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REVIEW ARTICLE

Novel Drying Techniques for Spices and Herbs: a Review

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Abstract Spices and herbs are important parts of human daily food consumption and play an essential role in seasoning and/or preserving food, curing illness, and enhancing cosmetics. Proper processing is necessary because the fresh produce has high moisture content and often high load of microorganisms. Dehydration is the most common method used to lower moisture content and hence the water activity to a safe limit which prolongs shelf life. However, consumers' demand on processed products with most of the original characteristics of the fresh plants has increased. Consequently, drying must be executed carefully in the interest of retaining the taste, aroma, color, appearance, as well as nutritional value of the plants to maximum possible extent. In addition to quality considerations, drying efficiency is another key aspect for evaluating drying performance. This article reviews recent developments in the production of high dried spices and herbs. It attempts to detail the relative merits of selected recently developed drying techniques with focus on solar-assisted and microwave-assisted hybrid drying techniques which offer high-quality drying with excellent efficiency. Outlook for future research trends and challenges for dehydration of spices and herbs is also discussed.

Keywords Spices and herbs · Drying techniques · Solar · Microwave · Quality

Introduction

Spices and herbs are mostly botanical origin plants that are especially valued by virtue of their taste, aroma, color, medicinal functionality, and preservative action [1–3]. Normally, such produce should be handled properly before being utilized to season and/or preserve food, cure illness, and enhance cosmetics [4–6]. Fresh harvested spices and herbs contain a high mount of moisture and numerous microorganisms; immediate preservation should be carried out to prevent biological deterioration after harvesting due to their perishable characteristics. Thermal drying is the most commonly used cost-effective means of post-harvest processing to avoid losses of these raw materials [7]. It is also necessary to avoid potential safety hazard due to formation of toxins [8, 9].

Drying is one of the oldest techniques for food preservation and it is an indispensable process in the food industry. It aims at lowering moisture content and water activity to safe limits that prolong shelf life, minimize packaging demand, as well as reduce shipping weights [10–12]. Therefore, this technique is widely used for dehydrating foodstuff such as vegetables, fruits, spices, herbs, and other products [13–16].

Nowadays, consumers' demand on processed products with most of the original characteristics of the fresh plants has increased. Consequently, drying must be executed carefully in the interest of retaining the flavor, aroma, color, appearance, and nutritional value of the plants as much as possible [17]. In addition to quality considerations, drying efficiency is another key aspect for evaluating drying performance, which involves energy consumption, drying time, drying rate, and so forth.

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Drying can be roughly described as a mass and heat transfer process consisting of the removal of water or another solvent by evaporation from a solid, semi-solid, or liquid [18]. However, the drying mechanism is quite complex to be accurately described and modeled because it involves concurrent heat, mass, and momentum transfer through a porous or nonporous substance with phase transition and with or without chemical reactions [19]. It is recognized as an energy intensive unit operation for most industrial processes [20–22], and certain evidences revealed that industrial drying consumes around 10–15% of national industrial energy in some developed countries [23–25], whereas around 30–40% of total energy consumption in several developing countries [26].

Various conventional drying techniques have been applied for spices and herbs including solar drying [27], hot air-drying [28], freeze-drying [29], and microwave drying [30]. However, most of these drying methods require long drying time and excessive energy consumption, thus causing the dehydrated products with undesirable quality [31, 32]. Since spices and herbs are heat-sensitive raw materials, it is desirable to process them under gentle drying conditions. Solo drying technique is generally incapable of providing both excellent product quality and high drying efficiency, and numerous innovative drying techniques have been established and adopt to improve drying efficiency (e.g., drying time, drying rate, and energy consumption) as well as to obtain premium quality products.

The objective of this review is to present an overview of the recent developments in the high quality and efficient drying of spices and herbs. The relative merits of selected novel techniques (mainly hybrid drying techniques) in offering the high quality drying with high efficiency and outlook for future research trends and challenges for spices and herbs dehydration are discussed.

Novel Hybrid Drying Techniques

Conventional "solo" drying techniques (e.g., solar drying, hot air-drying, freeze-drying) can rarely achieve high drying efficiency with least effect on quality of dried spices and herbs [33–35]. The combination of two or more different drying methods can provide a synergistic effect, resulting in diminished energy requirement and drying time while maintaining most quality attributes [36, 37].

Researchers have made considerable effort to devise novel hybrid drying techniques to further promote the drying performance, with respect to product quality (e.g., aroma, taste, nutrients, color, texture, etc.). Here, novel hybrid techniques are summarized, classified, and discussed.

Solar-Assisted Hybrid Drying Techniques

Solar energy is one of the most widely used renewable energy sources for drying of fruits [38], vegetable [39], spices and herbs [40, 41], etc. Solar drying is an economical and sustainable eco-friendly process for agricultural products [42]. However, this technology has its limitations such as poor quality and hygienic issues in the products, slow drying process, losses of product due to insects and birds, large space requirement, as well as high labor cost [43–45].

Based on solar energy utilization, solar drying can be sorted into three main groups: (a) direct or open-air sun drying where the product is directly exposed to the sun, (b) indirect solar drying or convective solar drying, and (c) mixed-mode or hybrid solar drying. Meanwhile, solar dryers are divided into two major categories: natural and forced convection solar dryers. From the structural aspects, solar dryers were also allocated to three major types: the greenhouse type, the collector type, and the heat pump-assisted type. Table 1 lists spices and herbs that are subjected to solar-assisted hybrid drying and what methods are used, and details are addressed in the following section.

Forced convection solar dryers are convenient to dry large amounts of raw materials [46]. Rabha et al. [47] conducted the comparative experiments to investigate the drying characteristic in the indirect-type forced convection solar tunnel dryer and open-air sun drying of thin layer ghost chili pepper. The indirect-type solar dryer consists of a semi-continuous-type tunnel dryer, two double-pass solar air heaters (SAH), a shell and tube heat exchanger, and a blower. Figure 1a shows a schematic layout of the dryer, and the cross-sectional profile of a solar air heater is presented in Fig. 1b. Their study showed that the drying time required to reduce the moisture ratio of ghost chili pepper from 589.6% (db) to 12% (db) was 123 h in solar tunnel dryer, while 193 h in open-air sun drying. In addition to its longer drying time process, open-air sun drying had undesirable effects on the color, texture, and quality of dried ghost chili pepper. El-Sebaii et al. [48] investigated the mathematical models of thin layer drying to specify the suitable model for depicting the drying behavior of thymus and mint in an indirect-mode forced convection solar dryer. Midilli and Kucuk model ($MR = 0.9891\ \exp(-0.0568t^{3.0459}) + 0.029\ t$) was suitable for describing the thin layer solar drying of mint. However, the Page ($MR = \exp(-6.2032 \times 10^{-8}\ t^{4.9107})$) and modified Page models ($MR = \exp(-(0.0341\ t)^{4.9107})$) gave the best model fit for dehydration of thymus. The cost of drying mint and thymus in the indirect-mode forced convection solar dryer was found to be 0.025 €/kg and 0.087 €/kg, respectively.

Solar dryer with greenhouse unit is used to store solar energy inside the greenhouse during the daytime or to transfer excess thermal energy from inside the greenhouse to a heat storage area [49]. Normally, this type of solar dryer utilizes

Table 1 Applications of solar-assisted hybrid drying for spices and herbs

Spices and herbs	Drying facilities	References
Ghost chili pepper	Forced convection solar tunnel dryer Sun	[47]
Thymus	Forced convection solar dryer	[48]
Peppermint (*Mentha pepperita* L.)	Forced convection solar tunnel greenhouse dryer	[49]
Java tea leaf and sabah snake grass leaf	Solar greenhouse dryer with integrated a heat pump	[50]
Habanero chili	Fluidized bed dryer coupled with a low temperature solar collector Sun	[51]
Mint	Forced convection solar dryer	[48]
	Solar-assisted fluidized bed dryer integrated with a heat pump	[52]
	Solar collector dryer	[53]
	Heat pump dryer	
	Solar-assisted heat pump dryer	
Parsley	Solar collector dryer Heat pump dryer Solar-assisted heat pump dryer	[53]
Roselle	Forced convection solar air heating collector system assisted with granite	[54]
Rosemary (*Rosmarinus officinalis* L.)	Forced convection solar dryer with a solar air collector and an auxiliary heater	[55]
Saffron	Photovoltaic–thermal solar dryer equipped with a heat pump	[56]
Misai Kucing (Orthosiphon stamineus Benth)	Solar-assisted heat pump dryer	[57]

transparent plastic tunnels as air heaters. Morad et al. [49] constructed three identical solar tunnel greenhouse dryers with a forced convection dryer for peppermint plants and leaves. Two suction air fans were installed to increase the air flow rates of the drying system. Drying rate, drying efficiency, product quality, and drying cost under different operational conditions were evaluated, and the experimental results showed that the drying rate was increased by 22.78% for whole plants with continuous fan operating system, while 24.8% for leaves with periodical fan operating system. The operational costs were reduced by 6.95% with periodical operating system for peppermint plants. Tham et al. [50] evaluated the drying characteristics of herbs using an industrial scale solar greenhouse dryer (SGD) with an integrated heat pump (HP) system. Results revealed that SGD integrated with HP system has successfully reduced the room relative humidity by 10–15%. Also, heat pump has mitigated the product rehydration issue by maintaining room relative humidity at a maximum value of 65% throughout the drying period. The drying rate of Java tea was improved three- to fourfolds, i.e., from 0.004–0.008 g H_2O/g dry matter (DM) min to 0.018–0.025 g H_2O/g DM min, whereas 10% drying time was saved for both Java tea leaf and Sabah snake grass leaf with the assistance of heat pump system. Meanwhile, the supply of dry air from the heat pump system with a magnitude of 0.25–0.50 m/s helps to enhance the drying rate of the herbs as well as minimize the non-uniformity of drying temperature and relative humidity inside the solar greenhouse dryer.

Solar air collectors are classified as single-pass, double-pass, or multi-pass collectors. A hybrid solar-assisted fluidized

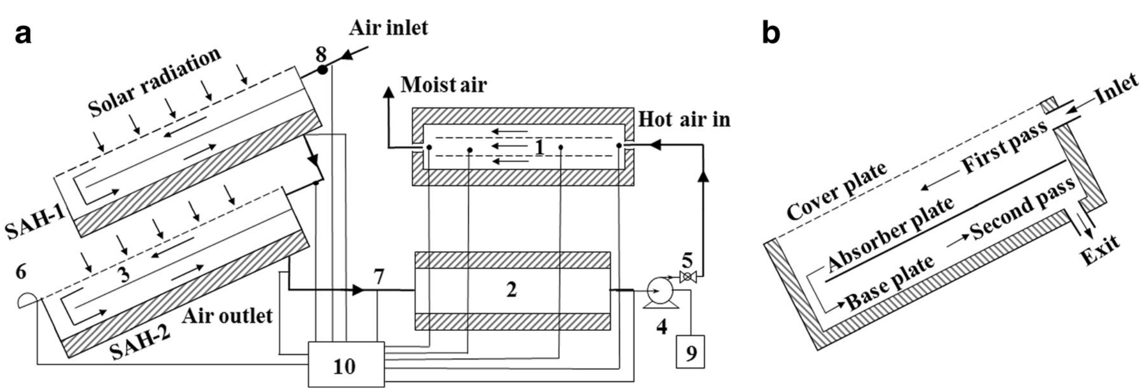

Fig. 1 **a** Schematic layout of a solar tunnel dryer and **b** cross-sectional profile of a solar air heater. **a** *1* Tunnel dryer, *2* shell and tube heat exchanger for energy storage, *3* solar air heater, *4* air blower, *5* ball valve, *6* pyranometer, *7* thermocouple, *8* flow meter, *9* energy meter, *10* data acquisition system [47]

bed dryer with a low temperature solar collector was proposed by Rodríguez et al. [51], the drying process conducted in two ensued systems: (1) an open sun dryer and (2) a pilot fluidized bed dryer coupled with a low temperature solar collector for air heating. The Habanero chili's moisture content was removed to 5% from 90% in 10.3 h, with good product quality. The mean drying time achieved a 50% reduction, also an energy reduction of 2.6 kW for every dried chili. Ceylan et al. [52] fabricated a mixed-mode, fluidized bed dryer with a solar air collector and investigated the drying kinetics of mint leaves. Their experimental system consists of a combination of a solar air collector, a parabolic trough collector, and a heat pump system. The solar air collector provided the required heat energy for the drying process during the daytime. Heated water in the parabolic trough collector was stored in the depot which would be used in the drying process during the night. The temperatures of the drying air for the solar air collector, the parabolic trough collector, and the heat pump operating modes were controlled with accuracies of ±0.35, ±0.444, and ±0.478 °C, respectively. Experimental results showed that a solar energy system can be used with temperature control for different applications, such as heating greenhouses and preheating in air conditioning systems. A new dryer with solar air collector was constructed by Şevik et al. [53], which consists of double-pass solar air collector (DPSAC) unit, heat pump (HP) unit, photovoltaic (PV) unit, measuring devices, and automatic control system (Fig. 2). In order to keep a constant drying air temperature during the drying process, a PID control unit is integrated. The coefficient performance of the systems for drying mint and parsley were calculated as 2.28 and 2.17, respectively. Energy utilization ratios of the dryer for drying mint and parsley were calculated as 0.18–0.25 and 0.2–0.26, respectively. On the other hand, experimental results indicated that the DPSAC, HP, PV unit, and PID control unit could work in coordination with each unit and the dried products with good physical properties such as color, shrinkage, and taste. Kareem et al. [54] evaluated the performance of a forced convective multi-pass solar air heating collector (MPSAHC) system assisted with granite for drying of Roselle. The experiments were conducted under the daily average relative humidity, solar irradiance, ambient temperature, and wind speed of 64.5%, 635.49 Wm^{-2}, 32.24 °C, and 0.81 m/s, respectively. An average drying rate of 33.57 $g(kgm^2h)^{-1}$ was achieved, while the system optical efficiency, collector efficiency, drying efficiency, and moisture pickup efficiency of 70.53, 64.08, 36.22, and 66.95% were obtained, respectively. MPSAHC dryer was 21 h faster with fair color retention comparing to open sun drying approach which was conducted under the same weather condition. The techno economic analysis reflected the system as a worthy investment with a payback period of 2.14 years. Mghazli et al. [55] studied the drying kinetics of rosemary in an indirect active solar dryer with a separate solar collector and a drying unit. The experiments were carried out at four different air temperatures (50, 60, 70, and 80 °C) and two air flow rates (300 and 150 m^3/h) for an ambient temperature in the range of 26–37 °C. Results showed that the increase of temperature could reduce drying duration. Midilli and Kucuk model ($MR = 0.9969 \exp(-0.0381t^{1.2702}) - 0.0022\ t$, under air temperature: 80 °C and air flow rate: 150 m^3/h) was found as best fit for thin layer drying when simulation was done for all the drying data. In the covered ranges, the effective moisture diffusivity values (Deff) were obtained between 9.74×10^{-11} and 1.48×10^{-10} m^2/s from the Fick's diffusion model. The Arrhenius relation with an activation energy value of 54.37 kJ/mol expressed the temperature effect on the diffusion coefficient.

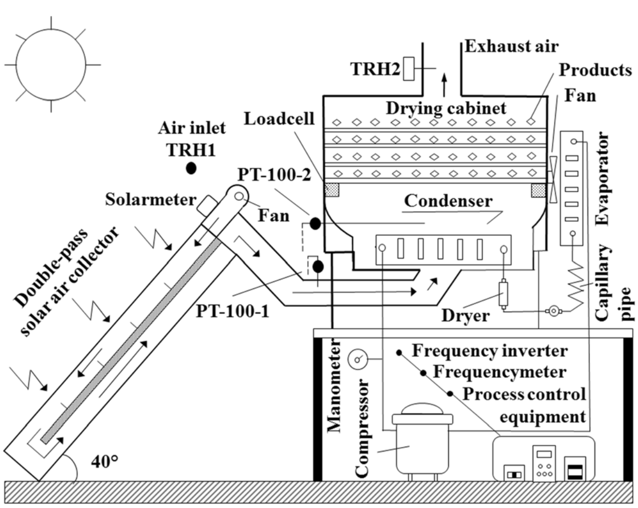

Fig. 2 Schematic of PID-controlled double-pass solar air collector-heat pump drying system [53]

By recovering waste heat in heat pump systems, they reduce energy consumption and thereby provide efficient and environmentally friendly technologies [56]. Hence, solar dryers with heat pump system have been widely developed. Mortezapour et al. [56] developed a hybrid photovoltaic–thermal solar dryer equipped with a heat pump system for drying of saffron (Fig. 3). The effect of air flow rate at three levels (0.008, 0.012, and 0.016 kg/s), drying air temperature at three levels (40, 50, and 60 °C), and two different drying modes (with and without the heat pump system) on the operating parameters of the dryer was investigated. The results showed that energy consumption and total drying time decreased as air flow rate and drying air temperature increased. Applying the heat pump unit increased the electrical efficiency of the solar collector, whereas decreasing the total energy consumption and drying time. The highest values for thermal and electrical efficiency of the solar collector were 28 and 10.8%, respectively. The maximum dryer efficiency of 72% and highest specific moisture extraction rate of 1.16 were gained at an air flow rate of 0.016 kg/s and air temperature of 60 °C with deployment of the heat pump system. Gan et al. [57] evaluated

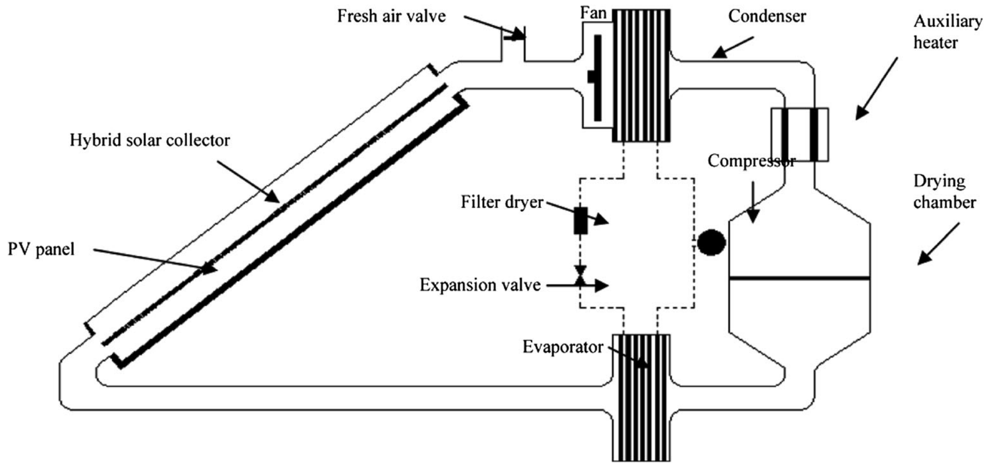

Fig. 3 Schematic of solar dryer equipped with a heat pump system [56]

the effect of different drying conditions by solar-assisted heat pump drying on drying kinetics and product quality of Misai Kucing. Experimental results showed that the drying rates by solar-assisted heat pump drying in all drying trials were higher than solar drying. The result shows that the effect of relative humidity and air velocity on drying rate is significant during the initial and later stage of drying. In addition to its long time process, solar dried samples had the greatest total color change as compared to solar-assisted heat pump dried samples. Besides, there is a significant difference ($p < 0.05$) between the content of sinensetin (SEN) in fresh samples and solar dried samples. SEN and rosmarinic acid (RA) retention among the dehydrated samples were maximum 83.07% in leaves and 92.54% in flowers, respectively, by solar-assisted heat pump drying method. For solar-assisted heat pump dried samples, there are no significant differences ($p > 0.05$) in the retention of SEN and RA as compared to fresh samples.

Microwave-Assisted Hybrid Drying Techniques

Microwaves are a form of electromagnetic energy generated by magnetrons under the combined force of perpendicular electric and magnetic fields, with frequencies between 300 MHz and 300 GHz while wavelengths range from 100 cm (300 MHz) to 0.1 cm (300 GHz) [58, 59]. The most common frequency of microwave used is 915 and 2450 MHz in the industrial food drying applications. The mechanism of microwave drying is that water molecules are bipolar and repeatedly rotate as a result of the rapidly alternating electromagnetic field, and heat is created throughout the material due to friction between the water molecules so the moisture will intensively evaporate and transfer to the surface [60].

Microwave drying has many advantages compared to conventional drying methods, such as rapid dehydration rate [61], short processing time [62], fast and accurate control [63], and clean process without bringing secondary waste [64]. However, single microwave drying method has some shortcomings that include non-uniform heating, possible textural damage, and limited penetration depth of the microwave field into the products [65]. Therefore, microwave is often combined with other drying methods to overcome the limitations of solo microwave drying. Table 2 displays the applications of microwave-assisted hybrid drying for spices and herbs, and it is discussed in detail in the following section.

Szadzińska et al. [66] studied the drying rate, the energy consumption, and the quality aspect of green pepper with combined convective-microwave-ultrasound (CVMU) dryer and convective (CV) dryer. The schematic of the experimental setup of the MUCV dryer is shown in Fig. 4, and this hybrid dryer allows convective drying with microwave and ultrasound enhancement independently as well as in different combinations. Experimental results have shown that reduction in drying time reached the highest level in microwave-enhanced convective drying up to 88%, and only 39% by ultrasound enhancement. The lowest energy consumption value (1.26 kWh) was obtained from microwave-enhanced convective drying process, and approximately 84% energy was saved compared to the energy usage of convective drying process that amounted to 7.97 kWh. For the nutritional aspect, it was demonstrated that convective-ultrasound drying allows remaining most of the vitamin C and up to 70%. For color, the best dried biological materials were obtained by implementing convection, microwave, and ultrasound simultaneously. Moreover, the CVMU drying process resulted in a low water activity and better rehydration ability for the dried green pepper.

Łechtańska et al. [67] investigated the effects of five different drying methods with different application of microwave and infrared radiation on drying kinetics, energy consumption, and quality of green pepper (Table 3). The results proved that enhancement of convective (CV) drying by both microwave and infrared radiation (CVMW + IR_{per} or CV + MW_{per} + IR_{per}) significantly reduced the drying time up to 76% as compared to pure CV drying. The highest degree of vitamin

Table 2 Applications of microwave-assisted hybrid drying for spices and herbs

Spices and herbs	Drying methods	References
Green pepper (*Capsicum annuum* L.)	Convective (CV) drying	[66]
	Convective-microwave-ultrasound drying	
	CV drying	[67]
	Convective drying enhanced with microwave (CVMW)	
	CVMW drying and periodically with infrared radiation	
	CV drying enhanced periodically with microwave and infrared radiation	
	CV drying enhanced periodically with infrared radiation	
Ginger (*Zingiber officinale* Roscoe)	Air-drying	[68]
	Freeze-drying	
	Infrared drying	
	Microwave drying	
	Intermittent microwave combined with convective drying	
	Microwave fluidized bed drying	[69]
Nutmeg mace (*Myristica fragrans*)	Pulsed microwave-assisted hot air-drying	[70]
Rosemary (Rosmarinus officinalis L.)	Microwave-vacuum (MV) drying	[73]
Marjoram (*Origanum majorana* L.) and sweet basil (*Ocimun basilicum* L.)	CV drying MV drying CV pre-drying and MV finish-drying	[74, 75]

C retention that amounted to 63.91% was attained by CVMW drying as compared to CV drying (46.54%). Meanwhile, the CVMW drying resulted also in the lowest energy consumption of 3.3 ± 0.1 kWh. CV + IR_{per} drying presented the highest energy consumption (6.9 ± 0.1 kWh), the lowest vitamin C retention (16.86%), and the worst dried samples from the visual appearance and color. The experiments proved that convective drying assisted with both microwave and/or infrared radiation significantly reduced the drying time and energy consumption, improved the color of the dried product, as well as enabled better vitamin C retention compared to pure convective drying.

An et al. [68] investigated the air-drying (AD), freeze-drying (FD), infrared drying (IR), microwave drying (MD), and intermittent microwave combined with convective drying (IM&CD) of ginger rhizome slices. Quality attributes of the dried samples were compared with respect to total phenolic content (TPC), total flavonoid contents (TFC), and pharmacologically active components (6-, 8-, 10-gingerols and 6-shogaol). Investigation results (Table 4 and Fig. 5) showed that FD, IR, and IM&CD had higher retention of TPC and TFC compared to AD and MD process. However, FD and IR had relative high energy consumption and drying time, especially freeze-drying. Therefore, considering both the quality aspects and energy consumption, IM&CD would be very promising for thermos-sensitive material due to its higher efficiency, good quality retention, and lower cost, which had a broad market prospect for commercial-scale application.

Lv et al. [69] introduced a new microwave fluidized bed drying (MFBD) method for ginger slices. The schematic diagram of this MFBD equipment is shown in Fig. 6. Material tray and vibration frame are fixed together in the dryer and

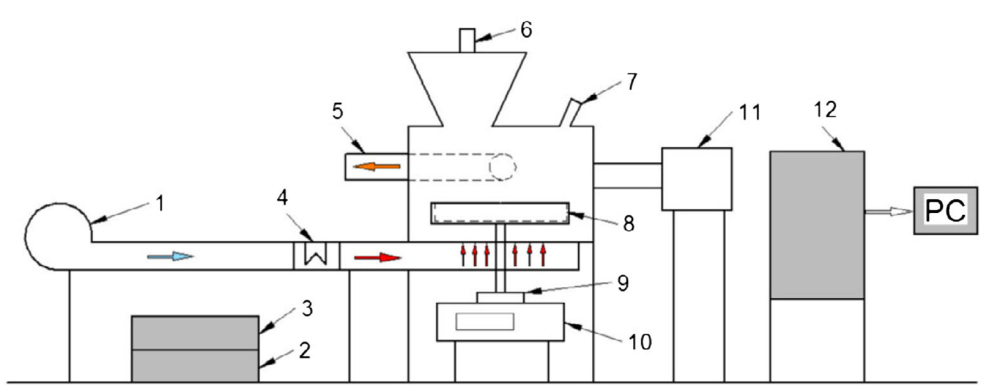

Fig. 4 Scheme of a hybrid dryer: *1* fan, *2* airborne ultrasound system (AUS), *3* ultrasound feeder, *4* electric heater, *5* air outlet, *6* ultrasound transducer AUS, *7* pyrometer, *8* rotating sample pan, *9* drive sample pan, *10* balance, *11* microwave generator, *12* control cupboard [66]

Table 3 Five different drying methods and their performances for green pepper [67]

Drying methods	Drying time (min)	Total energy consumption (kWh)	Water activity in the dried sample (aw)	Retention of vitamin C (%)
CV	1127 ± 28	6.5 ± 0.1	0.560 ± 0.03	46.54
CVMW	364 ± 9	3.3 ± 0.1	0.445 ± 0.03	63.91
CVMW + IR_{per}	274 ± 6	4.8 ± 0.1	0.412 ± 0.04	24.91
CV + MW_{per} + IR_{per}	345 ± 8	3.8 ± 0.1	0.419 ± 0.04	42.97
CV + IR_{per}	699 ± 19	6.9 ± 0.1	0.398 ± 0.03	16.86

CV pure convective drying throughout the whole process, *CVMW* convective drying enhanced with microwaves throughout the whole process, *CVMW* + IR_{per} convective drying enhanced with microwaves throughout the whole process and periodically with infrared radiation, *CV* + MW_{per} + IR_{per} convective drying enhanced periodically with microwave and infrared radiation, *CV* + IR_{per} convective drying enhanced periodically with infrared radiation

connected with vibration motor through damping spring, and the raw materials in the tray start rolling and are in a suspended state while the vibration motor works. Six magnetrons are evenly arranged at the top of the drying chamber independently. The problems of local overheating could be solved through even arrangement of magnetrons and fluidization system of materials. Good drying quality and high drying speed are obtained for MFBD at microwave power 2.0 to 0.4 W/g in different drying stages. Meanwhile, in order to understand the water flow characteristics of ginger slices in MFBD, low nuclear magnetic resonance was used to detect the materials in different drying stages. The state of water could be categorized as free water (FW), immobilized water (IW), and bonded water (BW). FW is the main water state in fresh ginger slices and converts to the IW quickly in the beginning stage, and then both FW and IW decreased until the final stage is reached.

Meetha et al. [70] conducted a study on application of novel combined microwave drying technology for better color retention of nutmeg mace. Pulsed microwave-assisted hot air-drying (PMHAD) was investigated at three different power levels (0.5, 1, and 1.445 kW) with 30-s pulsation at a hot air temperature of 45 °C, and the color values of nutmeg mace were compared with the market and fresh sample using colorimeter. For the dried nutmeg mace, the desired color is usually darker, more reddish, and less yellowish. Among the PMHAD-treated samples, power level of 1.445 kW was darker, 1 kW was more reddish, and 0.5 kW was less yellowish, while the market sample were lighter and yellowish. It is clear that PMHAD method has more color retention compared to market samples.

Microwave-vacuum (MV) drying combines the advantages of both microwave drying and vacuum drying and improves energy efficiency and product quality [71, 72]. Sánchez et al. [73] investigated the influence of the vacuum level and the microwave power on aroma compounds and sensory quality of rosemary dried by MV method. The time needed to dry rosemary was shortened with higher values of microwave power and vacuum intensity. Experimental data showed that the higher the vacuum intensity in the drying system at a specific microwave power and/or the higher the microwave power, the lower the total quantity of volatiles. However, the higher vacuum intensity and microwave power lead to the shorter drying time. The optimum conditions were 72–74 kPa and 360 W for 39 min to get the dried samples and 240 W and 0 kPa (56 min were required) compared to almost 180 min are required for drying of rosemary using pure CV drying. This study also revealed that MVD could be applied in drying of very sensitive materials, such as rosemary, and for this purpose, very high vacuum levels with low microwave powers should be applied. Sánchez et al. [74] evaluated the influences of drying method on the quality of marjoram. Convective drying (CVD), microwave-vacuum drying (MVD), as well as a combination of convective pre-drying and MV finish-drying (CVPD + MVFD) were carried out for dehydrating of marjoram. Volatile compounds from marjoram samples were extracted by hydro distillation and analyzed by gas chromatography. Thirty three compounds were

Table 4 Drying time, energy consumption, and extraction yield for different dried gingers [68]

Drying methods	Fresh	AD	IR	FD	MD	IM&CD
Drying time (h)	N/A	12.0 ± 0.5	6.0 ± 0.7	44.5 ± 2.0	1.8 ± 0.3	1.5 ± 0.2
Energy consumption (kWh/g H_2O)	N/A	3.30 ± 0.08	12.23 ± 0.24	33.7 ± 0.53	2.7 ± 0.12	3.21 ± 0.1
TPC (mg GAE/g d.w.)	11.97 ± 0.33	9.69 ± 0.54	11.35 ± 0.66	13.83 ± 0.31	8.41 ± 0.35	11.28 ± 0.40
TFC (mg Rutin/g d.w.)	13.49 ± 0.36	12.08 ± 1.17	14.52 ± 0.23	13.32 ± 0.52	12.55 ± 0.74	15.42 ± 0.87

AD hot air-drying, *IR* infrared drying, *FD* freeze-drying, *MD* microwave drying, *IM&CD* intermittent microwave-convection drying, *N/A* not applicable, *TPC* total phenolic, *GAE* gallic acid equivalents, *TFC* total flavonoids content

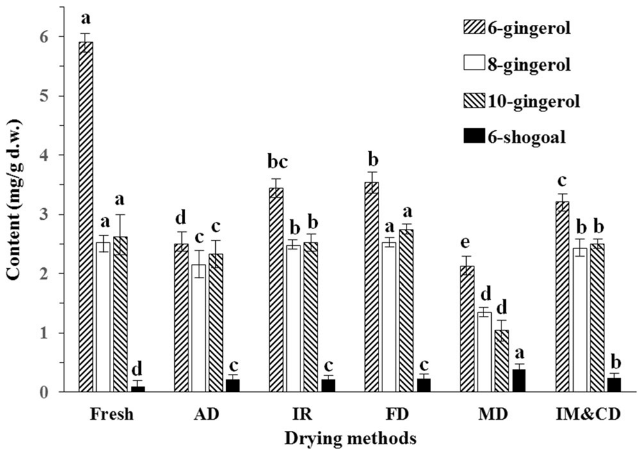

Fig. 5 Changes of 6-, 8-, 10-gingerol, and 6-shogaol content of ginger extract during AD, IR, FD, CM, and IM&CD drying processes. *AD* hot air-drying, *IR* infrared drying, *FD* freeze-drying, *MD* microwave drying, *IM&CD* intermittent microwave-convection drying. For each column, values followed by the same letter (*a*–*c*) are not statistically different at $P < 0.05$ as measured by Duncan's test [68]

tentatively identified and quantified, and among them cis-sabinene hydrate (229 mg/100 g dry basis, db) and terpinen-4-ol (169 mg/100 g, db) are the major components. Results showed significant differences in the aroma quality of marjoram dried by different methods. The total quantity of volatiles of fresh marjoram (825 mg/100 g, db) was considerably reduced by most of the drying methods, except for the MVD at 240 and 360 W. The MVD method at 240 W was the optimized option for drying marjoram followed by the combined method with 50 °C and 240 or 360 W: the drying time was relatively short (≈162 and 158 min, respectively) and has good aroma quality as observed by sensory analysis (high scores of fresh and vegetable odor). The same authors also studied the influence of drying methods on aroma compounds of sweet basil within the same drying methods mentioned before [75]. The total quantity of volatiles was considerably reduced from 32.1 g/kg of fresh sweet basil to 14.4 g/kg of dried sweet basil by employing both CVD and MVD. The CVPD at 40 °C and then MVFD at 360 W was the optimized process for drying sweet basil; the time required was relatively short (≈250 min), with a relative high quantity of volatile compounds (16.7 g/kg) and good aroma quality.

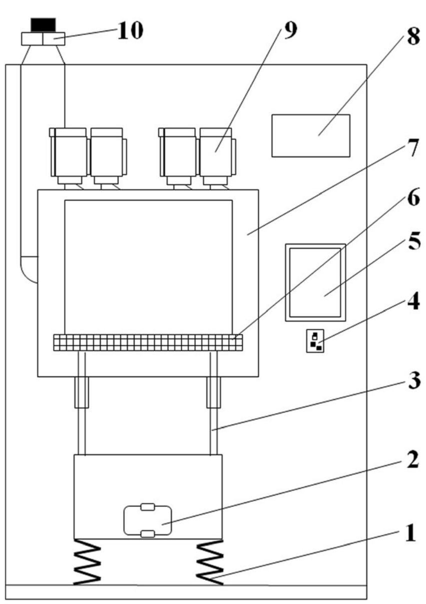

Fig. 6 Schematic diagram of a MFBD equipment: *1* damping spring, *2* vibration motor, *3* vibration frame, *4* frequency converter, *5* touch screen, *6* material tray, *7* MFD chamber, *8* monitor, *9* magnetron, *10* induced draft fan [69]

Other Drying Sources-Assisted Hybrid Drying Techniques

Apart from drying source of solar and microwave combined drying techniques, several conventional drying techniques combined with other methods have been developed and adopt for drying of spices and herbs.

Mihindukulasuriya et al. [76] established a laboratory-scale rotary dryer prototype (Fig. 7) that can operate in three different modes: hot air (HA), infrared (IR), and IR combined with hot air (IRHA) for drying of chili. The hot air mode consumed 60.4% more power than the IR mode as well as 33.5% more power than the combined mode at 70 °C. On the other hand, the redness of the chili was decreased by 30% in the IR mode compared to the hot air and IRHA modes at 70 °C. In the IR mode, at 70 °C, the loss in capsaicin content was 2 and 22% greater than hot air mode or combined mode, respectively. The quality characteristics in terms of capsaicin content and color were similar with IRHA mode and HA mode for temperatures ranging from 65 to 70 °C. A positive correlation was observed between retention time and power consumption with HA and

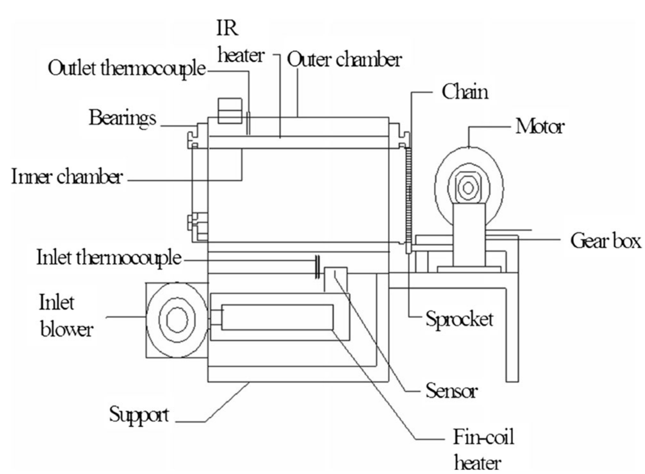

Fig. 7 Schematic illustration of a combined IR and hot air rotary dryer [76]

IRHA modes, while a negative correlation was identified in IR mode. Based on color, capsaicin content, power consumption, and retention time in each mode, the best overall performance with respect to drying chili was obtained at 70, 65, and 50 °C in HA, IRHA, and IR mode, respectively.

Different drying methods such as hot air (HA) drying (50 °C) with 58–63% relative humidity (RH), low humidity hot air (LHA) drying (50 °C and 28–30% RH), and radiofrequency (RF) drying (50 °C, 56–60% RH) were investigated for efficient dehydration of dill (*Anethum graveolens*) greens with optimal retention of color and constituents (Naidu et al. [77]). Results showed that the drying time of HA and RF was marginally higher (around 22%) compared to HA. Lightness, greenness, and yellowness of LHA dried sample were higher than those of the RF and HA dried dill greens. Extracts from dill greens dehydrated by LHA exhibited good free radical scavenging activities from 5 to 88%. Further, methanolic extracts of dill greens dehydrated by LHA drying had a noticeable effect on scavenging free radicals. Results of the consumer acceptance study have shown that up to 70 and 80% of the panelists gave the "Like Very Much" rating to a snack food "Vada" which made with fresh and dried dill greens, respectively.

Antal et al. [78] compared two drying methods, hot air-drying (HAD), high (150–250 Pa) and low pressure (10–30 Pa) of vacuum freeze-drying (VFD), used for the dehydration of spearmint leaves in terms of essential oil composition and rehydration ability of the final dried product. It was observed that drying time and essential oil content were strongly influenced by vacuum pressure. Higher chamber pressure increased the drying time but preserved the major volatile compounds of dried product. Comparing the quality of dried product, freeze-dried product is better than hot air-dried ones. Meanwhile, freeze-dried mint leaves also had higher rehydration rates (0.5 min) than hot air-dried ones (5 min) at water temperatures of 75 °C. It is recommended that the drying of spearmint leaves by VFD and the pressure in the drying chamber should not be too low.

Other Latest Novel Drying Techniques

Recently, some alternative novel technologies, such as nonthermal techniques, CO_2 drying and pretreatment of pulsed electric field (PEF), and osmotic dehydration (OD), can improve both product quality and drying efficiency.

The nonthermal technologies such as ultrasounds have shown promise for inactivating microorganisms at near-ambient temperatures, improving energy efficiency and reducing thermal degradation of food components, therefore consequently preserving the sensory and nutritional quality of food products [79, 80]. Rodríguez et al. [81] assessed the influence of high-intensity ultrasound (US) on transfer phenomena during the convective drying in a high-void bed of thyme leaves. Drying kinetics of thyme leaves were carried out at air velocity of 1, 2, and 3 m/s with different air temperatures (40, 50, 60, 70, and 80 ± 1.2 °C) and different levels of acoustic power density (0, 6.2, 12.3, and 18.5 kW/m^3). The drying time reduction obtained at an air velocity of 1 m/s at 40 or 50 °C was around 30% when US was applied. The obtained results also showed that the influence of the US power density applied on the internal resistance to the mass transfer was significantly lower than its influence of the external resistance; therefore, process intensification is mainly linked to external resistance. Nevertheless, the influence of the application of US on transport phenomena was only observed at air temperatures and air velocities below 70 °C and 3 m/s, respectively.

Bušić et al. [82] examined the effects of CO_2 drying, hot air-drying, and freeze-drying on the bioactive qualities and sensory properties of basil. The obtained results showed freeze-drying was recognized as the most suitable technique for preservation of color, essential oil content, bioactive compounds, and antioxidant capacity of basil. The essential oil content of basil ranged from 0.21 to 0.96% and decreased upon prolongation of CO_2 drying time. Among four identified phenolic acids (rosmarinic, chicoric, caftaric, and caffeic), rosmarinic acid was the most abundant in all samples. Longer CO_2 drying duration (4 h) also exhibited the most detrimental effect on the polyphenolic compound content and antioxidant capacity of dried basil. The taste and appearance of CO_2 dried basil were scored higher in comparison to air-dried basil, but further optimization of CO_2 drying is needed to improve its aroma properties. Optimized conditions for employing shorter CO_2 drying time (2 or 3 h) and pressures of 80–100 bar at 40 °C might be a good alternative to freeze-drying of basil.

Drying can be also combined with pretreatments to obtain some beneficially physical or chemical changes as well as application of various energy fields that enhance heat-mass transport and product quality [83]. Won et al. [84] identified the effects of PEF pretreatment on the drying characteristics of red pepper. The PEF treatment was conducted with electric field strength of 1.0–2.5 kV/cm using a fixed pulse width of 30 μs and at a pulse frequency of 100 Hz. The PEF treatment time was 1, 2, and 4 s. Drying of control and PEF-pretreated samples was conducted at 45 °C. The untreated control reached the target moisture ratio of 15% after 4.9 h of drying, whereas the PEF-pretreated sample (2.5 kV/cm, 100 Hz, 4 s) required only 3.2 h for the same moisture ratio, indicating a 34.7% reduction in drying time. Even the shortest PEF pretreatment (2.5 kV/cm, 100 Hz, 1 s) required 3.9 h to reach the target moisture ratio, which corresponded to a 20.4% reduction in drying time. A reduced drying time can be explained by PEF treatment-induced membrane disruptions, which might positively affect the drying properties by increasing the mass transfer of water. Moreover, the shorter drying time in the PEF-pretreated sample might lead to greater retention of carotenoid pigments. The results proved that a short PEF pretreatment can accelerate the drying efficiency of red pepper and benefit the quality of dried red pepper. The potential of osmotic dehydration (OD) as a pretreatment has been proven useful not only in a number of studies, assuring a high effectiveness of dehydration, but also in many cases a taste of improvement [85, 86]. Boggia et al. [87] optimized of both process variables and mixture composition for the OD process of PDO Genovese basil leaves allowed to enhance the quality of the dried products and to limit their changes in appearance, texture, flavor, and color. The experimental results ascertained that the appearance and the aroma of dried leaves were as much similar as possible to those of fresh PDO Genovese basil. As a sequence, this experimental approach could be successfully used, also on industrial scale, for the optimization of similar OD processes.

Final Remarks

Spices and herbs have been world-widely consumed not only for flavoring and preserving foods but also for coloring, medicinal, and cosmetic purposes. Novel technologies of food dehydration are a response to the latest consumer demands for dried products with superior quality while becoming more environmentally and economically sustainable. The recent application of solar-assisted, microwave-assisted, and other drying source-assisted hybrid drying methods as well as other latest novel drying techniques in regard to dehydrating of spices and herbs are presented in this article.

Some trends and future challenges for the dehydration of spices and herbs are the following:

- Develop cost-effective drying techniques, especially for heat-sensitive herbs and spices.
- Integrate other techniques (such as nano-technology, high hydrostatic pressure, and microencapsulation) with existing drying methods.
- Deploy on-line measurement tools to monitor the drying process and dynamically control of critical process parameters.
- Establish reliable mathematical models (especially in hybrid drying system) via computational fluid dynamic simulation, advanced analytical techniques as well as hybrid neuro-fuzzy approach.
- Develop environmental friendly drying systems, using sustainable or pollution-free resources.
- Fabricate automatic and continuous dryers to simplify operations and lower costs.

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