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REVIEW PAPER

# Novel Drying Techniques for the Food Industry

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**Abstract** The drying of foods is hugely important technique for the food industry and offers possibilities for ingredient development and novel products to consumers. In recent years, there have been many advances in technology associated with the industrial drying of food including pre-treatments, techniques, equipment and quality. Recent research has revealed that novel drying approaches such as microwave- or ultrasound-assisted drying, high electric field drying, heat pump drying and refractance window drying can be now taken to improve the efficiency and efficacy of drying so that energy consumption can be reduced whilst at the same time preserving the quality of the end product. However, whilst research has showed these technologies to be successful, commercial practitioners do not often know what techniques have the greatest potential in industry. The current work highlights recent developments of valuable novel drying techniques to promote sustainability in the food industry and points towards.

**Keywords** Novel drying techniques · Quality · Energy utilization · Efficiency

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## Introduction

Drying is among the most ancient and pre-eminent physical methods of food preservation. It is aimed at lowering the moisture content of foodstuff and is used predominately for foods such as fruits, vegetables, spices and other products with a high moisture content (>80 %), and ones which are considered ‘highly perishable’ [77]. Dried foods offer multiple benefits including: extended product shelf-life, reduced packaging, storage, handling and transportation costs, and extends the possibility of out-of-season availability and provides a wider range of products for consumers.

Over 85 % of industrial dryers are convective type with either hot air or combustion gases as the heat transfer medium [116]. Being a complex phenomenon involving simultaneous heat and mass transfer, the process of drying is energy intensive and accounts for roughly 12–20 % of energy consumed in the manufacturing industry [84]. Product quality in terms of nutritional, functional and sensorial attributes is another major concern. With conventional drying methods relying on conductive and convective modes of heat transfer, the end product can thus suffer from poor quality and the probability of product contamination can be augmented [67]. For this reason, over recent years, there has been significant technological advancement in food drying in terms of drying pre-treatments, techniques, equipment and quality [33, 68]. These works address the growing need to find improved drying techniques to preserve the quality of the end product at improved utilization of energy. Figure 1 outlines the main drivers for novel drying research and development.

A technique can be considered novel if it has proven innovative characteristics, shows better results with modifications in existing methodologies or finds new applications

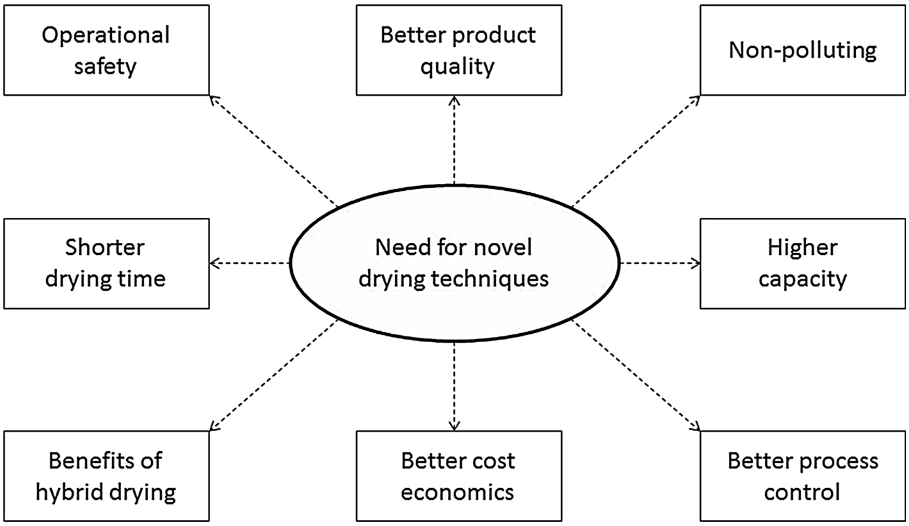


**Fig. 1** Major drivers for novel drying research and development

in different sectors. Novel drying techniques are emerging from research perspective that may yet prove to have a positive impact on the food industry both in terms of product quality and energy efficiency. These novel methods exploit different physical phenomena to enhance already commercial drying techniques, as in the case of ultrasound- or microwave-assisted drying, or else utilize totally recently revealed phenomena as in the case of superheated steam drying or refractance window drying. While a significant amount of scientific research has been carried out in the field of novel drying, there has been much less commercial exploitation of these systems because the capital costs and the energy efficiencies are not well understood [84]. Moreover, less work has been aimed at demonstrating the usefulness of these technologies for the commercial exploitation. With this in mind, the objective of this current work is to highlight some of the latest and most notable advancements in drying of foods, with main emphasis given to recent developments of practically valuable drying techniques.

## Assisting Drying with Novel Technologies

The drying of food products such as fresh produce and meats is typically controlled by the ability of gases to diffuse through the solid [109]. This places time constraints on the drying of foodstuff and cannot be surmounted without the assistance of other technologies that can impose other phenomena to reduce this resistance. With the reduction in developing moisture stresses (as observed predominantly in case of conventional drying), products dried with the assistance of novel drying techniques show superior quality [64]. Commonly used techniques include: ultrasound-, far-infrared-, microwave- and supercritical-assisted drying. The examples covered below include ultrasound and microwave-assisted drying, the ones in which extensive research for food applications has been carried out in the past 5 years.

### *Ultrasound-Assisted Drying*

High power ultrasound is characterized by low frequencies (20–100 kHz) at high intensities (typically 10–1,000 W/cm) [108]. The application of ultrasound to a porous food product in an aqueous medium induces the formation of micro-channels on its surface due to deformation of the porous solid material when exposed to ultrasound waves [42]. The process of drying can then be enhanced as the effects of case hardening are reduced, while at the same time high-intensity ultrasonic wave becomes coupled to material of the drying product to enable the liquid to permeate the solid medium through a rapid sequence of compressions and expansion—the so-called sponge effect owing to its similarity to when sponge is squeezed and released repeatedly [47]. The forces involved in this mechanical mechanism can be higher than surface tension which maintains the moisture inside the capillaries of the material creating microscopic channels which may make the moisture removal efficient with ultrasound [32].

The effects of high power ultrasound in dehydration are more significant at low temperature, thereby lowering the probability of food degradation [92]. The schematic of an experimental setup of an ultrasound-assisted freeze dryer is shown in Fig. 2. It is a prototype of a prospective innovative freeze-drying system that can offer promising results. In such systems, temperature generation by sonication can be kept under control by the freeze-drying process itself or by intermittent application of ultrasound power. Unlike conventional drying, in this case product moisture is removed without producing a liquid phase

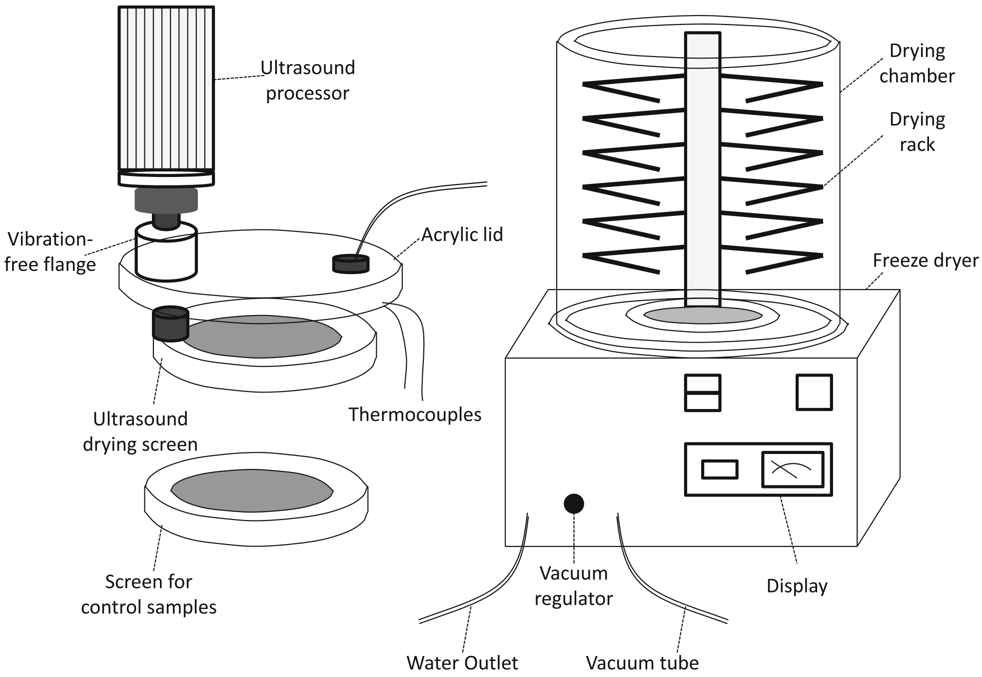


**Fig. 2** Ultrasound-assisted freeze-drying system (adapted from [93])

change [78]. Processing time is therefore lowered (up to 11.5 %, as reported by Schössler et al. [93]) due to the action of ultrasound energy in increasing the effective water diffusivity and decreasing the boundary layer thickness [16]. These may be further supplemented by using other synergistic techniques such as osmotic pressure developed during osmotic dehydration [45].

In addition, the role of ultrasound has been studied in combination with other drying techniques. Recent applications include the use of ultrasound power to assist osmotic dehydration, to lower drying time [43], hot air drying, to lower resistance to mass transfer [46], and infrared drying to retain product quality [36]. However, work needs to be done on tackling problems such as with high mass load densities [23], encountered during industrial scale-up.

### *Microwave-Assisted Drying*

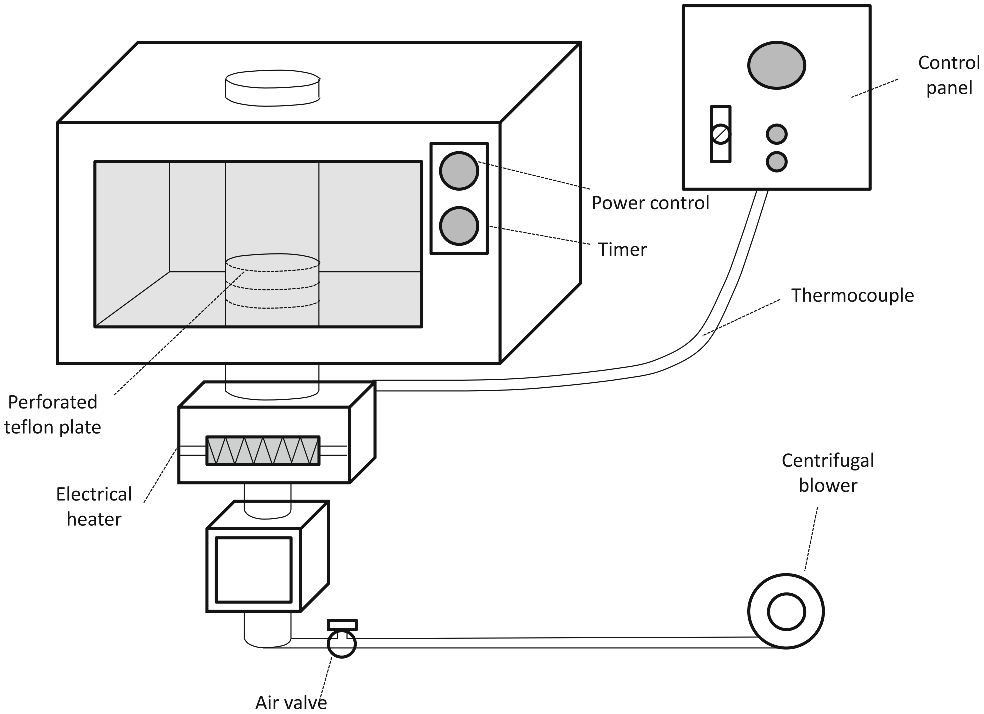
Microwave radiation is part of the electromagnetic spectrum with wavelengths ranging from 1 mm to 1 m. For food applications, the common frequencies used are 915 and 2,450 MHz. Microwaves are non-ionizing in nature, and the concept of application of microwave energy is considered as a fourth-generation technology [111]. There is an increase in interest in microwave-assisted dehydration [27]. Microwave-assisted drying has been studied in application with other several techniques to solve issues faced in conventional drying operations (Table 1). Among its successful applications is its significance in industrial drying of pharmaceutical, polymer, wood, agro-based and power-type products.

**Table 1** MW-assisted drying techniques

| Technique | References |
|---|---|
| MW + air drying | [35, 114] |
| MW + vacuum drying | [12, 69] |
| MW + spouted bed drying | [41, 56] |
| MW + freeze drying | [1, 37] |
| MW + fluidized bed drying | [7, 115] |
| MW + foam mat drying | [5, 104] |

Though microwave can be used in combination with different drying systems, the type of dryer and the drying temperatures involved are strongly associated with the drying rate and product quality. This is well explained by the study conducted on potato slices [89]. Figure 3 shows the schematic layout of a microwave heating unit modified for drying. Unlike conventional drying techniques, in microwave heating energy is delivered directly to the material through molecular interactions with the electromagnetic field. This principle of di-electric heating involves two basic mechanisms: dipolar rotation and ionic interaction/ionic conduction, and relies heavily on the product's dielectric permittivity and loss factor. Major process parameters are time–power level combinations used. Among the crucial product parameters is the moisture content of the product and its dielectric properties. Studies also show that intermittent microwave drying offers better results when compared to convective microwave drying [28]. This is because, intermittent application of microwave power lowers exposure time and the risk of overheating, whilst offering energy savings.

**Fig. 3** MW-assisted air-drying system (adapted from [89])



Microwave-assisted drying of various food materials has also shown excellent results. For example, up to 25–90 % reduction in drying time, up to 400–800 % increase in drying rate and 32–71 % reduction in energy consumption as compared to conventional drying techniques, superior product quality, even better than freeze dried foods, lesser floor-space requirements and better overall process control [113]. Microwave-assisted drying has also been used to dry macadamia nuts to overcome the issues of low industrial yields and inferior kernel quality, as encountered in conventional air-drying processes [99], in spinach to overcome quality losses due to over-heating [79] and in carrots to improve rehydration capacity [103]. The technique is likewise made use of at the falling rate period for finish drying for precise control over final moisture content. However, microwave drying is yet to overcome problems encountered with non-uniform heating that result in the formation of hot/cold spots in the course of heating. Recently, Wang et al. [112] on their study on carrot found that modifications in magnetron arrangement and quantity resulted in over 80 % variation in the uniformity of drying. However, most of the reported work in this field is based on laboratory scale systems [117]. Further research is needed to support its efficient use in the food industry.

## Novel Drying Technologies

### *Refractance Window Dehydration*

Refractance window dehydration is a suitable drying method to convert liquid foods into powders, flakes or sheets. As the product does not have direct contact with the heat transfer medium during refractance window dehydration, no cross-contamination occurs. Operated under atmospheric pressure and comparatively lower temperatures [73], the technique has emerged as a new possibility for a comparatively low-cost drying. It is apt for heat-sensitive foods [75]. Bio-active preparations may be dried at temperatures as low as 30 °C [29]. This is because of simultaneous evaporative cooling and convective heat transfer.

A schematic diagram of the industrial refractance window drying unit is shown in Fig. 4. Thermal energy from the hot water is conveyed to the wet feed material, which is deposited as thin film on a plastic conveyor belt. For dry feed materials, sensible heat of water is transferred only by conduction. Conversely for wet feed materials, heat transfer is by conduction and radiation. This is because of the absorption of electromagnetic energy by the water in the drying material. As drying proceeds, the created 'infrared window' gets closed gradually. From this point, the predominant heat transfer mode would be conduction. As the belt is in contact with the hot water, rapid drying occurs in the course of time. The product is then scraped off the conveyor using doctor blades.

The drying times are shorter, resulting in superior product quality. For example, strawberries and carrot purees dried with refractance window system showed better quality retention [3]. The technique also facilitates better retention of colour, vitamins and anti-oxidants contents, and offers higher thermal efficiencies and better cost

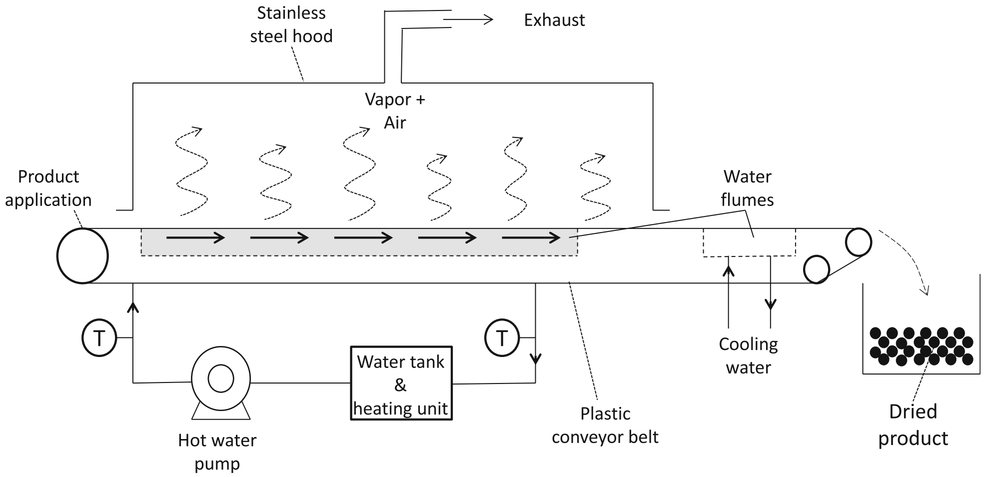


**Fig. 4** RW-drying system (adapted from [74])

economics [73, 106]. In recent years, refractance window drying has found its application in the commercial production of herbals (aloe vera), nutritional supplements, dehydrated fruits and vegetables, scrambled egg mixes and avocado powders [2, 71, 75]. A major limitation of the technique, however, is the low capacity of the system. Further, it is not very convenient to handle powders with high sugar content (as they tend to exhibit high stickiness owing to their hygroscopic nature).

### *Superheated Steam Drying*

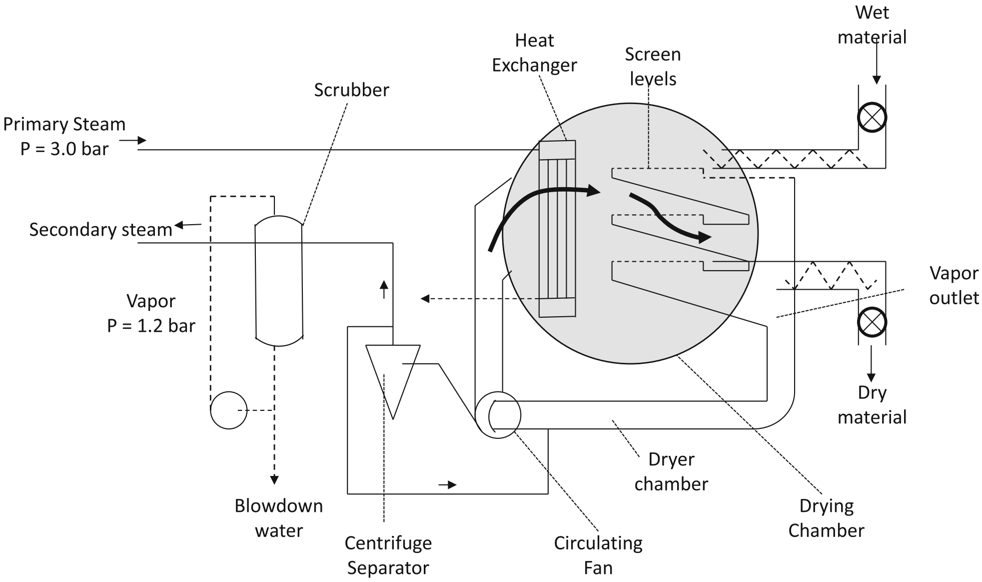
Superheated steam is a steam with temperature higher than the saturation temperature at a specified pressure. Superheated steam at atmospheric pressure is an alternative drying medium for dehydrating materials that can withstand temperatures above 100 °C [107]. The concept is distinguished by longer constant rate periods and lower critical moisture contents compared to conventional drying [102]. The degree of superheating increases with lowered operational pressures and appears to be the predominant process parameter. The advantages of superheated steam drying include: high drying efficiency, no risk of oxidation, non-polluting, smaller equipment, better microbicidal, insecticidal effects and lessened risk to fire and explosion [34].

A schematic diagram of an industrial setup of superheated steam dryer is shown in Fig. 5. With superheated steam as the drying medium, any convective dryer can be modified as a superheated steam dryer. Superheated steam forced over the food material results in boiling and steam evolution from the interior of the product. This has shown to offer beneficial effects on product porosity. With moisture removed from the product, superheated steam returns to saturated conditions. This unit operated at a sugar factory has lowered dryer equipment and operational costs by about 15 %. While conventional drying results in problems such as browning, dust explosion and burning, better results in terms of product quality and operational safety can be obtained using superheated steam drying technique, as in the case of oil palm empty fruit bunches [50].

Further, superheated steam at 150 °C was used to dry distillers' spent grain. Results indicated that superheated steam can be an excellent option for the product without any adverse effect on the protein and phenolic content [25]. With relatively shorter drying time, the drying mechanism is also found suitable for other heat-sensitive products such as pepper seeds [57], basil [15] and omega-3 fatty acid rich mackerel press-cake [17]. An interesting application is the simultaneous drying and cooking of raw Asian noodles to develop an instant product using superheated steam [82]. The drying kinetics of the product was also studied. Mathematical modelling explained the drying rates during processing. The noodles showed acceptable textural properties too [83].

Kudra and Mujumdar [59] suggested that there is good potential for utilizing combined microwave-superheated steam as a hybrid system to produce products with low apparent density. This can suit well for products such as cereals and selective snack-food that necessitate both drying and puffing processes. Also, as air is not the drying medium, the process offers reduced risk to oxidative reactions (whose rates increase with decreasing water activity). Sa-adchom et al. [91] studied the superheated steamdrying behaviour of seasoned and unseasoned pork, explaining the effects of sugar and salt solutions on effective diffusivity, based on the finite difference solution of the semi-empirical model they developed. The developed model can simulate superheated steam-drying

**Fig. 5** SS-drying system (adapted from [18])



processes at temperatures around 140 °C. Far-infrared radiation can be used in combination with superheated steam drying to overcome the problem of slow drying. Related studies conducted on banana have shown favourable results [72]. Limitations that require to be addressed in superheated steam-drying systems include the development of simpler superheated steam-drying systems and risk to deteriorative effects of condensation and glass transition.

### *High Electric Field Drying*

In high electric field (HEF) or electrohydrodynamic (EHD) drying, an alternating current (AC) or direct current (DC) at high intensity and normal frequency (around 60 Hz) is used for moisture removal during drying. Figure 6 shows the schematic of a high electric field drying unit. Potential difference generated between the electrodes showed direct effects with sample drying rate. The exothermic interaction of the electric field within the dielectric food material results in rapid evaporation. The heating effect is caused as a result of the secondary flow induced by the electric field [86]. This is termed as ‘corona wind’ or ‘ionic wind’. In short, the method creates forced convection using ionic injection, followed by subsequent acceleration between electrodes [49]. Parameters such as electrode size, electric field strength and inter-electrode spacing are major deciders of efficiency of the drying process. Studies have also been conducted to evaluate the electric parameters and fluid flow in turbulent conditions. The model developed by Ahmedou and Havet [4] explains this coupled phenomenon and can aid in future research in designing the high electric field drying process.

High electric field drying is a convective drying technique that can effectively remove product moisture whilst retaining heat-sensitive components including ascorbic acid. As a non-thermal drying technique, high electric field drying shows lower risk to browning. HPLC analysis conducted on dried spinach to explain the effect of high electric field drying on post-drying quality by Bajgai and Hashinaga [13] indicated that there was no formation of by-products. Also, high electric field-dried Japanese radish showed less shrinkage and improved water absorption characteristics and better rehydration [14]. High electric field drying offers high energy efficiency, reduction in drying time and lower power requirements compared to conventional drying techniques [6]. In comparison with oven and ambient air drying, high electric field proved to be the best method for drying sea cucumber, requiring less than 22 % electrical energy utilized in oven drying technique. But the issue of longer drying time requires to be addressed with future research [10]. Superior dried product quality attributes of shrimps in comparison with oven drying [8] further support the hypothesis that high electric field is a promising method for drying of seafoods. Similar conclusions were drawn from studies conducted on scallop muscle [11] and Spanish mackerel [9]. Though no distinct limitation of this technology has been reported, only sufficient research on various products under various drying conditions can justify its practicality in the food industry.

### *Infrared Drying*

Infrared radiation is part of the electromagnetic spectrum, ranging between 0.75 and 1,000 μm in wavelength. As a food processing technique, it offers several advantages including high heat transfer capacity, better process control and uniform heating [101]. Notable effects of infrared radiation on foods were that it increased porosity of banana

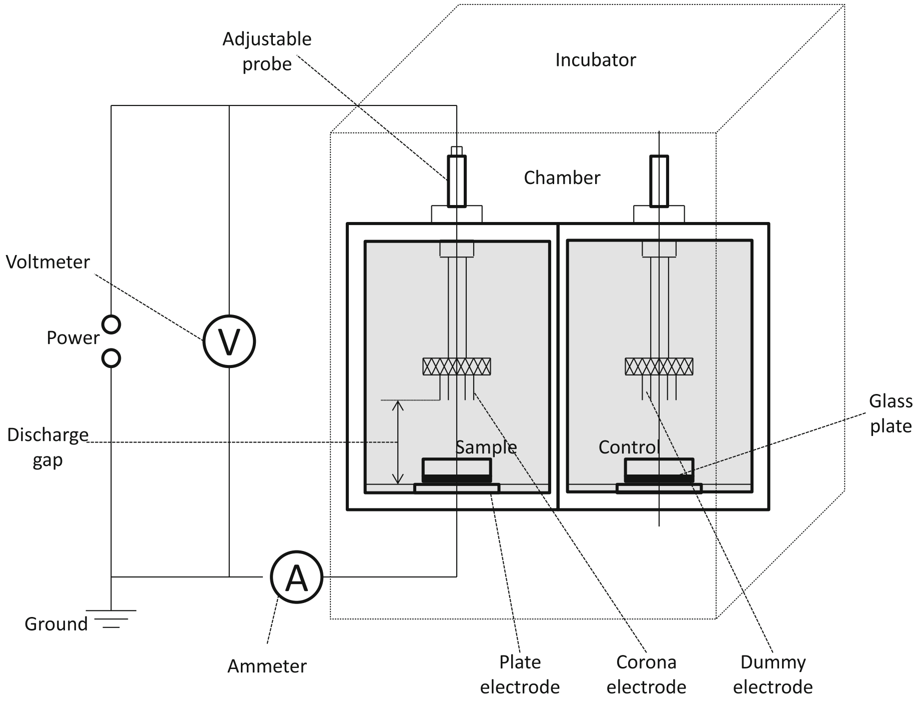


**Fig. 6** HEF-drying system (adapted from [22])

[60], increased rehydration potential of onion (Mongpraneet et al. 2002), reduced overall colour changes in pineapple and potatoes in spite of high drying rates [105], gave firmer-texture dried blueberries [96] and did not compromise on product quality when used in combination with freeze drying, as in sweet potatoes [62], yam and strawberries [98].

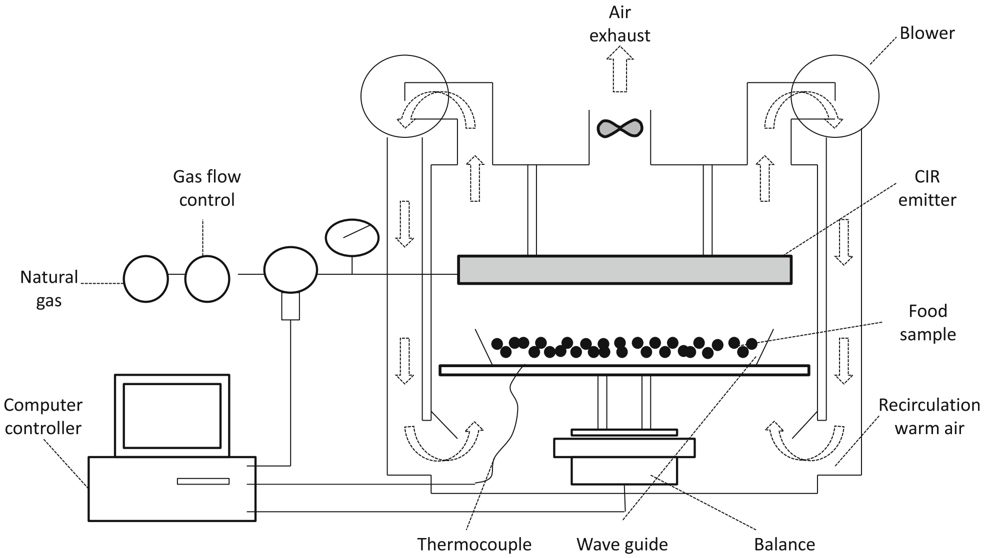
Infrared energy incident on the food material creates charges in electronic, vibrational and rotational states at atomic and molecular levels [58], without heating the surrounding air. Absorption wavelengths of various food components vary (water < sugars < lipids < proteins < unsaturated lipids) as summarized by Rosenthal [90]. Drying of agricultural products mainly takes place in the falling rate period, and the generated sensible heat and mass transfer co-efficient are functions of infrared power. A variant of the basic infrared drying system is the catalytic infrared (CIR) drying technique as shown in Fig. 7. As the CIR directly converts natural gas or propane to radiant energy by an intermediate catalytic reaction, it is more energy efficient than the typical infrared emitters that use electricity. To continue with safe product drying temperatures (around 80 °C), periodic on and off operations were required to control emitter temperatures (which were recorded to go up to around 750 °C, as in their study conducted by [44] on onions).

Simultaneous infrared dry blanching and dehydration process has been studied, and temperature and moisture prediction was done using finite element analysis [61]. Prediction of developed models was in close agreement with experimental data, offering the scope of use of the models in future studies involving concurrent blanching and dehydration. Infrared drying technique has also been successfully applied in food thawing [95], baking [80], blanching [19], roasting [110] and cooking [20]. To overcome issues with conventional drying operations, the scope of infrared-assisted drying has also been studied [70]. The uniqueness of the process is that infrared drying results in uniform temperature distribution (Mongpraneet et al. 2002) require less start-up time and less residence time. However, most work is done on solid foods, and there exists a need for research in processing of liquid foods [87]. Further, low rehydration capacities of IR-dried foods, particularly vegetables, constraint its application in developing instant foods [58].

### *Heat Pump Drying*

Unlike other drying systems that require new technology and capital investments, heat pump dryers can be developed with little modification of existing refrigeration systems. Hence, most commonly used heat pump units are closed-loop systems that work on the thermodynamic principle of vapour compression cycle. Heat pump dryers have the capability to convert the latent heat of vapour condensation into sensible heat of an air stream passing through the condenser. Figure 8 shows the schematic layout of an air source heat pump drying system. The

**Fig. 7** CIR-drying system (adapted from [44])



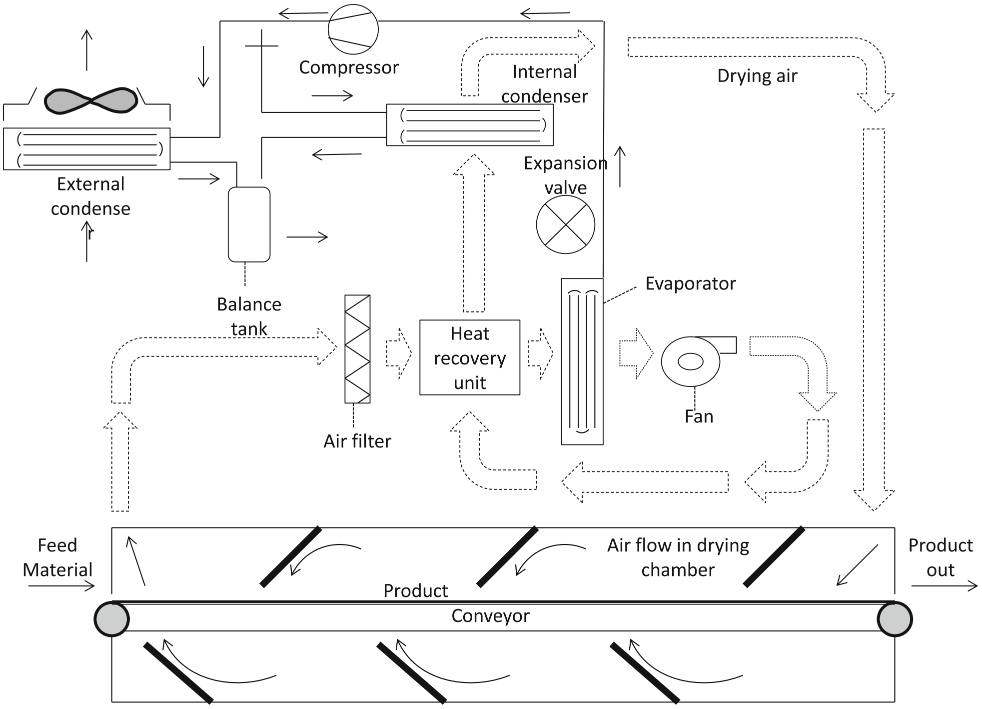


**Fig. 8** Heat pump drying system (adapted from [54])

basic components of the heat pump drying system encompass an expansion valve, two heat exchangers (evaporator and condenser), and a compressor and a dryer attachment. The evaporator functions as dehumidifier and the condenser as heater. More recently, chemical and hybrid (microwave, infrared and radiofrequency) heat pump sources have been developed, to improve process efficiency.

Drying temperature and air humidity in heat pump drying systems can be kept under control [48]. This has allowed heat pump dryers to be employed for both agricultural and pharmaceutical products [51]. Besides, they are suitable for highly heat-sensitive commodities including saffron, the most expensive spice. Mortezapour et al. [66] conducted studies on a hybrid photovoltaic thermal solar drying system to dry saffron and concluded that inclusion of a heat pump assistance unit resulted in 33 % reduction in total energy consumption and significant lowering of drying time, while producing a stable final product. Other analogous products include herbs [40], mint leaves [30], ginger [52], olive leaves [38] and Salak fruit [76]. Also, Shi et al. [97] suggested that heat pump drying

**Table 2** Unexplored drying techniques

| Other drying techniques | Principle | Process parameters/ performance | Features/inferences | Typical product | References |
|---|---|---|---|---|---|
| Pressure swing drying | Product placed in desiccated air is dried in successive compression cycles | Vacuum: 7–90 kPa<br>Time to attain pressure drop: 200 ms | Huge drying time savings of 480 and 700 min as compared to vacuum and hot air drying | Collagen gel | [63] |
| Radio frequency drying | Friction due to continuous re-orientation of polar molecules | Frequency: 27.12 MHz<br>Operational power: 6 KW | RF can only be used as a supplementary source and not as the major source | Macadamia nuts | [113] |
| Supercritical drying | Moisture removal at T and P above the critical point. | SCF: $Co_2$, P: 20 MPa and $T$: 40–60 °C | High-quality end product (sample retained freshness, close to original sample) | Carrot | [21] |
| Rotating jet spouted bed drying | Intermittent spout drying with periodic supply of heat | Significant tempering periods that allow moisture equilibration | Up to 40 % thermal energy savings | Corn | [55] |
| Impingement drying | Impinging jets of hot air/steam with high heat transfer co-efficient | $T$: 130–145° C, h: 100 W/m$^2$ °C | An already experimented technique in the food industry | Tortilla and potato chips | [65] |
| Atmospheric freeze drying | Water removal at atmospheric pressure from a material held at subfreezing temperatures using a desiccant | $T$: $-3$ to $-10$ °C | Environmental friendly refrigerants | Potato and carrot | [85] |
| Photocatalytic drying | Heat supply from dehumidification system and solar energy system | Drying air $T$: 40–45 °C | $TiO_2$ coating on the inner walls provides bactericidal effect | Pineapple slices | [26] |
| Ohmic dehydration | Electroporation | 57 % glucose solution, electric field intensity <100 V/cm | Up to 50 % process time savings | Raspberries | [100] |
| Desiccant drying | Drying using dehumidified air | $T < 40$ °C | Better colour retention and rehydration ratio | Mushroom | [94] |
| Vibration aided drying | Infrared radiation drying | Optimum frequency and amplitude of vibrations: 20–22 Hz and 8–9 mm | Major portion of drying was under the falling rate period | Paddy | [31] |

is the best method to produce intermediate moisture foods, particularly for applications in fish processing.

An attractive alternative to compression heat pumps with ozone-depleting fluids is the so-called chemical heat pump (CHP). A solar-assisted CHP is a feasible energy-efficient option for the tropics. It consists of solar collector, storage tank, CHP units and drying chamber. In short, the system alters the thermal energy stored by chemical substances (such as metal hydrides) utilizing reversible chemical reactions [53]. Fadhel et al. [39] have reviewed the recent advances in technologies for solar-assisted CHP dryers for agricultural produce, highlighting the uniqueness of utilizing renewable energy sources for drying.

## Other Drying Techniques

The development of foods dried using novel techniques introduces different challenges: the consumer perception, the approval of the novel technology and the retention of the physical, sensorial and nutritional quality of foods [24]. Extensive literature survey shows that there are several other emerging drying techniques. Table 2 shows few of the techniques which remain unexplored and exploited to maximum profitability at industrial level, highlighting principle of operation, common process parameters and unique features. Focus needs to be on why these technologies did not make it to prominence and on what modifications will allow their successful implementation, particularly for the ones that have found numerous applications in various other industries. With technology and market-driven demands, new dryers will continually be developed. In recent years, product quality and safety are given utmost preference, and it will be these same factors that essentially remain in focus among other parameters considered in selection of various drying techniques for specific food products. The suitability of such novel drying techniques is well justified in the context of product quality and safety. In comparison with conventional techniques, these techniques have shown to offer better retention of nutraceutical compounds, reduced thermal damage, better storage stability, significant log reduction in microbial count, lower risk to oxidative damage, beneficial effects on product texture, beneficial effects on product texture, minimal risk to cross-contamination, superior sensory quality (colour originality), higher retention of heat-liable vitamins and improved rehydration characteristics [73, 75, 81, 88].

## Conclusions and Directions for Future Research

The potential of novel technologies for drying and food preservation has gained increased industrial interest and has the potential to replace, at least partly, the traditional entrenched preservation methods, as the industry seeks to become more environmentally and economically sustainable. This paper identifies a group of technologies that have shown significant potential in food engineering research and development. Most importantly, this paper presents the novel technologies that permit the development of food products whilst maintaining food quality. Such information is required by the food industry in order to make educated decisions on the most suitable drying technologies for specific sectors.

Future research on developing various drying systems is required in:

1. developing environmental friendly drying systems, operated using renewable energy sources and those which are non-polluting;
2. applying computational fluid dynamics (CFD) analysis to study various drying mechanisms, facilitating improvements in process efficiencies;
3. developing cost-efficient technologies, particularly for heat-sensitive products;
4. developing sustainable alternatives for bulk drying of freshly harvested agricultural product (particularly those at high moisture content);
5. integration of expert systems in automated continuous-type drying units.

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