Research Progress on Drying Technology and Process for Granular Agricultural Products

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Abstract: Granular agricultural products are constituted as a staple food source for over 70% of the global population, are recognized as a core component within the food processing chain, and are accorded significant economic importance in international trade. It has been extensively documented that inadequate desiccation during harvest seasons is associated with the facilitation of mould proliferation, the induction of germination processes, and the acceleration of product deterioration. These outcomes are manifested through compromised food security and incurred economic losses. Nevertheless, the porous structural characteristics inherent to granular crops, combined with the stress fission challenges encountered during dehydration processes, render alternative methods such as solarisation and hot air drying frequently inadequate for meeting crop-specific drying requirements. In this study, the implementation and relative merits of microwave and infrared drying technologies for granular crops are systematically examined. Subsequently, the enhanced drying efficiency and quality parameters achieved through microwave-hot air, infrared-hot air, and infrared-microwave hybrid drying systems are quantitatively demonstrated in comparison with conventional single-mode drying approaches. A comprehensive synthesis is presented regarding experimental findings and research priorities associated with microwave-vacuum, far-infrared vacuum, and fluidised bed drying applications.The developmental potential of emerging desiccation technologies-including radio frequency, ohmic, and heat pump-based systems-is critically evaluated through comparative analysis of dehydration kinetics, energy efficiency metrics, and product quality indices. A theoretical framework is established for the optimization of novel drying equipment and operational parameters. This systematic investigation contributes substantively to the realization of energy-efficient, low-carbon, and quality-preserving drying objectives, thereby providing crucial technical support for global food security initiatives and sustainable agricultural practices.

Keywords: grain drying; drying technology; drying process; quality; energy consumption.

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颗粒状农产品干燥技术与工艺的研究进展

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摘要：颗粒状农产品是全球70%以上人口的主食来源，也是食品加工链的核心原料和国际贸易的重要经济杠杆。收获季节不及时干燥，易引发霉变、发芽或变质，直接导致粮食安全和经济损失。由于颗粒状农作物的多孔性和干燥过程中的应力裂变问题，日晒和热风干燥以及不能满足其干燥需求。本文首先介绍了微波，红外干燥在颗粒状农作物中的应用和优缺点接着引出了微波热风，红外热风，红外微波干燥相比于单一干燥技术的干燥速率和品质的提升，同时总结了微波真空，远红外真空，流化床干燥在该领域的应用成果和研究热点。文章最后论述了射频，欧姆，热泵干燥等新型干燥技术应用和发展展望。本文通过对比分析干燥速率、能耗与品质参数，为新型干燥装备研发与工艺优化提供理论支撑，助力实现“高效-低碳-高质”的干燥目标，对保障粮食安全与农业可持续发展具有重要意义。

关键词：谷物干燥；干燥技术；干燥过程；干燥品质；干燥能耗

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Grains are categorized into three main groups: oilseeds, pulses, and cereals. They are among the most important staple foods globally, accounting approximately 34.4% of the human diet and 65% of animal feed[1-3]. Oilseed, such as melon seeds, rapeseed, soybeans, peanuts, sunflower seeds, and cottonseed, are the most common types. Pulses, which are seeds from the legume family, includes peas, lentils, chickpeas, broad beans, and kidney beans. Cereals are the seeds of grassy plants, including wheat, rice, millet, corn, sorghum, oats, and rye [4-6].

Rice, wheat, corn, beans, and peanuts are widely consumed grains and rich in nutrients. These grains must be dried after harvest to facilitate better processing and storage. For instance, common ingredients like wheat flour and bean flour are produced after drying, underscoring the vital role of this process in grain preservation [3,7].

Drying is the first step of grain storage. Each year, improper drying leads to up to 5% of harvested grain's loss. Reducing these losses is a crucial measure for ensuring national food security[8]. Drying also consumes around 10%~25% of all industrial energy[9], making it the most energy-intensive operation. During drying process, the organoleptic, nutritional, and functional attributes of the product may be partially or completely affected . Therefore, selecting appropriate drying technologies is essential for fruits, vegetables, and grains[10].

Grain drying has evolved over thousands of years. Initially, most farmers used sun-dried method to address the problem of wet grain. Nevertheless, this method has several drawbacks: it was time-consuming and labor-intensive, and it was subject to constraints such as climate, drying sites, and other limitations. The pursuit of high-nutritional products and the protection of the ecological environment are ongoing concerns in the context of the continuous development of modern agricultural technology and the progress of agricultural mechanization, drying technology has advanced significantly. As a result, hot air drying[11], microwave drying[12], infrared drying[13], combined drying[14], and other emerging drying methods have been developed. These technologies play a vital role in grain storage, transportation, and processing[15].

This paper provides a detailed summary of the progression of drying technology for granular agricultural products , particularly rice, wheat, corn, beans, and peanuts. It outlines the optimization of the drying process and the evolution of various methods. Additionally, the paper evaluates different drying techniques based on their effects on drying rate, drying time, and drying quality. Furthermore, it discusses the working principles of cutting-edge drying technologies that have recently emerged, their role in enhancing grain drying, and their potential future development in this field.

1 Hot air drying

The earliest drying method used by humanity was natural drying. However, this method is time-consuming and labor-intensive. With the development of modern agriculture, hot air drying was developed. This method employs the hygroscopic properties of hot air and convective heat transfer to deliver heat to the grain, thereby evaporating water vapour.The phenomenon of desiccation is driven by a moisture gradient, which is formed by the condensation of water vapor from the surface of grain particles into the hot air stream, thereby propelling the drying process. Hot air drying is thermally efficient, non-toxic, uniform, and low cost. It's simple equipment structure, easy operation process, large production capacity, and wide adaptability make it the most widely used grain drying method[16-19].

In the early stages of research on the hot air drying of grain, the focus was primarily on investigating the factors influencing the drying rate, with little consideration given to the effects on grain quality. For instance, Mathur, et al[20]examined the impact of variables such as feed moisture content, bed depth, feed rate, and air temperature on the drying rate of wheat[21].

As modern agriculture advanced, the exploration of grain drying models began to evolve. Initially, in the drying model of corn kernel, researchers developed a one-component drying model; however, the significant discrepancies between the simulation results and actual outcomes necessitated further refinement[22-24]. Due to the heterogeneity of corn kernel components, researchers developed two-component mathematical models for drying. Two-component mathematical drying model more accurately simulate changes in kernel moisture distribution[25-27]. Recognizing this, researchers identified four main parts of the corn kernel: soft endosperm, the pericarp, germ, and hard endosperm[28]. The experimental drying data of four-component drying were used to develop a mathematical model that accurately estimated the moisture diffusion coefficient, moisture content, and drying temperature[29-31]. Subsequently, based on this research, Chen developed a multi-component nonhomogeneous mathematical model that enhances the prediction of moisture transfer during corn kernel drying[32-34] .Additionally, a comprehensive review of various thin-layer drying models for grains was conducted by Jayas, et al[35], and numerous theoretical, semi-theoretical, and empirical models have been developed for describing the thin-layer drying of chili peppers[36], cocoa bean [37], green peas[38], and coarse rice[39].

The quality of post-drying is a crucial concern for those seeking optimal drying methods. In a study by Xie, et al[40], the impact of hot air drying on peanut quality was examined. Results indicated that optimal conditions 40 °C air temperature and an air velocity of 0.5 $m\cdot s^{-1}$-enhanced the protein and fatty acid contents, as well as the germination rate of peanut kernels.In contrast, Qu, et al[41] discovered that peanut seed vigour diminished considerably when drying temperatures exceeded 50 °C, impacting vitamin E content, hardness, and brittleness. Moreover, exceeding a drying temperature of 45 °C markedly altered the red skin damage rate, acid value, breakage rate, and peroxide value of peanuts. The functional properties of peanut isolates also deteriorated with rising temperature. The results of these studies provide suitable peanut drying parameters for various peanut applications and suggest that peanuts should be dried with hot air below 45 °C to maintain their quality. It provides a reference for the selection of suitable drying temperatures for peanut end-use. Additionally, Vazquez, et al[42], explored the effect of hot-air drying on wheat quality, identifying as the most influential factor, followed by wheat variety and initial moisture content. Hot-air drying had a greater effect on the hardness of wheat, and drying temperatures of 80~100 °Cresulted in deterioration of wheat quality, gluten denaturation, and consequently viscoelasticity while drying temperatures of 40~60 °Cshowed some improvement in kernel quality.

Considering the energy consumption in the drying process and the quality of the grains after drying, hot air drying is subjected to different processes, such as variable temperature drying and retarded drying[43]. These drying processes not only retain the advantages of hot air drying but also improve grain quality and reduce energy consumption. For example, adding a retardation process to the drying process has a positive effect on grain drying. Dong, et al[44]posited that a 120-minute retardation process conducted at a temperature of 50 °C has the capacity to reduce the moisture gradient in the drying process by 80 per cent. Elbert, et al[45] showed that grain quality was positively related to retardation time and negatively related to drying temperature.Zhang, et al[46] findings suggest that employing a drying process with multiple retardation cycles may yield superior outcomes in comparison to a single cycle. This is attributable to the enhancement of the retardation process, which in turn leads to an augmentation in the drying rate. Jia, et al[47], reported that the tempering process could improve the uniformity of wheat drying. Xu, et al[48], used a two-stage variable temperature drying process to minimize rice fragmentation during drying. They concluded that the optimal two-stage method was a first stage at 60 °C, a second stage at 45 °C, and a total drying time of 12 minutes. Post-harvest losses were minimized by using different drying temperatures depending on moisture contents, achieving the best quality and minimized energy consumption to keep the crushing loss low.

Of course, the hot-air drying method also has some shortcomings. It has low thermal conductivity, requires a long drying time, and can result in a decline in nutritional value, color, and other sensory properties. Additionally, power consumption is high, drying heat is not uniform, and the quality of the dried product is often greatly reduced. These issues can lead to damage to the intrinsic qualities of the grain. Whilst the substitution of hot air drying machines with novel materials will engender considerable resource savings in the context of grain drying, concerns regarding quality control persist. Consequently, researchers are investigating the development of innovative drying technologies that prioritise energy and labour efficiency, with the objective of producing high-quality products[49-51].

2 Infrared radiation drying technology

Infrared radiation (IR) is part of the electromagnetic spectrum and is mainly responsible for the sun's heating effect. Infrared waves are categorized by wavelength into near-infrared (NIR) (0.78~ 1.4 μm), mid-infrared (MIR) (1.4~3 μm), and far-infrared (FIR) (3~1 000 μ m)[52,53]. The nature of infrared radiation makes it a non-contact method of transferring heat, as electromagnetic waves do not require a medium to propagate and can travel through vacuums. Infrared energy emitted by the heat source radiates directly onto the surface and penetrates into the material's layers. Infrared energy emitted by the heat source radiates directly onto the surface and penetrates into the material's layers. The energy in question is absorbed by molecules in different layers, causing an increase in their vibrational energy levels and the subsequent production of heat. This process leads to an increase in temperature and the achievement of the desired drying outcome.Infrared drying has a very high energy density due to the direct absorption of energy by material molecules. Compared to conduction and convection drying,The surface temperature of granular crops has been found to increase rapidly[54,55]. Infrared drying has become a vital technology in the drying industry due to its numerous advantages, including energy saving, high-quality dry products, uniform temperature distribution, easy control of process parameters, and a clean operation environment[56,57].

Infrared drying has mainly developed in two areas. The first area is the modeling and analysis of the infrared drying process, which includes establishing a drying model and conducting mathematical modeling analysis. scientists also study drying models tailored to different materials and methods to achieve a higher fit, laying the foundation for the development of related industries. The second area is the process optimization of infrared drying to determine the most suitable process parameters.

Abe, et al[58] proposed four mathematical drying models to identify the thin-layer infrared drying characteristics of coarse rice: the exponential model, the diffusion model based on the shape of spherical particles, the Page model, and the approximate diffusion model. According to their findings, the Page model is best suited to explain the thin layer of coarse rice dried under IR energy. Similarly, Das, et al[59] emphasized that the Page model adequately fits the drying characteristics of high-moisture rice. Wu, et al[60] experimentally dried rice kernels using infrared radiation and numerically analyzed their drying kinetics and internal stress. This study accurately described the moisture and temperature distributions of rice kernels using this drying model. Ranjan, et al[61] developed a set of three-dimensional equations utilizing infrared radiation to control the volumetric formulation with the moisture transfer equation and heat pressure equation. Simulation results showed that the 3D model could better predict moisture and temperature compared to the 2D mass heat transfer model, demonstrating good potential for application in the infrared drying of grain and biological materials.

The process optimization of infrared drying aims to find the most suitable process parameters. Researchers study various factors, such as infrared power and intensity, product thickness, wind speed, and the contact distance between the heat source and the material, to determine the optimal configuration. This optimization can provide a solution for large-scale industrial production. Table 1 shows some process parameters of infrared drying and the main conclusions obtained.

Table 1 Process parameters of infrared drying and the main conclusions obtained

Species	Drying conditions	Main results
barley	Afzal, et al[62] experimental parameters were infrared intensity (0.167~0.500 $W\cdot cm^{-2}$), wind speed (0.3~0.7 $m\cdot s^{-1}$), initial moisture content (25%~40% db.), and air humidity (36%~60%).	In terms of drying rate and barley drying, radiation intensity was found to be the most significant factor.
paddy	Nachaisin, et al[63] experimental parameters were IR intensity of 1~5 $kW\cdot m^{-2}$, temperature of 40 °C, and wind speed of 1 $m\cdot s^{-1}$.	A significant reduction in drying time, as well as a significant decrease in energy consumption, was observed to decrease with increasing radiation intensity. An increase in color change and rehydration capability was observed as well.
soybeans	Dundee, et al [64] experimental parameters were IR power 4, 6, and 8 kW, wind speed 4.5 $m\cdot s^{-1}$, air temperature 40 °C, and pellet bed depth 6 cm.	According to the results, drying rates increased as infrared radiation power increased. Soybean seed cracking and crushing are reduced with infrared drying, leading to a higher quality product.
paddy	Nosrati, et al[65] Experimental parameters 30~50 °C drying temperature and 0~2 000 $W\cdot cm^{-2}$ infrared intensity under	Increases in IR intensity increase the moisture diffusion coefficient and decrease drying time.

	the.	
paddy	Bualuang, et al[66] explored the effects of experiments on rice at drying temperatures of 60~ 100 °C, wind speeds of 1.0±0.2 m·s^{-1}, and infrared powers of 1 000 and 15 00 w.	As drying temperature and infrared power were increased, drying time and specific energy consumption decreased; effective diffusion coefficients increased with increased infrared power; the higher the infrared power, the higher the hardness, while drying temperature had no significant effect on hardness.
mung bean	According to Barzega, et al[67], drying temperatures were 30, 40, and 50 °C, infrared radiation intensity was 2 000, 4 000, and 9 000 kW·m^{-2}, no radiation was used (control), pea layers were 1, 2, and 3 layers, and vibration and fixed beds were used.	As the IR intensity increased, the electrical energy increased, but the drying time was shortened. Radiation distance and wavelength had no significant effect on energy consumption, total color change, rehydration capacity, or shrinkage. Based on quality and energy factors, we found that 50 °C drying air temperature, 4000 W·cm^{-2} infrared radiation, and 3 layers of product depth were optimal drying conditions and vibrating bed movement.
paddy	Ratseewo, et al[68] was irradiated with an IR power of 250 W. Infrared drying of rice was carried out under the conditions of infrared intensity of 2 W·cm^{-2}, drying temperature of 40 °C, and wind speed of 1.5 m·s^{-1}.	Infrared drying increased total phenolic and flavonoid content, anthocyanin content, tocopherol content, and antioxidant ability.

In summary, increasing the IR power, drying temperature, and intensity, and decreasing the IR distance can shorten the drying time. However, excessively high IR power, drying temperature, and intensity, as well as too short IR distances, should be avoided to prevent overheating of the food. There is no significant difference in food quality between different IR distances and wavelengths of radiation. The utilisation of infrared radiation technology in industrial settings has been demonstrated to offer numerous benefits, including enhanced efficiency and reduced energy consumption, as well as directional heating capabilities. The material absorption rate differences, safety hazards and other issues must be resolved through technical optimisation and scene adaptation. In the future, with the development of intelligence and new materials, the application potential of infrared radiation will be further realised[69,70]. To validate the practicality of this method, large-scale energy analysis will be needed in the future. Combining new drying technologies such as impact drying, pulsation vacuum drying, heat pump drying, and infrared drying could develop a new joint drying process, reducing the limitations of the infrared drying and improving grain drying quality. Future development trends include researching and developing high-efficiency infrared radiation materials and coating materials, establishing a mass heat transfer kinetic model for grain far-infrared drying, and reducing the energy consumption of the drying process[71].

3 Microwave drying technology

Microwave refer to electromagnetic waves with wavelengths ranging from 1 mm to 1 m, corresponding to frequencies from 300~300 000 MHz. To prevent interference with radar, communications, and broadcasting, international regulations allocate specific frequency bands for industrial, agricultural, scientific, and medical use. Currently, the frequencies 915 MHz and 2 450 MHz are widely used, with the 2 450 MHz band being most common in food production, particularly in consumer microwave ovens[72-74]. See Table 2 below:

Table 2 Internationally regulated microwave bands for civilian use

Frequency/MHz	wave band	center frequency/MHz	center wavelength/m
890~940	L	915	0.330
2 400~2 500	S	2 450	0.122
5 725~5 875	C	5 850	0.052
22 000~22 250	K	22 125	0.008

The principle of microwave drying involves applying an electromagnetic field to a product, causing ionic particles and water molecules to be agitated, raising the temperature, and evaporating water to dry the product[75,76]. The figure illustrating the new type of uniformly heated microwave drying device is shown in Fig.1. This process is significantly different from traditional drying methods, which rely on convection, conduction, and radiation heating[77]. Microwave drying offers several advantages, including high thermal conductivity within the product, a reduced footprint, precise process control, quick start-up and shut-down times, energy savings, reduced drying time, improved efficiency, superior product quality, prevention of over-drying, and the ability to penetrate and heat the interior of the product. Additionally, microwaves can serve as a non-chemical method for insect control due to their interaction with water molecules[78-82].

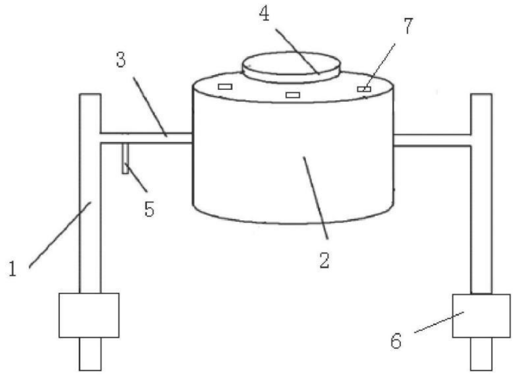

Fig.1 Microwave drying apparatus

explanatory note: 1. Support frame; 2. drying box; 3. spindle; 4.material cover; 5.connection shaft; 6.axis of activity; 7.microwave generator.

Researchers have emphasized the importance of optimizing the microwave drying process by studying the drying rate, energy consumption, and other drying characteristics. Holtz, et al[83], found that increasing microwave power increases the drying rate and decreases specific energy consumption. Liu, et al[84] conducted tests on corn at 70 W, and 280 W respectively. The results showed that under the same load, the energy consumption of microwave drying was less than 0.3 times than that of electric drying. Average drying rates are higher when microwave power is higher. However, the load showed the opposite trend. It is recommended that the corn load be increased appropriately based on energy consumption and drying quality. It is recommended that the microwave intensity in the experiment does not exceed 0.7 $W·g^{-1}$. Khoshtaghaza, et al[85] concluded that higher temperature and microwave power result in higher effective moisture diffusivity, while higher air velocity leads to lower diffusivity. The drying time was 10.5 min at 80 °C, 4.5 $m·s^{-1}$, and 500 W with minimum specific energy consumption, and the cracking rate of soybean grains was lowest at 80 °C, 1.8 $m·s^{-1}$, and 200 W. Hemis, et al[86] established that the moisture content of wheat is subject to a decrease in proportion to the increase in microwave power. Furthermore, it was determined that an elevated initial moisture content results in accelerated drying rates. However, it has been demonstrated that elevated levels of microwave power can exert a deleterious effect on the vigour of seeds and the process of germination. Hemis, et al[87] demonstrated that, while elevated microwave power accelerates the drying process, it concomitantly reduces the vigor of the seeds. Drying wheat with 910 W and 490 W microwave power reduced germination, whereas 245 W was sufficient to dry wheat without affecting quality. Grain drying characteristics are not the only factor affecting microwave drying: drying quality is also affected. Researchers have extensively studied the quality of microwave-dried grain. For example, Smith, et al[88] used an industrial microwave at 915 MHz, with power levels of 5, 10, and 15 kW, drying time of 4, 6, and 8 min, and initial moisture content (moisture content) of 24%, to study the effects on rice's surface lipid content, final viscosity, and protein content. Olatunde, et al[89] analyzed the effects of microwave drying on humidification of rice, that the microwave energy should be in the range of 450~600 kJ/kg to maintain the quality of rice. Shen, et al[90] found that a microwave intensity of 3~4 $W·g^{-1}$ is optimal for drying germinated brown rice. Jafari, et al[91] determined that the optimum microwave drying process for rice, with 90 W power and 18 mm thickness, achieved the highest energy and thermal efficiency, drying efficiency, lowest specific energy consumption, and minimal fragmentation. Vadivambal, et al[92] exposed wheat kernels to four microwave power levels

(250, 300, 400, and 500 W) for 28 and 56 seconds. The results showed that microwave treatment killed some pests but reduced germination rate. Faria, et al[93] evaluated the effect of microwave radiation on the physiological quality of maize seeds under different drying conditions. Seeds with 20% moisture were dried at 40, 50, and 60 °C with powers of 0 0.6, and 1.2 $W \cdot g^{-1}$. Results showed that drying time was reduced by about 5 hours at 40 °C and 0.6 $W \cdot g^{-1}$ compared to conventional drying, with no significant differences in seed vigor, germination, and longevity.

Microwave drying is a process that has been found to have various disadvantages, including poor accuracy and repeatability, uneven drying, reduced seed vigour, high cost, short generator life, and unsuitability for the drying of volatile compounds. Furthermore, rapid mass transfer may lead to quality impairment or "puffing", resulting in undesirable changes in food texture[94-96].

4 Combined drying technology

Many separate drying technologies, cannot fully ensure the safety, quality, and stability of the dried product. Therefore, scientists have explored combined drying technology, which can improve the quality of the final product, reduce the energy demand and the total drying time, and improve the drying efficiency, to achieve the purpose of reducing energy consumption and improve the quality of the joint drying is convenient for the operation, environmental protection, safety, and high efficiency, and can maximize costs reduction[97,98].

Different drying methods can be used in different drying stages with combined drying technology, utilizing the advantages of various drying technologies. The common joint drying in grain drying is microwave hot air drying[99], infrared hot air drying[100], and infrared microwave drying [101].

4.1 Microwave hot air combined drying

Hot air drying has three phases: a preheating period, a constant drying rate period, and one or more falling rate periods. Prolonged drying at high temperatures often leads to hardening, shrinkage, and discoloration of the final product. Microwave promote water movement from the interior to the surface, which is then removed by convective airflow. Combining hot air microwaves can minimize drying time and improve product quality by addressing issues associated with conventional hot air drying[102-104].

Wei, et al[105] concluded that combining hot air and microwave drying improved the uniformity and quality of the dried product. Ranjbaran, et al[106]. reported that microwave-hot air drying of soybeans resulted in higher drying rates compared to conventional hot air drying. Hemis, et al[107] found that combined microwave hot air drying safely dried soybean, canola, and corn seeds reduced cracking, and improve drying quality. Sharma, et al[108] found that combined microwave hot air drying can reduce the drying time of garlic cloves by 80%~90%. Drying cooked chickpeas using the microwave hot air method is a promising technique to produce highly rehydrated products in a short drying time. Sabat, et al[109] investigated the combination drying of precooked chickpeas at microwave power of 210, 300, and 560 W and hot air temperature of 23, 160, and 250 °C. The best results in terms of drying time, texture, rehydration time, and color were obtained with 210 W and 160 °C. Khouryieh[110] also studied precooked soybeans under similar conditions and found that combining microwave and hot air drying reduced drying time. Higher microwave power and air temperatures generally increased dehydration and rehydration rates and improved the color of rehydrated products.

4.2 Infrared hot air combined drying

The combined use of infrared energy and hot air drying in crop drying has been widely studied. Infrared energy leads to rapid internal heat generation, causing moisture to move quickly from the interior to the surface. Applying hot air then removes this moisture into the surrounding air. Compared to single hot-air drying methods, this new drying method improves the final product quality, reduces energy consumption and drying time, and significantly lowers operating cost, making it a promising drying technique [111,112].

Zhu, et al[113] studied the effects of spray bed drying with infrared assistance on the quality of flowers and fruits and their energy consumption. Comparing the hot air drying and infrared drying, this method reduced drying time by 40% and 33%, respectively. and energy consumption by 66% and 32%, respectively. As demonstrated by Nbariş, et al[114], the combination of drying methods is a more energy-efficient and effective process than single drying methods.This study suggested that IR-SBD is suitable for industrial application in peanut dewatering process for efficient, high-quality production. Dondee, et al[115] showed that infrared hot air drying reduces the moisture gradient and internal stresses in soybean seeds, thereby reducing the cracking and crushing and improving product quality. This study indicated that soybean seeds are effectively dried using a combination of infrared and fluidized bed drying.

4.3 Infrared microwave combined drying

Infrared drying technology can penetrate and heat the interior of the material to be dried, but its penetration ability is limited.Microwaves have been shown to possess effective penetration capabilities, rendering them an efficient method of food drying. The advantages of this approach include volumetric heating, the production of high-quality products, expeditious drying speeds, and a safe drying process. Combining infrared and microwave drying can improve post-drying quality and reduce drying time[116-118].

Najib, et al[119] investigated the drying kinetic behavior of tempered lentil seeds using microwave-assisted infrared thermography and developed a corresponding mathematical model. They found that increasing microwave power from 0.35 kW to 0.7 kW significantly reduced drying time. A low infrared power of 0.375 kW combined with different microwave power levels further reduced drying time, particularly at lower microwave power levels.

The addition of increased infrared power to various thermal processes did not significantly affect drying times. The results were compared those obtained under lower infrared power conditions.

This was compared to conditions using lower infrared power. Nanvakenari, et al[120] investigated the effects of infrared (1 000~2 000 W) and microwave (100~900 W), wind speed (1~5 $m \cdot s^{-1}$), and temperature (40~80 °C) on rice. The adapted hybrid system showed significantly higher dehumidification, grain extraction rate, and specific energy consumption than a single-drying system.

Optimal drying conditions were a temperature of 68 °C, an air velocity of 5 $m \cdot s^{-1}$, a microwave power of 900 W, and an infrared power of 1 479 W. These conditions resulted in the lowest specific energy consumption, highest dehumidification rate, and rice quality.

4.4 Vacuum far-infrared radiation drying

Vacuum far-infrared radiation drying involves the maintenance of a pressure range of 10 ~30 kPa. The utilisation of far-infrared radiation with a wavelength range of 3~1 000 μm enables the penetration of the material's molecular resonance to achieve synchronous heating both internally and externally for the purpose of material drying. The vacuum conditions can be employed to reduce the boiling point of water (30~40 °C), minimise the loss of heat-sensitive components, and elevate the radiation temperature. This can result in a substantial enhancement in the drying rate and a reduction in the drying time. For instance, during the drying process of honeysuckle, the effective moisture diffusion coefficient increases to 4.57×10^{-10} $m \cdot s^{-1}$ and the high-temperature radiation promoted the formation of micro-porous channels inside the material, thereby improving the migration efficiency of moisture[121]. This combination is especially suitable for granular crops with a dense structure. The vacuum environment can inhibit the enzyme oxidation reaction and retain heat-sensitive components such as chlorogenic acid and lignocellulose glycosides. It has been demonstrated that the process of drying is an effective method for the preservation of Chinese herbal medicine and functional agricultural products, which are characterised by a granular consistency[122]. The study indicates that the optimal balance between drying rate and product quality, including parameters such as colour, gloss, and active ingredient retention rate, is achieved when the temperature of far-infrared radiation is increased. Furthermore, the effective moisture diffusion coefficient of biomass, such as peanut, exhibits a significant increase with rising temperature under far-infrared radiation. It has been demonstrated that the porosity (5.056×10^{-9} $m \cdot s^{-1}$) is conducive to the enhancement of uniformity within the pore structure[123].

4.5 Vacuum microwave drying

The application of microwaves results in the polarisation of water molecules, with the generation of friction heat occurring as a consequence of a high-frequency electromagnetic field. The combination of these effects, namely the high-frequency electromagnetic field and the vacuum environment, serves to reduce the boiling point, thereby facilitating the process of low-temperature rapid drying. The following features are worthy of note:Rapid and uniform heating: microwave penetration can shorten the drying time to one-tenth of that of the conventional method (vacuum microwave drying of soya beans only takes 40 minutes). The maintenance of quality is contingent upon the ambient temperature; a low temperature environment has been demonstrated to diminish the loss of VC and chlorophyll (retention rate of more than 70%, respectively)[124]. This renders the product especially suitable for heat-sensitive granular crops. Sterilisation: The non-thermal effect of microwave radiation has been demonstrated to inhibit microbial activity and prolong the shelf life of products. A number of relevant studies have demonstrated that in the processes of sweet potato slice drying and hairy bean drying, the combination of ultrasound-assisted osmosis (USOD) pretreatment and microwave vacuum drying results in enhanced effective water diffusion coefficient of 1.249×10^{-7} m²/s, accompanied by significant optimisation of rehydration performance[125]. The VC retention rate of microwave vacuum drying (approximately 75%) approaches the VC retention rate of freeze-drying (82.1%), while the energy cost is reduced to approximately 30% of the latter[126].

The application of vacuum far-infrared and vacuum microwave drying in granular crops has evolved from a single technology to a combination of optimisation techniques. One such technique is microwave-far-infrared synergistic drying, which uses microwaves to quickly remove surface moisture, and then far-infrared radiation to promote internal diffusion. This reduces the total drying time and energy consumption. It has been demonstrated that analogous combinations have been employed in the context of asparagus drying. Specifically, the application of microwave pretreatment for a duration of two minutes, followed by freeze drying, has been shown to reduce the processing time by 40%, while concurrently enhancing the colour quality[127]. The process of hot-air-microwave segmented drying, involving the initial stage of hot-air drying to a medium moisture content and the subsequent stage of microwave vacuum drying, has been shown to facilitate a balance between efficiency and quality. The VC retention rate of the combined drying of hairy beans was found to be 70%, with the process taking a mere 50 minutes[128]. Ultrasonic pretreatment is a process that can be described as follows:

Ultrasonic treatment has been shown to be capable of destroying the cell wall structure and accelerating water migration. For instance, the microwave drying efficiency of sweet potato slices was increased by more than 30% after ultrasound-assisted infiltration[129].

In the future, it is imperative that this technology be further combined with intelligent regulation and new materials to achieve the goal of high efficiency, low consumption and high quality drying. The technological challenges associated with the development of this technology pertain to the uniformity of far-infrared drying, which is significantly influenced by the morphology of the material and the configuration of the radiation source, as well as the susceptibility of microwave drying to localised overheating. The precise control of power and vacuum is also paramount[130]. Research hotspots concentrate on the development of an intelligent control system to monitor material moisture and temperature changes in real time, and on exploring the synergistic effect of nanomaterials (e.g. Si-NPs) and drying technology to improve resistance and nutrient retention [131].

4.6 Fluidised bed drying

The process of fluidised bed drying is primarily accomplished by means of the fluidisation mechanism of the gas stream. This mechanism involves the suspension of dry particles in the gas stream, thereby forming a 'fluidised' state. The purpose of this process is to achieve full contact between the gas and solid phases, thus facilitating high heat transfer efficiency and expediting the drying rate. The field of fluidised bed drying research is predominantly concerned with the dynamic fluidisation state and the adjustment of amplitude and frequency to enhance mobility and prevent local overheating. This approach is particularly well-suited for fragile particles[132]. For instance, Burande, et al[133] demonstrated that at a temperature of 62 °C and an airflow rate of 2.1 m/s, the drying time was reduced to 45 minutes when compared to conventional hot air drying methods. Furthermore, the cracking rate was reduced to 0.5%, and the evaporation energy per unit of moisture was reduced by 35%. Manju, et al[134] employed a vibrating fluidised bed to dry maize seeds in simultaneous segments, and found that the germination rate was maintained at 95. Following the drying process, a rate of breakage of less than 0.3% was recorded, and the SEM analysis demonstrated that the integrity of the endosperm cell wall was well maintained. In a separate study, Nanvakenari, et al[135] employed a combined infrared fluidised bed for the drying of rice, and it was observed that the dehumidification rate (from 100% to 700%), grain extraction rate (from 5% to 40%), and specific energy consumption (from 80% to 10%) were all significantly higher in the novel hybrid system as compared to a single fluidised bed dryer.

The present study identifies the following areas of research as being of particular importance in the field of fluidised beds: The presence of high levels of sugar/starch particles results in these particles being easily bonded, leading to non-uniform fluidisation. The energy consumption of the blower accounts for 30%~50% of the total energy consumption, resulting in a significant pressure on energy resources. Fine particles (<100 μm) are easily carried by the airflow, and there are safety risks associated with the high dust concentration[136]. The primary method of compensating for the inherent limitations of the gas flow pattern of a fluidised bed involves the implementation of either an inert gas or auxiliary equipment[137].

5 Emerging Drying Technologies

New drying techniques have recently gained increasing research interest in preservation processes in related industries such as food and agriculture. Novel heating technologies including radiofrequency[138], pulsed electric fields[139], ultrasound, ohmic[140], and heat pumps[141] have been developed to partially or completely replace conventional drying methods. Significant advances have been made in pretreatment, technology, and equipment design for crop drying, improving process efficiency and the quality of the final dried product. These advanced technologies can be used as pre-treatments to redu

Ce initial moisture content or modify the crop's structure to shorten the drying process. These methods reduce moisture content drying time, and energy consumption compared to conventional drying methods, thus producing superior products.

RF drying is a volumetric heating method that generates heat oscillations within the material through molecular rotation and charged ions, allowing for uniform heating without thermal gradients and deeper penetration[142]. This technology also has offers fast drying speeds and large loading capacities[143]. RF has been successfully applied to macadamia nuts[144], sliced lettuce[145], peanuts[146], corn[147], rice[148], and so on. These studies have shown the advantages of RF drying, including short drying time and good quality, as well as its feasibility for agricultural products. Today, RF heating is commonly used for drying, enzyme inactivation, disinfection, pasteurization, sterilization, and defrosting of food and agricultural products.

Pulsed electric fields cause differences in transmembrane potentials, leading to membrane rupture or local structural changes. The cell membrane undergoes reversible or irreversible osmosis when its transmembrane potential exceeds a certain threshold. This leads to biochemical and physiological changes and even cell death[149,150]. Pulsed electric fields causes electroporation, promotes water diffusion, and enhances drying[151,152]. This technology offers environmental protection, low cost, short processing time, and low energy consumption while maintaining the organoleptic and nutritional qualities of the food, prolonging the shelf-life, avoiding chemical residues, and preventing environmental pollution. Therefore, it can be applied to sterilization, decontamination, defrosting, and drying of food[153,154].

Ohmic heating, also known as Joule heating, or resistance heating, involves heating food by passing an electric current through it. energy is radiated directly into the food[155]. Ohmic heating has many potential applications, including blanching, evaporation, drying, fermentation, sterilization, pasteurization, and food heating. The applied electric field causes cell membranes to electroporate, increasing extraction rates and reducing pasting temperature and enthalpy. Ohmic heating allows food to heat up faster while maintaining its color and nutritional value. The water absorption index, water solubility index, and thermal and pasting properties of the materials are subject to alteration under ohmic heating. This process leads to starch pre-gelatinisation, thereby reducing energy requirements during processing[156].

The basic principle of heat pump drying is to use the inverse Carnot principle to absorb heat from the air and transfer it to the drying room increase its temperature, enabling the drying of materials. A heat pump can be considered a heat engine running in reverse. Heat pumps work on the refrigeration principle, cooling the air stream and condenses the water in it. This process dries the air and restores the latent heat of evaporation by removing the water vapor, allowing the air to be recirculated[157,158].

Heat pump drying has great potential for energy saving, as it can recycle energy and has become one of the most promising drying technologies in the food industry.

Compared to traditional hot air drying, heat pump drying offers the low energy consumption, low cost, low drying temperature, high coefficient of performance (COP), high drying efficiency, high energy efficiency, short drying time, and minimal loss of product quality.

Currently, heat pump drying is more commonly applied to agricultural products, fruits, and vegetables, with less research in grain drying. However, based on its characteristics, heat pump drying has great development prospects and revolutionary potential for grain drying.

The research on heat pump drying of grains primarily concentrates on the following aspects: firstly, the basic low-temperature heat pump is applicable to primary processing plants, adopting a drying temperature of 35 °C, thus avoiding the damage to the quality of paddy grain caused by high temperatures, with a popping rate of only 1.3%, a unit energy consumption of 2 022 $kJ \cdot (kg \cdot water)^{-1}$, which is reduced by 30%~40% compared with that of hot-air drying, and the drying time is shortened by more than 80% compared with that of natural air drying[159]. Exhaust air heat recovery type high temperature heat pump drying is a suitable option for medium-sized farms with large-scale production, recovering exhaust air residual heat by means of a sensible heat exchanger and a microporous membrane corrugated filtration dust collector, with an improved COP value of 0.56, an increased SMER value of 0.11, and a hot air temperature of 70 °C. When combined with an optimized wind speed of 0.5 $m \cdot s^{-1}$, this approach has been shown to enhance drying efficiency while ensuring that the rate of paddy popping does not exceed 2%[160]. The intelligent control and dehumidification solution for warehousing drying systems is a suitable solution for large-scale production of high-value-added seeds or organic grains. The system integrates programmable logic controllers (PLC) and touch screens to achieve automatic adjustment of drying parameters. It has been demonstrated that the hot air temperature control has a precision error of ≤0.95 °C, and the grain temperature is stabilised at around 33 °C[161]. The system combines heat pump drive with drying under low temperature and low humidity conditions, which has been shown to reduce grain dry matter loss (≤0.5%) and improve whiteness value ,The unit energy consumption is as low as 2.5 $kW \cdot h \cdot (1\%\text{-}t)^{-1}$[162].

As new industrial applications of emerging processing technologies are still being developed, they have higher implementation costs than traditional processing technologies. However, with further technological advances and increasing industry application, future costs are expected to decrease.

Conclusion

The comprehensiveness of traditional drying systems has been validated through their evolution from empirical modeling to mathematical frameworks, accompanied by the progression from humidity-heat transfer simulations to the establishment of three-dimensional computational models. However, the advancement of these technologies is constrained by deficiencies inherent to unitary drying methodologies. For instance, the operational lifespan of microwave drying equipment is characterized by unpredictability, while its incompatibility with volatile substance treatment and deleterious effects on wheat germination rates have been documented as primary constraints on practical implementation. Comparable limitations have been observed across emerging desiccation technologies. Superior drying performance in both dehydration velocity and product quality management has been demonstrated through the sequential application of hybrid drying methodologies when contrasted with singular technological approaches. This paradigm has been extensively investigated within contemporary scholarly research. Nevertheless, critical challenges remain unresolved in multi-physical field coupling mechanisms and the complexity of coordinated equipment control within combined drying systems. The absence of a comprehensive drying parameter database has been identified as a critical barrier to technological progression, while machine vision-based moisture monitoring systems and adaptive control architectures have been recognized as pivotal yet underdeveloped components in technical promotion initiatives. Process optimization is being facilitated through the integration of intelligent moisture detection systems with visual recognition algorithms, enabling enhanced precision in drying operations alongside reduced carbon footprint. Future investigations must prioritize the refinement of vapor-liquid phase migration models within porous media matrices, a prerequisite for formulating bio-thermodynamic equations that incorporate critical parameters such as glass transition temperatures and cellular membrane permeability coefficients. The synthesis of these theoretical frameworks is essential for developing integrated assessment models combining life cycle analysis (LCA) with artificial neural network (ANN) predictive capabilities. Concurrently, the establishment of standardized drying protocols covering 27 major crop categories has been mandated as a strategic imperative. This systematic approach presents an innovative methodology for addressing persistent challenges in agricultural desiccation technologies.

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