Sustainable Energy Technologies and Assessments 75 (2025) 104205

Contents lists available at ScienceDirect

Sustainable Energy Technologies and Assessments

journal homepage: www.elsevier.com/locate/seta

Review article

Revolutionizing drying chambers for sustainable energy technologies in food and agriculture: A comprehensive review

Muhammad Aqil Afham Rahmat [a,b], Adnan Ibrahim [a,*], Muhammad Ubaidah Syafiq Mustaffa [a], Khaled M. Al-Aribe [c], Hariam Luqman Azeez [a], Sahibzada Imad Ud Din [a], Mahmoud Jaber [a], Monaem Elmnifi [d]

[a] *Solar Energy Research Institute, Universiti Kebangsaan Malaysia, 43600 Bangi, Selangor, Malaysia*
[b] *Department of Biological and Agricultural Engineering, Universiti Putra Malaysia, 43400 UPM Serdang, Selangor, Malaysia*
[c] *Department of Mechanical and Industrial Engineering, Abu Dhabi University, Abu Dhabi PO Box 59911, United Arab Emirates*
[d] *Department of Mechanical Engineering Technology, FSBEI "Belgorod State Technological University named after. V.G. Shukhov." 308012, Belgorod, st. Kostyukova 46, Russia*

ARTICLE INFO

Keywords:
Drying chamber
Drying technologies
Enhancement strategies
Heat transfer
Food and agricultural products
Drying performance

ABSTRACT

Energy efficiency and food security could be substantially improved by advancing and implementing drying chambers in diverse drying technologies. The drying chamber is critical for producing high-quality dried food and agricultural products while also ensuring excellent drying system performance. It has received much attention recently due to its primary effect on drying technologies. This research examines the drying chamber system in diverse drying technologies, using current literature to highlight significant shortcomings for future work on this subject and to demonstrate potential improvement techniques. Furthermore, the paper summarizes the examination of temperature and airflow distribution systems and different drying methods based on various heat transfer mechanisms. A thorough review of multiple previous research findings is also provided, and the limitations and prospects for its future use in drying are highlighted. In addition, further improvement strategies are recommended, including enhancing the heat source, optimizing the environmental conditions around the drying chamber, introducing jet impingement technology, establishing an advanced monitoring system, and adding a directed nozzle. Hybrid drying has been known as a viable approach for improving drying efficiency and uniformity. However, further research is required to minimize costs while improving such components' effectiveness and technical design.

Introduction

About 70 % more food production would be needed to feed 9 billion people by 2050 [1–3], and it was suggested the global population will peak in 2064 at 9.73 billion [4,5], increasing energy consumption [6]. Due to that, energy is essential for industrial development, modernization, and economic growth [7]. According to a United Nations Food and Agriculture Organization estimate, the worldwide prevalence of food insecurity grew from 25.3 % in 2019 to 29.6 % in 2022 [8]. In order to guarantee food security, substantial alterations must be implemented in the present methods of food production, storage, distribution, and consumption. Hence, drying is of the utmost importance in ensuring worldwide food security [9,10]. Drying requires an energy-intensive process. Energy is necessary for drying processes to eliminate moisture [11] from substances via evaporation of water, which is commonly accomplished with heat or airflow.

Ensuring the drying system's best performance is crucial to provide an effective drying process. Drying technology plays a significant role in attaining Sustainable Development Goal (SDG) 2 (Zero Hunger) via its ability to preserve food, minimize waste, and foster food security and economic development [12]. Other than that, the energy efficiency of the drying process helps to achieve SDG 7 (Affordable and Clean Energy) [13]. Recent research suggests that dryer manufacturers are interested in energy efficiency since it is a crucial determinant of market value in drying expenses. Hence, it is crucial to thoroughly examine the energy consumption profile and assess the efficiency of energy utilization in the drying process across various dryers [14]. Sustainable drying technology also provides environmental and economic advantages [15,16].

* Corresponding author.
E-mail address: iadnan@ukm.edu.my (A. Ibrahim).

https://doi.org/10.1016/j.seta.2025.104205
Received 9 July 2024; Received in revised form 15 January 2025; Accepted 20 January 2025
Available online 27 January 2025

As currently known, most existing review articles have concentrated on specific drying technologies, focusing on performance enhancement techniques and their applications across various industries. However, there is a lack of comprehensive reviews addressing the application and performance enhancement techniques of drying chambers across a range of drying technologies. This paper aims to fill that gap by providing a comprehensive analysis of the methods and strategies for improving the performance of drying chambers in diverse drying technologies, specifically for food and agricultural products. The review begins with a detailed examination of the principles underlying drying chambers in different drying technologies and the materials they process. The subsequent sections evaluate the effectiveness parameters of drying chambers based on recent publications and explore various methods for performance improvement. The paper also includes an illustrative overview flowchart of the drying chamber focusing on the heat transfer mechanisms, performance criteria, and performance enhancement strategies of various drying technologies, as shown in Fig. 1. Through this comprehensive review, the paper highlights the critical role of drying chambers for drying technologies in achieving energy efficiency and food security while also identifying future research directions and practical implications for industry professionals.

Overview of drying chamber

Drying technologies comprise many techniques, from traditional heat-based strategies to innovative methods [17]. The drying process is the most frequently encountered operation in the food processing industry, characterized by its high energy consumption. Incorporating sustainable drying technologies throughout the food supply chain will significantly mitigate post-harvest losses and optimize food product inventory management [18]. One of the important components in the drying system is the drying chamber, which plays an essential role in drying technologies. The drying chamber is a sophisticated and critical aspect of industrial operations aimed at removing moisture from various materials. This technique, which is used in industries such as food processing [19], textiles [20], and pharmaceuticals [21], uses controlled conditions to speed up the drying process while maintaining the materials' integrity.

Drying chambers guarantee effective water evaporation, avoiding degradation, high system efficiency, and increasing the shelf life of perishable commodities by controlling parameters such as airflow, humidity, as well as temperature. The drying process occurs through convection heat transfer, radiation heat transfer, and rarely conduction heat transfer. Depending on the exact context and industry in which it is used, a drying chamber can be referred to by a variety of names, including a drying oven [22], a drying room [23] or a drying cabinet [24]. A drying chamber is used in various drying technologies. Hence, the primary purpose of the drying chamber is to ensure a uniform drying process of the dried material [25–27]. Several drying techniques employ a drying chamber mainly in the agricultural industry, including heat pump drying [28], vacuum drying [29], infrared drying [30], spray drying [31], freeze-drying [32], fluidized bed drying [33], solar drying [34], and microwave drying [35]. There are additional drying processes that do not employ a drying chamber, such as solar drying [36] and field drying [37], which place dried materials in the open air.

Aside from that, drying chambers are categorized into two types of drying and several heat transfer processes. Batch and continuous-mode industrial dryers are the two types of drying chambers. Heat input to wet materials can be classified into numerous types, including convection, radiation, conduction, and a combination of heat transmission mechanisms. Convection drying is the most prevalent [38,39]. As a consequence of industrial needs, new dryers are constantly being developed [40]. On top of that, a brief overview of several drying technologies employing drying chambers for numerous industries is shown in Table 1.

Convection heat transfer

Heat transfer mechanisms play a vital role in drying technologies as they significantly influence the efficiency and quality of the drying process, particularly within drying chambers.

In convective heat transfer, heat is transferred between two entities via the motion of a gas or fluid. Natural convection occurs when cooler air or water replaces heated air or water that ascends. Forced convection effectively removes heat for drying by propelling air over the body's surface, similar to wind or wind-generated water currents [76]. Fig. 2a serves as an illustration of the frequent use of convection heat transfer in drying processes. The inlet provides the heat input into the drying chamber, while the heat energy utilized by the drying chamber is indicated at the outlet.

Several drying technologies make use of drying chambers for convection drying purposes. The drying chamber was used by Koca et al. [59] in the spray drying process. Using seven different conditions in the drying chamber, the authors investigated the quality of cheese powder. The research is focused on the inlet temperatures of 160 °C, 195°C, and 230 °C, atomization pressures of 294, 441, and 588 kPa, and output temperatures of 60 °C, 80 °C, and 100 °C. It was found that outlet air

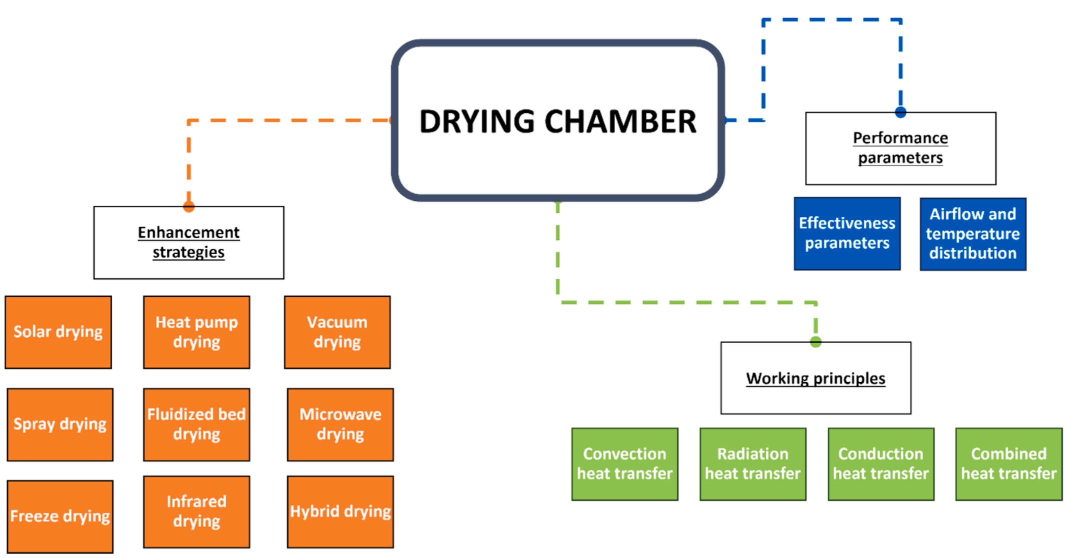

Fig. 1. General overview of drying chamber's working principles, performance metrics and performance enhancement strategies in various drying technologies.

Table 1
A brief overview of drying methods includes drying chamber usages with heat transfer mediums and industries involved.

Drying technologies	Drying chamber utilizations	Primary heat transfer mechanisms	Sectors used
Heat pump drying	Recycling heat to sustain ideal drying temperatures and minimize energy consumption.	Convection	• Food and agriculture industry [41–44] • Wastewater sludge industry [45,46]
Vacuum drying	Minimizing pressure to accelerate moisture extraction at reduced temperatures, thereby preserving heat-sensitive materials.	Convection	• Food and agriculture industry [47–49] • Oil and gas industry [50] • Paper and pulp industry [51] • Manufacturing industry [52] • Power generation industry [53]
Infrared drying	Heating materials directly via radiation, facilitating rapid and uniform moisture elimination with effective energy use.	Radiation	• Ceramics industry [54] • Textile industry [55] • Food and agriculture industry [56,57]
Spray drying	Atomizing liquid into small droplets, facilitating rapid and efficient moisture evaporation under a regulated airflow.	Convection	• Food and agricultural industry [31,58,59] • Pharmaceutical industry [60]
Fluidized bed drying	Suspending particles in heated air to guarantee effective and uniform heat transmission while facilitating quick moisture removal.	Convection	• Food and agriculture industry [61,62] • Power generation industry [63] • Pharmaceutical industry [64]
Solar drying	Utilizing solar energy to provide reliable, cost-effective heating for moisture extraction in an environmentally sustainable way.	Radiation or convection	• Food and agriculture industry [65,66] • Power generation industry [67] • Marine industry [68] • Steel wire industry [69]
Microwave drying	Using microwave radiation to directly heat moisture inside the product facilitates expedited and uniform drying.	Radiation	• Food and agriculture industry [35,47] • Mining industry [70] • Stainless steel industry [71] • Automotive industry [72]
Freeze drying	Sublimating frozen moisture in the materials at low pressure to preserve structure and quality.	Conduction	• Food and agriculture industry [73,74] • Pharmaceutical industry [75]

temperature affected cheese powder qualities, notably at 100 °C, which enhanced browning and changed sensory features. Cheese powder moisture was below 2.85 % in all situations, confirming microbiological safety.

Azadbakht et al. [24] discovered that convective heat transfer and the drying chamber are crucial to the drying efficiency of eggplants in a fluidized bed dryer, with optimum conditions established at lower temperatures and air velocities. The lowest energy consumption and exergy losses were found at a temperature of 40 °C, an air velocity of 3 m/s, and a sample diameter of 13 mm, demonstrating the relevance of these parameters in improving heat transfer efficiency throughout the drying process.

Parihar et al. [77] analyzed the design and performance assessment of a revolutionary cabinet solar dryer that uses a UV sheet to dry banana slices. The solar dryer included a drying chamber with six different-sized trays and was equipped with a fan and a PV panel for forced convection drying. The impact of varying sample masses (100, 200, and 300 g) and temperatures (40, 50, and 60 °C) on the drying properties and final product quality of Roselle calyx was examined by Tajudin et al. [78] through the utilization of a heat pump dryer. Through the use of heat pump drying technologies in conjunction with a drying chamber, the authors demonstrated that convection drying can be completed in a significantly reduced amount of time without sacrificing product quality.

Radiation heat transfer

Heat radiation results from separating two bodies with opposite temperatures through space or when they are not in direct contact. Solid, liquid, and gaseous substances emit electromagnetic radiation due to molecular and atomic rotation and vibration [79]. Unlike convection and conduction heat transfer, it conveys thermal energy directly to the substance to be dried in the context of drying. Various drying techniques have used drying chambers that employ radiation as a medium for heat transfer. Dolgun et al. [80] used a drying chamber in a combined infrared and heat pump drying technology in order to investigate the impact of the heat transfer mechanism and the bi-directional penetration of the heat into the product in accordance with the energy-exergy analysis. The infrared-assisted heat pump drier (IRAHP) reduced drying time to 640 min from 800 min for the heat pump (HP) dryer, saving 10 % energy and 20 % time. Energy efficiency (EE) values for IRAHP varied from 0.29 % to 7.94 %, whereas HP values were between 0.28 % and 6.54 %, indicating the better performance of the IRAHP in energy-exergy analysis and its prospective use in large-scale nut drying chambers.

Horuz et al. [22] studied the drying kinetics of apricot halves using a microwave-hot air household hybrid oven. Drying rates and the optimal drying model could be determined by applying the drying oven, which had adjustable microwave power and hot air temperature. Jibril et al. assessed the application of a drying chamber for infrared drying via radiation heat transfer [81]. The researchers investigated the characteristics of corn flour dried at various temperatures utilizing graphene far-infrared (gFIR) technology. An innovative solar drying technique for sewage sludge was invented by Wang et al. [82]. This method utilized a sandwich-like chamber with a thin layer and adjusted the solar radiation intensity and bed thickness to optimize the drying process. The utilization of the drying chamber enabled the efficient and economical drying of the sewage sediment by facilitating the transmission of radiation heat, as illustrated in Fig. 2b.

Conduction heat transfer

The process of conduction heat transfer refers to the process by which thermal energy is transferred through solids, liquids, and gases without significant bulk motion. Conduction refers to the process by which energy is transferred from particles of a substance with higher energy to particles with lower energy as a result of the interaction between the particles [84]. When it comes to drying, just a few kinds of drying technologies conduct heat transfer into practice, such as freezing drying through the sublimation process [85] and solar conductive drying [86].

In order to comprehend the atypical heat transfer observed during vial freeze-drying, specifically the heat transfer differences between vials situated at the edge and those in the center of the shelf, Scutellà et al. [85] described the construction of a three-dimensional

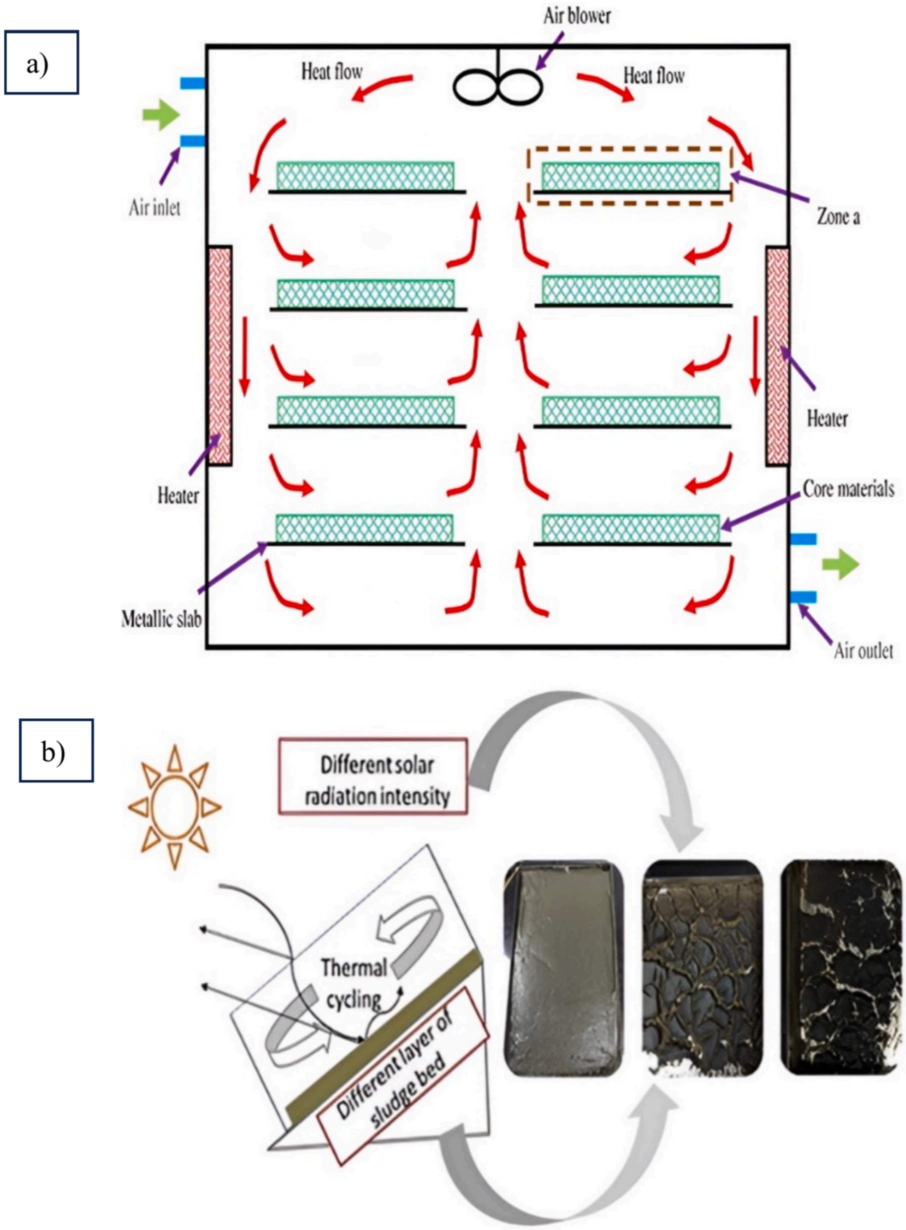

Fig. 2. Heat transfer mechanisms in drying chamber, a) Convection-based drying in the oven structure chamber [83]; b) The process of radiation heat transfer during solar drying [82].

mathematical model. Multiple heat transmission mechanisms are accounted for in the model, such as conduction via low-pressure water vapor, radiation heat transfer, and conduction between solids, as presented in Fig. 3a. Borah et al. [86] investigated how the solar conduction drier (SCD), which uses conduction as the main mode of heat transmission, improves drying efficiency by lowering processing time by 40 % when compared to conventional methods. The SCD provides four stainless steel drying chambers for efficient heat conduction and moisture removal, resulting in average effective moisture diffusivity values of 1.852 × 10–10 m2/s for sliced turmeric and 1.456 × 10–10 m2/s for whole turmeric. The dryer's thermal efficiency was 55 %, suggesting that the conduction heat transfer mechanism in the drying chambers maintains appropriate drying conditions, limiting fungal development in high humidity situations.

Combined heat transfer

The implementation of combined heat transmission mechanisms during the drying process has the potential to enhance its overall efficiency. The findings by Dolgun et al. [80] reveal that the combined heat transfer of convection and radiation with bi-directional penetration of the heat to the product improved the system performance, according to energy-exergy analysis. Dubkovetskiy et al. [87] studied integrated heat transfer methods for pasta drying, focusing on gluten-free maize flour pasta. The study found that a thermo-radial-convection method improves drying and product quality over the thermo-radiative method by reducing energy usage.

Swasdisevi et al. [88] presented a mathematical model for far-infrared and vacuum-drying banana slices to predict moisture content and temperature. The research revealed that the predicted temperature in the center of a banana slice was higher than the observed temperature for the first 50 min of drying but agreed later. Heat convection, heat conduction, heat radiation, and moisture movement inside the banana slice were also addressed in the model. The predicted and experimental results were evaluated at drying chamber absolute pressures of 5, 10, and 15 kPa with regulated banana center temperatures of 50 °C, 55 °C,

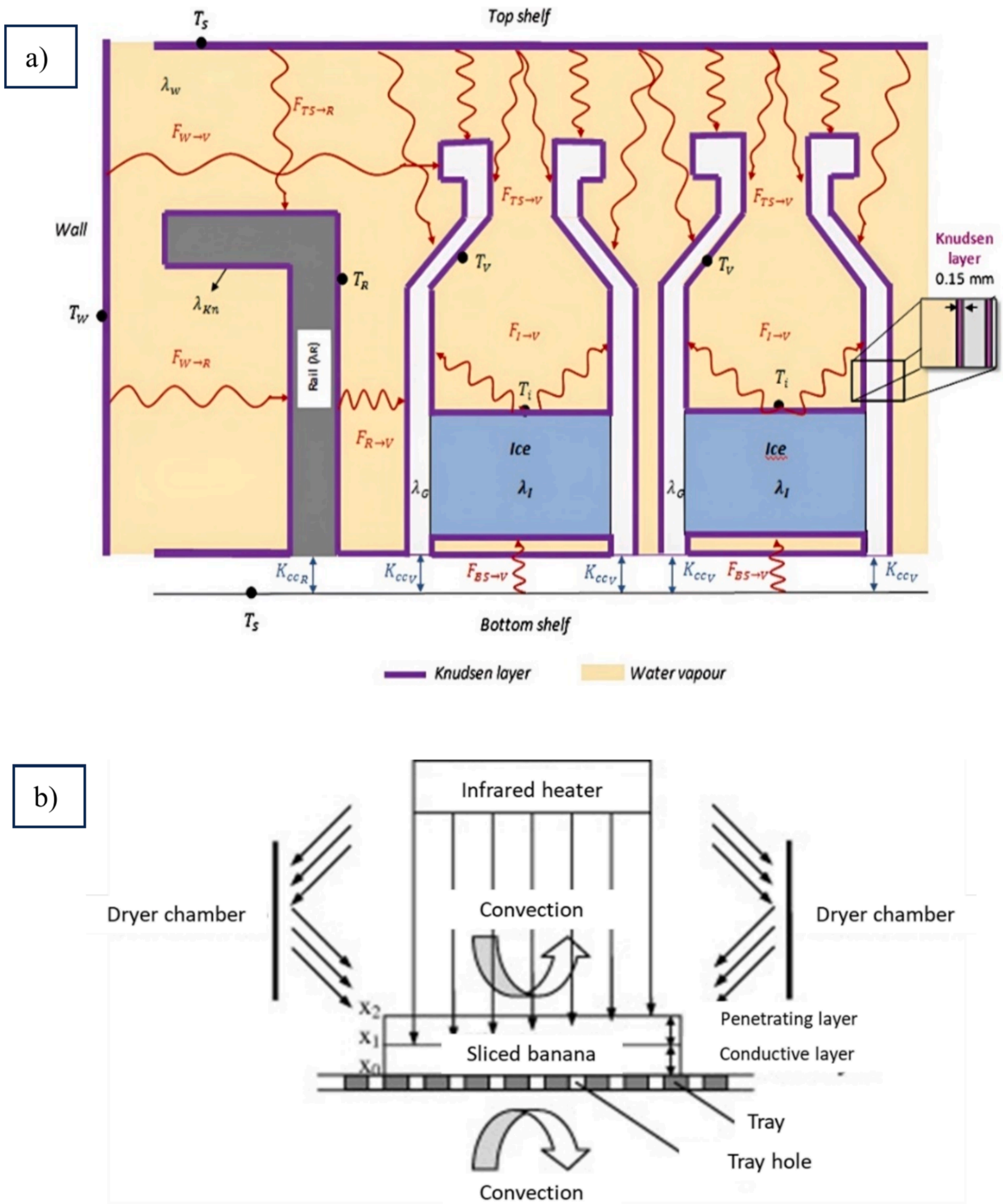

Fig. 3. Heat transfer mechanisms in drying chamber, a) The involvement of conduction heat transfer in freezing drying [85]; b) Combined heat transfer of convection, conduction, and radiation for integrated vacuum and far-infrared drying [88].

and 60 °C. Comparing the predicted and experimental data revealed that the model accurately predicted the variations in moisture content. Fig. 3b illustrates the combined heat transfer of convection, conduction, and radiation for banana slices drying. Plaza et al. [89] revealed that the hybrid dryer enhances the drying process using different heat transfer modes such as conduction, convection, and radiation. The aerothermal system, which circulates air via a subsurface heat exchanger, efficiently heats the working fluid before it reaches the drying chamber. With a maximum working temperature of 52 °C and a stabilization time of 40 min, the hybrid dryer used 80 % solar energy. It saved 3 to 5 kW/day on clear days with energy efficiency of around 60 % to 70 %.

Performance evaluation parameters

The assessment of drying chambers' effectiveness is heavily reliant on performance evaluation indicators. These indicators are of utmost importance as drying chambers are critical equipment in various drying methods. Examining performance parameters offers valuable insights into the intricate dynamics of the drying process, enabling operators to optimize the prevailing conditions to achieve optimal productivity levels while simultaneously upholding the desired quality standards of the product.

Parameters to evaluate the effectiveness of a drying chamber

Nowadays, there are several issues caused by drying chambers, which, as stated by past researchers, degrade the performance of the drying chamber itself:

- According to Román et al. [90], uneven air distribution is a key issue in batch dryer performance. The issue causes inefficiency and excessive energy usage in batch dryers.
- As stated by Guangbin et al., the uniformity of moisture contents is an essential indicator for assessing the degree of drying of wet materials throughout the entire drier. It is useful for optimizing the drying room's design [91].

- Another issue is investigated by Babu et al. [92], in which hot air is often injected above the top tray in typical tray dryers and flows through the other trays. The top trays get the most energy and can over-dry leaves. In contrast, the bottom trays may not receive enough owing to increased relative humidity and decreased air velocity and temperature.
- Tuncer et al. [93] stated that specific drying chamber designs require extensive time and energy.
- A research conducted by Wang et al. [94] on okara products employing air jet impingement drying, factors such as increased temperature, increased air velocity, and decreased loading density were shown to lead to a faster drying rate.
- As stated by Nanang Ruhyat [95], irregular spray drying can occur due to material adhesion to the walls of the drying chamber.

In response to these problem statements, numerous indicators can be used to assess the effectiveness of the drying chamber:

1. Drying efficiency [96]
2. Specific moisture extraction rate (SMER) [97]
3. Drying time [98]
4. Drying rate [99]
5. Energy efficiency [100]
6. Specific energy consumption (SEC) [101,102]
7. Coefficient of performance (COP) [103]
8. Heating capacity [104]
9. Nusselt number [100,105]
10. Thermal efficiency [106,107]
11. Coefficient of energy [108]

Airflow and temperature distribution

Non-uniform air velocity and temperature can result in uneven drying and non-homogeneous product quality due to under or over-drying [109]. Therefore, the uniformity of airflow and temperature in the drying chamber is crucial to providing higher drying performance, enhancing the quality of the product, and improving system performance. Moreover, suitable air circulation can expedite the reduction of moisture in agricultural products, thereby enhancing the dehydrated product's quality [110–113]. In order to meet the requirements for an effective drying chamber system, it is necessary to ensure that the drying chamber is equipped with conditions below:

1. Uniform temperature [92,114–118].
2. Uniform velocity [115,92,90,118–121].

Uniform air temperature and velocity distributions can be analyzed using computational fluid dynamics (CFD), statistical, and thermal imaging techniques. Table 2 lists the airflow and temperature distribution analysis tools of previous studies.

Table 2
Analysis techniques for velocity and temperature distribution in the drying chamber.

Analysis methods	Description of methods	Past references
CFD analysis	Simulation and optimisation of fluid flow and thermal behaviour in a system using CFD analysis show temperature and velocity uniformity.	[92,90,115–121]
Statistical analysis	Statistical analysis quantifies measurement consistency and variability throughout a system to determine temperature and velocity uniformity.	[122–124]
Thermal imaging analysis	Thermal imaging captures and displays surface temperature distributions in real time to show uniformity.	[114,116,125]

However, the literature review shows that the homogeneity of air distribution and air temperature are analyzed majorly and effectively by CFD analysis. Several researchers have conducted intensive research using various approaches to the drying chamber's air and temperature distribution system.

Temperature uniformity

Temperature distribution in a drying chamber corresponds to the range of temperature variation that transpires across the chamber, thereby exerting an impact on the drying rate and uniformity of the material undergoing processing. Guangbin et al. [91] analyzed the temperature distribution in a double-layer drying chamber. They discovered that the starting temperatures of the seeds and air were the same. However, once fresh air entered the room, the temperature rose quickly, particularly in the lower chamber. The simulated and experimental findings exhibited a favorable correspondence, as the moisture content of the seeds exhibited a quick decrease in the first 30 min, followed by a gradual change until the end of the drying period, suggesting the presence of a non-uniform temperature distribution inside the drying chamber. Fig. 4a depicts temperature homogeneity for a duration of 2.5 h.

Song et al. [126] investigated temperature uniformity in a combined thermal and microwave (CTMW) drying technique for silica gel. It was discovered that temperature and moisture content gradients occurred mostly in the vertical direction, as seen in Fig. 4b, with the temperature difference between the layers reaching 5 °C. Furthermore, when the hot air temperature and microwave power rose, the drying rate improved, but the drying uniformity dropped. Gu et al. [127] analyzed the uniformity of temperature distribution of dried banana slices using vacuum radiofrequency treatment. They compared this approach with conventional and microwave drying techniques. The study revealed that RF-vacuum drying exhibited superior heating uniformity and drying rates. The top layer of samples had the lowest moisture content, followed by the middle and bottom layers, demonstrating enhanced uniformity across various layers.

Airflow uniformity

Airflow distribution in a drying chamber pertains to how air is cycled inside the chamber during drying. Airflow can be described as the contour of air velocity inside the drying chamber. Using computational fluid dynamics, Román-Roldán et al. [128] examined the enhancement of airflow velocity distribution within a greenhouse solar dryer, as illustrated in Fig. 5a. It was discovered that the air velocity across the trays was not uniform, with some configurations exhibiting low velocities and non-uniform distribution. However, adding internal elements and air recirculation systems enhanced the airflow uniformity and velocity.

Zhang et al. [130] used CFD modeling with experimental validation to examine the airflow velocity in a belt dryer for varying feed thicknesses. The findings revealed that a 40 mm feed thickness provided the best consistency of airflow velocity distribution, exhibiting equivalent simulated and experimental values at different points on the dryer surfaces. Another study by Zhang et al. [131] utilized the Computer Fluid Dynamics (CFD) technique to examine feed thickness's impact on airflow velocity distribution within a conveyor dryer. The findings indicate that the influence of feed thickness on airflow velocity is substantial. A narrower feed thickness corresponds to greater uniformity and more consistent airflow distribution, whereas a broader feed thickness generates a greater range of airflow velocities.

Abdulmalek et al. [129] used numerical analysis and design adjustments to improve air velocity distribution within a multi-chamber solar drying box. Fig. 5b displays air velocity magnitudes at 5 cm above the three splitters. High velocity above the bottom splitter is about 0.2–0.1 m/s, whereas low velocity is recorded above the top splitter at 1.5–0.01 m/s. Additionally, downstream velocity is reduced owing to the increased chamber cross-sectional area. The velocity difference at the

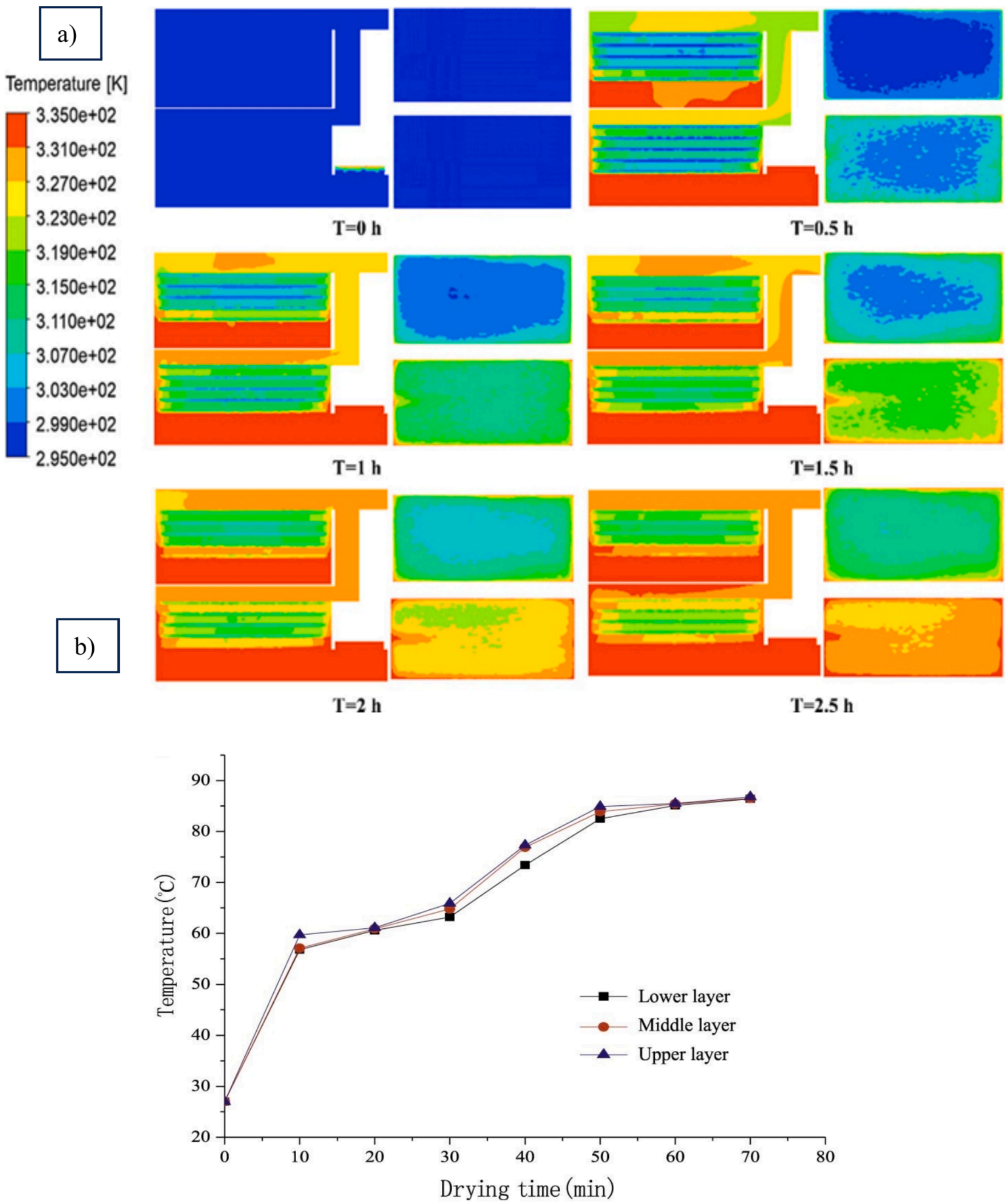

Fig. 4. Overview of temperature uniformity, a) Temperature contour of double-layer drying chamber [91]; b) Temperature changes for three layers [126].

leading of splitters is around 0.05 m/s and grows downstream. Overall, removing chamber cross-section area expansion improves velocity homogeneity.

Drying chamber airflow and temperature homogeneity are crucial for reliable and efficient results [132,133]. A drying process's quality, uniformity, and efficiency rely on air circulation within the chamber. Airflow and temperature evenness can be improved by considering air velocity, temperature across the chamber, distribution methods, and chamber design, which, in turn, can improve the drying process and decrease variance in the finished product. In order to enhance the management and accuracy of consistent airflow patterns and heat distribution in drying chambers, it is recommended to employ a focused nozzle [134] and a jet impingement system [135–137], capitalizing on technological advancements.

Strategies for improving drying chamber in drying technologies

The effectiveness of the drying process is significantly influenced by the performance of the drying chambers. One of the most important functions of the drying chamber is to guarantee uniform drying of the drying technologies [92,138,139]. Estimating critical parameters such as drying time, moisture content, energy consumption, and temperature and velocity distribution within the drying chamber offers valuable insights that can inform economic and practical development [140]. Moreover, numerous researchers in the past have taken airflow uniformity within the drying chamber as a criterion for determining the optimal drying chamber design [91,92,140].

A method that effectively improves the drying chamber is required to ensure air uniformity and maximize the drying system's performance. In previous research, various techniques were implemented in the drying chamber of various drying technologies to improve the drying

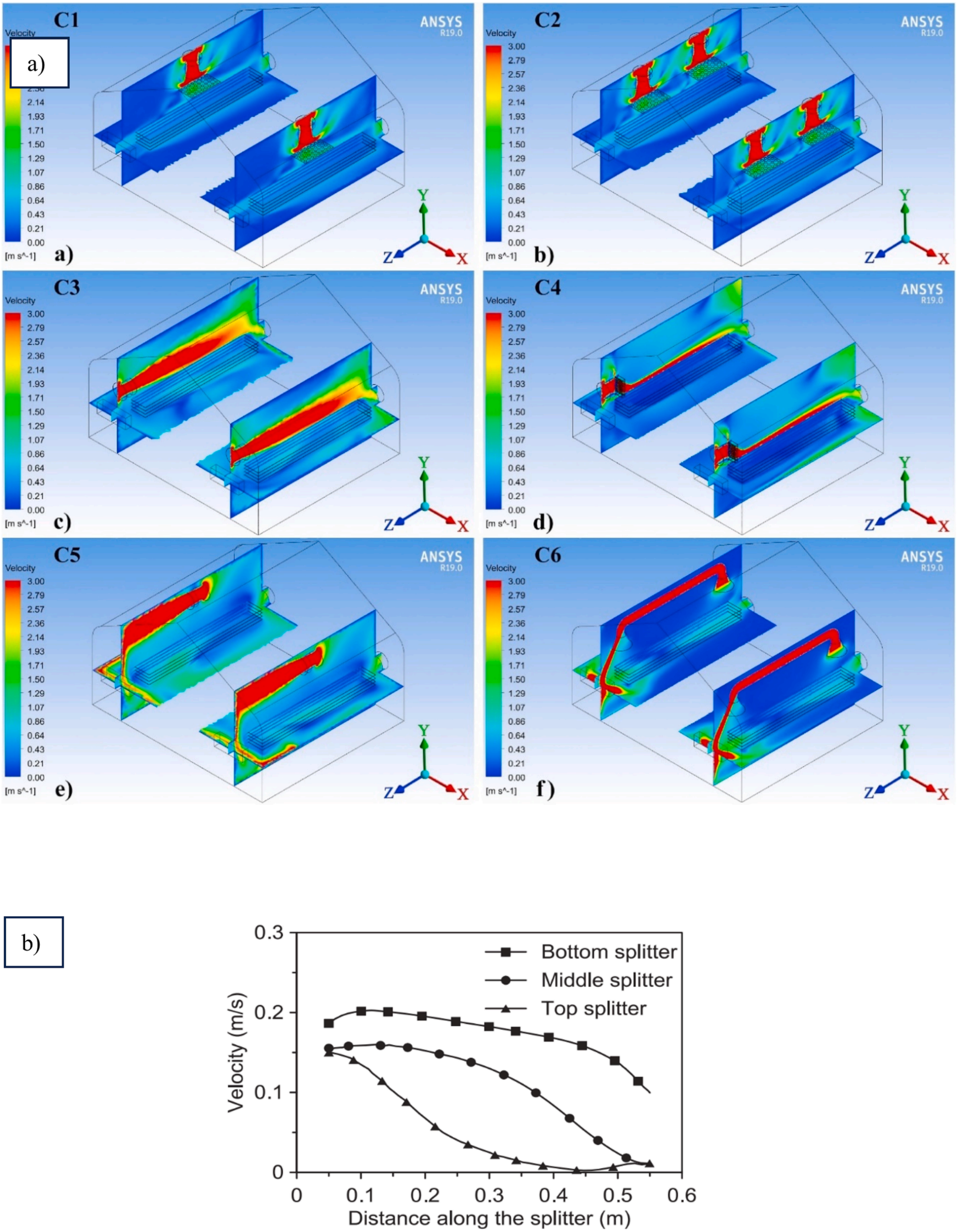

Fig. 5. Overview of velocity uniformity, a) A variety of configurations' air velocity distribution patterns [128]; b) Results of air velocity at 5 cm over the splitters [129].

efficiency, and the parameters in the drying chamber were highlighted and measured. Furthermore, these enhancement solutions are applied to address the issues stated in Section 3.0.

Solar drying

Solar energy is a type of renewable energy [141–143] that plays a crucial role in achieving food security by supplying energy for energy refrigeration and food preservation, which is a key component of SDG 2 [144], SDG 7 [145], and SDG 13 [146]. A solar dryer is a technological innovation that utilizes solar energy to facilitate the drying process of fruits, vegetables, and harvests, enhancing their preservation [147]. The solar drying chamber controls heat transfer, ventilation, and contamination to ensure efficient and high-quality drying [148]. Numerous researchers have recently modified the drying chamber utilized in solar drying to improve its performance.

Tuncer et al. [93] investigated the performance of a unique convex-type solar absorber drying chamber in dehumidifying municipal sewage sludge. The study aims to develop a cost-effective and ecologically friendly approach for drying municipal sewage sludge using convex solar absorber technology in the drying chamber. The findings show that convex solar absorbers can improve drying performance and energy efficiency [93,149]. Patel et al. [108] examine four new portable greenhouse solar dryer (PGHSD) modes for drying onion slices. The four modes are the active greenhouse solar dryer (AGHSD), AGHSD with recirculating fans, AGHSD with recirculating fans and an evacuated tube-type solar air heater (ETAH), and AGHSD with ETAH and an airflow system. The AGHSD with recirculating fans, ETAH, and airflow system decreased the onion slice moisture ratio to 5.32 % in a single day, in comparison to 19.99 % for AGHSD and 46 % for open sun drying. Recirculating fans, solar air heaters, and airflow systems enhanced heat utilization and drying efficiency, making the PGHSD a suitable agricultural product drying option. For AGHSD, the drying efficiency is 41.40 %, while it is 59.97 % with circulating blowers, ETAH, and an airflow system. Furthermore, optimized drying efficiency was much higher than 20.86 % for sun drying.

Khanlari et al. [150] improved the performance by including a transparent solar-capturing drying chamber. A transparent drying chamber improves solar sewage sludge drying efficiency and time. Experiments demonstrated that a transparent drying chamber lowered drying time by 75–90 min. This solar collector absorbs additional solar energy and speeds up drying. The new drying chamber has an SEC of 1.87–1.98 kWh/kg, as opposed to the old dryer's 2.49–2.68 Kwh/kg. SMER was improved by modifying the drying chamber.

Heat pump drying

Heat pumps are highly efficient heating devices that convert a low-quality heat source into a functional, high-quality heat source by utilizing the thermodynamic cycle of the cooling medium within the system. Heat pump drying technology has many benefits over conventional drying processes, including energy efficiency, reduced consumption, environmental friendliness, superior drying quality, and high automation [151]. However, the heat pump drying system has some issues that disturb its performance, such as longer drying time, high energy consumption, and poor quality of dried material [152,109]. The drying chamber component is essential to the heat pump drying system [153]. By integrating a drying chamber, the heat pump can effectively eliminate moisture from either the air or the substance undergoing drying while regulating its temperature.

Previous studies have focused on improving the drying chamber of heat pump dryers. Aktas et al. [140] developed a unique cylindrical drying chamber design for drying mint leaves using a drying system with a heat recovery unit. The drying chamber's design allows consistent airflow distribution and prevents the spread of lightweight samples. The heat pump system's coefficient of performance (COP) shows that the heat recovery unit can recover much energy, conserving drying energy. The highest heat pump and system COPs are 4.06 and 2.64, the average drying air temperature is 35 °C, and three trials used 3 kWh.

Babu et al. [154] reported the results of an experimental study on thin-layer drying of Amaranth leaves in a heat-pump-aided tray-type batch drying chamber. The drying chamber's two-level tray design ensures optimum air circulation and little pressure drop, resulting in consistent drying of the leaves [92,154]. The study focuses on the optimized operating conditions, such as a coefficient of performance (COP) of 4.60, specific energy consumption of 1.16 kW/kg, and the effect of air temperature and velocity on the drying process, providing valuable insights for efficient leaf drying in a heat pump dryer.

Singh et al. [155] examine banana and potato chips' drying kinetics energy and exergetic performance in closed and open-cycle batch-type heat pump dryers. The drying chamber comprises several aluminum strip trays to circulate air and remove moisture from both sides of the food chips. A stainless-steel net and optimal tray spacing promote drying. Average drying temperature, time, and initial-final moisture were better in the closed system. Compared to the open system, it consumed less energy and had superior volumetric heating. Open-cycle heat pumps and systems have a higher COP. The heat pump's average COP for banana and potato chips was 3.09 and 2.85 in the closed system and 3.89 and 3.93 in the open system.

Olejnik et al. [121] developed a vertical airflow drying chamber (Fig. 6). Simulation results presented three-chamber dryers with heat pump designs and vertical direction of the airflow system. The improved chambers, especially with the revolving disc, achieved more consistent beef dryness based on water activity (Wa) and water content (Wc). The results showed that the meat dried in a chamber system with a spinning disc had an average water content of 19 % after 10 h, whereas meat dried in a chamber system with a fan had 22 %.

Vacuum drying

A vacuum dryer is a dryer that uses a reduced-pressure environment to encircle the material that is being dried [156]. The drying chamber functions as the core of the vacuum drying procedure, offering the regulated setting essential for the most effective elimination of moisture while preserving the authenticity and excellence of the materials undergoing dehydration. In order to increase the drying effectiveness of the dried materials, previous research on vacuum drying has used several enhancement methodologies on its drying chamber component.

Suryanto et al. [157] tested a vacuum dryer with a steam ejector to save energy and dry cocoa and coffee beans faster. To enhance the efficiency of the steam ejector in vacuum drying using medium and low-temperature dryers, the original design was altered to incorporate thermal insulation, numerous ejectors, and a mechanism for controlling temperature and pressure. The vacuum dryer, equipped with a steam ejector, consumed 11–12 % less energy and achieved drying times 1–2 h

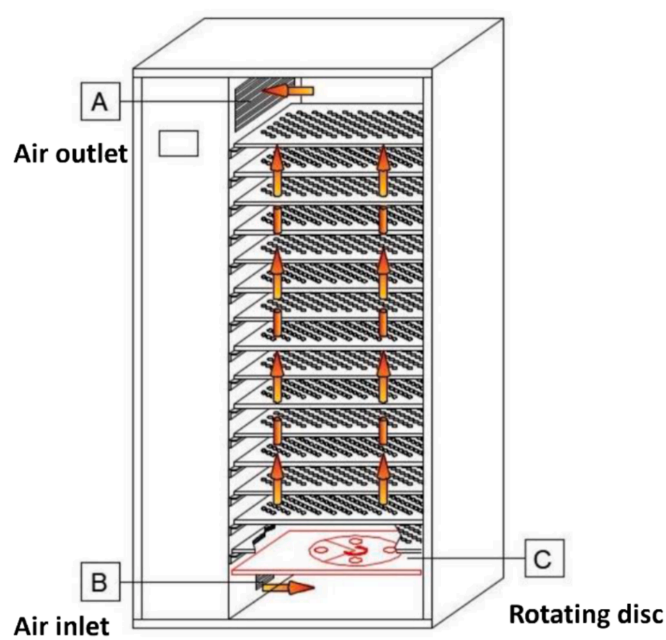

Fig. 6. Drying chamber with several design modifications and rotating disc [121].

shorter than a drier operating at nearly atmospheric pressure. Nozzle injectors were utilized as an alternative to vacuum pumps to conserve energy.

Liu et al. [158] implemented far-infrared radiation heating-aided pulsed vacuum drying (FIR-PVD) technology in the drying chamber to improve blueberry drying efficiency and reduce energy usage. Cyclic fluctuations between air and vacuum pressure in the drying chamber induce a tunneling effect that enlarges blueberry micropores and speeds drying. Furthermore, using far-infrared radiation as a heat source under pulsed vacuum circumstances saves energy while improving drying uniformity. Alongside this, Zhang et al. [130] incorporated infrared technology within a pulsed vacuum chamber. The carbon fiber sheet electrical infrared (IR) emitters allow for the efficient emission of IR wavelengths, effectively drying the material.

Spray drying

The process of spray drying involves the atomization of a solution, slurry, or emulsion that contains one or more components of the desired product into droplets through spraying. The droplets are subsequently rapidly evaporated into solid powder by heated air at a specific temperature and high pressure [159]. Previous research has investigated several methods to improve the efficiency of spray drying chambers. Langrish et al. [160] investigated a new drying chamber spray drier design and analyzed its performance under different operating situations. The research compares the decrease in wall deposition between the new box and conventional four-inch designs. In terms of wall deposition reduction, 8.8 wt% feed solids concentration and 170 °C intake air temperature work well. The research also evaluates how increasing feed solids concentration and intake air temperature affect the new box design. Fig. 7 shows that the new design has lower wall deposition fluxes and less wall adhesion under these circumstances, implying operating efficiency and wall deposition reduction.

The effect of the location of the drying air inlet within a chamber on material adhesion to walls was investigated by Nanang Ruhyat [95]. According to the results, an inlet angled away from the diameter of the chamber promotes more uniform drying. In contrast, an inlet positioned in the center induces irregular material accumulation. The uniformity facilitates a more homogeneous blending operation between the liquid substance and drying air, resulting in an extended period of retention for the particulates and an accelerated rate of evaporation.

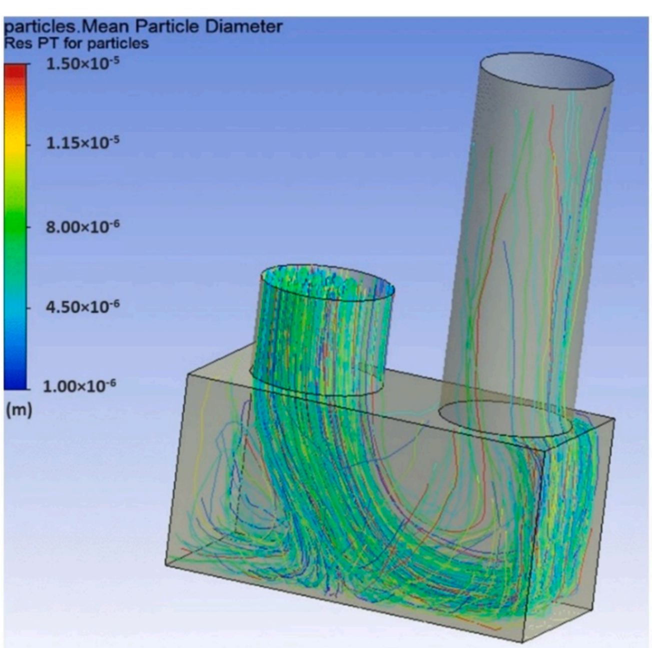

Fig. 7. The newly designed box drying chamber design illustrates particulate deposition paths on the wall [160].

Fluidized bed drying

The fluidized bed drying (FBD) drying chamber involves forcing hot air through a distributor to suspend solid particles in a fluidized condition while resisting gravity forces. This process happens when air velocity overcomes gravitational force and bed resistance, enabling particles to be fluidized by balancing drag force and particle weight [161]. FBD is widely regarded as an attractive technology for expediting evenly-dried material production. However, its primary drawbacks are excessive electrical power consumption, undesired pressure dips, and subpar fluidization quality (including channeling, agglomeration, reverse particle mixing, and bubble formation) in some goods [162]. As a result, several previous studies have included enhancements to the drying chamber of FBD to enhance its drying efficiency.

Philippe Eliaers and Juray De Wilde [163] used a vortex chamber to create a rotating fluidized bed in a static geometry (RFB-SG) and compared its performance to a conventional fluidized bed (FB) for drying woody biomass. The RFB-SG worked at a substantially greater gas flow rate than the standard FB, although air use efficiency was maintained for a given biomass output moisture content. This shows that the RFB-SG increased specific biomass feed rates while conserving air. The RFB-SG intensified the drying process by increasing gas–solid slip velocities, particle bed density, and homogeneity and optimizing the drying chamber design to reduce air utilization.

Majumder et al. [164] made several adjustments to the drying chamber. It was discovered that the active drying time could be decreased by implementing intermittent drying strategies, including vacuum intermittent and open-air intermittent drying. Among these, open-air intermittent drying requires the least amount of time. Active drying time is reduced by a greater magnitude (approximately 2.5 h), and specific energy consumption is decreased by 42.44–43.83 % when intermittent open-air drying is employed instead of continuous drying. Minimizing thermal stress also increased the rehydration capability of desiccated material by 22.15 % and decreased product shrinkage by 12 %. Momenzadeh et al. [160] examined green peas' drying characteristics in a fluidized bed dryer assisted by microwaves, with varying levels of microwave energy and drying air temperature. As demonstrated by the study, the addition of microwave radiation reduced the drying time by as much as 78.8 %.

Microwave drying

The drying chamber functions as a containment structure for the material undergoing drying, enabling the efficient transmission of microwave energy to remove moisture and attain the intended degree of dryness. Previous research has innovatively developed many improvements to the microwave drying chamber, bringing its performance to new heights via a variety of adjustments. Lv et al. [165] demonstrate a substantial enhancement in the drying efficiency and quality of apple slices by implementing ultrasound-assisted techniques within the drying chamber of microwave drying. This is accomplished by increasing the rate of moisture migration, which decreases the dielectric constant, improves uniformity, and expedites the drying process. Next, Shen et al. [166] applied the continuous drying concept to the microwave drying chamber. The findings reveal that the consistent motion of the grain layer along a conveyor belt in the continuous microwave dryer successfully mitigates the excessive absorption of microwave energy, thereby ensuring a relatively uniform temperature and moisture content distribution.

Guo et al. [167] employed a self-developed pilot-scale microwave dryer to compost dewatered sewage sludge mechanically. The microwave chamber operates in constant temperature and voltage conditions. The microwave output power, starting mass, as well as heating mode were employed to investigate the microwave drying performance. Specific energy consumption, energy efficiency, and drying efficiency were greatly influenced by the output power, with constant temperature and starting mass following in that order. The energy consumption of mechanically dewatered sewage sediment was reduced by 14 %. The average drying rate increased by 6 % and energy efficiency by 20 % for every 1 kW increase in output power. A 3 kW composter dried dewatered sewage sludge over 80 °C. In terms of operational safety and product quality, the constant temperature mode outperformed the constant power mode. Optimizing material load in microwave drying chambers can boost efficiency and energy consumption, according to Soysal et al. [168]. The research indicated that increasing the material load in microwave-drying parsley leaves increased drying efficiency by 9.5 % and decreased specific energy consumption by 18 %.

Freeze drying

Freeze drying is ideal for preserving biological materials and is a standard for a high-quality drying process. By sublimating water from solid to vapor without a liquid phase, much of the raw material's appearance, shape, taste, color, and flavor is preserved [169]. The freeze-drying chamber creates a controlled atmosphere with low pressure and temperature for sublimation. Previous research has resulted in enhancements such as heat transfer enhancement technology [170] for greater energy efficiency and upgraded monitoring systems [171,172] for precise management of the drying process. Piechnik et al. [170] concentrated on creating a three-dimensional coupled Computational Fluid Dynamics (CFD) model for small-scale freeze-dryers with an integrated freeze-drying chamber and ice trap to predict and reduce freezing time. The CFD model was created and verified to improve the form of the freeze-dryer unit, resulting in a 50 % reduction in freezing time over the reference design. Freezing time improvements automatically minimize energy use and match customer demand for high-quality, minimally processed, preservative-free food.

Lietta et al. [172] examined using an infrared (IR) camera as a monitoring tool during the freeze-drying of medicinal items. IR camera positioned inside the drying chamber monitors vial temperature to estimate the primary drying finishing point, heat transfer coefficient to product, and dried product vapor flux resistance. The findings demonstrate that the IR camera is a reliable process analytical device for freeze-drying since its readings are comparable to those of thermocouples.

Infrared drying

Infrared drying operates by converting the energy of the infrared radiation that enters the material into heat, resulting in a more uniform removal of water [173]. The drying chamber utilized in infrared drying enables the precise administration of infrared radiation to effectively eliminate moisture from substances, guaranteeing consistent drying and enhanced processing parameters. Prior investigations have explored various approaches to improve the effectiveness of drying chambers utilized in infrared drying.

Zhang et al. [174] sought to create an effective drying process for poria cubes, a traditional herb known for its health advantages. The authors used air impingement and infrared drying in the chamber. Comparisons include drying kinetics, product quality, and energy use. This research found that IR-AID decreased drying time by 46.3 % and used the least energy (1.38 MJ/kg). This shows that infrared-assisted air impingement drying has the lowest drying time, energy usage, and greatest quality. Özdemir et al. [175] used artificial neural networks (ANNs) to anticipate sliced kiwifruit's energy consumption and drying kinetics by combining the incoming air with the air from a heat recovery unit. This prediction was made at various drying temperatures. An increase in temperature from 40 °C to 55 °C reduced drying time by 51 %. The obtained energy efficiency ratings ranged from 2.85 % to 32.17 %.

Hybrid drying

Using hybrid drying techniques in the drying chamber is also a smart initiative to produce better-quality products. Additionally, the use of hybrid techniques for drying inside the drying chamber is a strategic endeavor that is a sensible move to generate products of higher quality [176]. Chojnacka et al. [15] stated that hybrid technologies can achieve energy savings of up to 80 %. Researchers have studied several combinations of drying methods to improve the drying system performance. Sivakumar et al. [177] address the benefits of heat pump technology in agricultural fluidized bed drying (FBD). Heat pump-assisted inside the FBD chamber are 2–3 times more energy efficient than traditional methods, depending on the product's drying characteristics.

Wei et al. [178] used a combination of hot air drying (HAD) with low-power intermittent microwave vacuum drying (LPIMVD) and high-power intermittent microwave vacuum drying (HPIMVD) inside the chamber to dehydrate the taro slices. The study revealed that microwave-only drying exhibited the maximum drying rate but with the lowest drying uniformity. Conversely, the combination of heat-assisted drying (HAD) and microwave drying demonstrated enhanced uniformity and better quality of the dried items. The taro slices that were dried using HAD HPIMVD LPIMVD exhibited a significant decrease of 62.5 % in drying time compared to the IMVD with the HAD method.

The design and performance evaluation of a cabinet hybrid shrimp drying chamber, which incorporates solar energy and an auxiliary infrared source, was reported by Abedini et al. [179] as illustrated in Fig. S1 (Supplementary material; Fig. S1). In order to compare and evaluate the drying time, received energy, drying effectiveness, and appearance of dried shrimp, the study employs a variety of pre-treatments and drying methods. Dried shrimp meat dries most effectively and appears its finest when pre-treated with simmering in a 2 % (w/v) water-salt solution, according to the results of the hybrid drying method. At this capacity, the drying device is estimated to have an efficiency rating of 16.37 % and a capacity of 2500 g. As an auxiliary source, the infrared lamp substantially affects the drying procedure and the ultimate quality of the dried crustaceans.

Jiang et al. [125] discovered pulse-spouted microwave freeze-drying (PSMFD). An electromagnetic valve periodically introduces air into the drying chamber, enabling pressure to fluctuate. The airflow rate is manually managed to maintain pressure variation in the drying chamber from 0.080 kPa to 1.2 kPa during the spout duration and a recovery time of fewer than 30 s. This dynamic air input modulation improves drying and product quality. Anum et al. [180] tested a novel hybrid sun dryer for drying onion, ginger, and cabbage in Pakistani climates. The dryer reduced product moisture using solar energy during the day and a backup source at night, achieving an average efficiency of 42.79 %, reducing postharvest losses and increasing growers' net income.

Summary and discussion

An extensive number of studies have been done in this field, and specific issues still need to be researched since some gaps hinder the development of this technology from being widely used. Due to that, enhancements must be made to the drying system's energy efficiency and performance parameters to facilitate an effective drying process. Studies conducted in the past have shown that the hybrid drying method is the most promising strategy among the several available methods. However, none of the papers reviewed addressed the issue of increasing heat transfer between the surrounding environment and dried materials and uniform airflow and temperature distribution across the chamber by enhancing the heat source, modifying the surrounding environment, and adding a directional nozzle and jet impingement.

Table 3 summarises references to drying chamber enhancement techniques with different drying technologies. Fig. 8 shows some of the chosen benchmarks' resulting performance characteristics (Fig. 8a for the drying efficiencies and drying durations, while Fig. 8b for the

Table 3
Summary of related past research on enhancing drying chambers in diverse drying technologies.

Authors [Ref]	Analytical methods	Drying technologies	Enhancement strategies	Dried products	Locations	Yrs
Soysal et al. [168]	Experimental	Microwave drying	Modifying the material load to optimize the performance of the drying chamber.	Parsley leaves	Turkey	2006
Momenzadeh et al. [181]	Experimental	Fluidized bed drying	Microwave drying technology was used in the chamber to assist the drying process.	Green pea	Iran	2012
Philippe Eliaers and Juray De Wilde [163]	Experimental	Fluidized bed drying	Developed a revolving fluidized bed in static geometry using a vortex chamber.	Beechwood particles	Belgium	2013
Jiang et al. [125]	Experimental	Hybrid drying (microwave freeze drying)	Combined microwave, freeze, and spouted bed drying in the drying chamber.	Bananas	China	2015
Anum et al. [180]	Experimental	Hybrid drying (solar drying with gas-fired)	A hybrid dryer with solar energy and a gas-powered source was used.	Ginger, onion, cabbage	Pakistan	2016
Aktas et al. [140]	Experimental	Heat pump drying	Used a cylindrical form of drying chamber with the heat recovery unit	Mint leaves	Turkey	2017
Özdemir et al. [175]	Experimental	Infrared drying	Incoming air is combined with heat recovery unit air into the drying chamber and predicted using artificial neural networks (ANNs).	Kiwifruit	Turkey	2017
Wei et al. [178]	Experimental	Hybrid drying (hot air drying with microwave drying)	Combined hot air drying (HAD) with low- and high-power intermittent microwave vacuum drying (LPIMVD and HPIMVD) inside the chamber.	Taro slices	China	2018
Zhang et al. [130]	Experimental	Vacuum drying	It included infrared technology within a pulsed vacuum chamber.	Goji berries and grape	China	2019
Lv et al. [165]	Experimental	Microwave drying	Implemented ultrasound-assisted techniques in the drying chamber.	Apple slices	China	2019
Lietta et al. [172]	Experimental	Freeze drying	Installed an infrared camera inside the drying chamber to monitor the temperature of the vials.		Italy	2019
Tuncer et al. [93]	Experimental and numerical	Solar drying	Developed a unique convex-type solar absorber drying chamber	Sewage sludge	Turkey	2020
Khanlari et al. [150]	Experimental and numerical	Solar drying	The drying chamber design includes a transparent cover to facilitate direct solar radiation.	Sewage sludge	Turkey	2020
Babu et al. [154]	Experimental	Heat pump drying	A batch drying chamber with many trays enables thin-layer drying of delicate, heat-sensitive food products like edible leaves.	Edible leaves	India	2020
Singh et al. [155]	Experimental	Heat pump drying	A convective batch dryer with air recirculation control and enhanced tray design for optimal performance.	Banana and potato chips	India	2020
Suryanto et al. [157]	Experimental	Vacuum drying	The vacuum dryer is equipped with a steam ejector	Cocoa and coffee beans	Indonesia	2020
Langrish et al. [160]	Numerical	Spray drying	Developed a novel geometry and airflow of the spray drying chamber.		Australia	2020
Sheng et al. [166]	Experimental and numerical	Microwave drying	Implemented the notion of continuous drying into the microwave drying chamber application.	Germinated brown rice	China	2020
Olejnik et al. [121]	Numerical	Heat pump drying	Modified drying chamber with a rotating disc	Beef jerky	Poland	2021
Guo et al. [167]	Experimental	Microwave drying	The dryer uses a self-developed pilot scale to dry mechanically and compost dewatered sewage sludge.	Sewage sludge	China	2021
Zhang et al. [174]	Experimental	Infrared drying	Utilized air impingement and infrared drying within the chamber.	Poria Cocos (China root)	China	2021
Liu et al. [158]	Experimental	Vacuum drying	The vacuum drying chamber has a far-infrared radiation heating element, pressure sensor, and weighing sensor.	Blueberries	China	2022
Majumder et al. [164]	Experimental and numerical	Fluidized bed drying	The fluidized bed dryer is facilitated by solar energy technology and is connected to a liquid desiccant dehumidifier.	Ginger	India	2022
Abedini et al. [125,179]	Experimental	Hybrid drying (solar drying with infrared drying)	The chamber is equipped with solar energy and an auxiliary infrared source.	Shrimps	Iran	2022
Nanang Ruhyat [95]	Numerical	Spray drying	Changed the location and the design of the drying chamber's air inlet.		Indonesia	2023
Patel et al. [108]	Experimental	Solar drying	Four different operational dryer systems	Onion slices	India	2024
Piechnik et al. [170]	Experimental and numerical	Freeze drying	Implemented an ice trap in the freeze-drying chamber.	Potato	Poland	2024

specific energy consumptions and specific moisture extraction rates). It is noticeable that the drying efficiency varies substantially among the studies, with values ranging from 36 % to 76 %. The drying time also exhibits a significant range, with the longest being 532 min and the shortest being 19 min. Furthermore, it can be shown that the SMER parameters reached the greatest SMER of 5.37 kg/kWh, suggesting a highly effective drying process, while other studies recorded SMER values of less than 1 kg/kWh, indicating inefficient drying. The SEC values in this comparison vary greatly, from around 1.77 kWh/kg to 4180 kWh/kg. Higher SEC values imply a more energy-intensive drying process, while lower SEC values represent a more energy-efficient strategy.

According to Table 3 and Fig. 8, drying chamber research in drying technologies continues to be significant for scientists. The fact that the majority of the research described was published over the past several decades provides evidence of this. The chosen studies differ significantly in terms of drying efficiency, drying durations, SEC, and SMER. This variation is caused by the drying method, materials utilized, the drying chamber design and system, and the drying process operating conditions. Asian countries constituted the majority of the investigation. The majority of the research has been undertaken in hot locations or high-temperature environments. This point can be regarded as crucial since large drying efforts are predicted in the future. As importantly, these outcomes highlight the need for further study into improving drying

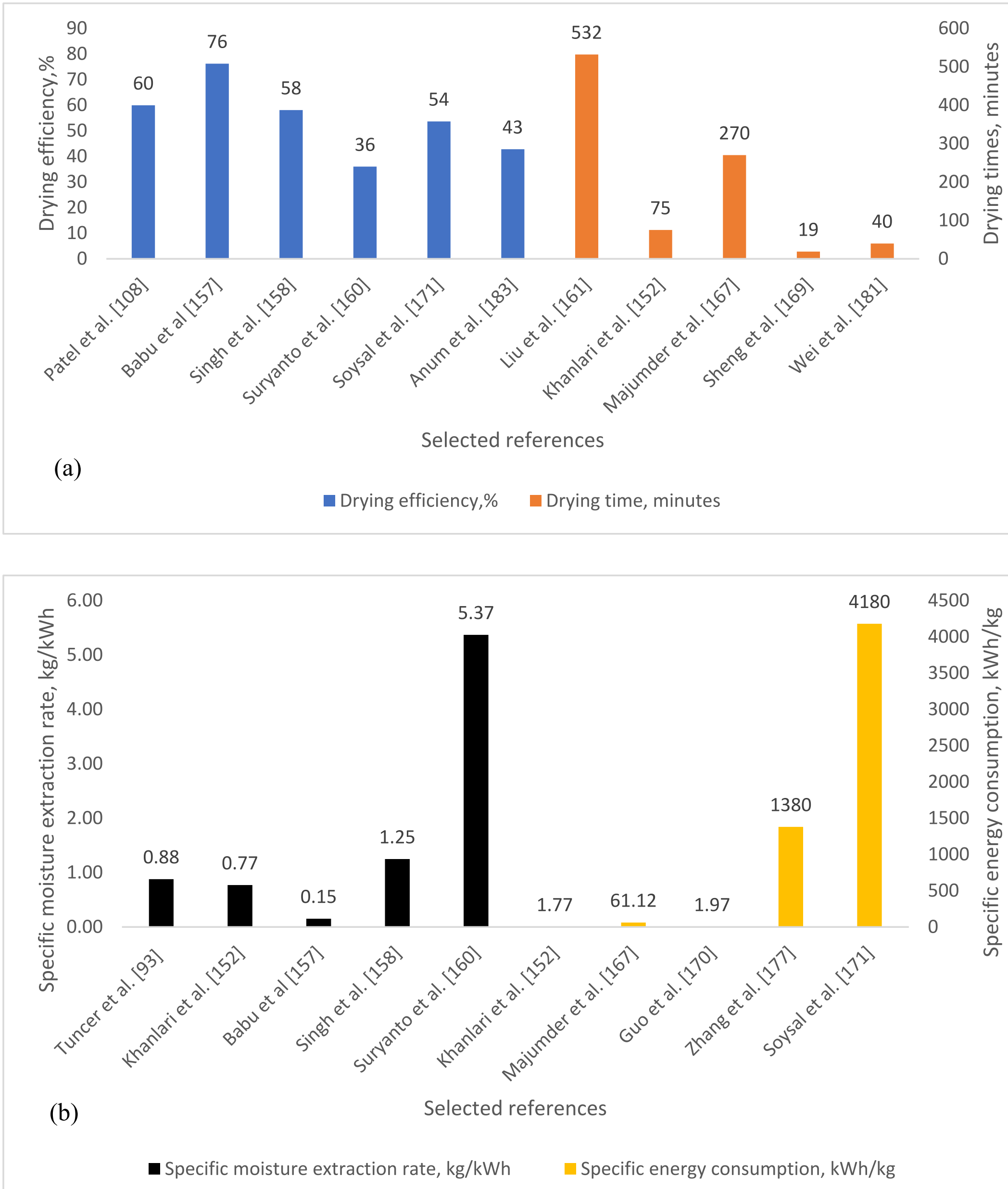

Fig. 8. Comparison of performance parameters among past researchers: a) Drying efficiency and drying durations of previous studies; b) SMER and SEC of previous studies.

chamber designs to improve energy efficiency and food security.

Point of departure

By emphasizing these strategies, researchers can surmount the challenges identified in prior research and make a meaningful contribution to the ongoing advancement of drying technologies that satisfy the needs of the food and agriculture industries. During the last several decades, extensive studies have been conducted about drying chambers in drying technologies. Previous research has confirmed the significance of these studies in successfully implementing drying chambers as an effective means of drying. Nevertheless, the drying chamber is now undergoing development and exhibits several aspects and deficiencies that need further investigation. Researchers face many obstacles that must be addressed in order to build an efficient drying chamber component. Following an extensive literature review, certain challenges and hotspots for future research have been identified and listed below:

- Drying methods requiring a drying chamber are widely employed in food and agriculture. As a result, further drying studies across different industries are needed to increase the drying chamber's versatility and use.
- The design and system of the drying chamber determine the variation in moisture content removal, temperature, and velocity distributions. Therefore, it is essential to use effective strategies that provide a consistent distribution of heat transmission throughout the drying chamber to get a uniform drying rate.
- The location and design of the heat source's inlet and outlet determine airflow and temperature uniformity. As a result, a study on numerous inlets and outlets at different places is necessary, especially on convection drying such as heat pump drying, solar drying, vacuum drying, spray drying, and fluidized bed drying to provide a consistent spreading of heat energy and enhanced drying uniformity.
- A highly effective heating and ventilation system in the drying chamber is required to optimize performance parameters, including

drying efficiency, drying times, SEC, SMER, and system energy efficiency.

- Enhancing the effectiveness of the heat source, optimizing the environment around the drying chamber, incorporating jet impingement technology into the drying chamber, and adding a directed nozzle are some further enhancement strategies that can be used.
- Obtaining an efficient drying process while maintaining the quality of the dried materials can be challenging, especially when certain products have specific operational parameters. Hence, implementing an advanced monitoring system is important to get accurate results for an effective drying procedure that provides high-quality dried products.
- Radiation modes of drying chambers such as microwave, infrared, and solar dryers offer faster and more uniform drying than other technologies. Thus, further research should be done on hybrid drying, which combines radiation mode dryers with various testing on food and agricultural products in the chamber to provide a wide range of alternate drying methods.
- A significant number of studies have been conducted on the subject of hybrid drying technologies. Still, it has yet to be shown how these technologies would affect the economy or the environment. This could be critical since these technologies need detailed feasibility studies before being adopted in real-world applications.
- The benefit of integrating renewable energy technology with various drying technologies has not been studied. Thus, conducting more research towards fulfilling the SDGs, fostering net zero emissions, and contributing to environmental sustainability is crucial.
- There is a substantial difference in the performance parameter values shown in previous investigations of drying chambers using various drying methods. Exploring the key findings from these variations among different technologies can offer valuable insights into their strengths and limits.

Conclusion

The drying chamber is utilized in drying technologies to conduct the drying process. This review examines various drying chamber designs created over the past forty years, focusing primarily on their performance. The discussion encompassed the performance metrics, enhancing strategies, heat transfer mechanisms, applications, limitations, and potential areas for future research on the drying system. The reviews were categorized into solar drying, heat pump drying, vacuum drying, spray drying, fluidized bed drying, microwave drying, freeze drying, infrared drying, and hybrid drying. During the previous few decades, the emphasis has been on novel techniques, designs, and the incorporation of advanced technologies into drying chambers. We found that the hybrid drying technique is the most promising strategy for improvement. The study showed many comparisons based on performance criteria, including drying efficiencies, drying durations, SMER, and SEC, along with significant findings. Besides that, the researchers' findings and work have been evaluated. The research in the literature was compared to the drying chamber's ability to improve the performance of the drying technology used. A critical evaluation was conducted to identify the shortcomings in the research, and many aspects have been emphasized for researchers to consider in their future work and potential enhancements. Based on the above assessment, we propose adopting the following solutions to resolve the identified concerns: improving the heat source, adjusting the environmental conditions, applying jet impingement, and adding a directed nozzle to achieve better drying. Next, it is recommended that the monitoring system for drying be improved, economic and environmental impact analysis performed, and renewable energy technology for long-term sustainability integrated.

CRediT authorship contribution statement

Muhammad Aqil Afham Rahmat: Writing – original draft, Methodology, Formal analysis, Conceptualization. **Adnan Ibrahim:** Supervision, Methodology, Funding acquisition, Conceptualization. **Muhammad Ubaidah Syafiq Mustaffa:** Writing – review & editing, Supervision, Methodology. **Khaled M. Al-Aribe:** Writing – review & editing, Supervision, Methodology. **Hariam Luqman Azeez:** Writing – original draft, Methodology, Formal analysis, Conceptualization. **Sahibzada Imad Ud Din:** Validation, Formal analysis. **Mahmoud Jaber:** Validation, Formal analysis. **Monaem Elmnifi:** Validation, Formal analysis.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.seta.2025.104205.

Data availability

Data will be made available on request.

References

[1] Doering O, Sorensen A. The land that shapes and sustains us. How to Feed the World 2018:46–58. https://doi.org/10.5822/978-1-61091-885-5.
[2] Cole MB, Augustin MA, Robertson MJ, Manners JM. The science of food security. NPJ Sci Food 2018;2(1):Dec. https://doi.org/10.1038/s41538-018-0021-9.
[3] Béné C, et al. Feeding 9 billion by 2050 – putting fish back on the menu. Food Secur Apr. 2015;7(2):261–74. https://doi.org/10.1007/s12571-015-0427-z.
[4] Vollset SE, et al. Fertility, mortality, migration, and population scenarios for 195 countries and territories from 2017 to 2100: a forecasting analysis for the Global Burden of Disease Study. Lancet 2020;396(10258):1285–306. https://doi.org/10.1016/S0140-6736(20)30677-2.
[5] Kincharov A, Demina E, Kincharova M, Taranova T, Chekmasova K. Accelerated adaptation of spring wheat to climate change necessary. BIO Web of Conferences EDP Sciences Nov. 2023. https://doi.org/10.1051/bioconf/20237101049.
[6] EL-Mesery HS, EL-Seesy AI, Hu Z, Li Y. Recent developments in solar drying technology of food and agricultural products: a review. Renew Sustain Energy Rev 2022;157:112070. https://doi.org/10.1016/j.rser.2021.112070.
[7] Ortiz-Rodríguez NM, Condorí M, Durán G, García-Valladares O. Solar drying Technologies: A review and future research directions with a focus on agroindustrial applications in medium and large scale. Appl Therm Eng 2022;215 (July). https://doi.org/10.1016/j.applthermaleng.2022.118993.
[8] Tracking progress on food and agriculture-related SDG indicators 2023. 2023. doi: 10.4060/cc7088en.
[9] Xiao HW, Mujumdar AS. Importance of drying in support of human welfare. Drying Technol 2020;38(12):1542–3. https://doi.org/10.1080/07373937.2019.1686476.
[10] Devahastin S. Food security: impact of climate change and technology. Drying Technol Aug. 2020;38(11):1538. https://doi.org/10.1080/07373937.2019.1638108.
[11] Sivakumar R, Saravanan R, Elaya Perumal A, Iniyan S. Fluidized bed drying of some agro products – a review. Renew Sustain Energy Rev 2016;61:280–301. https://doi.org/10.1016/j.rser.2016.04.014.
[12] Olabi AG, et al. Progress in Solar Thermal Systems and Their Role in Achieving the Sustainable Development Goals. Dec. 01, 2022, MDPI. doi: 10.3390/en15249501.
[13] Fernandes FAN, Rodrigues S. Ultrasound applications in drying of fruits from a sustainable development goals perspective. Ultrason Sonochem 2023;96:106430. https://doi.org/10.1016/j.ultsonch.2023.106430.
[14] Mondal MHT, Shiplu KSP, Sen KP, Roy J, Sarker MSH. Performance evaluation of small scale energy efficient mixed flow dryer for drying of high moisture paddy. Drying Technol Sep. 2019;37(12):1541–50. https://doi.org/10.1080/07373937.2018.1518914.
[15] Chojnacka K, et al. Improvements in drying technologies - Efficient solutions for cleaner production with higher energy efficiency and reduced emission. J Clean Prod 2021;320:128706. https://doi.org/10.1016/j.jclepro.2021.128706.
[16] El Hage H, Herez A, Ramadan M, Bazzi H, Khaled M. An investigation on solar drying: A review with economic and environmental assessment. Energy 2018;157:815–29. https://doi.org/10.1016/j.energy.2018.05.197.

[17] Xiao H-W, Pan Z, Martynenko A, Law C-L, Nema PK. Innovative and emerging drying technologies for enhancing food quality. J Food Qual 2018;2018:6943078. https://doi.org/10.1155/2018/6943078.
[18] Kaimal AM, Tidke VB, Mujumdar AS, Thorat BN. Food security and sustainability through solar drying technologies: a case study based on solar conduction dryer. Mater Circ Econ 2022;4(1):7. https://doi.org/10.1007/s42824-022-00051-9.
[19] W. L. Kerr, "Chapter 14 - Food Drying and Evaporation Processing Operations," in Handbook of Farm, Dairy and Food Machinery Engineering (Third Edition), M. Kutz, Ed., Academic Press, 2019, pp. 353–387. doi: https://doi.org/10.1016/B978-0-12-814803-7.00014-2.
[20] U. Akyol, A. Erhan Akan, and A. Durak, "Simulation and thermodynamic analysis of a hot-air textile drying process," The Journal of The Textile Institute, vol. 106, no. 3, pp. 260–274, Mar. 2015, doi: 10.1080/00405000.2014.916062.
[21] Sharma A, Khamar D, Cullen S, Hayden A, Hughes H. Innovative Drying Technologies for Biopharmaceuticals. Int J Pharm 2021;609:121115. https://doi.org/10.1016/j.ijpharm.2021.121115.
[22] Horuz E, Bozkurt H, Karataş H, Maskan M. Drying kinetics of apricot halves in a microwave-hot air hybrid oven. Heat and Mass Transfer/Waerme- und Stoffuebertragung Jun. 2017;53(6):2117–27. https://doi.org/10.1007/s00231-017-1973-z.
[23] Wang D, Tan L, Yuan Y, Lu Y. CFD simulation and optimization on airflow uniformity of material drying room used in steam blanching and hot-air vacuum drying equipment. J Mech Sci Technol 2023;37(10):5463–74. https://doi.org/10.1007/s12206-023-0945-0.
[24] M. Azadbakht, M. V. Torshizi, A. Ziaratban, and H. Aghili, "Energy and exergy analyses during eggplant drying in a fluidized bed dryer," 2017. [Online]. Available: http://www.cigrjournal.org.
[25] Zhao HB, Wu K, Zhang JF. Simulation study on active air flow distribution characteristics of closed heat pump drying system with waste heat recovery. Energies (Basel) 2021;14(19):Oct. https://doi.org/10.3390/en14196358.
[26] M. I. M. I. H. K. A. A. A. Hang Qu M. H. Masud and A. Karim, "Sustainable food drying technologies based on renewable energy sources," Crit Rev Food Sci Nutr, vol. 62, no. 25, pp. 6872–6886, 2022, doi: 10.1080/10408398.2021.1907529.
[27] Bourdoux S, Li D, Rajkovic A, Devlieghere F, Uyttendaele M. Performance of Drying Technologies to Ensure Microbial Safety of Dried Fruits and Vegetables. Compr Rev Food Sci Food Saf 2016;15(6):1056–66. https://doi.org/10.1111/1541-4337.12224.
[28] Ardita IN, Wirajati IGAB, Susila IDM, Suherman IK. In: Drying Spices by Utilizing the Dehumidification Process and the Heat Condensor in the Refrigeration System. Atlantis Press; 2024. p. 49–56. https://doi.org/10.2991/978-94-6463-364-1_6.
[29] Xu C, Ma H, Wang S. Thermal digestion characteristics of kitchen waste based on high temperature heat pump combined with vacuum drying. Appl Therm Eng 2024;244:122703. https://doi.org/10.1016/j.applthermaleng.2024.122703.
[30] Nguyen T-V-L, Nguyen P-B-D, Tran TTV. Kinetics of infrared drying of avocado (Persea americana) pulp with different formulations. Cogent Food Agric Dec. 2024;10(1):2303835. https://doi.org/10.1080/23311932.2024.2303835.
[31] Hinostroza-Quiñonez G, Alcántara-Mucha L, Espinoza-Silva C, Quispe-Solano M, Saavedra-Mallma N. Physicochemical and functional properties of microcapsules of papaya seed extract (Carica papaya L.) obtained by spray drying. NFS J 2024:100164. https://doi.org/10.1016/j.nfs.2024.100164.
[32] Teba HE, Khalil IA, Gebreel RM, Fahmy LI, El Sorogy HM. Development of antifungal fibrous ocular insert using freeze-drying technique. Drug Deliv Transl Res 2024. https://doi.org/10.1007/s13346-024-01527-8.
[33] Akhtaruzzaman M, Kamal MM, Alam SMS, Sarker MSH, Mondal MHT. Impacts of two-stage drying techniques on drying characteristics, physical and nutritional quality of maize. J Agric Food Res 2024:101046. https://doi.org/10.1016/j.jafr.2024.101046.
[34] Kong D, Wang Y, Li M, Liang J. A comprehensive review of hybrid solar dryers integrated with auxiliary energy and units for agricultural products. Energy 2024;293:130640. https://doi.org/10.1016/j.energy.2024.130640.
[35] Kusuma HS, et al. Experimental investigation in the drying process of moringa leaves using microwave drying: drying kinetics, energy consumption, and CO2 emission. Appl Food Res 2024;4(1):100401. https://doi.org/10.1016/j.afres.2024.100401.
[36] Olabiǹjo O, Sama M. Evaluating the Effects of Drying Temperatures on the Nutritional and Bioactive Quality of Ackee Aril Apples. Turkish J Agric Eng Res 2023;4(2):289–300. https://doi.org/10.46592/turkager.1384004.
[37] Jr. Robert E. Perdue, "Field Drying Plant Material Collected for Chemical and Biological Screening. I. Portable Facility for Sun Drying," Econ Bot, vol. 36, no. 4, pp. 369–372, 1982, [Online]. Available: http://www.jstor.org/stable/4254421.
[38] Yong CK, Islam MR, Mujumdar AS. Mechanical means of enhancing drying rates: Effect on drying kinetics and quality. Drying Technol 2006;24(3):397–404. https://doi.org/10.1080/07373930600616678.
[39] Ortiz-Jerez MJ, Ochoa-Martínez CI. Heat Transfer Mechanisms in Conductive Hydro-Drying of Pumpkin (Cucurbita maxima) Pieces. Drying Technol Jun. 2015;33(8):965–72. https://doi.org/10.1080/07373937.2015.1009538.
[40] A. S. Mujumdar and A. S. Mujumdar, "Classification and selection of industrial dryers," 2000. [Online]. Available: https://www.researchgate.net/publication/265533511.
[41] Xiao T, et al. Heating performance, exergy, and economic analysis of a heat pump drying system with an independent operating ability for drying shiitake mushrooms. J Clean Prod 2023;426:138982. https://doi.org/10.1016/j.jclepro.2023.138982.
[42] Uthpala TGG, Navaratne SB, Thibbotuwawa A. Review on low-temperature heat pump drying applications in food industry: Cooling with dehumidification drying method. J Food Process Eng Oct. 2020;43(10):e13502. https://doi.org/10.1111/jfpe.13502.
[43] K. K. Patel and A. Kar, "Heat pump assisted drying of agricultural produce - An overview," Apr. 2012. doi: 10.1007/s13197-011-0334-z.
[44] Loemba ABT, Kichonge B, Kivevele T. Comprehensive assessment of heat pump dryers for drying agricultural products. Energy Sci Eng Aug. 2023;11(8):2985–3014. https://doi.org/10.1002/ese3.1326.
[45] Yuan G, Chu KH. Heat pump drying of industrial wastewater sludge. Water Pract Technol Apr. 2020;15(2):404–15. https://doi.org/10.2166/wpt.2020.029.
[46] Zheng Q, Cao L, Ni L, Huang G. Operating characteristics of sludge heat pump dryer and influencing factors of performance: A field experiment in an electroplating factory. Appl Therm Eng 2022;212:118602. https://doi.org/10.1016/j.applthermaleng.2022.118602.
[47] Pu Y-Y, Sun D-W. Combined hot-air and microwave-vacuum drying for improving drying uniformity of mango slices based on hyperspectral imaging visualisation of moisture content distribution. Biosyst Eng 2017;156:108–19. https://doi.org/10.1016/j.biosystemseng.2017.01.006.
[48] Xu G, Yin H, He X, Wang D, Zhao Y, Yue J. Optimization of microwave vacuum drying of okra and the study of the product quality. J Food Process Eng Feb. 2020;43(2):e13337. https://doi.org/10.1111/jfpe.13337.
[49] Zhao L, Li Y, Xie H, Zhang J, Wu Z. Drying characteristics and product quality of whole blueberry pulp in vacuum drying process 2021;17(10):755–69. https://doi.org/10.1515/ijfe-2021-0130.
[50] Singh DK, Villamayor A, Gwatida P. Analysis of the modified vacuum drying process in industrial heat exchanger. AIP Conf Proc Feb. 2021;2317(1):050006. https://doi.org/10.1063/5.0036116.
[51] He Z, Yang F, Peng Y, Yi S. Ultrasound-assisted vacuum drying of wood: Effects on drying time and product quality. BioResources 2013;8(1):855–63. https://doi.org/10.15376/biores.8.1.855-863.
[52] O. M. Brenes Angulo, B. H. Bond, H. Quesada -Pineda, and E. Kline, "The Impact of Vacuum-Drying on Efficiency of Hardwood Products Manufacturing".
[53] Abdollahzadeh Delazi M, Amiri Chayjan R, Kaveh M. Optimizing the GHG emissions and energy consumption of power plants in the industry of vacuum drying using a controlled atmosphere method (case study: apple pulp). Clean Technol Environ Policy 2024. https://doi.org/10.1007/s10098-024-02778-2.
[54] Restrepo Román A, Bedoya ID, Amell AA. Comparative, numerical, and experimental study of the influence of infrared radiation on a radiative-convective drying system for kaolin clay. Case Stud Therm Eng 2023;49:103329. https://doi.org/10.1016/j.csite.2023.103329.
[55] Zhan L, Yang Y, Li W, Wang G, Li Y, Wang N. Drying kinetics and mechanical properties of low temperature microwave dried cashmere fibers. Text Res J Jun. 2020;90(23–24):2745–54. https://doi.org/10.1177/0040517520929361.
[56] Sakare P, Prasad N, Thombare N, Singh R, Sharma SC. Infrared Drying of Food Materials: Recent Advances. Food Eng Rev 2020;12(3):381–98. https://doi.org/10.1007/s12393-020-09237-w.
[57] Pawar SB, Pratape VM. Fundamentals of infrared heating and its application in drying of food materials: a review. J Food Process Eng Feb. 2017;40(1):e12308. https://doi.org/10.1111/jfpe.12308.
[58] Samborska K, et al. Innovations in spray drying process for food and pharma industries. J Food Eng 2022;321:110960. https://doi.org/10.1016/j.jfoodeng.2022.110960.
[59] Koca N, Erbay Z, Kaymak-Ertekin F. Effects of spray-drying conditions on the chemical, physical, and sensory properties of cheese powder. J Dairy Sci 2015;98(5):2934–43. https://doi.org/10.3168/jds.2014-9111.
[60] Poozesh S, Bilgili E. Scale-up of pharmaceutical spray drying using scale-up rules: A review. Int J Pharm 2019;562:271–92. https://doi.org/10.1016/j.ijpharm.2019.03.047.
[61] Sarker MSH, Ibrahim MN, Abdul Aziz N, Punan MS. Energy and exergy analysis of industrial fluidized bed drying of paddy. Energy 2015;84:131–8. https://doi.org/10.1016/j.energy.2015.02.064.
[62] Rosli MI, Nasir AMimA, Takriff MS, Chern LP. Simulation of a fluidized bed dryer for the drying of sago waste. Energies (Basel) 2018;11(9):Sep. https://doi.org/10.3390/en11092383.
[63] Si C, Wu J, Wang Y, Zhang Y, Shang X. Drying of low-rank coals: a review of fluidized bed technologies. Drying Technol Feb. 2015;33(3):277–87. https://doi.org/10.1080/07373937.2014.952382.
[64] Chen H, Rustagi S, Diep E, Langrish TAG, Glasser BJ. Scale-up of fluidized bed drying: Impact of process and design parameters. Powder Technol 2018;339:8–16. https://doi.org/10.1016/j.powtec.2018.07.087.
[65] Barba FJ, et al. Solar radiation as a prospective energy source for green and economic processes in the food industry: From waste biomass valorization to dehydration, cooking, and baking. J Clean Prod 2019;220:1121–30. https://doi.org/10.1016/j.jclepro.2019.02.175.
[66] Tagnamas Z, et al. Energy and exergy analyses of carob pulp drying system based on a solar collector. Renew Energy 2021;163:495–503. https://doi.org/10.1016/j.renene.2020.09.011.
[67] Xu C, et al. Energy, exergy and economic analyses of a novel solar-lignite hybrid power generation process using lignite pre-drying. Energy Convers Manag 2018;170:19–33. https://doi.org/10.1016/j.enconman.2018.05.078.
[68] Murali S, Amulya PR, Alfiya PV, Delfiya DSA, Samuel MP. Design and performance evaluation of solar - LPG hybrid dryer for drying of shrimps. Renew Energy 2020;147:2417–28. https://doi.org/10.1016/j.renene.2019.10.002.
[69] Ferreira AG, Gonçalves LM, Maia CB. Solar drying of a solid waste from steel wire industry. Appl Therm Eng 2014;73(1):104–10. https://doi.org/10.1016/j.applthermaleng.2014.07.047.

[70] Ullah H, Shahab A, Rashid A. Volatilization characteristics of selenium during conventional and microwave drying of coal slime: an emerging contaminant in mining industry. Environ Sci Pollut Res 2020;27(10):11164–73. https://doi.org/10.1007/s11356-020-07757-w.

[71] Lv W, Xin Y, Elliott R, Song J, Lv X, Barati M. Drying Kinetics of a Philippine Nickel Laterite Ore by Microwave Heating. Miner Process Extr Metall Rev Jan. 2021;42(1):46–52. https://doi.org/10.1080/08827508.2020.1801433.

[72] Sibel Y, Guray S, Kamil SN, Gokhan Y. Microwave Drying of Automotive Industry Paint Sludge. J Hazard Toxic Radioact Waste Oct. 2018;22(4):04018015. https://doi.org/10.1061/(ASCE)HZ.2153-5515.0000407.

[73] Liu Y, Zhang Z, Hu L. High efficient freeze-drying technology in food industry. Crit Rev Food Sci Nutr Apr. 2022;62(12):3370–88. https://doi.org/10.1080/10408398.2020.1865261.

[74] Ma Y, Yi J, Jin X, Li X, Feng S, Bi J. Freeze-Drying of Fruits and Vegetables in Food Industry: Effects on Phytochemicals and Bioactive Properties Attributes - A Comprehensive Review. Food Rev Intl Oct. 2023;39(9):6611–29. https://doi.org/10.1080/87559129.2022.2122992.

[75] Pisano R, Fissore D, Barresi AA, Rastelli M. Quality by Design: Scale-Up of Freeze-Drying Cycles in Pharmaceutical Industry. AAPS PharmSciTech 2013;14(3):1137–49. https://doi.org/10.1208/s12249-013-0003-9.

[76] I. Sokolova, "Temperature Regulation," in Encyclopedia of Ecology: Volume 1-4, Second Edition, vol. 3, Elsevier, 2019, pp. 633–639. doi: 10.1016/B978-0-12-409548-9.11129-7.

[77] Singh Parihar J, et al. Development of novel cabinet solar dryer using UV sheet and its performance evaluation: An experimental study. Sol Energy 2022;239:1–9. https://doi.org/10.1016/j.solener.2022.04.043.

[78] Aktaş M, Şevik S, Aktekeli B. Development of heat pump and infrared-convective dryer and performance analysis for stale bread drying. Energy Convers Manag Apr. 2016;113:82–94. https://doi.org/10.1016/j.enconman.2016.01.028.

[79] Ganji DD, Sabzehmeidani Y, Sedighiamiri A. Radiation Heat Transfer. Nonlinear Systems in Heat Transfer Elsevier 2018:105–51. https://doi.org/10.1016/B978-0-12-812024-8.00003-5.

[80] Karaca Dolgun G, Aktaş M, Dolgun EC. Infrared convective drying of walnut with energy-exergy perspective. J Food Eng 2021;306:110638. https://doi.org/10.1016/j.jfoodeng.2021.110638.

[81] A. N. Jibril et al., "Effects of graphene irradiation plates and infrared temperature on the physiochemical, morphological, structural, and pasting properties of corn flour," Powder Technol, p. 119610, Mar. 2024. doi: 10.1016/j.powtec.2024.119610.

[82] Wang P, Mohammed D, Zhou P, Lou Z, Qian P, Zhou Q. Roof solar drying processes for sewage sludge within sandwich-like chamber bed. Renew Energy 2019;136:1071–81. https://doi.org/10.1016/j.renene.2018.09.081.

[83] Li C-D, et al. The effect of drying condition of glassfibre core material on the thermal conductivity of vacuum insulation panel. Mater Des 2013;50:1030–7. https://doi.org/10.1016/j.matdes.2013.03.021.

[84] Shahidian A, Ghassemi M, Mohammadi J, Hashemi M. "Introduction," in Bio-Engineering Approaches to Cancer Diagnosis and Treatment. Elsevier 2020:1–22. https://doi.org/10.1016/b978-0-12-817809-6.00001-7.

[85] Scutellà B, et al. 3D mathematical modelling to understand atypical heat transfer observed in vial freeze-drying. Appl Therm Eng 2017;126:226–36. https://doi.org/10.1016/j.applthermaleng.2017.07.096.

[86] Borah A, Hazarika K, Khayer SM. Drying kinetics of whole and sliced turmeric rhizomes (Curcuma longa L.) in a solar conduction dryer. Information Processing in Agriculture 2015;2(2):85–92. https://doi.org/10.1016/j.inpa.2015.06.002.

[87] I. Dubkovetskiy, V. Yurchak, V. Rak, T. Burlaka, and V. Kazmiryshen, "Research of methods and modes of drying of gluten-free pasta," 2019.

[88] Swasdisevi T, Devahastin S, Sa-Adchom P, Soponronnarit S. Mathematical modeling of combined far-infrared and vacuum drying banana slice. J Food Eng 2009;92(1):100–6. https://doi.org/10.1016/j.jfoodeng.2008.10.030.

[89] Delgado-Plaza E, et al. Thermal evaluation of a hybrid dryer with solar and geothermal energy for agroindustry application. Appl Sci (Switzerland) 2019;9(19):Oct. https://doi.org/10.3390/app9194079.

[90] Román F, Strahl-Schäfer V, Hensel O. Improvement of air distribution in a fixed-bed dryer using computational fluid dynamics. Biosyst Eng 2012;112(4):359–69. https://doi.org/10.1016/j.biosystemseng.2012.05.008.

[91] Guangbin L, Kaixuan X, Qichao Y, Yuangyang Z, Liansheng L. Flow field and drying process analysis of double-layer drying chamber in heat pump dryer. Appl Therm Eng Jun. 2022;209. https://doi.org/10.1016/j.applthermaleng.2022.118261.

[92] A. K. Babu, G. Kumaresan, V. Antony Aroul Raj, and R. Velraj, "CFD studies on different configurations of drying chamber for thin-layer drying of leaves," Energy Sources, Part A: Recovery, Utilization and Environmental Effects, vol. 42, no. 18, pp. 2227–2239, Sep. 2020, doi: 10.1080/15567036.2019.1607935.

[93] Tuncer AD, Sözen A, Afshari F, Khanlari A, Şirin C, Gungor A. Testing of a novel convex-type solar absorber drying chamber in dehumidification process of municipal sewage sludge. J Clean Prod Nov. 2020;272. https://doi.org/10.1016/j.jclepro.2020.122862.

[94] Wang G, et al. Optimization of air jet impingement drying of okara using response surface methodology. Food Control Jan. 2016;59:743–9. https://doi.org/10.1016/j.foodcont.2015.06.047.

[95] Ruhyat N. Comparison of the dryer air inlet position on the spray dryer with a double condenser to produce a rotating flow throughout the drying chamber: CFD analysis. Int J Innov Mech Eng Adv Mater Apr. 2023;5(1):16. https://doi.org/10.22441/ijimeam.v5i1.21605.

[96] Yi J, Li X, He J, Duan X. Drying efficiency and product quality of biomass drying: a review. Drying Technol Nov. 2020;38(15):2039–54. https://doi.org/10.1080/07373937.2019.1628772.

[97] Çetin N. Prediction of moisture ratio and drying rate of orange slices using machine learning approaches. J Food Process Preserv Nov. 2022;46(11):e17011. https://doi.org/10.1111/jfpp.17011.

[98] M. Kaveh, Y. Abbaspour-Gilandeh, H. Fatemi, and G. Chen, "Impact of different drying methods on the drying time, energy, and quality of green peas," J Food Process Preserv, vol. 45, no. 6, Jun. 2021, doi: 10.1111/jfpp.15503.

[99] S. Suherman, H. Hadiyanto, M. A. Asy-Syaqiq, A. A. Brastayudha, and M. W. Fahrudin, "Drying banana slices using photovoltaic ventilation solar dryer," Food Res, vol. 8, no. Supplementary 1, pp. 90–102, Mar. 2024, doi: 10.26656/fr.2017.8(s1).13.

[100] Borkakoti S, Das B, Gupta A. Environmental and economic assessment of single-slope solar greenhouse dryer for ginger and turmeric drying in north-eastern region of India. J Stored Prod Res 2024;106:102299. https://doi.org/10.1016/j.jspr.2024.102299.

[101] Ying T, Spang ES. Paddy Drying Technologies: A Review of Existing Literature on Energy Consumption. Processes Mar. 2024;12(3):532. https://doi.org/10.3390/pr12030532.

[102] O. İsmail, B. Beyribey, İ. Doymaz, "Effect of drying methods on drying characteristic, energy consumption and color of nectarine," 2015. [Online]. Available: http://eds.yildiz.edu.tr/.

[103] Tunckal C, Doymaz İ. Performance analysis and mathematical modelling of banana slices in a heat pump drying system. Renew Energy 2020;150:918–23. https://doi.org/10.1016/j.renene.2020.01.040.

[104] Meng Z, et al. Experimental study on thermal performance of a closed heat pump drying system. Case Stud Therm Eng 2023;51:103590. https://doi.org/10.1016/j.csite.2023.103590.

[105] Alnak DE, Karabulut K. Analysis of heat and mass transfer of the different moist object geometries with air slot jet impinging for forced convection drying. Therm Sci 2018;22(6):2943–53. https://doi.org/10.2298/TSCI160721151A.

[106] A. A. Martynenko and G. N. Alves Vieira, "Sustainability of drying technologies: system analysis," Jun. 20, 2023, Royal Society of Chemistry. doi: 10.1039/d3fb00080j.

[107] Ebrahimi H, Samimi Akhijahani H, Salami P. Improving the thermal efficiency of a solar dryer using phase change materials at different position in the collector. Sol Energy 2021;220:535–51. https://doi.org/10.1016/j.solener.2021.03.054.

[108] Patel PM, Rathod VP, Patel VK. Development and enhancement in drying performance of a novel portable greenhouse solar dryer. J Stored Prod Res Feb. 2024;105. https://doi.org/10.1016/j.jspr.2023.102228.

[109] K. S. Yang, K. Hamid, S. K. Wu, U. Sajjad, and C. C. Wang, "Experimental analysis of a heat pump dryer with an external desiccant wheel dryer," Processes, vol. 9, no. 7, Jul. 2021, doi: 10.3390/pr9071216.

[110] Silalahi PG, Siburian AH, Ambarita H, Romauli NDM. "Experimental study on open cycle heat pump chilli dryer with refrigerant R32," in Journal of Physics: Conference Series. Institute of Physics 2023. https://doi.org/10.1088/1742-6596/2421/1/012044.

[111] Moon Y, Kim KH, Kweon M. Effects of flour quality and drying rates controlled by temperature, air circulation, and relative humidity on the quality of dried white-salted noodles. Cereal Chem Nov. 2019;96(6):1011–21. https://doi.org/10.1002/cche.10206.

[112] Bhavsar HP, Patel CM. Performance investigation of natural and forced convection cabinet solar dryer for ginger drying. Mater Today Proc 2021;47:6128–33. https://doi.org/10.1016/j.matpr.2021.05.050.

[113] Lee YH, Chin SK, Chung BK. Drying Characteristics and Product Quality of Lemon Slices Dried With Hot Air Circulation Oven and Hybrid Heatpump Dryers. All rights reserved Int J Sci Eng (IJSE) 2015;8(1):69–74. https://doi.org/10.12777/ijse.8.1.69-74.

[114] Sabat M, Kotwaliwale N, Giri SK. Thermography for performance evaluation of a compact, air disperser equipped hot air dryer. J Food Process Eng 2021;44(9):Sep. https://doi.org/10.1111/jfpe.13777.

[115] Amanlou Y, Zomorodian A. Applying CFD for designing a new fruit cabinet dryer. J Food Eng Nov. 2010;101(1):8–15. https://doi.org/10.1016/j.jfoodeng.2010.06.001.

[116] ElGamal RA, Kishk SS, ElMasry GM. Validation of CFD models for the deep-bed drying of rice using thermal imaging. Biosyst Eng Sep. 2017;161:135–44. https://doi.org/10.1016/j.biosystemseng.2017.06.018.

[117] Zhang Y, et al. Temperature Field Simulation and Energy Analysis of a Heat Pump Tobacco Bulk Curing Barn. Energies (Basel) 2022;15(22):Nov. https://doi.org/10.3390/en15228655.

[118] Mecha P, Yali F, Awuah E, Odero Alele J, Zhang J, Kunjie C. Deflectors as the Performance Booster. Component 2023;27(6B):4989–5004. https://doi.org/10.2298/TSC230305130M.

[119] Shamsuddeen MM, Cha DA, Kim SC, Kanemoto T, Kim JH. Performance Study of a Hybrid Heat Pump Dryer based on Numerical Analysis and Experimental Set-up. J Therm Sci Jan. 2021;30(1):111–22. https://doi.org/10.1007/s11630-020-1384-1.

[120] Mondal S, Dutta S, Pande P, Naik-Nimbalkar V. Intensify staple fibre drying by optimizing air distribution in multistage convective dryer using CFD. Chem Eng Process - Process Intesif Mar. 2022;173. https://doi.org/10.1016/j.cep.2022.108807.

[121] Olejnik TP, Mysakowski T, Tomtas P, Mostowski R. Optimization of the beef drying process in a heat pump chamber dryer. Energies (Basel) 2021;14(16):Aug. https://doi.org/10.3390/en14164927.

[122] Tong Y, Kozai T, Nishioka N, Ohyama K. Greenhouse heating using heat pumps with a high coefficient of performance (COP). Biosyst Eng 2010;106(4):405–11. https://doi.org/10.1016/j.biosystemseng.2010.05.003.
[123] Al-Kayiem HH, Gitan AA. Flow uniformity assessment in a multi-chamber cabinet of a hybrid solar dryer. Sol Energy Aug. 2021;224:823–32. https://doi.org/10.1016/j.solener.2021.06.058.
[124] Mariani VC, Perussello CA, Cancelier A, Lopes TJ, Da Silva A. Hot-air drying characteristics of soybeans and influence of temperature and velocity on kinetic parameters. J Food Process Eng Dec. 2014;37(6):619–27. https://doi.org/10.1111/jfpe.12118.
[125] Jiang H, Zhang M, Mujumdar AS, Lim RX. Drying uniformity analysis of pulse-spouted microwave–freeze drying of banana cubes. Drying Technol Apr. 2016;34(5):539–46. https://doi.org/10.1080/07373937.2015.1061000.
[126] Song CF, Wang Y, Wang S, Cui ZW, Xu Y, Zhu H. Non-uniformity investigation in a combined thermal and microwave drying of silica gel. Appl Therm Eng Apr. 2016;98:872–9. https://doi.org/10.1016/j.applthermaleng.2015.12.089.
[127] Gu Y, Zhen L, Jiang H. Mathematical analysis of temperature distribution uniformity of banana dried by vacuum radio frequency treatment. Drying Technol Nov. 2020;38(15):2027–38. https://doi.org/10.1080/07373937.2019.1611595.
[128] N. I. Román-Roldán, J. F. Ituna Yudonago, A. López-Ortiz, J. Rodríguez-Ramírez, and S. Sandoval-Torres, "A new air recirculation system for homogeneous solar drying: Computational fluid dynamics approach," Renew Energy, vol. 179, pp. 1727–1741, Dec. 2021, doi: 10.1016/j.renene.2021.07.134.
[129] S. H. Abdulmalek, H. H. Al-Kayiem, M. K. Assadi, and A. A. Gitan, "Development of multi chamber technique to improve the uniformity in drying application," in AIP Conference Proceedings, American Institute of Physics Inc., Nov. 2018. doi: 10.1063/1.5075555.
[130] Zhang WP, et al. Design and performance evaluation of a pilot-scale pulsed vacuum infrared drying (PVID) system for drying of berries. Drying Technol Jul. 2020;38(10):1340–55. https://doi.org/10.1080/07373937.2019.1639725.
[131] Zhang P, Wu P, Zhang Q, Shi Z, Wei M, Jaberi-Douraki M. "Optimization of feed thickness on distribution of airflow velocity in belt dryer using computational fluid dynamics," in Energy Procedia. Elsevier Ltd 2017:1595–602. https://doi.org/10.1016/j.egypro.2017.12.536.
[132] Welsh Z, Kumar C, Karim A. "Preliminary Investigation of the Flow Distribution in an Innovative Intermittent Convective microwave Dryer (IMCD)," in Energy Procedia. Elsevier Ltd 2017:465–70. https://doi.org/10.1016/j.egypro.2017.03.170.
[133] Srisiriwat N, Wutthithanyawat C. Temperature Distribution of Hot Air Flow in Heating Zone for Drying Application. Appl Mech Mater 2014;627:153–7. https://doi.org/10.4028/www.scientific.net/AMM.627.153.
[134] W. Jacek and W. Krzysztof, "The improvement of the pneumatic pulsator nozzle according to the results of the continuous adjoint for topology optimization." [Online]. Available: http://repo.pw.edu.plPublikacja/Publicationhttp://repo.pw.edu.pl/info/article/WUTec2517c166054b8ca6cf8adcb5e8f982/.
[135] M. A. A. Bin Ishak, A. Ibrahim, K. Sopian, M. F. Fauzan, A. A. Rahmat, and N. J. B. Yusaidi, "Performance and economic analysis of a reversed circular flow jet impingement bifacial PVT solar collector," International Journal of Renewable Energy Development, vol. 12, no. 4, pp. 780–788, Jul. 2023, doi: 10.14710/ijred.2023.54348.
[136] I. Ts et al., "Heat Transfer Performance of a Novel Circular Flow Jet Impingement Bifacial Photovoltaic Thermal PVT Solar Collector INTERNATIONAL JOURNAL of RENEWABLE ENERGY RESEARCH Heat Transfer Performance of a Novel Circular Flow Jet Impingement Bifacial Photovoltaic Thermal PVT Solar Collector," 2023. [Online]. Available: https://www.researchgate.net/publication/371990080.
[137] M. A. A. Bin Ishak, A. Ibrahim, A. Fazlizan, M. F. Fauzan, K. Sopian, and A. A. Rahmat, "Exergy performance of a reversed circular flow jet impingement bifacial photovoltaic thermal (PVT) solar collector," Case Studies in Thermal Engineering, vol. 49, Sep. 2023, doi: 10.1016/j.csite.2023.103322.
[138] Rosli MAM, Jing HS, Azhar NIM, Saputra M, Ali S. A Simulation Study of Drying Chamber for Marine Product. International Journal of Integrated Engineering 2021;13(6):62–9. https://doi.org/10.30880/ijie.2021.13.06.005.
[139] Misha S, Mat S, Ruslan MH, Sopian K, Salleh E. The Prediction of Drying Uniformity in Tray Dryer System using CFD Simulation. Int J Mach Learn Comput Oct. 2013;3(5):419–23. https://doi.org/10.7763/ijmlc.2013.v3.352.
[140] Aktaş M, Khanlari A, Aktekeli B, Amini A. Analysis of a new drying chamber for heat pump mint leaves dryer. Int J Hydrogen Energy Jul. 2017;42(28):18034–44. https://doi.org/10.1016/j.ijhydene.2017.03.007.
[141] Rahmat MAA, et al. An Analysis of Renewable Energy Technology Integration Investments in Malaysia Using HOMER Pro. Sustainability (Switzerland) 2022;14(20):Oct. https://doi.org/10.3390/su142013684.
[142] Ismail FB, Rahmat MAA, Kazem HA, Al-Obaidi ASM, Ridwan MS. Maximizing energy via solar-powered smart irrigation: An approach utilizing a single-axis solar tracking mechanism. Irrig Drain Jul. 2024;73(3):829–45. https://doi.org/10.1002/ird.2937.
[143] Luqman Azeez H, Ibrahim A, Omer Ahmed B, Al-Waeli AHA, Jaber M, Aqil Afham Rahmat M. Energy and exergy analysis of a novel collector design in a photovoltaic thermal system: an experimental study. Appl Therm Eng 2024;256:Nov. https://doi.org/10.1016/j.applthermaleng.2024.124125.
[144] Obaideen K, et al. On the contribution of solar energy to sustainable developments goals: Case study on Mohammed bin Rashid Al Maktoum Solar Park. Int J Thermofluids 2021;12:100123. https://doi.org/10.1016/j.ijft.2021.100123.
[145] Elavarasan RM, Nadarajah M, Shafiullah GM. Multi-criteria decision analysis of clean energy technologies for envisioning sustainable development goal 7 in Australia: Is solar energy a game-changer? Energy Convers Manag 2024;321:119007. https://doi.org/10.1016/j.enconman.2024.119007.
[146] K. Obaideen et al., "Solar Energy: Applications, Trends Analysis, Bibliometric Analysis and Research Contribution to Sustainable Development Goals (SDGs)," Jan. 01, 2023, Multidisciplinary Digital Publishing Institute (MDPI). doi: 10.3390/su15021418.
[147] M. Kamran, "Chapter 2 - Energy sources and technologies," in Fundamentals of Smart Grid Systems, M. Kamran, Ed., Academic Press, 2023, pp. 23–69. doi: https://doi.org/10.1016/B978-0-323-99560-3.00010-7.
[148] A. B. Demirpolat, "Investigation of Mass Transfer with Different Models in a Solar Energy Food-Drying System," Energies (Basel), vol. 12, no. 18, 2019, doi: 10.3390/en12183447.
[149] Abdullah AS, Omara ZM, Ben Bacha H, Younes MM. Employing convex shape absorber for enhancing the performance of solar still desalination system. J Energy Storage 2022;47:103573. https://doi.org/10.1016/j.est.2021.103573.
[150] A. Khanlari, A. Doğuş Tuncer, A. Sözen, C. Şirin, and A. Gungor, "Energetic, environmental and economic analysis of drying municipal sewage sludge with a modified sustainable solar drying system," Solar Energy, vol. 208, pp. 787–799, Sep. 2020, doi: 10.1016/j.solener.2020.08.039.
[151] Dong X, Zhao H, Kong F, Han J. Parameter optimization of multistage closed series heat pump drying system. Appl Therm Eng Nov. 2022;216. https://doi.org/10.1016/j.applthermaleng.2022.119124.
[152] Kang H, et al. Design of a Greenhouse Solar-Assisted Heat Pump Dryer for Kelp (Laminaria japonica): System Performance and Drying Kinetics. Foods 2022;11(21):Nov. https://doi.org/10.3390/foods11213509.
[153] Yu M, Zou L, Yu J. Experimental investigation on the drying characteristics in a solar assisted ejector enhanced heat pump dryer system. Sol Energy 2024;267:112265. https://doi.org/10.1016/j.solener.2023.112265.
[154] Babu AK, Kumaresan G, Antony Aroul Raj V, Velraj R. Experimental Investigations of Thin-layer Drying of Leaves in a Heat-Pump Assisted Tray-type Batch Drying Chamber. Strojniski Vestnik/J Mech Eng 2020;66(4):254–65. https://doi.org/10.5545/sv-jme.2019.6510.
[155] A. Singh, J. Sarkar, and R. R. Sahoo, "Experimental energy-exergy performance and kinetics analyses of compact dual-mode heat pump drying of food chips," J Food Process Eng, vol. 43, no. 6, Jun. 2020, doi: 10.1111/jfpe.13404.
[156] de Melo Ramos F, Ubbink J, Silveira Júnior V, Prata AS. Drying of Maltodextrin solution in a vacuum spray dryer. Chem Eng Res Des 2019;146:78–86. https://doi.org/10.1016/j.cherd.2019.03.036.
[157] Suryanto S, Hamzah N, Taufik A. The novel vacuum drying using the steam ejector. Drying Technol 2021;39(7):905–11. https://doi.org/10.1080/07373937.2020.1728307.
[158] Liu ZL, et al. Improvement of drying efficiency and quality attributes of blueberries using innovative far-infrared radiation heating assisted pulsed vacuum drying (FIR-PVD). Innov Food Sci Emerg Technol May 2022;77. https://doi.org/10.1016/j.ifset.2022.102948.
[159] C. H. Voon, K. L. Foo, B. Y. Lim, S. C. B. Gopinath, and Y. Al-Douri, "3 - Synthesis and preparation of metal oxide powders," in Metal Oxide Powder Technologies, Y. Al-Douri, Ed., Elsevier, 2020, pp. 31–65. doi: https://doi.org/10.1016/B978-0-12-817505-7.00003-8.
[160] Langrish TAG, Harrington J, Huang X, Zhong C. Using CFD simulations to guide the development of a new spray dryer design. Processes 2020;8(8):Aug. https://doi.org/10.3390/PR8080932.
[161] N. S. Haron, J. H. Zakaria, and M. F. Mohideen Batcha, "Recent advances in fluidized bed drying," in IOP Conference Series: Materials Science and Engineering, Institute of Physics Publishing, Sep. 2017. doi: 10.1088/1757-899X/243/1/012038.
[162] Majumder P, Deb B, Gupta R, Sablani SS. A comprehensive review of fluidized bed drying: Sustainable design approaches, hydrodynamic and thermodynamic performance characteristics, and product quality. Sustainable Energy Technol Assess 2022;53:102643. https://doi.org/10.1016/j.seta.2022.102643.
[163] Eliaers P, De Wilde J. Drying of Biomass Particles: Experimental Study and Comparison of the Performance of a Conventional Fluidized Bed and a Rotating Fluidized Bed in a Static Geometry. Drying Technol Jan. 2013;31(2):236–45. https://doi.org/10.1080/07373937.2012.726304.
[164] Majumder P, Deb B, Gupta R. Design and development of solar assisted fluidized bed dryer integrated with liquid desiccant dehumidifier: Theoretical analysis and experimental investigation. Energy Convers Manag 2022;270:116281. https://doi.org/10.1016/j.enconman.2022.116281.
[165] Lv W, Lv H, Jin X, Cui Z, Su D. Effects of ultrasound-assisted methods on the drying processes and quality of apple slices in microwave drying. Drying Technol Sep. 2020;38(13):1806–16. https://doi.org/10.1080/07373937.2019.1666274.
[166] Shen L, et al. Modelling of moving drying process and analysis of drying characteristics for germinated brown rice under continuous microwave drying. Biosyst Eng Jul. 2020;195:64–88. https://doi.org/10.1016/j.biosystemseng.2020.05.002.
[167] Guo J, Zheng L, Li Z. Microwave drying behavior, energy consumption, and mathematical modeling of sewage sludge in a novel pilot-scale microwave drying system. Sci Total Environ Jul. 2021;777. https://doi.org/10.1016/j.scitotenv.2021.146109.
[168] Soysal Y, Öztekin S, Eren Ö. Microwave Drying of Parsley: Modelling, Kinetics, and Energy Aspects. Biosyst Eng Apr. 2006;93(4):403–13. https://doi.org/10.1016/j.biosystemseng.2006.01.017.
[169] M. Marin, "FREEZE-DRYING | Structural and Flavor (Flavour) Changes," in Encyclopedia of Food Sciences and Nutrition (Second Edition), B. Caballero, Ed., Oxford: Academic Press, 2003, pp. 2701–2705. doi: https://doi.org/10.1016/B0-12-227055-X/00520-4.

[170] Piechnik E, et al. Experimentally validated CFD-tool for a freezing simulation in a small-scale freeze-dryer. J Food Eng Apr. 2024;367. https://doi.org/10.1016/j.jfoodeng.2023.111888.
[171] Gui C, Tao L, Zhang Y. Experimental study on improvement of freeze-drying process for porcine aorta. Drying Technol 2022;40(2):401–15. https://doi.org/10.1080/07373937.2020.1802744.
[172] Lietta E, Colucci D, Distefano G, Fissore D. On the Use of Infrared Thermography for Monitoring a Vial Freeze-Drying Process. J Pharm Sci Jan. 2019;108(1):391–8. https://doi.org/10.1016/j.xphs.2018.07.025.
[173] J. W. Zartha Sossa, G. L. Orozco, L. M. García Murillo, M. Peña Osorio, and N. Sánchez Suarez, "Infrared Drying Trends Applied to Fruit," May 14, 2021, Frontiers Media S.A. doi: 10.3389/fsufs.2021.650690.
[174] W. Zhang, C. Chen, Z. Pan, and Z. Zheng, "Vacuum and infrared-assisted hot air impingement drying for improving the processing performance and quality of poria cocos (Schw.) wolf cubes," Foods, vol. 10, no. 5, May 2021, doi: 10.3390/foods10050992.
[175] Özdemir MB, Aktaş M, Şevik S, Khanlari A. Modeling of a convective-infrared kiwifruit drying process. Int J Hydrogen Energy 2017;42(28):18005–13. https://doi.org/10.1016/j.ijhydene.2017.01.012.
[176] Chou SK, Chua KJ. New hybrid drying technologies for heat sensitive foodstuffs. Trends Food Sci Technol 2001;12(10):359–69. https://doi.org/10.1016/S0924-2244(01)00102-9.
[177] R. Sivakumar, R. Saravanan, A. Elaya Perumal, and S. Iniyan, "Fluidized bed drying of some agro products - A review," Aug. 01, 2016, Elsevier Ltd. doi: 10.1016/j.rser.2016.04.014.
[178] Wei Q, et al. Effects of different combined drying methods on drying uniformity and quality of dried taro slices. Drying Technol Feb. 2019;37(3):322–30. https://doi.org/10.1080/07373937.2018.1445639.
[179] Abedini E, et al. Evaluation of operational parameters for drying shrimps in a cabinet hybrid dryer. Sol Energy Feb. 2022;233:221–9. https://doi.org/10.1016/j.solener.2022.01.045.
[180] R. Anum, A. Ghafoor, and A. Munir, "Study of the Drying Behavior and Performance Evaluation of Gas Fired Hybrid Solar Dryer," J Food Process Eng, vol. 40, no. 2, Apr. 2017, doi: 10.1111/jfpe.12351.
[181] L. Momenzadeh, A. Zomorodian, and D. Mowla, "Applying Artificial Neural Network for Drying Time Prediction of Green Pea in a Microwave Assisted Fluidized Bed Dryer," 2012.