disadvantages in terms of time duration, energy efficiency, and cost. Conventional freeze drying occurs by transfer of energy subsequently from the dried layer to the low-conductive frozen layer through the bulk of the food involving long drying duration and energy requirement [20]. Microwaves when employed together with freeze drying reduce the drying time as compared to freeze drying [21] due to the volumetric heating by microwaves. As ice has low loss factor, microwave energy penetrates only the organic portion of the frozen food, thus warming up all regions of the food instead of layer-by-layer heating in case of conventional freeze dry method. The merits of microwave freeze drying are enumerated as follows:

a. Microwaves penetrate deep into the frozen product

b. The energy is dissipated rapidly through the food material

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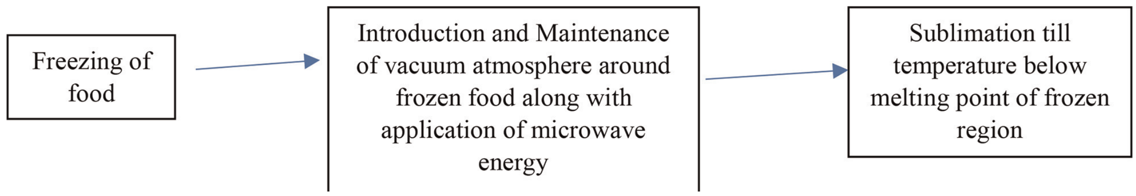

Figure 1.
Steps in hybrid dying by microwave freeze drying [20].

c. Microwaves adapting automatically to the products dynamic dielectric property

d. Less of energy required during efficient drying at the falling rate stage [22]

Microwaves in freeze drying can be subjected in two ways:

a. Simultaneously microwave drying and freeze drying of food wherein the microwave is applied right from the onset of the freeze drying occurring in vacuum condition, to provide necessary energy for sublimation.

b. Two-phased drying initiated with freeze drying followed by microwave drying. Herein, freezing of the product is first completed followed by introduction of microwave energy at vacuum condition in the storage chamber containing the dried product. As the energy from microwaves heat the frozen food, its bulk temperature starts increasing and the frozen water gets evaporated directly to gaseous state escaping in the vacuum chamber. The transition creates an interface between frozen part and dried part, which gradually reduces with time to finally obtain a uniformly dried product (**Figure 1**)

Wang and Chen (2007) [21] proposed use of dielectric bars or spheres for microwave freeze drying of materials lower in solid content or solid products having low loss factor, thus demonstrating 20% reduction in drying time. Skim milk was microwave freeze-dried using silicon carbide as the dielectric material, wherein the drying time was significantly lesser then freeze drying. Duan et al. 2007 [22] reported application of microwave freeze drying to cabbages, which exhibited lower drying time and sterilization effect. Similar was the finding by Duan and Zhang (2008) [23], wherein drying time was reduced to almost half in comparison with conventional freeze drying of sea cucumbers.

5.4 Microwave fluidized bed drying

The prime drawback faced during microwave drying is the nonuniform drying of the product at a given time. Such kind of demerit is overcome by combining fluidized bed drying to the microwave process. In fluidized drying process, the food to be dried is subjected to hot air at high pressure through a porous bed causing agitation to the food particles at which if microwave is introduced, each particle will receive the radiation leading to uniform heating and a subsequent reduction in the diffusion time of drying [24]. The disadvantage of fluidized bed drying is the undesirable size reduction of food particles due to the collision among the particles. Hence, drawbacks of both kinds of drying techniques are minimized in the hybrid drying as described by

Goksu et al. (2004) [25] who studied the drying pattern of macaroni beads subjected to fluidized bed and microwave drying. On comparison of drying time, it was observed that it reduced by 50% when both the methods were applied synergistically with 2.1 and 3.5 W/g of microwave energy in a fluidized bed dryer as against application of microwave and fluidized bed drying individually. Rehydration capacity is another determining factor to ensure the success of a given drying process. Khoshtaghaza et al. (2015) [24] observed that microwave-fluidized drying of soyabeans had better rehydration ratio when subjected to high power of microwave and low velocity of air, because expansion of cell walls occurred as its elasticity and starch hydration increased due to the applied heat and high pressure generated internally in the kernels by the microwave energy.

The selection of microwave energy and temperature of hot air in fluidized bed drying is crucial to obtain the ideal combination for energy efficiency and uniform drying. On application of high-power microwave, the temperature of the particles on surface will be higher than the air temperature of fluidized bed dryer; thus, airflow cools the particles instead of evaporating moisture. Taheri et al. (2019) [26] designed a fluidized bed microwave dryer, as depicted in **Figure 2**, to study the drying curves and moisture diffusivity of lentil seed at different exposure time. Drying was experimented with 0, 300, 400, and 500 W microwave powers at 50 and 60°C fluidized hot air, which aided disinfection along with drying of lentil seeds. Moisture diffusivity varied from 0.44×10^{-10} (when subjected only to air heated to 50°C) to 3.06×10^{-10} m^2/s (when microwave power of 500 W is used with air heated to 60°C) by considering convective boundary condition for the seeds as per Fick's second law of diffusion [26].

5.5 Microwave with vacuum drying

The volume heating in case of vacuum drying is apt for bulk-drying of products with low thermal conductivity and high heat sensitivity such as the viscous and sugar-

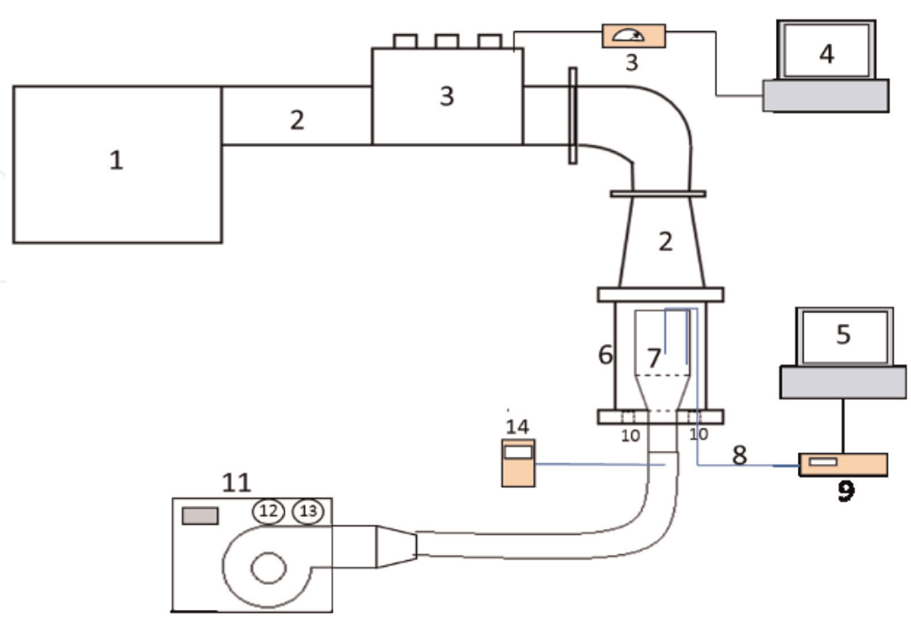

Figure 2.
Schematic diagram of fluidized bed microwave dryer [26]. Where 1 = magnetron, 2 = waveguide, 3 = tuner, 4 = power monitor, 5 = data and microwave power control system, 6 = microwave cavity, 7 = sample holder, 8 = fiber optic probes, 9 = temperature monitor, 10 = vents, 11 = airblower, 12 = air speed potentiometer, 13 = air temperature potentiometer, 14 = inlet air temperature monitor.

rich products [27]. In vacuum, moisture evaporates at temperatures lower than that at atmospheric pressure, thus protecting the products from high temperatures. As air is not involved in this format of drying, incidence of oxidation reactions is eliminated which helps to keep the taste, flavor, color, etc., intact [28] favoring its application in horticultural produces. The advantages of vacuum drying if imbibed into the microwave drying method are the merits of the hybrid model is manifold in terms of rapid heating, energy efficiency, quality retention, and uniform heating. The moisture in food is rapidly heated to vaporize at the requisite low temperature of vacuum environment by developing microwave-induced electric field on the food's water molecules [29].

The benefits of the process are almost equal to freeze drying method in terms of minimization of nutrient loss, structural and flavor change due to short heating duration at low temperatures, but with comparatively lower cost indulgence. Moreover, structural collapse is reduced with the development of porous structure as the moisture migrates from the high-pressure core zone of the food, developed by microwave heating, to the vacuum zone surrounding the material, the phenomenon being referred to as "puffing" [30]. Efficiency of a microwave vacuum dryer calls for consideration on the following details:

a. The dielectric property of sample

b. Distribution of microwave energy homogeneously through the cross section of sample bed

c. The rate of product throughput

d. Vacuum depth

e. Use of DC microwaves to avoid peaks in electric fields as vacuum reduces breakdown field strength, hence, if exceeded may result plasma or sparks

The microwave vacuum dryers can be either fabricated as static dryers or rotary dryers. The static dryers are similar to the domestic microwave oven with an additional vacuum chamber. The design is cost-effective and efficient for thin-layer products. The basic schematic representation of the design is represented in **Figure 3** [31, 32]. With samples having multiple layers, the design is challenging as drying duration increases due to the long time taken by microwaves to penetrate the layers causing

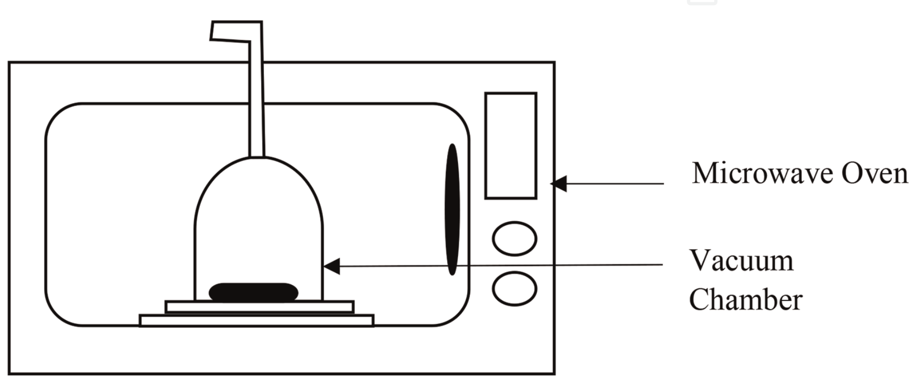

Figure 3.
Schematic diagram of static microwave vacuum dryer [31, 32].

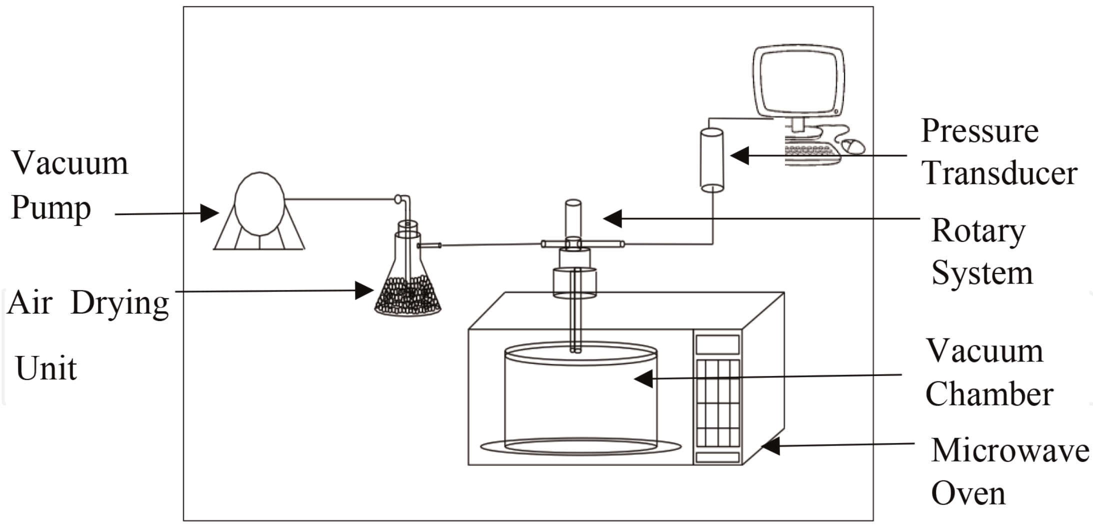

Figure 4.
Schematic diagram of rotary microwave vacuum dryer [27].

nonuniform temperature spectrum. The disadvantage of static dryers have given way to the development of rotary microwave vacuum dryers, wherein a rotating mechanism is introduced for rotation of the cylindrical basket or high HDPE drum inside the microwave oven. The rotational speed of the rotary system is controlled to avoid electric arc damage and ensure uniform heating of drying sample through homogeneous dissemination of microwave energy, which penetrates the multiple layers of food diligently [33]. The schematic representation of the design is represented in **Figure 4** [27].

This hybrid method of drying has shown impressive results. Monteiro et al. (2015) [27] designed the model as in **Figure 4** and experimented with samples such as grapes, banana, tomato, and carrot slices to obtain dried products close to the quality of freeze-dried products within 20 minutes as against 14–16 hours in freeze drying. Cranberries dried in microwave vacuum system retained the antioxidant activity and the bioactive compounds, which is not the case when dried solely with microwaves [34]. Drying process of garlic granules from 21 percent moisture content to 3 percent was the most efficient by microwave vacuum drying in comparison with microwave hot air drying as related to drying rate and product temperature [35]. By implementing automatic temperature control in microwave vacuum drying of strawberry, moisture could be reduced to 6.85 and the rehydration achieved about 55% keeping color, texture, and flavor intact [28].

5.6 Advantages of microwave energy

The microwave heating has its own set of advantages, tapping of which is feasible by imbibing into other drying methods. The advantages of this volume heating can be glanced to note as follows.

1. A high partial pressure is developed in the product due to higher internal temperatures as compared to the surface, which drives the moisture out from within the material, thus enabling to maintain permeable surface layers instead of over drying of surfaces.

2. Deep penetration by microwaves

3. Selective heating of water and organic solvents because of waters' higher dielectric losses compared with other molecules

4. Efficient drying of high-moisture products with low thermal conductivity

5. Control of energy transport speed feasible

6. Automation feasible

7. Shorter processing duration

6. Conclusion

Microwave energy synergized with different drying methods augments the drying efficiency by tapping its adventitious characteristics. The positive features of the technique also neutralize its certain negative features such as nonuniform drying and high electric charge rates. Imbibing microwave drying into hybrid drying technology is not only a way to enhance the drying rates but also a novel approach to retain the quality of the product. Hot air drying accelerates the escape of moisture from the core to the surface and then to the environment, while freeze drying aids to conserve the bioactive compounds and nutritional status of the products. Fluidized bed drying and vacuum drying help attaining better rehydration ratio and uniform heating of the products. Hence, holistic approach is the key to a profound hybrid drying setup bringing in efficiency and quality together.

Hybrid drying has embarked and popularized in recent times due to its immense versatility and drying efficiency. Its potency will enhance further in the future time if there is more of studies on the combination of different drying methods in a single or multiple setup and if more of initiative is exhibited on the transfer of technology to implementation level which is the need of the hour. Minimization of the fabrication cost will boost the use of hybrid drying in small-scale food industries as well. The individual methods in hybrid drying should be selected considering the need to obtain quality finished product with minimum environment stress. The efficiency of the techniques can further enhance with the use of sensors to keep a real-time check on the quality, hence adding a new perspective to it. The deterioration of quality and degradation of heat-sensitive nutrients have always been cause of concern and deciding factors for judging the efficiency of drying methods. Hence, the implication of sensors is manifold for detecting deterioration of molecules such as ascorbic acid, phytochemicals, or other such heat-sensitive antioxidant compounds during runtime, which can subsequently be communicated to the operator or automatically process optimized through the use of appropriate software [36].

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Conflict of interest

The authors declare no conflict of interest.

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