Food Engineering Reviews (2023) 15:548–576
https://doi.org/10.1007/s12393-023-09333-7

Recent Advances in the Drying Process of Grains

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Received: 10 January 2023 / Accepted: 19 January 2023 / Published online: 8 February 2023

Abstract

Grain drying is a vital operation in preparing finished grain products such as flour, drinks, confectioneries and infant food. The grain drying kinetics is governed by the heat and mass transfer process between the grain and the environment. Incomplete, improper and over-drying are crucial to the grain quality and negatively influence the acceptance of the grain by the consumers. Dried grain moisture content is a critical factor for developing grain drying systems and selecting optimal performance by researchers and the grain processing industry. Many grain drying technologies such as fluidised bed dryers, fixed bed dryers, infrared dryers, microwave dryers, vacuum dryers and freeze dryers have been used in recent years. To improve the drying process of grain, researchers have combined some drying technologies such as microwave + hot air, infrared + hot air and microwave + a fluidised bed dryer. Also, they introduce some treatments such as ultrasound dielectric and dehumidification. These methods enhance the dryer performance, such as higher moisture removal, reduced processing time, higher energy efficiency and nutrient retention. Therefore, this review focused on the drying conditions, time, energy consumption, nutrient retention and cost associated with the reduction of moisture content in grain to a suitable safe level for further processing and storage.

Keywords Crops · Processing of crop · Dehydration process · Heat and mass transfer · Drying model and simulation

Introduction

Grains are divided into three main categories: oil seeds, legumes and cereals, as shown in Fig. 1. They are among the world's most important staple foods, making up a significant portion of the human diet (~ 34.4%) and animal feed (~ 65%) (FAO, IFAD, UNICEF, WFP and WHO [1], OECD/FAO, [2]). Edible oils are produced from oilseeds such as melon, rapeseed, soybean, peanut, sunflower seed and cotton seeds. They are the most prevalent oilseeds grown worldwide. Pulses are the type of grains that come from the Fabaceae or Leguminosae family. Peas, chickpeas, lentils, kidney beans, broad beans and navy beans are among the dry seed devoured as a pulse plant product. Rice, wheat, corn, millet, sorghum, oat, sorghum and rye belong to the cereals which are among the seeds of grass in the Poaceae family [3–5]. Grains are important sources of vitamins, minerals, fibres, crude fat, proteins, essential fatty acids, carbs and inorganic elements, all of which are important for human health [6]. Daily consumption of white and brown rice contributes 334 to 341 kcal to the total dietary energy gained by the human body [7]. Rice, wheat, corn, peas, beans, peanuts and sunflower seeds are the widely consumed grains. In contrast, less consumed grains include cottonseeds, rapeseeds, chickpeas, rye and sorghum. However, all the grains are good sources of nutritional composition such as carbs, protein, minerals and vitamins (Guerrieri and Cavalleto [8]).

Dried grains are used as a raw material for producing various valuable products such as alcoholic and non-alcoholic drinks, extracts, beverages and vinegar. Flour is

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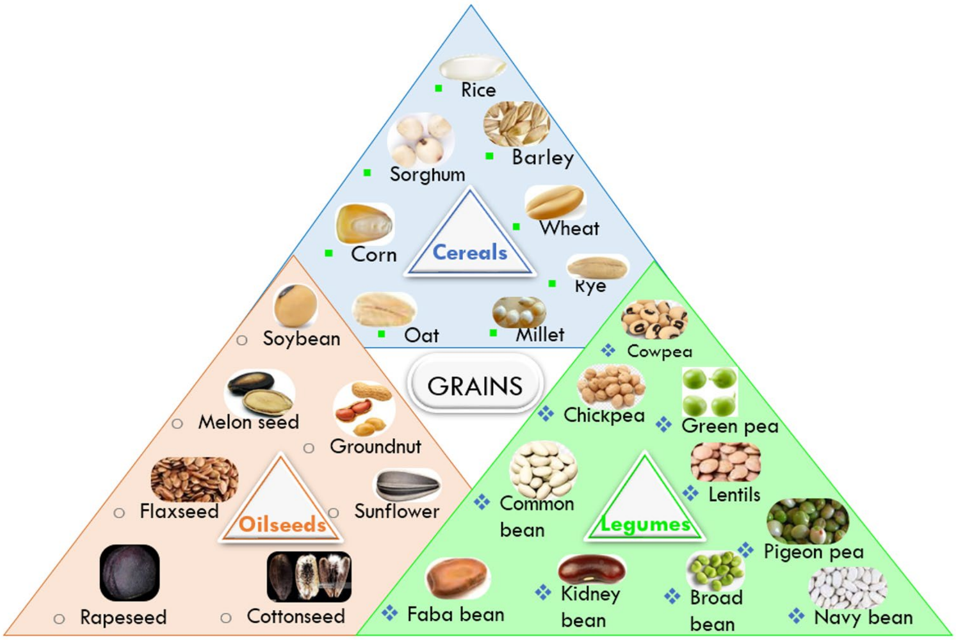


Fig. 1 Classification of grains: Cereals, legumes and oilseeds

another commercially available dried grain product, such as rice flour, wheat flour, sorghum flour, cowpea flour and bean flour. It is usually used for making baked food such as cakes, bread, pastries and cookies. In addition, grain flour is essential in producing other food such as noodles, snacks, spaghetti confectionery and baby food [9]. Consumption of grain-based food offers balanced nourishment and aids in treating various ailments caused by nutritional deficiencies. From an environmental standpoint, including plant-based foods in the human diet, with a focus on legumes, cereals and seeds as a sustainable alternative to protein intake, could reduce the environmental impact of food [3]. Such plant-based foods emit fewer greenhouse gases and are highly reliable protein and other nutrient sources [10]. Nonetheless, different factors such as plant cultivars, seed quality and planting procedures significantly impact the quality of the finished grain products [11]. However, these pre-harvest factors have less impact than the drying process of grains [11].

Drying is the most widely used preservation method and the most diversified unit activity in agricultural grain processing [12] and serves as a pre-process to other main processes [13]. The drying process significantly affects the quality of dried grains. It plays a vital role and has a significant impact on the performance of milling and grinding operations [14]. The drying process include a combination of heat, moisture and momentum interactions in which the moisture in the grain is decreased to a desirable level (e.g. 8.5 to 13.0% for rice, 8.0–13.5% for corn, 8.0–15% for beans and 4.5 to 7% for peanuts [15], ASAE-D245.5, 2001; [16]. Several drying methods and different processing conditions, such as heat intensity, air velocity, drying duration and the initial condition, could significantly affect the quality of the final dried products, such as high moisture, cracks, burnt grains, etc. [17]. For instance, fungal development, germination, respiration and mould growth in dried grain is associated with high grain moisture. This makes it inappropriate for long-term storage [18]. If the moisture content of a properly dried grain is less than 9%, it can be kept for more than a year [15]. Freshly harvested grains have high moisture levels (20 to 36%). Before it can be marketed or used as feed or seed, the moisture content must be reduced to less than 15% for extended storage [19]. Grain post-harvest losses can be reduced by 2 to 5% by selecting a proper drying technology (Nguyen [20]).

Drying of grain accounts for a large portion (27 to 70%) of industrial energy usage, depending on the final product of the process [21]. An efficient drying process is critical to the grain processing industries [22]. Currently, the drying operations must satisfy the demand of both grain farmers and processors. This includes the request for high-quality products, adherence to government energy regulations, increased production capacity and improved economic and eco-friendly practices [23]. In pursuit of this goal, researchers have investigated the potential of combined drying procedures. The hybrid dryers involve a technique where two or more drying method mechanisms are combined into one operation. Also, additional treatments such as ultrasound, vibration and dehumidification can be combined with the drying procedures. Although grain drying technologies have been recently improved and enhanced, to date, grain dryers perform at the peak of their potential with constraints. Therefore, this study reviews the fundamentals of the drying process, the drying conditions, time, energy consumption, nutrient retention and cost for effective drying of the three different classes of grains namely: cereal, legumes and oilseed, over the last 5 years.

Fundamentals of the Grain Drying Process

Moisture and Phase Change

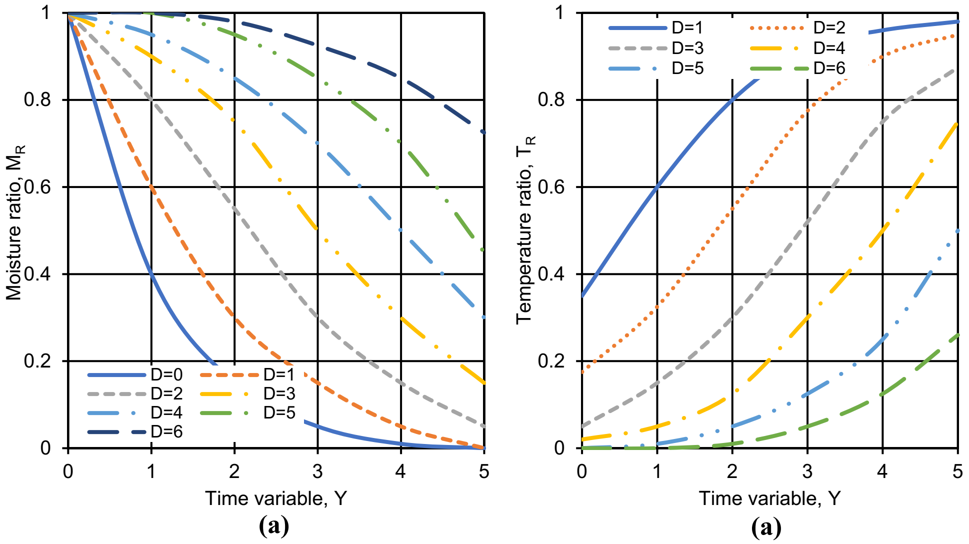
Moisture and its phase shift are found in a variety of engineering and biotechnological applications where heat and mass exchange are inextricably linked. In the drying phenomenon, the water is evaporated from a product and the water vapour is removed from the dryer at the same time [24, 25]. Similar to grain moisture removal, partial evaporation of the liquid phase occurs inside the substrate and the exposed surface. The liquid is transformed into a vapour phase that is evacuated from the substrate. Removal of the reducing moisture level facilitates postharvest handling and avoids microbiological deterioration, hence, improves the nutrient retention and economic value of the grain.

The primary characteristic that guides the drying of agricultural grains is the combination of heat transfer (environment to grain) and moisture migration (grains to the environment). The temperature, relative humidity, velocity, moisture and solid elements of the grain determine the heat and mass transfer during grain drying. The physicochemical properties such as texture, size, minerals and proximate composition of the grain have a huge impact on the drying kinetics of the material [26]. The moisture loss of the grains during the drying process is sensitive to the number of grain layers subjected to the drying process and quantifies the process by the moisture ratio profile of the dried grain under different layers (D). The path of moisture migration is shown in Fig. 2(a) and the corresponding temperature profile of the grain during the drying process is illustrated in Fig. 2(b) [27].

Mass Transfer

The moisture inside biological products can be classified as vacuolar, cytoplasmic, extracellular water and others. The transformation between different moisture types has been defined as a function of changes in cell structure during drying by considering the variation in mass because of moisture migration. The moisture has been further classified into four categories: highly mixed water, combined water, free water and others [28]. Due to its comprehensive theoretical foundation, this categorisation approach is currently frequently employed. Although the influence of this moisture class is not addressed during the drying process, the mass transfer regulates the transition of this within the several moisture-binding kinds in the grain and the surroundings [29]. During the drying process of grain, the air-grain mass transfer is described by a mass kinetic equation [30]. The reduction of the grain moisture content to a safe storage level involves mass transfer processes of which kinetics are defined in several studies based on the mass of the grain before and after drying. The magnitude of the transfer phenomenon in grain drying is quantified based on the instantaneous moisture content (time-dependent moisture content), moisture ratio, drying rate and equilibrium moisture content which are determined from Eqs. 1–4, respectively [15, 27, 31].

$$\mathrm{MC}_{wb} = \frac{W_w - W_d}{M_w};\ \mathrm{MC}_{db} = \frac{W_w - W_d}{M_d} \tag{1}$$



(a) (a)

Fig. 2 Moisture ratio-time (**a**) and temperature–time (**b**) relationship pattern for the grain drying process. D = different dryer layers [27] where MC_{wb} and MC_{db} are the moisture content on a wet and dry basis (%) respectively, W_w is the grain wet mass (g) and W_d is the grain dry mass (g).

$$\mathrm{MR} = \frac{M_g - M_e}{M_0 - M_e} \tag{2}$$

where MR is the moisture ratio (dimensionless), M_g is the grain moisture at a specific time (%), M_e is the equilibrium moisture content (%) and M_o is the initial moisture content (%).

$$\mathrm{DR} = \frac{dm}{dt} = \frac{M_g - M_0}{t_g - t_0} \tag{3}$$

where DR is the drying rate (%/s), M_g is the grain moisture at a specific time (%), M_o is the initial moisture content (%),t_g is the specific drying time (s) and t_0 is initial drying time (s).

$$M_e = \frac{a + bT}{(100RH - 1)^{1/c}} \tag{4}$$

where M_e is the equilibrium moisture content (%), T is the temperature (K), RH is the relative humidity and a, b and c are the constant parameter.

Diffusion regulates the movement of moisture vapour throughout the drying period. Liquid diffusion through a porous solid media and molecular diffusion are the main examples of diffusion in grain drying. Effective moisture diffusivity is a term that describes how fast the moisture moves. The moisture diffusion is usually calculated using Fick's second rule of diffusion Eq. (5) [32].

$$\frac{dm}{dt} = D_{eff}\nabla^2 m \tag{5}$$

where dm is the change in moisture content (%), dt change in time (s), D_{eff} is the effective moisture diffusivity (m^2/s) and m is the moisture content (%).

There are easy analytical solutions to Fick's equation: When the size reduction is insignificant or not considered, internal movement is the principal resistance, with no exterior movement resistance, and influences the external and internal heat transmission, with the initial thermal transient being ignored. For distinct geometrics: slab, cylinder and sphere, the solution of the Fickian diffusion equation with a one-dimensional standpoint is shown in Eq. 6−8 respectively [33–35].

$$\mathrm{MR} = \frac{M_g - M_e}{M_0 - M_e} = \frac{8}{\pi^2}\sum_{n=1}^{\infty}\frac{1}{(n-1)^2}\exp\left[-(2n-1)^2\frac{\pi^2 D_{eff} t}{L^2}\right] \tag{6}$$

where MR is the moisture ratio (dimensionless), M_g is the grain moisture at a specific time (%), M_e is the equilibrium moisture content (%), M_o is the initial moisture content (%), D_{eff} is the effective moisture diffusivity (m^2/s) and L is the slap thickness (m).

$$MR = \frac{M_g - M_e}{M_0 - M_e} = \sum_{n=1}^{\infty}\frac{4}{\beta_n^2}\exp\left[-\frac{\beta_n^2 D_{eff} t}{r^2}\right] \tag{7}$$

where MR is the moisture ratio (dimensionless), M_g is the grain moisture at a specific time (%), M_e is the equilibrium moisture content (%), M_o is the initial moisture content (%), D_{eff} is the effective moisture diffusivity (m^2/s), β is the root of the Bassel function

$$\mathrm{MR} = \frac{M_g - M_e}{M_0 - M_e} = \frac{6}{\pi^2}\sum_{n=1}^{\infty}\frac{1}{n^2}\exp\left[-n^2\frac{\pi^2 D_{eff} t}{r^2}\right] \tag{8}$$

where MR is the moisture ratio (dimensionless), M_g is the grain moisture at a specific time (%), M_e is the equilibrium moisture content (%), M_o is the initial moisture content (%), D_{eff} is the effective moisture diffusivity (m^2/s) and r is the radius of cylinder or sphere (m).

Equation 9 expresses the relationship between the effective moisture diffusivity and the mass transfer coefficient [36–38].

$$h_m = \frac{D_{eff}}{d}(2 + 0.552Re^{0.5}Sc^{0.33} \tag{9}$$

where h_m is the mass transfer coefficient, Pr is the Prandtl number, Re is the Reynold number and Sc is the Schmidt number.

The relationship between the mass flow rate of air molecules and the grain drying rate is shown in Eq. 9. This gives the link between the air molecules in the drying system and the grain moisture migration throughout the drying process [30]. Using the Lewis law to define fluid transport in a biological material (Eq. 10), the sensitivity of the moisture content of the grain to time (drying rate) is calculated as illustrated in Eq. 11 [15, 30, 38].

$$\rho_a V_a \frac{dX_a}{dx} = -(1 - \varepsilon_o)\rho_g \frac{dm}{dt} \tag{10}$$

where ρ_a is the density of the air (kg/m^3), V_a is the volume of the air (m^3), ε_o is the void ratio, x is the depth of the drying layer (m), ρ_g is the density of the grain (kg/m^3), dm is the change in moisture content (%) and dt is the change in time (s).

$$\frac{dm}{\partial t} = k\left(M_e - M_0\right)\exp(-kt) \tag{11}$$

M_e is the equilibrium moisture content (%), M_o is the initial moisture content (%), t_g is the specific drying time (s), dm is the change in moisture content (%) and dt is the change in time (s).

During the grain drying process, the air-mass conservation of the drying system is represented in Eq. 12.

$$X_a(x,t) = \frac{\Delta x(1-\varepsilon)\rho_g}{\rho_a V_a} k\left(M_e - M_0\right)\exp(-kt) + X_{a,0} \tag{12}$$

where X_a is the humidity of air (kg/kg dry basis), ε_o is the void ratio, x is the depth of drying layer (m), V_a is the volume of the air (m^3), ρ_a is the density of the air (kg/m^3), ρ_g is the density of the grain (kg/m^3), M_e is the equilibrium moisture content (%), M_o is the initial moisture content (%), t_g is the specific drying time (s) and t_0 is initial drying time (s).

Heat Transfer

The temperature difference between the grain and the immediate surroundings is used to study heat transmission during grain drying. They act as a driving force that monitors heat transfer from a hot (heating) situation to a cooler zone (grain). The modes of heat transmission during grain drying include conduction, convection and radiation [30]. Regardless of the drying system, both conduction and convection modes of heat transfer occur in grain drying. The energy transmission during grain drying is governed by the following phenomena: (1) external heat transfer from the drying chamber to the grain surface via conduction or convention; (2) internal heat transfer within the grain to conduct the necessary energy for the transformation of water into vapour, energy via conduction; (3) internal water is transferred either in liquid or vapour phases by various processes including capillarity for liquid form, and molecular diffusivity for both liquid and vapour phases. Mechanisms are regulated by the gradients of respectively water content and partial vapour pressure as driving forces. (4) External vapour transport from the surface of the grains towards the exit is the principal driving force of dehydration [30, 38]. The internal energy of the grain during the drying process is a function of the amount of heat necessary to increase the temperature of the grain to a specified level and the energy required for the evaporation of moisture from the grain is indicated in Eq. 13.

$$h_c A(T_a - T_g) = m_g C_g \frac{dT_g}{dt} + mL \tag{13}$$

where h_c is the heat transfer coefficient (W/m^{2}K), A is the surface area, L is the latent heat of vaporisation (J/kg), m_g is the mass of the grain (kg), C_g is the specific heat capacity of the grain (Jkg^{-1} K^{-1}), m is the mass of moisture removed from grain (g), T_a is the air temperature (K) and T_g is the grain temperature (K).

The heat transfer rate, which is the most important variable in simulating the space and time-dependence of heat transmission, is defined as shown in Eq. 14–16 for the conductive, convective and radiative modes of heat transfer, respectively [32, 39, 40].

$$q = -kA\frac{dT}{dx} \tag{14}$$

where q_{cond} is the heat transfer rate (W/m^2), A is the surface area of the grain (m^2), k is the thermal conductivity (W/mK), dT is the change in temperature and dx is the change in the drying layer.

$$q = \frac{hC}{x}\left(Re^m Pr^n\right) \tag{15}$$

where q_{conv} is the heat transfer rate (W/m^2), h_c is the heat transfer coefficient (W/m^{2}K), Pr is the Prandtl number, Re is the Reynold number, x is the depth of drying layer (m) and m and n are constant parameters.

$$q = \sigma\varepsilon Af\left(T_s^4 - T_g^4\right) \tag{16}$$

where q_{rad} is the radiative heat transfer rate (W/m^2), σ is the Stefan-Boltzmann constant (5.67×10^{-8} W/m^{2}K^4), A is the surface area of the grain (m^2), f is the shape factor, ε is the emittance of the source of radiation, T_s is the temperature from the source of radiation (K) and T_g is the grain temperature (K).

Energy Efficiency and Energy Consumption

Grain drying is one of the most energy-intensive unit operations during grain processing. According to industrial statistics, the drying process in the developed world accounted for between 10 and 20% of all industrial energy use. The performance efficiency of the dryer hinges on the quality of the dried product and the energy consumption [41]. The energy needed for grain drying is significantly influenced by the latent heat of vaporisation of water, which has a huge energy value (2257 kJ/kg), as well as the sensible heat that must be removed from the dryer. In most conventional dryers, the heat required to raise the temperature of the products and evaporate the moisture is defined in Eq. 17 [23].

$$E_c = m_p c_p \Delta T + m_w c_w \Delta T + m_w L \tag{17}$$

where E_U is the energy required for the grain drying (J), m_p is the mass of the dried grain product (kg), Cp is the specific heat capacity of the dried grain product (kJ/kg), m_w is the mass of the moisture removed from the grain (kg), C_w is the specific heat capacity of the moisture (kg) and L is the latent heat of vaporisation of moisture (kJ/kg).

Furthermore, the projected efficiency of the dryer is significantly reduced by bad dryer design and inadequate insulation [23]. The operating principle underpins the estimation of the energy usage of a grain dryer. According to Eq. 18, the amount of electrical energy used to dry grains relies on the power rating of the heater and the drying duration [42].

$$E_c = 3.6Pt \tag{18}$$

where E is the energy consumption (J), P is the power rating of the heater (kW) and t is the drying time (h). The energy consumption is sometimes estimated based on the specific heat of dry air, mass flow rate and temperature difference as shown in Eq. 19 [43].

$$E = Q_a C_a \Delta T t \tag{19}$$

where Q_a is the airflow rate (m^3/s), C_a is the specific heat (kJ/kg/°C), ΔT is the change in temperature and t is the drying time (h).

In a convective and fluidised hot air dryer, Eq. 20 includes the power rating of the blower in the overall energy usage throughout the drying process [38].

$$E = 3.6\left(P_h + 2.6P_b\right)t \tag{20}$$

where P_h is the rated power of the heating source and P_b is the rated power of the blower. For direct and indirect-fired furnace dryers, burning biomass provides the heat needed for the drying process. Equation 21 defines the thermal energy used by the dryer [38].

$$E = M_b Sb + 2.6P_b t \tag{21}$$

where M_b is the mass of the biomass (kg) and S_b is the calorific value of the biomass (J/kg), P is the power rating of the blower (kW) ($P = 0$ in the direct-fired furnace) and t is the drying time. According to Eq. 22, the energy consumption of steam dryer is determined by the gravimetric characteristics and heating value of the gas (mostly Liquefied petroleum gas (LPG) [42].

$$E = \rho_g V_g HHV \tag{22}$$

Where ρ_a is the density of the gas (kg/m^3), V_g is the volume of the gas and HHV is the heating value of the gas.

Energy efficiency is typically the bedrock for grain dryer performance effectiveness. Energy efficiency measurements can be obtained instantaneously (at a specified time) or cumulatively throughout the drying process. Equation 23 provides a general definition of energy efficiency [44].

$$\eta = \frac{E_u}{E_C} \tag{23}$$

where η is the energy efficiency (%), E_U is the required energy and E_C is the consumed energy.

Other equations have been considered to measure the energy effectiveness of dryers, such as the microwave vacuum dryer, convective solar dryer [45] and hot air dryer [44], which are each depicted in Eqs. 24–26.

$$\eta = \frac{t_d P(1 - m_e)}{M(m_0 - m_e)} \tag{24}$$

where η is the energy efficiency (%), t_d is the drying time, P is the microwave power (kW), M is the mass of the grain (kg), m_0 is the initial moisture content (g/g) and m_e is the final moisture content (g/g).

$$\eta = \frac{E_u}{A_c I_{sr}} \tag{25}$$

where η is the energy efficiency (%), A_c is the area of the solar collector (m^2) and I_{sr} is the intensity of solar radiation (W/m^2).

$$\eta = \frac{T_i - T_o}{T_i - T_W} \tag{26}$$

where η is the energy efficiency (%), T_i is the input temperature (K), T_2 is the output temperature (K) and T_w is the ambient temperature (K).

To determine the performance of the dryer during drying grains, specific moisture extraction rate (SMER), specific energy consumption (SEC) and the energy payback time (EPBT) in Eqs. 27–29 are other important energy-related indicators [36, 46, 47].

$$\text{SMER} = \frac{\lambda}{E} \tag{27}$$

where SMER is the specific moisture extraction (kg/kJ), λ is the mass of moisture removed (kg) and E is the energy consumed (kJ).

$$\text{SEC} = \frac{E}{m} \tag{28}$$

where SEC is the specific energy consumption (kJ/kg$_{\text{mosture}}$ or kJ/kg$_{\text{grains}}$), E is the energy consumed (kJ) and m is the mass of moisture removed or mass of grain (kg).

$$\text{EPBT} = \frac{E_c}{E_{\text{out}}} \tag{29}$$

where EPBT is the energy payback time (years), E_c is the total energy required for producing a dryer (kWh) and E_{out} is the annual energy output of the dryer (kWh).

Table 1 shows the energy performance of recent grain drying studies. There is a dearth of information available regarding the efficiency of other grain dryers over the last 5 years. Most of the studies concerned corn, green peas, paddy and soya beans, with corn and paddy being the most significant. The energy efficiency of convective hot air dryers ranged from 26.52 to 71.75% and 50.30 to 59.80% for corn [44] and paddy [38], respectively. The specific energy

Table 1 Energy performance of recent grain dryers

Grains	Dryer	Drying variable	Energy performance	References
Corn	Fluidised bed	Temperature (40 to 60 °C), Ultrasound power (11.1 to 18.7 kW/m^3), and Frequency (20 to 30 kHz)	SEC: 21.10 to 56.15 MJ/kg$_{H2O}$	Abdoli et al. [46]
Corn	In bin	Temperature (50 to 90 °C) Air flow rate (0.3 to 0.9 kg/m^2), and Initial moisture content (0.21 to 0.30 g/g db)	SMER: 0.19 to 0.227 kg/MJ SEC: 4.4 to 5.3 MJ/ kg$_{H2O}$	Amantea et al. [36]
Corn	Mixed flow	Temperature (40 to 80 °C), and Air velocity (3.0 to 60 m/s)	EE: 26.52 to 71.75%	Mondal et al. [44]
Corn/Soybean	Bin dryer	The energy source (electricity and natural gas (fuel)); and Harvest seasons (2016, 2017, and 2018)	SEC$_{corn}$ = 3.8 to 5.0 MJ/ kg$_{H2O}$ SECsoybean = 5.8 MJ/ kg$_{H2O}$	Epstein et al. [52]
Green pea	Hot air (HAD) Freeze (FD); Infrared (IRD); Microwave (MD); Hot air—Infrared (HA-IR), Hot air—Microwave (HA-MD); Sun (SD)	FD temperature (-50 °C); HA (Temperature, 60 °C, and air velocity, 1 m/s); IR (infrared intensity, 500 W); MW (power, 450 W); SD (Temperature, ~ 25 °C)	SEC (MJ/ kg$_{H2O}$): HAD: 142.73; FD: 254.54; IRD: 47.22; MD: 22.5; HA-IRD: 65.7; HA-MD: 35.26;	Kaveh et al. [48]
Green pea	Hot air-Infrared-rotary	Temperature (40 to 70 °C), infrared intensity (250 to 750 W) and speed (5 to 15 rpm)	SEC:107.49 to 252.6 MJ/ kg$_{H2O}$	Kaveh and Abbaspour-Gilandeh [53]
Paddy	Industrial convective dryer	Temperature (80 to 120 °C) and air velocity (2.86 to 6.41 m/s)	EE: 50.30 to 59.80% and SEC: 14.75 to 29.32 MJ/ kg$_{H2O}$	Islam et al. [38]
Paddy	Infrared	Temperature (30 to 50 °C), infrared intensity (0 to 2000 W/m^2) and tempering ratio (0 to 6)	SEC: 106.1 to 241.5 MJ/ kg$_{H2O}$	Nosrati et al. [49]
Paddy	Microwave	Power (0.4 to 1.0 kW/kg), tempering time (30 to 60 min) and water application rate (30 to 90 mL/10 min)	SEC: 22.43 to 106.84 MJ/ kg$_{H2O}$	Behera and Sutar [50]
Paddy	Mixed flow	Temperature (45 °C) and air velocity (5.0 m/s)	SEC: 4.14 MJ/ kg$_{H2O}$	Mondal et al. [51]
Parboiled rice	Coaxial two-impingement stream drying	Temperature (150 to 190 °C); air velocity (15 to 25 m/s), feed rate (80 to 250 kg$_{dry\ solid}$/h) and exhaust air cycle (0 to 80%)	SEC: 4 MJ/ kg$_{H2O}$	Thuwapanichayanan et al. [40]
Soybean	Direct-fired furnace	Drying mode (intermittent and continuous)	SEC: 11.87 MJ/ kg$_{H2O}$	Quequeto et al. [22]
Soybean	Fixed bed	Drying mode (intermittent and continuous)	SEC: 453 to 971 kJ/ kg$_{H2O}$	Defendi et al. [54]

EE is the energy efficiency, *SEC* is the specific energy consumption, *SMER* is the specific moisture extraction ratio, *EE* is the energy efficiency consumption in convective bin drying of corn ranged from 4.4 to 5.3 MJ/ kg_{H20} [36] and a higher value was reported for fluidised dryers [46]. In convective hot air drying of green peas, the specific energy consumption was 142.73 MJ/kg_{H20}. The combination of infrared and microwave heating with the hot air-drying method reduced the SEC by 54.3% and 75.3%, respectively [48]. The significant reduction in the SEC was accredited to the pronounced reduction in the drying time by the combined methods. In contrast, the infrared [49] and microwave dryer [50] had a higher SEC compared to the convective drying for the paddy [38, 51].

Grain Drying Technology

There are many types of grain drying technology, and the choice of drying technology in the grain processing industries depends on moisture removal, energy consumption, time-saving and nutrient retention. Incomplete and over-drying of grain are detrimental to grain nutrient retention [44, 51]. The critical moisture content level of dried grain is presented in Table 2. When the final moisture content of the dried grain is higher than the range of critical moisture levels, the grain drying process is incomplete. Therefore, the dried grain is susceptible to mould growth, insect infestation and high-quality deterioration [55–57]. The dried grains with lesser moisture content compared to the range of critical moisture content levels are overdried and the grains are liable to lose their nutritional value and germination potential [58, 16].

Cereal Drying

The application of different drying technologies for the reduction of moisture of cereal grain over the last 5 years is summarised in Table 3. The three main drying methods used for drying cereals are thin layer, deep bed and continuous flow drying methods. The analysed cereals in this study include barley, corn, germinated brown rice, millet, paddy, sorghum and wheat.

Barley/Sorghum/Millet

From Table 3, barley, sorghum and millet were dried in a fluidised bed dryer. The moisture content of the grains reduced the moisture content of the grains to < 10%db in ~ 33 min. The region in which drying took place in the fluidised bed dryer was referred to as the zone of desorption. It indicated the maximum altitude at which the heated inflow gas in the dryer became saturated. At this point, the heated gas could not remove moisture from the grains. The zone of desorption varied with the type of grain (maximum of 140 mm for barley, 110 to 150 for sorghum, 212 for millet). It therefore determines the capacity and height of the dryer. Other factors that were significantly correlated to the zone of desorption and moisture removal capacity of the dryer included the inflow temperature, mass flow rate and saturation temperature of the gas [61]. In a continuous belt dryer with variable heat supply, the drying kinetics of barley was studied based on the temperature distribution in the grain layer and the allowable range of thermal-humidity conditions. The dryer was constructed with a changeable grain layer height in the drying chambers and a particular grain load per gas distribution and this allowed homogeneous grain drying energy use. The grain moisture content was reduced by the drying system from about 22% after harvesting to ~ 13% [62].

Table 2 Optimal range of moisture content level for dried grains

S/N	Grain	Minimum acceptable moisture content level for dried grain (%)	Maximum acceptable moisture content level for dried grain (%)
1	Barley	8.0	13.0
2	Corn	8.0	13.5
3	Millet	11.0	16.0
4	Sorghum	9.0	13.5
5	Wheat	9.5	13.5
6	Oat	4.5	9.0
7	Paddy	9.0	15.0
8	Rice	8.5	13.0
9	Peas	8.5	17.0
10	Beans	8.0	15.0
11	Rapeseed	5.0	10.0
12	soybeans	7.5	15.0
13	Groundnut/peanut	4.5	7
14	Copra	4.5	7

FAO [59]; ASAE D245.7 [19]; Kumar and Sharma [60]

Table 3 Summary of different drying technologies for the cereals

Cereal	Methods	Drying system	Drying condition	Model/Simulation	FMC	Findings	References
Barley/Millet/ Sorghum/	Continuous flow	Fluidised bed dryer	Amaranth: T = 58.0 to 68.8 °C Millet: T = 40 to 69 °C Sorghum: T = 40 to 70 °C Barley: T = 39.3 to 60.5 °C	Numerical Method	< 10% db	The height of desorption in which drying gas approaches the adiabatic saturation temperature varied around the constant height of the bed The height of desorption is an important factor that determines the height of the dryer	Szabo and Poos [61]
Barley	Continuous flow	Belt type dryer	T = 55 to 65 °C	Empirical model	12.3 to 13.5%wb	The moisture content of the grain was reduced to the final level (~ 13%) in 60 min. The changeable grain layer allowed the homogenous use of drying energy	Ostrikov et al. [62]
Corn	Thin layer	In-field drying	Ambient	GAB model	20 to 25%WB	The ecological region affects the equilibrium moisture content and significantly contributes to the drying time of the grain	Gao et al. [37]
Corn	Continuous flow	Fluidised bed dryer	US treatment = 11.1 to 18.7 kW/m^3 T = 40, 50, and 60 °C	ANN/ANOVA	16 ± 0.5%db	The application of ultrasound treatment reduces the drying time by 43%	Abdoli et al. [46]
Corn	Continuous flow	Mixed—Flow dryer	T = 40 to 80 °C V = 3.0 to 6.0 m/s	RSM	12%wb	The drying temperature increases energy utilisation and exergy improvement potential	Mondal et al. [44]

Table 3 (continued)

Cereal	Methods	Drying system	Drying condition	Model/Simulation	FMC	Findings	References
Corn	Deep bed	Tower-type dryer	T = 130 °C V = 1 to 3 m/s		10%	The velocity effectively improves the drying rate of the Grain until 23% of the moisture was removed in the first 50 min	Celik et al. [63]
Corn	Deep bed	On-farm bin dryer	Energy sources = electricity, and natural gas (fuel) Harvest seasons = 2016, 2017 and 2018	Numerical method		The low-temperature drying using electricity is cost intensive compared to high-temperature drying powered by gas but reduce greenhouse gas emission by up to 90%	Epstein et al. [52]
Corn	Deep bed	Heat pump dryer (HPD)/ Fluidised bed dryer (FBD)	HPD: T = 40 °C; V = 1.8 m/s FBD: T = 53 °C; V = 2.3 m/s	Numerical method	HP: 10%db FB: 12.3%db	In 80 min, the dryer reduced the moisture content of the grain to an equilibrium point	Rudobashta and Zueva [64]
Corn	Deep bed	In-bin dryer	T = 50 to 90 °C Flow rate = 0.3 to 0.9 kg/(m^2s) IMC = 21–30%db	FEM	12%db	The factors (temperature and flow rate) significantly affect the energy and exergy performance of the dryer except for the initial moisture content	Amantea et al. [36]
Corn	Thin layer	Laboratory oven	T = 40 to 80 °C	Empirical model	8.7%wb	The increase in drying temperature significantly affects the cell tissue and reduces the fat, starch and ethanol yield of the grains	Coradi et al. [65]
Corn	Thin layer	Microwave dryer	T = 40 to 60 °C Power: 0 to 1.2 W/g	MMF model	12%wb	microwave power (0.6 W/g) reduces the drying time from 12 h 35 min to 5 h with reduced impact on the grain's physical properties	De Faria et al. [66]

Table 3 (continued)

Cereal	Methods	Drying system	Drying condition	Model/Simulation	FMC	Findings	References
Corn	Thin layer	Open-air sun drying	Ambient	–	12.7 ± 1.1%wb	The open-air sun drying of corn cost US$ 2.46/tonne/%moisture	De Groote et al. [67]
Corn	Thin layer	Microwave Dryer	Power = 700 W	FEM	< 10%wb	The absorption of microwave energy is reduced with low dielectric properties and leads to low temperature and evaporation rate	Zhou et al. [68]
Germinated brown rice	Continuous flow	Microwave dryer	V = 0 to 2.0 m/s Drying time/pass = 2 to 10 min Layer thickness = 4 to 14 cm Power Intensity = 1 to 5 W/g	FEM/ANOVA	10.3 to 14%wb	2 W/g microwave power, 1.0 to 1.5 m/s velocity, 6 min drying pass and 8 mm thickness gave the optimal drying performance (highest utilisation efficiency of microwave energy)	Wang et al. [77]
Germinated brown rice	Continuous flow	Microwave dryer	V = 0 to 2 m/s Power intensity = 1 to 5 W/g Drying time/pass = 2 to 10 min	FEM	17 to 18%wb	2 W/g microwave power, 1.0–1.5 m/s velocity, 6 min drying pass and 8 mm thickness gave the most suitable physical properties (fissure degree and formation of golden yellow)	Shen et al. [39]
Germinated brown rice	Continuous flow	Fluidised bed dryer	T = 130 to 150 °C	ANOVA	18.2 to 22.6%wb	High temperature (130 °C) and grain depth improve the head brown rice yield, and hardness of the cooked and reduce the stickiness The dryer energy consumption of 1.13 MJ/kg and costs 0.17 USD/kg respectively	Mitsiri et al. [42]

Table 3 (continued)

Cereal	Methods	Drying system	Drying condition	Model/Simulation	FMC	Findings	References
Brown rice kernel	Thin layer	Hot air dryer	T = 40 to 80 °C V = 3 and 6 m/s	–	–	The effect of air velocity on the drying kinetic is minimal compared to the air temperature	Zhao et al. [32]
Grain	Thin layer	Solar grain dryer	Orifice diameter = 10 to 15 cm T = 77 °C	FEM	–	Inlet orifice size has a higher impact on the heat transfer in the dryer and leads to higher temperature distribution in the drying chamber	Chavan et al. [69]
Paddy	Continuous flow	Mixed flow dryer	T = 45 °C V = 5.0 m/s	ANOVA	12%wb	The specific electrical and thermal consumed for the reduction of grain moisture content from 25 to 12% were 0.97 and 3.17 MJ/ kg_{H2O}	Mondal et al. [51]
Paddy	Continuous flow	Convective dryer	T = 40 to 90 °C RH = 40 to 95%	BPNN	14 to 14.5%wb	The BPNN significantly reduces the controller error by 75.4% during the drying process	Jin et al. [70]
Paddy	Continuous flow	Bed dryer	T = 40 to 60 °C Bed Condition = Fixed and Fluidised	ANOVA	18.0 to 21.3%wb	90% of the grain moisture content was removed in the first 30 min of the drying process A fluidised bed with dehumidification had a positive effect on the moisture removal from the grain	Luthra and Sadaka [71]
Paddy	Deep bed	Industrial LSU dryer	T = 40 to 120 °C V = 2.86 to 6.41 m/s	–	< 10%db	The dryer requires 7 to 10 h to reduce the moisture content of the grain from 14% The capital productivity is affected by the drying temperature, relative humidity, feeding rate and processing time	Islam et al. [38]

Table 3 (continued)

Cereal	Methods	Drying system	Drying condition	Model/Simulation	FMC	Findings	References
Paddy	Deep bed	Bin drying	–	FEM		The fan control was responsible for the drying rate	Atungulu et al. [72]
Paddy	Deep bed/ Continuous flow	Superheated steam dryer (SSD) Hot air dryer (HAD) Fluidised bed dryer (FEB)	SS: T = 160 °C HAD: T = 50 °C FBD: T = 80 °C	ANOVA	8.1 to 13.7%wb	Hot water soaking and multistage intermittent drying methods reduce the hardness of the rice sample by 20% to 33%	Jittanit and Angkaew [73]
Paddy	Thin layer	Microwave rotary drum dryer	Power intensity = 0.25 to 1 kW/kg	Empirical model/ Optimisation	12 ± 1%wb	The optimal condition for an effective drying process was 1 W/g, 60 min, and 90 mL/10 min for power density, treatment time and water application rate respectively	Behera and Sutar [50]
Paddy	Thin layer	Hot air dryer	T = 60 °C Drying time = 20 to 60 min	ANOVA	14%wb	For an effective drying process, the optimal conditions were 160 to 200 min of tempering after 40 min drying	Ghasemi et al. [74]
Paddy	Thin layer	Infrared dryer	Wavelength = 2.58 μm	FEM	15 to 23%db	The highest moisture content and stress remain on the surface of the grain for 110 s during the drying process	Jiazheng et al. [75]
Parboiled rice	Continuous flow	Coaxial two-impinging stream dryer	T = 150 to 190 °C V = 15 to 25 m/s Feed rate = 80 to 250 kg dry solid/h Exhaust air recycle = 0 to 80%	Energy and mass balance	22 to 25%db	Drying at a lower temperature, higher velocity and feed rate consumed more energy Exhaust air recycling reduces specific energy consumption by 40 to 45%	Thuwapanichayanan et al. [40]

Table 3 (continued)

Cereal	Methods	Drying system	Drying condition	Model/Simulation	FMC	Findings	References
Wheat	Deep bed	Fixed bed dryer	T = 43.35 to 87.75 °C	Numerical method	< 20%wb	The effective moisture diffusivity and activation energy of the grain is 9.51 × 10–12 with 31.78 kJ/mol respectively	De-Mattos et al. [76]
Wheat	Thin layer	Oven drying	IMC = 74.9 to 71.6%	Distribution fitting	23.1 to 25.0%wb	The moisture in the grain is not uniformly distributed The moisture in the endosperm is the lowest and that of the embryo is higher	Hu et al. [29]
Wheat	Thin layer	Oven drying	T = 60 to 80 °C	–	10%wb	The grain drying process of grain is affected by temperature, initial moisture content and the proportion of the water components (Free water, Weakly bonded, cell wall, extracellular, and strongly bonded water) in grain	Jia et al. [28]

T is drying temperature, *RH* is relative humidity, *V* is air velocity, *ANN* is an artificial neural network, *BPNN* is the backward propagation neural network, *ANOVA* is an analysis of variance, *RSM* is response surface methodology, *FMC* is the final moisture content and *FEM* is finite element method

Corn

The effective drying of corn in recent years has been achieved using convective drying (mixed-flow dryer, laboratory oven, open-air sun drying), microwave dryer, microwave vacuum dryer, fluidised bed dryer and heat pump dryer. Recently, corn drying gained the most attention and covers ~ 35% of the drying studies on cereal in the last 5 years (Table 3). In the convective dryer, temperature and air velocity are correlated to the moisture reduction of corn. The moisture content of corn was reduced from 22 to 10%wb and this took roughly 80 min of drying time. The small quantity of corn and continuous increase in temperature was reported as the main reason for the shorter drying time in a laboratory-scale tower dryer [63]. The drying air temperature had the greatest impact on the starch content and ethanol output of corn grains during processing [65]. The first and second principles of thermodynamics were used to optimise cereal (corn) grain dryers using transient spatial–temporal analysis. A time-adaptive radial basis function was used to solve the models. Comprehensive sensitivity analysis revealed that the incumbent moisture content and air velocity affect the quantitative temporal profiles of the output air temperature, moisture content, integrated energy and exergy efficiency. The exergy recovery of the dryer was highly related to high drying temperatures (The most essential factor) and faster drying times. The specific moisture extraction rate was suitable for designing in-bin or low-temperature dryers in terms of applicability [36].

The total drying time of corn grain was 12 h and 35 min in a convection dryer under a dried air temperature of 40 °C [66]. In microwave drying, the drying time was reduced to 5 h under a microwave intensity of 0.6 W/g. Microwave drying under 0.6 W/g had no significant effect on the colour and size of dried corn compared to convective drying. A lower drying time (< 70 min) was achieved with a 60 °C air temperature and a microwave intensity of 1.2 W/g but the colour and size were compromised [66]. The microwave drying of corn via heat transfer through a porous and double-porous medium was modelled using the three-dimensional electromagnetic model. The geometry considered the entire microwave oven, with pilled corn serving as an example of double porous media. The installation of an active pellet bed was an added advantage for the modelling of microwave drying of pilled corn monitored with computer vision techniques as shown in Fig. 3. The double-porous model outperformed the porous model in terms of accuracy [68].

In a fluidised bed-shelled core dryer, the drying time, moisture content, specific energy consumption and quality characteristics such as ultimate compressive strength, toughness, shrinkage and colour of corn kernels were investigated. The drying factors were used to forecast characteristics using artificial neural network (ANN) simulation model, and the colour and shrinkage were assessed using non-destructive techniques (machine vision). Lower-frequency ultrasound demonstrated better penetration at lower temperatures resulting in a considerable decrease in drying time. The use of ultrasound lowered the final compressive strength and the specific energy consumption of the drying process. The dried corn was toughened, and this played a key role in shrinkage and colour change, the developed ANN model made good predictions [46].

Germinated Brown Rice

Hot air, microwave and a fluidised bed dryer have been recently employed drying technologies for the drying of germinated brown rice. In the last 5 years, germinated brown rice has occupied ~ 9% of the selected drying studies on cereal (Table 3). In a hot air dryer, a three-dimensional body model was fitted into the geometry of the brown rice kernel using image processing techniques. The hot air temperature was identified as the single most important element influencing the brown rice drying process. In the modelling of the drying process, the largest difference between

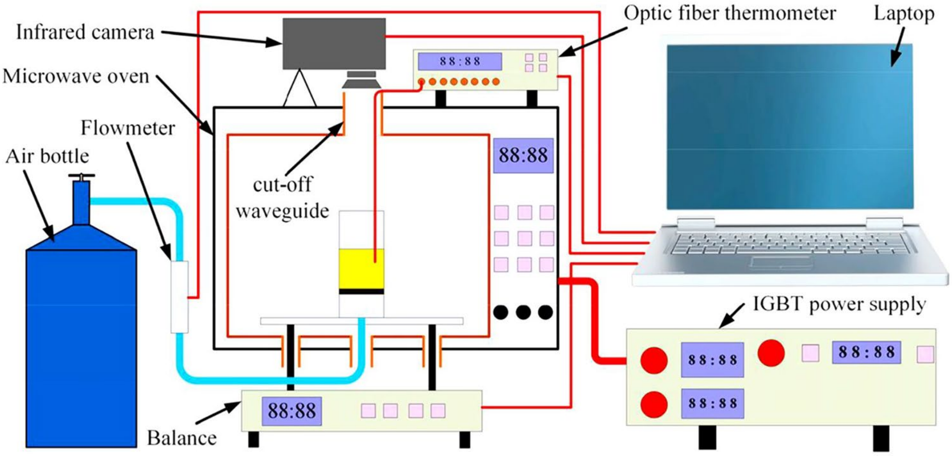


Fig. 3 Setup of microwave drying of pilled corn monitored with computer vision technique [68]

the simulated and the experimental data was roughly 8% during the drying process at 40 °C. The temperature difference in the rice kernel only lasted a few minutes during the early drying time [32]. In the continuous fluidised bed dryer, a drying temperature of around 130 °C was determined to be the most efficient and cost-effective drying condition for paddy when compared to the conventional approach. The energy consumption of the dryer at the optimal temperature was 1.13 MJ/kg and the operating cost was 0.17 USD/kg. The gelatinisation, head brown rice output and hardness of the cooked germinated brown rice were satisfactory [42].

The microwave (1 to 3 W/g) drying properties of germinated brown rice were investigated using a continuous belt microwave dryer (Fig. 4). To simulate moisture evaporation, the microwave energy was transformed into thermal energy within the layer of germinated brown rice during the early drying time. The microwave intensity was proportional to the grain temperature and the moisture removal from the germinated brown rice. The overall energy usage of the microwave dryer was strongly dependent on the drying time, grain temperature and microwave intensity. An increase in the end temperature of the dried germinated brown rice signified higher microwave energy consumption. A decrease in the drying time of brown rice indicates less microwave energy input and lower thermal consumption. The temperature transmission pattern of the germinated brown rice layer was in the order of rising >> constant >> re-rising stages for all the microwave intensities [77].

Paddy

Convective hot air dryers (mixed flow dryers, hot air dryers, industrial LSU dryers and in-bin dryers), fixed bed dryers, fluidised bed dryers, microwave rotary drum dryers and infrared dryers were the drying technologies employed for the moisture removal from paddy in the last five years. Paddy drying is the second most studied cereal after corn, and it covers ~ 27% of the drying studies concerning cereal (Table 3). The convective hot air dryer was the most commonly used. Three drying parameters, namely temperature, air velocity and relative humidity, were reported as the factors that influenced moisture removal in the convective dryer [38, 51, 70, 74]. In 7 h, the industrial paddy dryer at Louisiana State University (LSU) reduced the moisture content of the paddy to 14%wb. The specific electrical and thermal energy of the industrial LSU dryer ranged from 0.34 to 0.51 and 14.41 to 28.81 MJ/kg respectively. The drying efficiency and exergy efficiency of the dryer increased from 50.30 to 59.80% and 43.63 to 67.21% respectively with an increase in the air outflow [38]. The fluidised bed and fixed bed dryers with desiccant (silica gel) and dehumidifier (Fig. 5) improved the rate of moisture removal in paddy. About 87% to 90% of the moisture was eliminated within 30 min of starting the drying process. The moisture removal of the fluidised bed was 15% greater than the fixed bed at 60 °C without dehumidification [71].

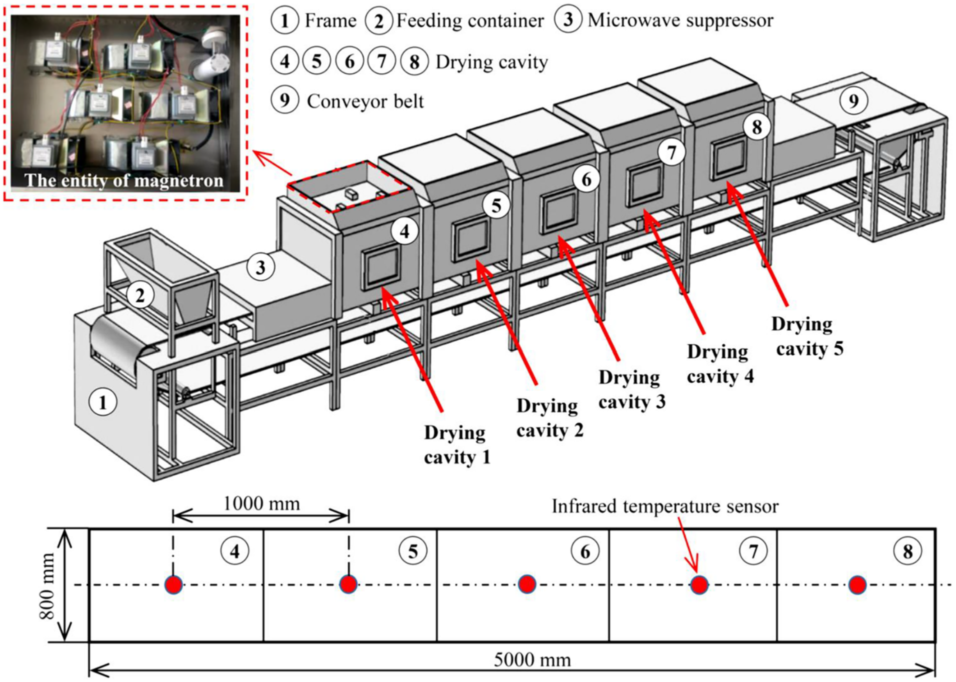


Fig. 4 Continuous belt-microwave dryer [39, 77]

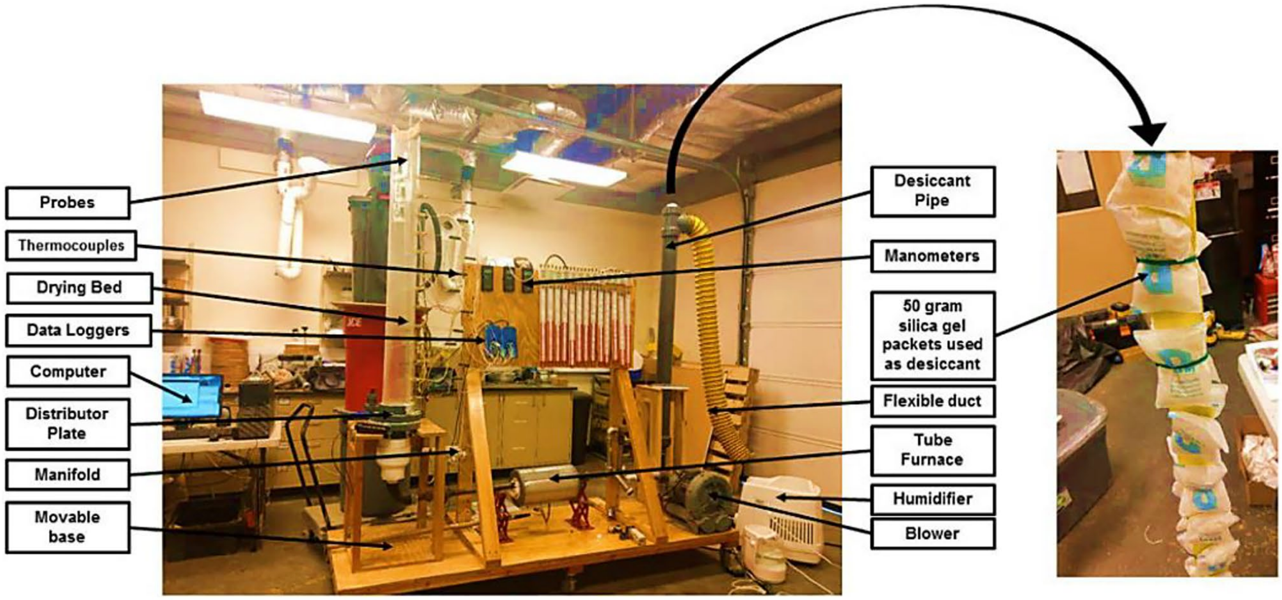


Fig. 5 Fluidised bed dryer with dehumidifier and desiccant [71]

The modelling and simulation of the drying process of paddy were carried out using neural networks and numerical methods in recent years. For the neural network, the working mechanism of a continuous grain dryer and the principle of grain drying (heat and mass transfer mechanism) were modelled. The model used a backward propagation neural network (BPNN). According to the BPNN, the moisture content of the dried grain was mostly affected by the pace at which the dryer discharged the grain. The developed neural network model effectively regulated the grain dryer performance by considering the nonlinearity, robust coupling and hysteresis of the parameters utilised in defining the grain drying process, which makes it a precise management of the drying system challenges. The comparison of the experimental findings with the analysis from the BPNN intelligent control system demonstrated that the produced intelligence had the benefit of higher stability and noise management [70].

In a thin infrared layer, the drying process of rice was simplified based on infinity and zero penetration depth models and the impact of penetration on the drying parameters of the dried rice kernel. Both models successfully forecast the temperature and moisture content (MC) of the brown rice during drying. This was due to the highest temperature difference across the rice kernel in both models being consistently less than 15 °C and thermal stresses caused by nonuniform temperature was not significant. Changes in temperature and moisture throughout the drying process induced stress on the grain on the surface of the endosperm and the middle of the grain. The highest MC in the endosperm was found near its surface, where it reached 190 m^{-1} at 110 s, and the maximum stress was found at the same location, where it hit 7 MPa at 160 s a few seconds later [75].

The head rice yield (HRY), strength and appearance (colour and size) are the commonly used parameters for quantifying dried paddy quality and a few studies have addressed nutrient retention of the dried paddy. The appearance of the paddy tends to diminish due to hot air drying at a high temperature of 80 °C in an attempt to shorten the drying time [78]. The head rice yield of dried paddy in a mixed-flow dryer varied from 50 to 54% respectively. This was posed as a positive prospect of quality improvement of the dried product and improvement in the energetic and exergies response of the dryer [38]. The humidified hot air produced better quality dried paddy (greater HRY and a lower number of white belly grains) than the hot air in the fluidised bed dryer [79]. The milling quality and hardness of the paddy were improved by 38.76 to 55.19% and 20 to 33% under hot air or fluidised bed drying by replacing the conventional parboiling treatment with a superheated steam treatment [73]. Using zero dehumidification improved the whiteness of milled paddy under a fluidised bed dryer at 60 °C. Dehumidification gave a high head rice yield of 64.6% in the fluidised bed dryer at 40 °C, whereas zero dehumidification gave a higher head rice yield (HRY = 66.7%) in fixed bed drying [71].

Wheat

Convective and fixed bed dryers have been recently used for the drying of wheat in the last 5 years. Wheat drying occupies ~ 9% of the recent drying studies of cereal. In convective drying, low-field nuclear-magnetic-resonance (LF-NMR) relaxation time measurements were used to track the moisture content of wheat during drying. The surface water was the dominant source of water loss during the first drying phase. Water flowed in both directions between the components. Water migration was also influenced by the wheat moisture content and the proportions of the five water components. In addition, the high temperature was to produce a high drying rate throughout the drying process. Using a thermal oscillatory method with an early drying temperature of 80 °C and then switching to 70 °C reduced the heat consumption by 4.81% while increasing the drying time by 9.61% [28].

For the fixed bed dryer, a robust model based on Fick's law was built for the drying of wheat grains. The model worked for temperatures ranging from 17 to 87 °C with ultimate moisture concentrations of 10 to 25% db. When compared to the more stringent model, ignoring internal temperature gradients, exterior mass transfer resistance, and the difference between grain and air temperature saved 18% of execution time. However, simulations using a simpler model that merely used the average moisture content of the grain gave a lower drying rate (De-Mattos et al. 2020).

Legume Drying

The recent drying methods and technologies applied for the safe drying process of legumes are summarised in Table 4. The table depicts the method used for the drying process as well as the simulation and modelling techniques that were adopted for the proper understanding of the intrinsic behaviour of legume grains during the drying process. The analysed legumes include broad beans, red kidney beans, chickpeas and green peas.

Beans

Vacuum and hot air dryers are the recent drying technologies applied for bean drying. Approximately 42% of the drying studies on legumes focused on bean drying over the last 5 years. In the vacuum dryer, the vacuum pressure and the low temperature are highly correlated with the moisture content of the dried bean grains. The cellular-level morphological alterations of broad bean seeds during dehydration in a low-temperature vacuum dryer in Fig. 6 was analysed using an SEM-based approach. The cell size and shape distribution of the seeds was significantly altered with the dehydration duration and moisture content. During dehydration, the overall change in cell size and distribution at 8 °C was more uniform. Higher temperatures induced higher contraction in more cells, due to cell rupture. Smaller cells were less prone to shrinkage and distortion during dehydration. A strong correlation of 0.96 was observed between moisture loss and shrinkage [85]. The effect of diffusion on the seed structure during the drying process at a low temperature and vacuum pressure was observed in the experiment. The drying period was decreased, and the drying rate was improved when the temperature and vacuum degree was raised from 0 to 8 °C and 95 to 99 kPa respectively. Lowering the thickness of the beans, the vacuum degree had a significant impact on the shrinkage, with an equilibrium moisture content of 5 to 11%, and the effective moisture diffusivity varies from 0.65 to 2.97×10^{-10} m^2 [35]. Also considered were the shrinkage and irregular shapes in the 3D finite element of red kidney beans under different drying conditions. The relationships between the transient heat and mass transfer coefficients, transient water diffusivity, temperature and moisture content were estimated. It was discovered that there was a strong relationship between the transient heat and mass transfer coefficients, moisture diffusivity and ratio coefficients. The Lewis number was 27, and the ratio of transient heat over mass transfer coefficient at 30 and 40 °C was 10,765 Jm^3/K and 10,729 Jm^3/K at 50 °C [87].

Static and dynamic methods were used to investigate the sorption isotherms and the drying characteristics of red kidney beans. Sorption was observed at 10 to 60 °C temperature and 32 to 91% relative humidity (RH). The drying characteristics were investigated using a thin layer dryer with an air temperature of 30 to 50 °C and RH of 35 to 50%. The modified Chung-Pfost and modified Guggeheim-Anderson-deBoer (GAB) equation provided the best fit for the sorption isotherms. The Henderson and Pabis model, as well as the page model, provided the best fit for the thin layer drying data [34].

Pea

In pea drying, the drying system such as hot air, fluidised bed, microwave, infrared, freeze, hot air + microwave and hot air + infrared dryer was used in the last 5 years. Pea drying has recently gained the most attention and covers ~ 58% of the total drying studies on the legume. In a convective dryer, the greenness of the pea decreased with increased drying temperature. The relative crystallinity decreased from 23 at 50 °C to 19% at 70 °C. Conversely, as the drying temperature was raised, the in vitro digestibility of both carbohydrates and protein in the green pea flour increased. The protein was denaturalised, and its digestibility rose from 76.26% at 50 °C to 85.87% at 70 °C [81]. In the fluidised bed dryer, the shrinkage of the peas in real-time and offline mode was tracked using computer vision (Fig. 7) during the drying process. The method recognised and analysed only seeds that were built to compute the average area, perimeter and diameter at precise intervals during the drying process. The offline approach indicated a continuous increase in shrinkage. The output of the real-time shrinkage curve in the first 15 min was highly similar to those of the offline curves. A high deviation was recorded between the two methods during the later drying time [80].

Table 4 Summary of different drying technologies for the peas and beans

Legumes	Drying method	Drying system	Drying conditions	Model/Simulation	FMC	Findings	Reference
Green peas	Continuous flow	Fluidised bed dryer	T = 50 to 60 °C	–	24%wb	The initial area of grains reduced by 65% in the first 30 min of drying	Iheonye et al. [80]
Green peas	Thin layer	Hot air dryer	V = 15 m/s T = 50 to 70 °C	Empirical model/ANOVA	5%wb	The increase in the temperature from 50 to 70 °C significantly reduced the relative crystallinity from 23 to 19% The rapid digestibility of starch and protein digestibility increased with the temperature from 15.94 to 36.48% and 76.26 to 85.87% respectively	Gonzalez et al. [81]
Green peas	Thin layer	Freeze Dryer (FD) Hot-air dryer (HAD) Infrared dryer (IRD) Microwave dryer (MWD) Sun-drying (SD) Hybrid (HAD–IRD) Hybrid (HAD–MWD)	FD: T = -50 °C HAD: T = 1 m/s, 70 °C MWD: 450 W SD: T = ~ 25 °C	Empirical model/ANOVA	12%wb	The microwave dryer had the lowest specific energy consumption. The freeze dryer had the lowest change in the colour of the green pea	Kaveh et al. [48]
Green peas	Thin layer	Hot-air infrared-assisted dryer (HAD)	T = 30 to 50 °C IR intensity = 0 to 0.6 W/cm^2 V = 0.5 to 1.5 m/s	FEM	< 25%wb	The effective moisture diffusivity was a factor that defined the accuracy of the drying process simulation and ranged between 1.39×10^{-10} to 5.72×10^{-10} m^2 s^{-1}	Zare et al. [82]
Green peas	Thin layer	Heat pump dryer	T = 30 to 50 °C US treatment: 28 kHz + 60 W, 28 kHz + 100 W, 40 kHz + 60 W	Empirical model	5.32 to 8.80%wb	The ultrasound application reduced the drying time by ~ 3.8 to 14.6% and increased the effective moisture diffusivity by ~ 45.5 to 46.7%	Yang et al. [83]
Pea/Chickpea	Thin layer	Hot air dryer	T = 30 to 50 °C	–	–	High temperatures preserved the starch in chickpeas (68.58%) and peas (61.99%)	Yu et al. [84]
Broad beans	Thin layer	Vacuum dryer	T = 0 to 8 °C Pressure = 97 kPa	Empirical model	11 to 14%wb	The distribution of the cellular morphology (varied continuously with drying time and temperature	Zhang et al. [85]

Table 4 (continued)

Legumes	Drying method	Drying system	Drying conditions	Model/Simulation	FMC	Findings	Reference
Broad beans	Thin layer	Vacuum dryer	T = 0 to 8 °C Pressure = 95 to 99 kPa	–	5 to 11%wb	The effective moisture content ranged between 0.65×10^{-10} to 2.97×10^{-10} m^2 s^{-1} The shrinkage of the grain increased by 10.9% with the increase in the vacuum pressure from 95 to 99 kPa	Wang et al. [77]
Green soybean	Thin layer	Microwave vacuum dryer (MVD) Pulse-spouted microwave vacuum dryer (PSMVD) Pulse-spouted microwave dryer (PSMD) Microwave freeze (MFD)	MVD: Power = 800 W Vacuum pressure = 0.09 MPa PSMVD: Power = 800 W Vacuum pressure = 0.09 MPa Pulsed spouted time = 60 s PSMD: Power = 800 W Chamber pressure = 0.1 to 0.12 MPa Pulsed spouted time = 60 s MFD: T = -45 °C Power = 0.1 to 0.6 kW Vacuum pressure = 0.09 MPa		5%wb	Microwave freeze drying had the least colour change but the longest drying time (> 800 min) The PSMD had the fastest drying rate with a drying time of 220 min	Cao et al. [86]
Red kidney	Thin layer	Hot air dryer	T = 30 to 50 °C RH = 35 to 50%	FEM	< 10%wb	The ratio of the transient heat to mass transfer ranged from 10.73 to 10.77 kJm^{-3} k^{-1} under the temperature of 30 to 50 °C Transient water diffusivity has a low correlation with the grain shrinkage	Jian and Jayas [87]
Red kidney	Thin layer	Hot air dryer	T = 30 to 50 °C RH = 35 to 50%	Empirical model	< 10%wb	The drying rate of the grain depended on the migration of the moisture from the internal parts to the surface of the grain after the initial surface water was removed in 1 h	Jian and Jayas [34]

T is drying temperature, *RH* is relative humidity, *V* is air velocity, *ANN* is an artificial neural network, *ANOVA* is an analysis of variance, *FMC* is the final moisture content and *FEM* is the finite element method

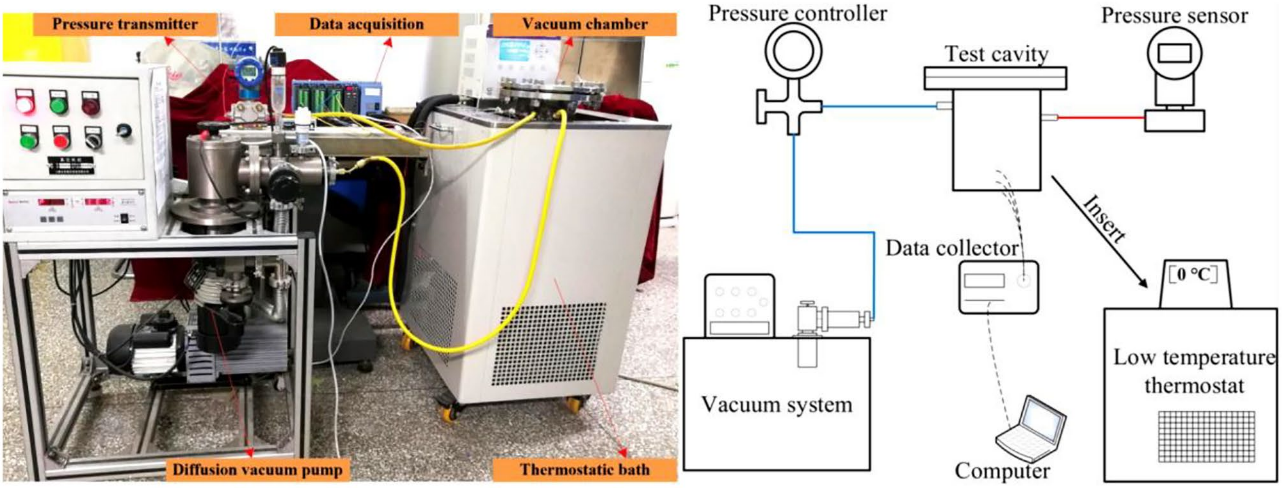


Fig. 6 Low-temperature vacuum dryer [35, 85]

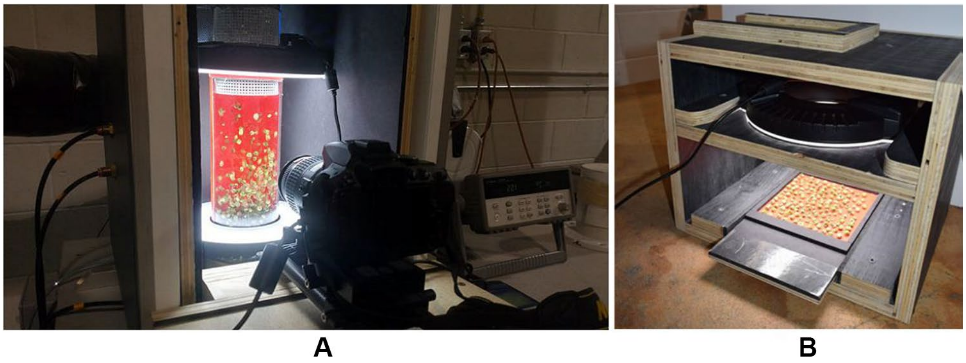
Two treatments, namely cooking and ultrasound treatment, have been noted as the recent methods of improving the drying process of peas. The cooking was correlated with the glycaemic indices (GI) digestible starch (RDS), slowly digested starch (SDS), and resistant starch (RS) of pea and chickpea grains. The combination of high-temperature cooking and drying kept the starch in the peas and chickpeas at 68.58% and 61.99% of dry matter, respectively, with increased RDS and reduced RS. The GI of The HCHD peas (59.02) and chickpeas (49.15) were significantly higher than those processed by low-temperature cooking and drying (peas: 32.63; chickpeas: 31.91) [84]. The drying temperature and ultrasound power + frequency in an ultrasonic-assisted heat pump dyer (Fig. 8) were examined for the drying kinetics and the germination index of pea seed. The drying kinetics of pea seed was improved by using high temperature and ultrasound treatment which reduced the drying time and increased the diffusion coefficient from 3.5×10^{-11} to 57×10^{-11} m^2/s. The page model had the most potential for modelling the drying curve under a variety of experimental settings. The use of high ultrasonic power increased the germination percentage and index, as well as gave a reduction in the mean germination time of the seed [83].

Comparing the drying kinetics of the green pea under the sun, hot air, freeze and microwave drying to the hybrid drying technology (hot air + microwave and hot air + infrared), the page model had the best performance in predicting the drying kinetics of the green pea. The HA-MW and FD techniques yielded the fastest and slowest drying period respectively [48]. The drying behaviour of green peas in the combined infrared and hot-air dryer was forecast using the finite element method (FEM). The developed mathematical model produced a predicted average moisture content that was reasonably close to the experimental data with a low error value: RMSE = 2.18 and MAPE = 5.08% [82].

Oil Seed Drying

The primary purpose of drying the oilseed was to reduce the moisture content to a specific level and enhance the oil yield

Fig. 7 Fluidised grain measurement using machine vision **A** real-time **B** offline [80]



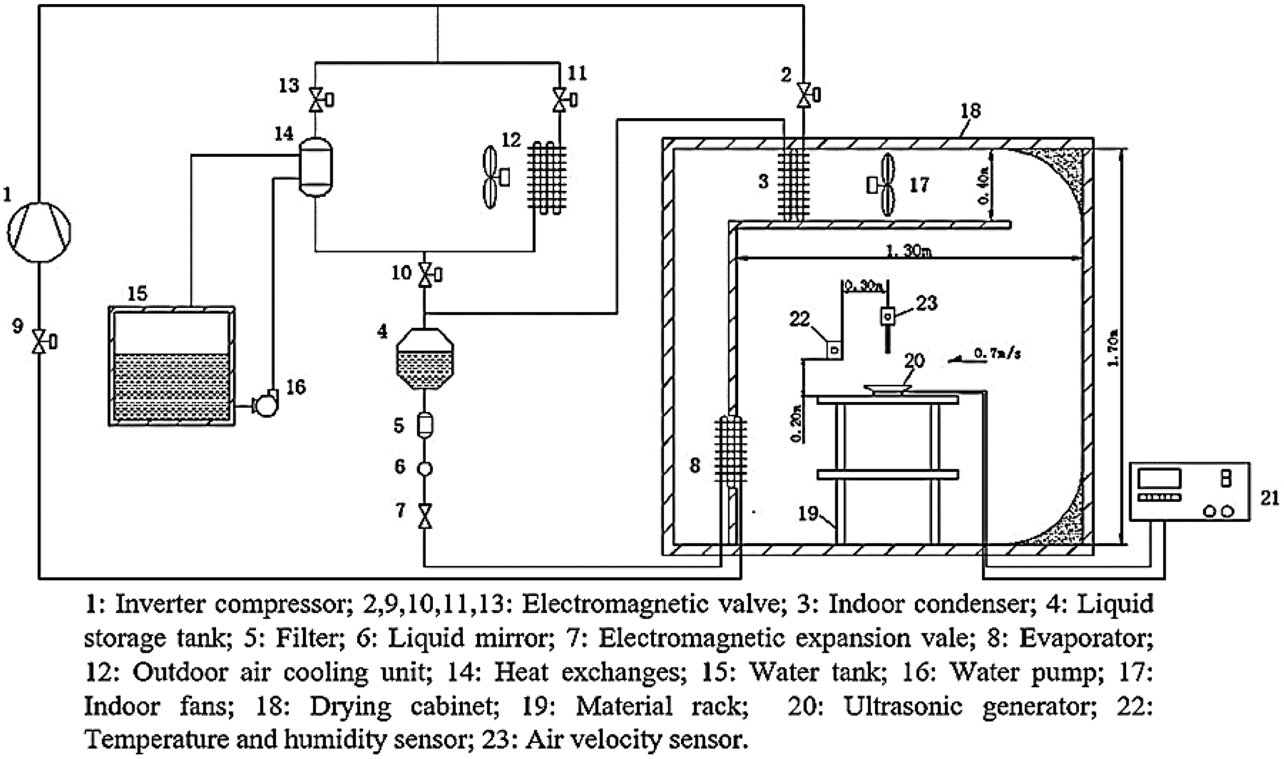


Fig. 8 Ultrasound-assisted heat pump dryer [83]

and maintain the oil quality of the dried seed oil extraction or expelling. The recent drying methods and technologies applied for drying the oilseed to a safe moisture level are shown in Table 5. The analysed oilseed included groundnut, melon, rapeseed, soybean and sunflower.

Groundnuts

In groundnut drying, natural drying methods such as open sun drying, solar drying and open-air drying are unquestionably the most cost-effective strategy for groundnut drying. However, the naturally dried ground nuts are liable to contamination and low nutrient retention due to long drying and exposure to the ambient environment [96]. In the last 5 years, ~25% of the drying studies on oilseed have focused on groundnut. Recently, a study examined the forced convective mode for seed drying to obtain higher-quality seeds. The influence of the weight on convective heat and mass transfer ranged from 0.61 to 1.10 W/m^2 °C, and it improved in proportion to the amount of the groundnut [96]. The heat transfer coefficient of ground nut drying in an indoor forced convective dryer was between 2.4 and 2.5 W/m^2 °C [97]. The value reduced to the range of 0.41 to 1.85 W/m^2 °C in a forced convective greenhouse dryer. Sahdev et al. (89, 90 formulated a Lewis model for thin layer drying of groundnuts under a natural and forced convection greenhouse dryer and found the heat transfer coefficient reduced with increasing wire mesh size. Drying ground nuts to a safe storage moisture level of 8 to 11% using a natural, forced and indoor forced convective greenhouse dryer had a payback period of approximately 1.66, 1.72 and 4.67 years respectively. The dryer satisfied the requirement of greenhouse drying with reduced CO$_2$ and provided a premium reason to decrease pollution emissions [47].

Melon

Melon seeds were dried in a combined fluidised bed and microwave drying system. The seeds had a moisture diffusivity ranging from 6.51×10^{-10} to 6.59×10^{9} m^2/s and rose with increased air temperature and microwave power. The percentage of melon seed shrinkage ranged from 15.09 to 46.99%. In the model study, the Aghbashloo et al. model accurately described the moisture ratio of the seed based on the drying time with $0.991 << R^2 << 1.000$; $0.000 << \chi^2 << 0.002$ and $0.023 << RMSE << 0.823$ (Golpour et al. [33]).

Rapeseed

Ren et al. [91] explored the impact of microwave (MW) drying on rapeseed oil yield and microstructure, as well as the

Table 5 Summary of different drying technologies for the oilseeds

Oilseed	Methods	Drying system	Drying Condition	Model/Simulation	FMC	Findings	References
Bambara groundnut	Thin layer	Infrared dryer (IRD) Microwave dryer (MWD) Hybrid (IRD – MWD)	Treatment time = 0 to 10 min IRD: T = 45 to 75 °C MWD: Power = 1200 W	ANOVA	6.1 ± 0.45 to 9.3 ± 1.03%wb	Compared to infrared, the microwave has a higher penetration depth and causes dipolar rotation and ionic conduction of water	Mukwevho and Emmambux [88]
Groundnut	Thin layer	Greenhouse dryer	Hot air Forced air Natural air	–	8 to 10%wb	Proper utilisation of greenhouse drying significantly reduces CO_2 emission The natural and forced convective methods reduce the energy payback time by 64.5% and 63.2% compared to a hot air dryer	Kumar et al. [47]
Groundnut	Thin layer	Greenhouse dryer	Hot air Forced air Natural air	Lewis model		Convective heat transfer increased with the mass of the grains	Sahdev et al. [89, 90]
Melon seed	Thin layer	Microwave-assisted fluidised bed dryer	Power = 270 to 630 W	Empirical model	5%	The effective moisture diffusivity ranged from 6.51×10^{-10} to 6.59×10^{-9} m^2/s The air temperature had a positive effect on the moisture diffusivity and shrinkage of the grain	Golpour et al. [33]
Rapeseed	Thin layer	Microwave dryer	Power = 200 to 600 W	ANOVA	–	The microwaves severely damaged the structure of the rapeseed and therefore improved the oil extraction yield and oxidative stability of the oil	Ren et al. [91]
Rapeseed	Thin layer	Radio-frequency dryer (RFD) Microwave dryer (MWD) Hybrid (RFD–MWD)	RFD: Power = 27 W MWD: Power = 915 W and 2450 W	ANOVA	7.91 ± 0.50%wb	The oil extraction yield and grain temperature increasing rate were improved (12.28–22.08%) by the frequencies	Xu et al. [92]

Table 5 (continued)

Oilseed	Methods	Drying system	Drying Condition	Model/Simulation	FMC	Findings	References
Soybean	Deep bed dryer	Fixed bed dryer	Mode: Intermittent and continuous	Heterogeneous model	12.4 to 13.6%db	The air temperature and velocity modulation improved the drying rate of the grain The intermittent drying had equal energy consumption and drying time under modulation	Defendi et al. [54]
Soybean	Deep bed dryer	Direct fired furnace	T = 34 ± 3.11 °C	–	12.11%wb	The grain dryer had 75.61% efficiency without compromising the quality of the grain	Quequeto et al. [22]
Soybean	Deep bed dryer	Hot air–spouted bed dryer	T = 50 to 70 °C	ANOVA	12 to 13%wb	Lower air velocity had a lower degree of seed deterioration	Brito et al. [93]
Soybean	Deep bed dryer	In-bin dryer	v = 0.2 m/s	Empirical model/ ANOVA	12%db	Air velocity control plan significantly affected energy consumption	Atungulu and Olatunde [94]
Soybean	Deep bed dryer		Harvest seasons = 2016, 2017 and 2019	Numerical method	–	The low temperature in the fixed bed dryer reduced greenhouse gas emissions by 90% compared to high-temperature fossil fuel-based drying	Epstein et al. [52]
Sunflower	Thin layer	Hot air dryer	T = 45 to 75 °C	Empirical model		The air temperature affected the isosteric heat desorption, and grain physical properties, and reduced oil yield	Coradi et al. [95]

T is drying temperature, *V* is air velocity, *FMC* is the final moisture content and *ANOVA* is an analysis of variance differences in oxidative stability, tocopherol content and flavour attributes of rapeseed oils extracted via cold press and solvent-based methods. The moisture content of the rapeseed was amended to 15% and the seed was subjected to MW power of 200 to 600 W. MW power increased the oil yield by 9 to 23% and the total tocopherol content by 17 to 23% when compared to the rapeseed that was not subjected to MW power. The effect of dielectric treatment on the drying characteristics of rapeseed and the physicochemical attributes of cold-pressed oil were studied by Xu et al. [92]. Before oil extraction, the rape seeds were adjusted to 15% moisture content and subjected to dielectric treatment via a cold press at a frequency of 27 to 2450 MHz for 22 to 45 min. The temperature rising rate of the 2450 MHz dielectric heat was the highest, but temperature distribution was the most non-uniform. Oil extraction yields were increased by 12.28%, 17.25% and 22.08% for 27, 915 and 2450 MHz dielectric treatment, respectively compared to the untreated sample.

Soybean

Soybean drying is the most studied oilseed drying method over the last 5 years. It covers about 42% of the drying studies on oilseed. The drying of soybean was recently studied using convective, in-bin drying, automatic furnace dryer, pulse-spouted vacuum microwave, pulse-spouted microwave and microwave vacuum dryers. In a convective dryer, the air temperature and velocity modulation are directly related to the drying rates of soybean as a proportion of vaporised moisture in intermittent and convectional operation conditions with similar energy consumption. Under intermittent operation, higher drying rates were obtained, and a validated model could be reasonably used to forecast temperature and moisture content profiles. According to the simulation, the optimal modulation patterns of the air qualities were a function of several system parameters, including the incumbent temperature and moisture content of both the soybean and air. However, when the dryer was at a high temperature and used a consistently low velocity, there was a tendency to lower energy usage [54]. In the simulation of in-bin drying and the storage of soybean with various fan control options and drying methodologies were applied. The fan control techniques, air flow rates, harvest date and moisture content of soybean are the key factors that determine the drying time. The non-difference qualified level of the soybean was revealed in the layer-by-layer statistical analysis since the total average relative deviation was even less than 10% and the overall chi-square was 0.88 [94]. Cao et al. [86] explored the drying kinetics and predicted the quality of dried green soybean using several modified microwave drying procedures. When compared to the fresh sample, the microwave freeze-dried green soybean exhibited a minor difference in the bright colour, and its drying time was the longest of all the procedures. The bright colour values of the pulse-spouted vacuum microwave, pulse-spouted microwave and microwave vacuum dryer were 79.77, 71.43 and 55.45, respectively, with a slight difference in drying time. Based on product quality enhancement, pulse-spouted vacuum microwaves and pulse-spouted microwave dryers outperformed the microwave vacuum dryers. Quequeto et al. [22] studied the performance of soybean grain drying quality using an automatic furnace dryer fed with eucalyptus chips. After drying, the average moisture content of the grains decreased from 14.47 to 12.11%wb. The dryer efficiency for drying the grains was 75.61%, and the fuel consumption was 21.78 kg of chips per tonne of dry grains. To remove 1.0 kg of water, the specific energy consumption was 11,871.80 kJ. Drying in general did not degrade the ultimate quality of the soybeans.

Sunflower

In a hot air dryer, the drying kinetics of sunflower seeds was studied. The effectiveness of the drying process was defined based on the effect of temperature (45 to 75 °C) on the oil yield. The effective diffusivity and isosteric heat desorption were produced by an increase in the drying temperature, interfering with the physical qualities of the grain and lowering the yield and quality of the extracted oil. The Wang and Singh model was chosen as the most appropriate model to forecast the drying kinetics. Sunflower grain effective water diffusivity ranged from 2.83×10^{-6} to 2.93×10^{-6} m^2/s and the physical properties of the sunflower grains were affected by drying air temperatures. The Correa et al. model better fitted the volumetric shrinkage data of the sunflower grain. The use of raffia packaging mitigated the deleterious impacts of drying and storage conditions. The drying temperature of 45 °C, the storage temperature of 20 °C and 60% RH gave higher oil yield for the grain [95].

Future Trends

Food grain drying studies in recent years have been cantered on reducing grain moisture content while retaining grain nutrients with maximised energy utilisation. The loss of nutrients and quantity during the drying process contributes noticeably to the total postharvest loss of grain. Therefore, the search for knowledge on sustainable ways of reducing postharvest losses is still inevitable [12].

With a basic overview of grain drying kinetics and the capacity of the dryer, a convective hot air dryer is mostly used to achieve the appropriate moisture reduction of grains. Several studies improved the drying process by focusing on the modification of the convective dryer. Future research should explore the ways of improving the drying process by modifying the properties of the grain, either by grain pre-treatment or modification of the drying process pattern, which could be a good catalyst for the process when improved or advanced drying systems are not available, accessible or economical.

Despite several attempts (such as ultrasonic, desiccant and vacuum-assisted drying) to improve process quality and lower the energy consumption during the processing of grain to a final product, the grain drying process continues to consume the most energy in the grain processing line. Therefore, further research should consider the utilisation of spent energy exiting the grain drying system for other purposes such as material tempering and converting to electrical energy to reduce the processing cost.

It is important to note that a real-time and online monitoring system is less considered in grain drying studies. Despite the current trend in the adoption of online monitoring systems, several studies focused on the modelling and simulation of the grain drying process, where the relationship between the drying parameters and drying performance such as nutrient retention, time and energy consumption were addressed using different offline methods [85]. Further research should consider real-time modelling and simulation using an online monitoring system through virtually controlled devices or sensors such as cameras, e-noses, acoustic sensors and thermal sensors. This could be integrated into the grain drying system to save energy and the cost of grain drying.

In several studies, the best drying parameters such as heat intensity, air velocity and treatments were primarily chosen based on selected drying performance. Meanwhile, grain drying kinetics is highly connected to all the responses such as dried grain quality, time, energy consumption and processing cost associated with the drying process. Therefore, future studies should investigate the adoption of optimisation of the global drying process to identify the ideal drying conditions that concurrently meet all the goals of the drying process.

Conclusion

Several drying techniques have been applied to different grain classes, namely: cereals, legumes, and oilseeds in the recent years. The goal of grain drying is to increase the shelf life of grain and retain the nutrient in the grain while saving the cost of production and energy consumption during the drying process. Therefore, this study reviewed the grain drying process over recent years and concluded that the drying parameters, drying conditions and optimum moisture removal capacity significantly affect the quality of the dried grains. Compared to the untreated conventional drying method, the quality of grains was improved by the application of treatments such as superheated steam (~ 55% of milling quality and ~ 33% hardness of rice), ultrasound (~ 13% of shrinkage compressive strength), humidification (increased head rice yield and lower grain chalkiness) and dielectric frequency (~ 22% of oil yield).

Improper, incomplete and over-drying of grains are detrimental to the quality of the grains. Dried grain with moisture content above the range of the critical moisture level shows incomplete drying. Partially dried grains are susceptible to mould growth, insect infestation and high-quality deterioration. The dried grains with moisture content below the critical moisture content level are over dried and the grains are liable to lose their nutritional value and germination potential.

The design and evaluation of different drying technologies for grain drying processes, such as fluidised bed dryers, fixed bed dryers, vacuum dryers, infrared dryers, microwave dryers and hybrid dryers (a combination of two or more different drying technologies), have shown a significant contribution to time, cost savings and efficient drying processes. Convective hot air was found to be the most time and energy-consuming drying method while more energy was saved during the drying process using a microwave (84%), infrared (~ 67%), microwave + hot air (~ 75%) and infrared + hot air (~ 54%) drying method.

Author Contribution The study was conceptualized by Kabiru Ayobami Jimoh and Norhashila Hasim. Original draft was writing by Kabiru Ayobami Jimoh. The manuscript was critically revised and edited by Norhashila Hashim, Rosnah Shamsudin, Hasfalina Che Man, Mahirah Jahari and Daniel I. Onwude. The final manuscript was read and approved by all authors.

Funding The authors acknowledge the financial support of the Ministry of Higher Education, Malaysia, through the Transdisciplinary Research Grant Scheme Project (TRGS/1/2020/UPM/02/7).

Data Availability The available data that are related to this study were included in the article.

Declarations

Competing interests The authors declare no competing interests.

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