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A Review of Drying Methods Assisted by Infrared Radiation, Microwave and Radio Frequency

Nguyen Hay, Le Quang Huy and Pham Van Kien

Abstract

The study focused on reviewing modern and effective drying methods assisted by infrared radiation, microwave and radio frequency. In which, the drying results of previous studies were reviewed to clarify the drying efficiency of drying methods with the support of infrared radiation, microwave and radio frequency. The review results showed that the radiant heating mechanism of infrared radiation and the volumetric heating mechanism of microwave and radio frequency supported the process of material heating and moisture diffusion within the material. As a result, the drying process achieved high drying efficiency, the drying time was significantly shortened and the quality of the dried products was improved both in terms of sensory quality and nutritional quality. The study of the application of infrared radiation, microwave and radio frequency in drying technique had a high scientific, technological and practical significance. This would be the foundation for finding suitable drying methods and drying modes to improve drying efficiency as well as the quality of dried products.

Keywords: infrared radiation, microwave, radio frequency, drying efficiency, volumetric heating mechanism, product quality, energy consumption

1. Introduction

The fresh harvested agricultural products often contain high moisture content, which can easily spoil the products by the risk of decay as oxidation, hydrolyzation, and microbial spoilage during processing, transit, and storage [1]. Nowadays prolonging the storage time of products and increasing the product quality both in terms of sensory quality and nutritional quality has been becoming an important target of a sustainable agriculture.

Drying has played an important role in food processing and preservation. Drying can reduce the water activity in order to improve the stability of drying products and long-time preservation. Because the harmful microbial activity would be significantly decreased at lowering water activity during storage [2]. In the drying process, the drying methods and drying parameters should be considered to achieve the effective drying process as drying rate and product quality [3].

Generally, a suitable and effective drying technique should achieve several requirements such as high drying rate, required final moisture content, high retention

in color, appearance, flavor, long shelf life and high ingredient retention of dried products, as well as low energy consumption [4]. In the drying of agricultural products, hot air drying, solar drying, vacuum drying, freeze drying and fluidized bed drying are popular conventional drying techniques [5, 6]. In the conventional drying, the heat from drying air will transfer to the drying material and the moisture of the material evaporates back to the drying air by convection and conduction. However, the convective drying method has many drawbacks such as longer drying time, low product quality, low efficiency and high energy consumption [7, 8]. Hot air and solar drying with the heating convection mechanism have been becoming common drying methods because of low cost of equipment, large drying capacity and simple operation [9]. However, the hot air drying offers a time and energy consuming because of the large amount of heat losses to the air [10]. The solar drying can save energy consumption, but the solar dryer works in natural environment, which makes dried products be affected by insects and microorganisms. Besides, hot air drying and solar drying methods can easily cause shrinkage, surface hardening, microstructure collapse, high color change index and nutrient degradation [11]. Vacuum and freeze-drying methods with low drying temperature are suitable drying methods for the preservation of nutritional components, but the requirement of special operation condition as low temperatures or pressures cause high energy consumption and cost of equipment. Fluidized bed drying could improve the energy efficiency with the contact between the air and materials, but this drying method is almost appropriate for granular food [5]. Thus, many new drying techniques have been created by the combination between the conventional drying and infrared radiation (IR) drying, microwave (MW) drying, radio frequency (RF) drying and ultrasound wave drying [12]. In which, effective heating mechanism of IR, MW and RF would support the drying process effectively and could enhance the efficiency of drying process as high drying rate, high dried product quality and low energy consumption. However, the application of these hybrid drying methods has been studied and continues to be studied to perfect both drying technology and drying parameters to achieve the highest drying efficiency.

2. The heating principle of infrared radiation, microwave and radio frequency

2.1 The heating principle of infrared radiation

The infrared region lies between the visible and microwave region of the electromagnetic spectrum. Infrared waves have a wavelength ranging from 0.75 to 1000 μm . Generally, IR can be divided into three different categories such as: near-infrared (NIR), mid-infrared (MIR) and far-infrared (FIR) corresponding to the wavelength of 0.75–2 μm , 2–4 μm and 4–1000 μm (see **Figure 1**) [13].

The effect of the electromagnetic radiation on drying material surface causes changes in the electronic, rotational and vibrational states of atoms and molecules [14]. The different type of electromagnetic radiation wavelength has different heating mechanism. The heating mechanism of IR radiation is the changes in the vibrational state of the molecule in material. When the materials absorb IR radiation energy, the constituent molecules will vibrate at a frequency of 60,000–150,000 MHz and the intermolecular friction occurs which results in the internal heating within material [15]. In which, the surface temperature increases quickly, which is much faster than

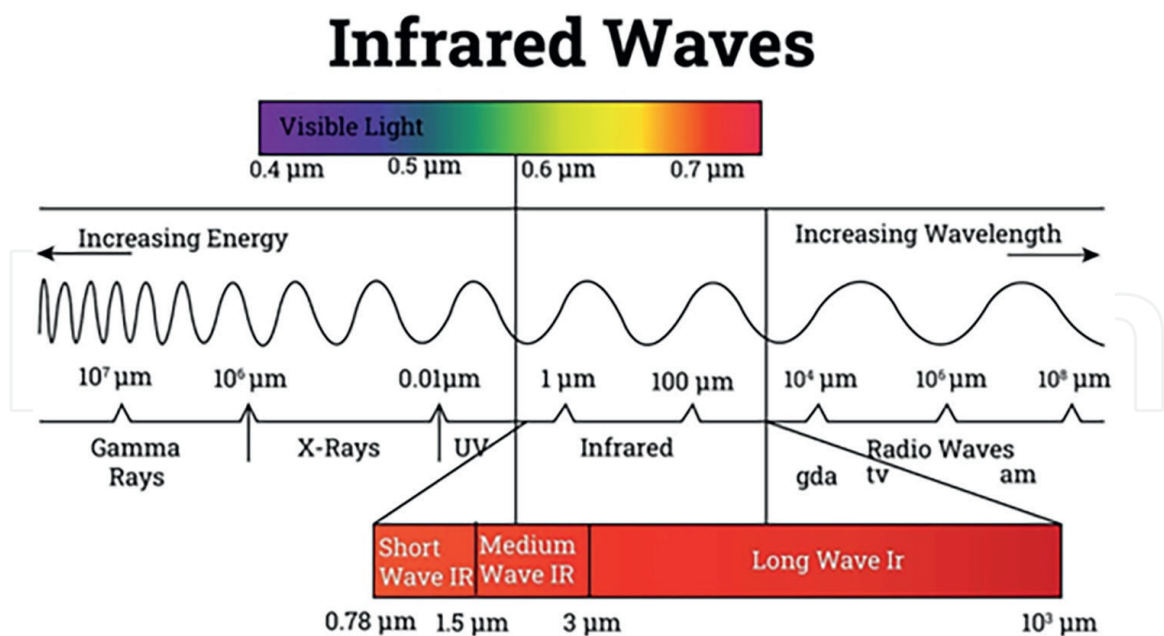


Figure 1.
The infrared region.

that in conduction and convection heat transfer [16]. IR radiation can propagate into the material without any medium and heating the surrounding air [17]. The most important advantages of infrared radiation are preventing the energy losses and maintaining the quality of the drying product.

The IR radiation has a specific penetration depth (PD) at which the radiation intensity inside the material reaches the value of approximately 37% of its value at the surface [18, 19]. PD of IR radiation depends on the composition of material such as solid, liquid or gas, and the properties of material such as density, porosity and water content [20].

2.2 The heating principle of microwave and radio frequency

Radio frequency (RF) and microwave (MW) are two kinds of electromagnetic waves. In which, RF has frequencies varying from 10 to 300 MHz and only three radio frequencies of $13.56 \text{ MHz} \pm 6.68 \text{ kHz}$, $27.12 \text{ MHz} \pm 160.00 \text{ kHz}$ and $40.68 \text{ MHz} \pm 20.00 \text{ kHz}$ were applied in industrial, scientific, and medical applications [21]. Microwave has the frequency range of 300 MHz to 300 GHz and MW with frequency of 2450 MHz was the most commonly used in the heating technique. The frequency range of RF and MW was described in **Figure 2**.

RF heating mechanism is volumetric heating and is described in **Figure 3**. In which, the RF is generated between two electrodes of an RF operator. The material is placed between the electrodes and absorbed RF energy. RF energy causes the wet molecules within material to migrate and rotate continuously at high speeds under the effect of the RF alternating electric field. The volumetric heat was generated within the material by the friction resulting from the movement of the molecules and the space-charge displacement.

In the case of microwaves, the electric field interacts with molecules of material via two modes as dipolar rotation and ionic conduction (**Figure 4**). In dipolar rotation, the molecules within material rotate back and forth constantly under the

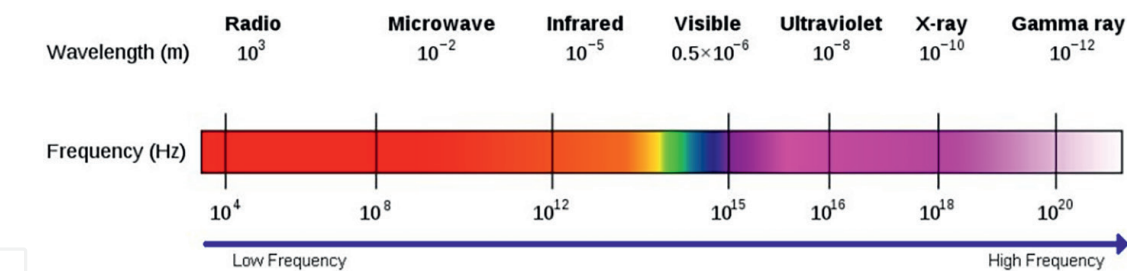


Figure 2.
The frequency range of electromagnetic wave.

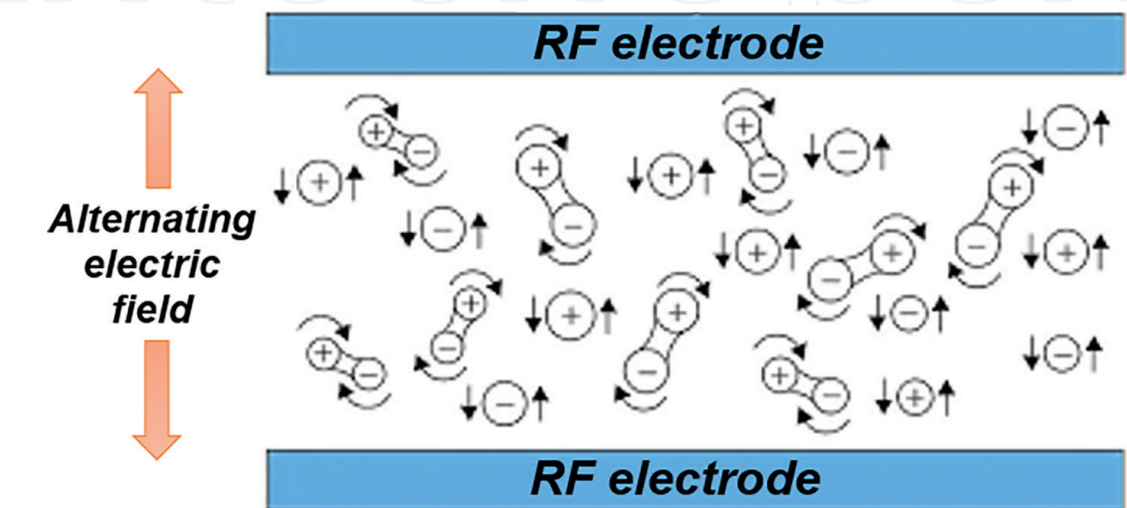


Figure 3.
RF heating mechanism.

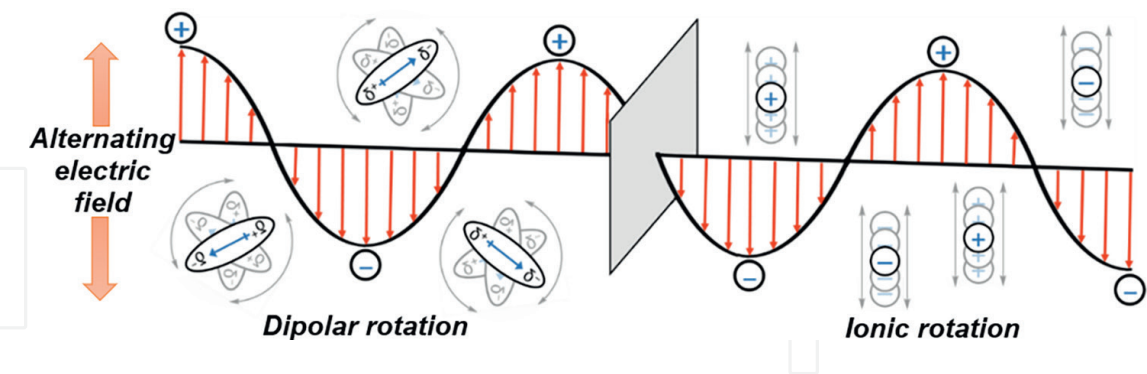


Figure 4.
MW heating mechanism.

ever-oscillating electric field. The friction of rotating molecules results in heat generation through the material mass. In ionic conduction, a free ion or ionic species moves translationally through space under the alternating electric field. The friction of these moving species results in heat generation.

Both RF and MW heating mechanism is volumetric heating. In which, the heating rate is high and the moisture gradient and temperature gradient are in the same direction, which supports the moisture diffusion. Thus, the drying rate and the quality of the drying product would significantly increase.

3. Review of the drying techniques using infrared radiation, microwave and radio frequency

3.1 Review of the drying techniques using infrared radiation

The drying techniques using infrared radiation has several advantages compared to conventional drying system such as higher heating rate, shorter drying time and higher drying product quality [22]. Thus, the drying techniques using infrared radiation have become one of the popular methods of drying of food, vegetables, grains, fruits and other high-value products [23–25]. Combining IR with other drying methods as hot air drying, heat pump drying, vacuum drying and freeze drying can give an effective drying process [26–29].

Wanyo et al. [30] conducted the experimental drying of mulberry leaves by two drying methods as far IR-hot air drying and hot air-only drying. The results showed that the far IR-hot air-drying time was only 50 min and the higher total phenolic content within mulberry leaves was retained, while hot air-drying time required 6 hours. Chen et al. [31] studied the drying kinetics and quality product in drying of jujube slices by hot-air and short-and medium-wave infrared radiation and the results showed that the short- and medium-wave IR drying time could reduce 17–67% as compared with hot air drying. Orikasa et al. [32] reported that the far infrared (FIR) drying of Komatsuna leaves consumed 17% less energy consumption and achieved the higher product quality with higher cyclic adenosine monophosphate content within Komatsuna leaves after drying as compared with hot air drying.

The combination between vacuum drying and IR heating could result in high drying rate, improvement of energy efficiency and product quality [33]. Salehi and Kashaninejad [34] studied the drying kinetics during the combined infrared-vacuum drying of lemon slices and the results confirmed that the moisture diffusivity within material increased from 2.92×10^{-10} to $1.58 \times 10^{-9} \text{ m}^2/\text{s}$ and the color change index decreased appreciably when the IR lamp power was increased from 300 to 400 W, which improved the drying rate considerably Salehi and Kashaninejad [35] investigated the effects of IR-vacuum drying parameters with infrared power of 300–400 W on the drying kinetics of grapefruit slices. The results were that the effective moisture diffusivity increased in the range of 5.83×10^{-10} and $2.13 \times 10^{-9} \text{ m}^2/\text{s}$ and the color change intensity of dried material decreased as IR power increased.

The combined IR-freeze drying could improve the freeze-drying process that could reduce drying time and energy consumption. Wu et al. [28] compared the effect of the freeze drying and the IR-freeze drying of Cordyceps militaries, in which, the IR-freeze dryer used infrared lamps replacing the electric heating plate and the drying parameters as drying time, energy consumption and nutritional properties were considered. The results indicated that IR-freeze drying achieved high-quality dried products and more effective drying process such as the drying time could be reduced 7.21–17.78% and the energy consumption was reduced 1.88–18.37% at a constant drying temperature in comparison with the freeze drying.

Khampakool et al. [36] conducted the producing process of banana snacks using IR-assisted freeze drying, in which, the drying kinetics, energy consumption, and product quality were estimated. The results indicated that the continuous IR-assisted freeze drying could save the electrical energy consumption appreciably and reduce the drying time up to 213 min as compared with freeze drying (696 min). Besides, the crispness of banana snacks could be improved in IR-assisted freeze drying.

Antal (2015) [37] compared the effect of three drying of apple cubes methods as IR-assisted freeze drying, hot air-assisted freeze drying and single-stage freeze drying and the results reported that the drying time was reduced by 45.5 and 27.3% and energy consumption by 45.1 and 34.5% corresponding to IR-assisted freeze drying, hot air-assisted freeze drying as compared with FD.

Krsti (2002) [38] proposed a prototype rotary dryer with combining IR with heat pump drying method for drying of herbs and vegetables (leaves of birch, rosebay willowherb, dandelion, red beet and carrot). The results showed that the drying time was shortened significantly and the quality of the dried products as color and ingredient retention within the material got requirement.

Based on the results of the previous studies mentioned above, IR heating is an effective supporting technique when combined with other drying methods such as hot air drying, heat pump drying, vacuum drying and freeze drying to significantly improve drying efficiency including drying rate and product quality as well as saving energy consumption of drying process as compared with drying methods without IR assistance. In particular, IR heating assistance could reduce the drying time by 67% and the energy consumption by 17% as compared to hot-air drying. The combination between vacuum drying and IR heating could significantly improve the effective moisture diffusivity of drying material and the quality of the dried products. In the combined IR-freeze drying, the drying time could be reduced by 45.5% and the energy consumption reduced by 45.1% in comparison with the freeze drying. The combining IR with heat pump drying method could shorten the drying time significantly and retain the color and ingredient content within the material. Besides, the assistance of IR improved the quality of the dried products as color and nutrients, that is one of the most important factors of drying technique.

3.2 Review of the drying techniques using microwave

The volumetric heating mechanism of MW has many advantages compared to conventional methods. MW has been widely applied in drying technique for drying food, vegetable, fruit and high-value material. When MW combines with other conventional drying methods, MW heating mechanism can improve the efficiency of drying process as heating rate, drying rate and quality of dried products [39]. There have been many studies of drying techniques using MW to find out the suitable drying methods and drying parameters to improve the drying process and quality of dried products.

Soysal (2004) [40] studied the effects of MW output power on drying time, drying rate and color of product in MW drying of parsley leaves, in which, seven different MW output powers were used ranging from 360 to 900 W. The results indicated that drying time considerably decreased with the increase in the MW output power and a good green color was maintained close to that of the original fresh parsley leaves.

Yanyang et al. [41] studied the wild cabbage drying method by a combination of hot-air drying and microwave vacuum drying. The results confirmed that the combination of drying with hot air drying followed by microwave-vacuum drying could shorten drying time and greatly retain the content of chlorophyll and ascorbic acid within the dried product.

Therdthai and Zhou (2009) [42] carried out the drying of mint leaves with MW-vacuum drying (8.0 W/g, 9.6 W/g and 11.2 W/g at pressure 13.33 kPa) and hot air drying (60°C and 70°C). The MW-vacuum drying could reduce drying time by

85–90% as compared with the hot air drying. The color of dried mint leaves was retained in light green/yellow color while the hot air-dried mint leaves were changed in to dark brown.

Wang et al., (2009) [43] dehydrated instant vegetable soup mix using the MW-freeze drying. The vegetable soup was successfully dried and the drying process achieved a shorter drying time as MW power increased. The energy consumption of MW-freeze dryer reduced significantly as compared to freeze dryer.

Patil et al., (2015) [44] carried out the experimental drying of green leafy vegetable (fenugreek, coriander, spinach, mint, shepu and curry leaves). The results reported that as the MW power increased from 135 to 675 W, the drying time reduced appreciably by 64% and the dried green leafy vegetables could be stored for about 21 days in metalized polyester under the condition of 45°C and 95% RH. Besides, the shelf life of dried green leafy vegetables could last up to 6 months as being stored in metalized polyester under the condition of 65% RH and 30°C.

Akal and Kahveci (2016) [45] conducted the microwave drying of carrot slices, in which, MW power levels were 350, 460 and 600 W and thickness of carrot slices was 1 and 2 cm. The results showed that the drying rate increased as the drying thickness decreased and MW power increased. When MW power increased from 350 to 600 W, the drying time reduced up to 50%.

Horuz et al., (2017) [46] determined the effect of hybrid (MW convectional) and convectional drying of sour cherries, in which, the MW power was 120, 150 and 180 W and hot air was 50, 60 and 70°C. The results determined that the energy consumption efficiency of hybrid drying technique was higher than the convectional drying method and in hybrid drying, the drying time was reduced significantly and the dried products could achieve the higher quality parameters as total phenolic content, antioxidant capacity and vitamin C.

Deepika and Sutar (2018) [47] conducted the drying of lemon slices using IR, MW and hot air combination, in which, IR-hot air drying was implemented and followed by MW-hot air to complete the drying process. The results found that the drying process could save energy consumption and drying time and the quality of the dried product was also maintained as compared to hot air drying.

Rodriguez et al., (2019) [48] evaluated the effect of solar drying and microwave drying of raspberries. The results showed that MW drying method could significantly reduce the drying time as compared to solar drying. The quality of dried products indicated that in both drying methods, the surface color of dried products was retained close to the color of fresh raspberries.

Jinwoo et al., (2021) [49] studied the influence of microwave power in MW-assisted freeze drying of biopharmaceuticals. The results showed that the combination between MW volumetric heating and heat conduction reduced drying times by 80% as compared to freeze drying. While the quality of dried products in MW-assisted freeze drying was close to freeze drying.

Based on the results of the previous studies mentioned above, the drying technique using MW showed its outstanding advantages that have greatly improved drying efficiencies such as appreciably shortening drying time, saving energy consumption and improving the quality of dried products in terms of color and the content of important nutrients within the dried products. Drying technique using MW could be considered as a suitable and effective drying method for many types of materials such as food, vegetable, fruit and high-value material. In particular, MW heating assistance could reduce the drying time by 64% as increasing MW power in specific value range. The combining MW with other drying methods as hot-air

drying, vacuum drying, solar drying and freeze drying could improve the drying rate by shortening the drying time by 80% and achieve the higher quality dried products as color, vitamin and nutrients as compared to the drying method without MW assistance.

3.3 Review of the drying techniques using radio frequency

Radio frequency has been studied and applied for various purposes in food processing such as cooking [50], tempering [51], stabilization [52], disinfestation [53], pasteurization [54], roasting [55] and drying [56]. Drying using RF was one of the most important and effective application of RF. RF has been applied in combining with other drying methods as hot air drying, heat pump drying, vacuum drying and freeze drying in order to achieve the high drying efficiency.

Roknul et al. (2014) [57] compared the effect of four drying methods including hot-air drying, hot-air-assisted IR drying, hot-air-assisted MW drying and hot-air-assisted RF drying of stem lettuce slices, in which, the drying characteristics and quality of stem lettuce slices were considered. The results showed that the drying time of hot-air-assisted RF drying was the shortest (120 min), following by hot-air-assisted MW drying (140 min), hot-air-assisted IR drying (180 min), and hot-air drying (360 min). In the hot-air-assisted RF drying, the heating was uniform and the color change index of dried samples got the smallest value.

Zhou et al., (2018) [58] carried out the experimental drying of kiwifruit slices using RF-vacuum drying and hot air drying, in which, RF had the working parameter of 27.12 MHz, 3 kW. The results demonstrated that RF-vacuum drying was supported by RF volumetric heating and achieved a rapid drying resulting in 65% reduction of hot air drying (60°C) time. Moreover, RF-vacuum drying dried kiwifruit slices retained a better color stability, higher content of vitamin C as compared with hot-air-dried samples.

Zhou et al., (2018) [59] compared three drying methods including hot air drying, vacuum drying and hot air-assisted RF drying, which were experimentally compared and analyzed for drying of in-shell walnuts. The results showed that the drying time of the hot air-assisted RF drying method was the shortest (138 min), followed by vacuum drying method (185 min) and hot air-drying method (300 min). The walnuts after hot air-assisted RF drying process contained more unsaturated fatty acid than those by hot air-drying process and the vacuum drying, and hot air-assisted RF drying had little effect on the total antioxidant capacity and total phenolic concentration of walnuts during the drying process and storage.

Zhou et al., (2019) [60] determined the drying time, energy efficiency and product quality of three drying methods as RF-vacuum drying, hot air drying and RF-vacuum + hot air drying in drying of 6 mm thick kiwifruit slices. The results indicated that the total drying time of RF-vacuum drying was the shortest (480 min), followed by RF-vacuum + hot air drying (600 min; 20% longer) and hot air drying (900 min, almost double). In the RF-vacuum + hot air-drying process, a more uniform moisture distribution within the fruit slices and better product quality as color retention, shrinkage ratio was achieved. Besides, RF-vacuum + hot air-drying method could save the average energy efficiency up to 22.93% as compared to hot air-drying method.

Zhang et al., (2019) [61] studied the hot air-assisted RF as the second stage drying method for mango slices, in which, hot-air drying was used in the first drying stage to reduce the moisture content to about 40% (w.b), then hot air-assisted RF drying

was used to reduce moisture content to 18%. The results showed that the drying time of the two-stage drying process was about 5 hours, which was lower than that of hot-air drying (8 hr) or vacuum drying (7 hr). The quality of dried mango slices after the two-stage drying was better than that after hot-air drying, and close to that after vacuum drying, in which, the minor vitamin C retention rate achieved 91%.

Ran et al., (2019) [62] applied the hybrid drying method of RF-assisted vacuum drying to produce chicken powders. The results showed that the total drying time of RF-assisted vacuum drying was the shorter (100 min) while that for vacuum drying was 180 min. Besides, RF-assisted vacuum-dried chicken powders had a high quality with a maximum umami flavor among the obtained powders.

Peng et al., (2019) [63] proposed a hybrid drying method for apple slices (6 mm thickness), in which, air jet impingement (65°C) was applied at the first drying stage, and hot air-assisted RF (hot air temperature of 60°C) was used at the second drying stage to complete the drying process. The result found that apple slices dried by the air jet impingement combined hot air-assisted RF drying achieved the shortest drying time and the best product quality including color, total phenolic and Vc retention.

Wang et al., (2020) [64] conducted the experimental drying of inshell hazelnuts with hot air drying and hot air-assisted RF drying. The results found that as compared to hot air drying, hot air-assisted RF drying achieved much higher drying rate and effective moisture diffusion with lower energy consumption. Besides, hot air-assisted RF-dried nuts retained higher total phenolic content (0.43 mg GAE/g dry kernel) than that of hot air drying.

Wang et al., (2021) [65] investigated the efficiency of hot air-assisted RF drying of carrot. In which, the hot air (60°C)-assisted RF heating at the electrode gap of 100 mm was used for drying of carrot slices for 270 min first and then followed by hot air drying to complete the drying process. The results showed that the combined drying method could improve the drying rate up to 30% and maintain higher content of heat-sensitive ingredient within carrot slices.

Shewale et al., (2021) [66] studied the efficiency of the sequential drying method using RF and low-humidity air (LHA, 40°C) for drying of apple slices. The combined drying method of LHA + RF could reduce the drying time by 37% and energy consumption by 52% as compared to LHA. The LHA + RF dried apple slices were preserved the polyphenols (98%), flavonoids (87%) and ascorbic acid (77%) and the color change index was so small ($\Delta E = 7.4 \pm 0.7$).

Le Anh Duc et al., (2022) [67] studied thin layer drying model for RF-assisted heat pump drying of *Ganoderma lucidum*, in which, drying parameters included drying temperature of 40, 45 and 50°C and RF power of 0.65, 1.3 and 1.95 kW. The results indicated that the effective moisture diffusivity value increased with an increase in RF power that reduced the drying time by 10% and 21% at RF power of 1.95 kW as compared to RF power of 1.3 kW and 0.65 kW.

Nguyen Hay et al., (2022) [3] studied the RF-assisted heat pump drying of *Ganoderma lucidum*, in which, the drying parameters included drying air temperature of 40°C, air velocity of 1.2 m/s, and an RF power of 1.95 kW, 0.65 and 0 kW. The results showed that the increasing in RF power improved the heating rate and shortened the drying time significantly. In RF-assisted heat pump drying, the dried material got a uniform moisture distribution and temperature distribution and the color of dried products also maintained with the original red-brown color of fresh *Ganoderma lucidum*.

Based on the results of the previous studies mentioned above, RF heating technique is a suitable and effective choice for drying technology, in which, RF is

combined with different drying methods to dry different types of materials. The advantage of RF volumetric heating mechanism can improve the heating rate, drying rate and quality of dried products both in terms of sensory quality and nutritional quality as well as the shelf life of dried products. In particular, the combination between RF with other drying methods as hot-air, vacuum and heat pump drying could reduce the drying time by 67% and the dried products got the higher quality as color, surface appearance and high ingredient retention of 98% as compared with the drying methods without RF assistance. However, the drying method using RF has to invest a high-cost equipment and the safety in operating RF drier must be considered as RF drier operates at high electric voltage.

4. Conclusions

With the increasing requirements of the agricultural and food processing industry, product quality in terms of sensory quality and nutritional quality as well as long storage time would play a crucial role. Besides, the cost of energy consumption also plays a significant role in reducing the processing cost and the price of dried products. The studies for finding out a suitable and the most effective drying technique has been, is and will be done. In particular, the hybrid drying technique with the combination of traditional drying technologies and IR, MW and RF has created a breakthrough both in terms of technology and economy. The effective support of the heating mechanism of IR, MW and RF greatly improves the drying efficiency such as high heating rate, short drying time, high drying product quality as well as saving considerable energy consumption of the drying system. The research, application and development of these hybrid drying technologies will certainly create a breakthrough for the agricultural and food processing industry in the future.

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Conflict of interest

The authors declare no conflict of interest.

Nomenclature

FD	Freeze drying
FIR	Far-infrared
IR	Infrared radiation
LHA	Low humidity air
MW	Microwave
MIR	Mid-infrared
NIR	near-infrared
RF	Radio frequency

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