Nano World Journal

https://doi.org/10.17756/nwj.2023-s4-068

Review Article Open Access

A Brief Overview of Sustainable Food Drying Technologies

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Received: September 15, 2023
Accepted: November 27, 2023
Published: November 30, 2023

Citation: Aqil LAK, Bhattad A, Pittam SR. 2023. A Brief Overview of Sustainable Food Drying Technologies. *Nano World J* 9(S4): S401-S408.

Published by United Scientific Group

Abstract

Food waste is a major problem, and it is estimated that up to 40% of the world's food is lost or wasted. This waste has a negative impact on the environment and the global food crisis. Improper post-harvest processing is a major cause of food loss, and it disproportionately affects low-income countries. The article discusses the use of renewable energy-based sustainable food drying technology as a way to reduce food waste. This technology uses heat pumps, thermal energy storage (TES), and solar energy to dry food, which can help to reduce energy consumption and improve the quality of the dried food. The article also discusses the importance of government policy in supporting the implementation of this technology. Overall, renewable energy-based sustainable food drying technology is a promising way to reduce food waste and improve food security.

Keywords

Phase change material, Solar food drier, Thermal conductivity, Thermal storage

Introduction

Solar food drier highlights the significant problem of food wastage due to poor post-harvest processing, particularly in low-income developing and least developed countries [1]. The wastage of food is a critical issue, especially when almost one billion people suffer from acute hunger and inadequate nutrition [2]. The burden of energy, infrastructure, and resource management in each stage from harvesting to wastage handling falls on farmers, producers, businesses, and governments [3].

The most common technique of food preservation in the world is drying, however present commercial food drying systems use a lot of energy up to 25% of all industrial energy use. The major reason for this high energy consumption is that drying processes, particularly microscale morphological changes that occur during drying and their impact on product and process design, are not well understood at a fundamental level [4, 5]. Researchers worked on the need for improved post-harvest processing and more sustainable and energy-efficient food drying methods [6]. Addressing these issues can significantly reduce food wastage and improve food security in low-income developing and least developed countries while also reducing the burden on farmers, producers, businesses, and governments.

Now a days, nanotechnology is highly impacting in food technology. The manufacture of more nutritious, secure, and superior functional foods that are persistent and semi-perishable in nature could be led qualitatively and quantitatively by nanomaterials. By altering the particle size, potential cluster growth, and charge on the surface of food nanomaterials, nanotechnology applications improve the accessibility, flavour, texture, and consistency of food [7].

Traditional drying systems powered by fossil fuels have a lengthy history dating back to antiquity. Fossil fuel-based conventional drying systems must be replaced with effective and renewable energy-based drying systems due to their dwindling supply and environmental pollution [8]. Because solar energy is intermittent, it is essential and a difficult challenge to build a solar dryer that is effective and appropriate for certain agricultural goods.

Drying Technologies Based on Sustainable Energy Sources

Food drying requires a significant amount of energy in the form of latent heat for evaporating moisture. Conventional convection drying (CD) requires a lot of time and energy due to the humidity (which is essentially bound water) acting as a barrier at a decreasing rate [9]. As a result, Mahiuddin et al. [10] found that it was often challenging to strike a balance between the three factors. As much as 25% of the energy used in food processing is used by drying systems as a whole, which has a significant negative impact on the sustainable development of the environment today. Therefore, the main obstacle to ensuring environmental sustainability is the development of environmentally friendly food drying technologies [10]. Solar energy is the most accessible and well-liked environmentally friendly power source. However, other renewable resources with high potential for application in food preservation include geothermal energy and biomass [11].

Solar Drying Using TES

For farmers in under-developed nations, solar dryers with reasonable costs and efficiency are appealing alternatives to open-air sun drying. Current uses in engineering use three basic forms of TES: sensible thermal, latent thermal, and thermal-chemical. The development of thermal-chemical storage systems for energy is still ongoing. Thermal storage, both sensible and latent, are well-developed and widely used in industry. Phase change material (PCM), which continually melts while producing latent heat and solidifies while absorbing latent heat, is the foundation of latent thermal storage.

The potential use of solar energy for winter building heating and drying of agricultural products. Solar energy may be retained utilising thermal, electrical, chemical, and mechanical processes. TES is possible thanks to the sensible heat, latent heat, and chemical heat principles of heat accumulation [12]. In figure 1, examples of each concept are shown.

Solar dryers are divided into two broad categories: natural and forced convection solar dryers. They may be classed as direct, indirect, mixed mode, and hybrid sun dryers. In solar dryers operating in direct mode, the material being dried is heated by solar radiation directly, and hot air is present inside the drier enclosure. A solar air heater, a drying chamber, and a fan used to channel the hot air into the drying chamber make up indirect solar dryers. The substance that needs to be dried gets heated in mixed-mode solar dryers through solar radiation and the warm air from the solar air heater.

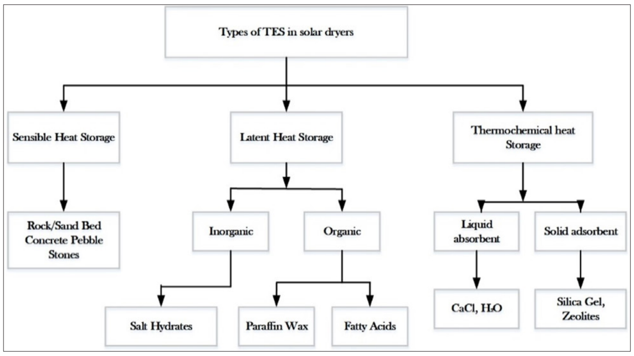

Figure 1: Types of TES integrated in solar dryer systems.

Overall, solar drying systems have significant potential for reducing energy consumption and improving sustainability in the agricultural sector. Different types of solar dryers can be used depending on the specific application and available resources, and improvements in solar energy storage and thermal performance can enhance the effectiveness and efficiency of these systems.

This passage highlights the energy efficiency challenges of convective dryers, which may operate at less than 50% efficiency even with proper design and operation [13]. This is particularly relevant in developing countries facing energy limitations, where conventional drying technologies may be unaffordable [14]. The need for a balance between efficiency, quality, and cost of food drying is emphasized, particularly for low-energy drying technologies that rely on renewable energy resources such as solar, geothermal, and biomass. However, the application of sustainable energy resources in drying technologies requires significant scientific studies to improve their effectiveness and efficiency. Overall, this suggests that the development of sustainable and low-energy drying technologies is critical for promoting food security and reducing energy consumption in developing countries [15].

The use of PCM in solar drying systems for potatoes can improve the efficiency of the drying process and increase the quality of the final product [16]. PCM can store thermal energy during the day when the solar energy is available and release it at night or during cloudy periods, thus maintaining a consistent temperature inside the dryer and reducing the drying time [17]. This results in a better-quality product with minimal loss of nutrients and reduced spoilage. Several types of PCM have been tested in potato drying systems, including paraffin wax and salt hydrates, and their effectiveness in reducing energy consumption and improving product quality has been demonstrated in various studies [18]. Overall, the use of PCM in solar drying systems can provide a sustainable and cost-effective solution for potato processing in developing countries, where access to conventional drying technologies is limited.

In order to develop a solar air-drying system with paraffin-based TES, several challenges must be addressed. These include determining the optimal location and volume for the PCM, enhancing heat transfer between the PCM and the heat transfer fluid, and minimizing energy consumption and heat loss in the system. Recent research has proposed solutions to these challenges, including the use of metal fins or inserts to increase surface area for heat transfer [19], and the use of PCMs as TES mediums [20].

Advantages using TES in solar drying

Increased effectiveness: By storing heat during the day and releasing it at night, TES devices can contribute to increasing the effectiveness of sun drying. This can assist to maintain a constant drying temperature while also reducing the amount of energy required to dry food. Improved quality: By preserving a constant drying temperature, TES systems can aid in enhancing the quality of dried foods. This can assist to stop the decomposition of flavor and the loss of nutrients. Extended drying season: TES systems enable continuous drying even when the sun isn't shining, extending the drying season. In regions with brief growth seasons or erratic weather patterns, this may be significant.

Difficulties using TES in solar drying

The cost of TES systems can be higher than that of conventional solar drying systems. Complexity: TES systems have the potential to be more difficult to run and construct than conventional sun drying systems. Maintenance: To make sure TES systems are functioning correctly, they need to have regular maintenance. TES can be a useful addition to sun drying systems overall. It might aid in enhancing sun drying's effectiveness, quality, and adaptability. TES systems, however, can be more costly and intricate than conventional sun drying systems.

Geothermal Heating Based Drying

Food may be dried in a sustainable and energy-effective way using geothermal heating. It evaporates water from food using the heat from the planet's interior. This technique can offer a dependable and sustainable supply of electricity for drying, making it particularly advantageous in regions with geothermal resources. Geothermal drying systems come in two primary categories: Direct geothermal drying: This method directly heats the food by using hot water or steam from a geothermal well. Indirect geothermal drying: Using a heat exchanger, indirect geothermal drying transfers heat from geothermal water or steam to the air that is used to dry the food.

Although direct geothermal drying systems are more effective, their installation costs might be higher. Despite being less effective, indirect geothermal drying systems are less expensive to construct. Geothermal drying is superior to other drying techniques in a variety of ways, including:

- It is a renewable and sustainable source of power.
- It uses little energy.
- Many different food products can be dried with it.
- It can create premium dry food.
- However, there are several difficulties with geothermal drying as well.
- Initial installation costs may be substantial.
- To guarantee that the food is not contaminated, the system must be correctly developed and installed.
- To make sure the system is functioning correctly, it must undergo routine maintenance.

Geothermal drying is an overall promising approach for food drying. It is a practical, cost-effective, and environmentally friendly way to dry food. To guarantee that the food is not contaminated, the system must be professionally built and deployed, which might have a significant initial cost. A theoretical barrier may be used to divide the use of geothermal power into near-ground as well as deep subterranean uses; the deep geothermal uses are further divided into high enthalpy and low enthalpy sources [21]. Vegetables and fruits may be dried using energy from geothermal sources that have a small enthalpy at temperatures below 150 °C [22]. Geothermal water wells are used for extracting heat in the form of moisture or steaming water. Geothermal drying may make use of a significant percentage of the waste heat produced by geothermal power facilities [23]. The operating cost of food drying utilising geothermal power is quite cheap [24]. As a result of their proximity to the boundaries of the plates, several developing nations, including India, Bangladesh, Chile, Paraguay, Peru, and Ethiopia, have abundant geothermal as-sets [25]. Consequently, inexpensive geothermal power could serve as a great source for environmentally friendly drying techniques in underdeveloped nations located along the global boundaries of plates.

Since producing electricity is the primary use of geothermal energy, the two can be combined to provide an application that is cost-effective. A cascade geothermal system for combined ice-making and agricultural goods (chili, tomato, and avocado) drying was shown by Ambriz-Diaz et al. [26]. The financial implications of drying were considerably enhanced by cascading, and drying tomatoes was shown to have a one-year repayment period. It is clear that different geothermal drier types may be employed for a range of items under various drying circumstances. As was just said, those dyers are especially suited for large dryers. Since geothermal energy is a plentiful supply in the developing world, these kinds of dryers may be popular there.

Biomass Based Drying System

Food is dried using a biomass-based drying system, which generates heat from biomass like wood, agricultural waste, or animal dung. Given that biomass is a renewable resource, this drying technique is sustainable and renewable. Systems for drying biomass-based materials fall into two categories: Direct biomass drying: In this approach, the food is dried using the heat generated by the burning of biomass. Indirect biomass drying: Using a heat exchanger, the indirect biomass drying system transfers heat from the burning biomass to the air that is used to dry the food. Systems for drying biomass directly are more effective, but they might also be riskier. Systems for indirect biomass drying are less effective but less harmful. Several benefits of biomass-based drying systems over conventional drying techniques include:

- They are renewable and sustainable.
- They use less energy.
- Many different food products may be dried using them.

- They are able to create premium dry food.
- However, there are several difficulties with biomass-based drying methods as well.
- Initial installation costs may be substantial.
- To guarantee that the food is not contaminated, the system must be correctly developed and installed.
- To make sure the system is functioning correctly, it must undergo routine maintenance.

The productivity of bed fluidized dryers can be negatively impacted by crust development, incorrect sample conveyance, and plug-flow parameters. These issues may be lessened with increased air movement in the feeding area and bed vibrations. To limit absorption to elevated temperatures, the vibrating apparatus should be installed beyond the dryer [27]. Additionally, solar power collectors are able to be connected to a biofuel drier. Rizal and Muhammad [28] investigated on the solar-assisted biomass fish drier. About 100 kg of fish had been dried in their research over the course of 15 h. Due to the dryer's short repayment period of 2.6 years, it was financially viable. It is clear that solar-assisted biofuel dryer can be used constantly, affordably, and in tandem with one another.

Overall, food drying systems based on biomass are a promising technology. They are efficient in terms of energy use and effective in drying food. To guarantee that the food is not contaminated, the system must be professionally built and deployed, which might have a significant initial cost.

Heat Pump-based Hybrid Drying

A drying technique known as "heat pump-based hybrid drying" combines the use of a heat pump with another drying technique, such as solar, biomass, or geothermal drying. Compared to conventional drying techniques, this hybrid approach can provide various benefits, including: Efficiency in terms of energy: Heat pumps are particularly effective at transporting heat, therefore they can aid in lowering the energy required to dry food. Flexibility: Heat pumps are adaptable to many situations and applications since they may be utilised with a range of drying techniques. Sustainability: Heat pumps are a sustainable drying solution since they may be fuelled by renewable energy sources like solar or geothermal energy.

In terms of heat pump-based hybrid drying systems, there are two primary categories: Direct heat pump drying: In this technique, the air that is used to dry the food is heated directly by the heat pump. Indirect heat pump: Drying using an indirect heat pump involves heating a heat transfer fluid, such as water or glycol, with the help of the heat pump. This heated air is then used to dry the food.

Although direct heat pump drying systems are more effective, their installation costs might be higher. Despite being less effective, indirect heat pump drying systems are less expensive to install. A technique that has promise for food drying is heat pump-based hybrid drying. It is a practical, cost-effective, and environmentally friendly way to dry food. Heat pumps save energy by utilizing thermal energy from the environment around them. Airflow-based energy-efficient heat pump dryers are presently the most popular kind for drying purposes since air can be employed as a drying environment successfully [29]. The greatest amount of the loss of heat in these appliances is due to the energy that is still present in the wet air released from the atmosphere's convection dryer and the inadequate thermal boundary in the chamber used for drying. Heat pump-convective combination dryers have the potential to consume up to 50% less energy than traditional dryers since heat is recovered [30]. As demonstrated by Hou et al. [31] while processing jujube, heat pump drier not only save energy but also improve the nutritional value of food that has been dried. Ismaeel and Yumrutas [32] claim that a heat pump dryer has considerably greater energy efficiency. All convective dryers can be coupled with a heating and cooling system, with the exception of those that re-quire a lot of drying air, such as sprays or flash dryer [33].

These dryers have been demonstrated to utilize less energy while producing items of higher quality. Nevertheless, despite this field's immense potential, not enough research is being done in it. Qiu et al. [34] developed a solar assisted environmentally friendly drier with heat recovery and fluid thermal backup. They found significant energy savings of 40.53%, 53.39%, and 58.17% as compared to hot air drying using a completely open damper, paralleled solar heat pump drying, and hot air-drying using a partially opened damper. The payback period ranged from 2 to 6 years, depending on the component of the commodity that needed to be dried out.

Comparison of Various Drying Technologies

There isn't a versatile, energy-efficient dryer available yet that can effectively dry every sort of food-related commodity in any drying environment. The requirements, such as the characteristics of the commodity that has to be dried, the required level of product efficacy, and the dryer's running costs, must be taken into consideration while selecting the optimal drying technique. When raw materials can be converted into goods of considerable value after drying, MD may be helpful commercially [35]. However, in order to consider every pertinent aspect, a comprehensive inquiry is necessary. Table 1 contrasts the key economic and technological characteristics of pertinent renewable energy-based drying approaches to those of conventional convection and microwave-based drying techniques [36-37].

Food drying typically leads to product degradation from all angles, including sensory, physicochemical, and nutritional. The standard drying techniques are more prone to physical and chemical deterioration in the finished product, as was previously discussed in the sections above. For this reason, it's crucial to utilise the proper drying technique for each product and pick the right circumstances to minimise potential alterations. Some of the physical characteristics impacted by the drying techniques are explained in the section that follows. Additionally, table 2 provide an overview of all drying techniques and how they affect the quality metrics mentioned in this section.

There are two distinct ways to dry food: microwave and

Table 1: A comparison of traditional and renewable drying techniques.

Classification	Characteristics	Food stuff to be dried	Economic	Drying time	Drying quality
Convective	Most common, more drying time, easy to develop	Various crops	Cheap	1 - 6 h	Low to medium
Microwave	Better drying efficiency, Can be combined with methods	Cash crops	High, almost twice the hot air convective	30 s - 5 min	Medium to high
Heat pump	Exhaust heat recovery, better product quality	heat sensitive commodities	High investment and maintenance cost	5 - 60 min	Low to medium
HPMCD	Combination of heat pump, microwave and (solar) convective drying	Heat sensitive commodities	Potential to achieve the cost effectiveness due to the use of solar heat	30 s - 5 min	High
Solar	Abundant and accessible resource, performance enhanced heat storage (PCM or rock-bed)	Various crops	Viable if extra capital cost can be balanced by fuel saving, or government subsidy	6 - 10 h	Medium
Geothermal	Depend on local resource, use geothermal resource below 150 °C	Ordinary crops	Viable if extra capital cost can be balanced, government subsidy	10 h	Low to medium
Biomass	Abundant, performance can be enhanced by advanced mass and heat transfer mechanism	Ordinary crops	Viable if extra capital cost can be balanced, government subsidy	30 - 60 min	Low

Table 2: Effects of drying techniques on dried materials' quality.

Classification	Color	Structural properties	Antioxidant activity
CD	Changes in color, usually a darkening of the product (black mulberries, blueberries) in the case of blackcurrant powder, better color	When paired with ultrasounds, a product's characteristics of hardening, high shrinkage, density, low porosity, and bulk density increase its potential to dehydrate foods like mushrooms, Brussels sprouts, and cauliflower.	Antioxidant activity has significantly decreased in a variety of goods (chokeberries, blueberries, chokeberries, mango cubes)
MD	Improved color preservation than CD	Research on potatoes and carrots used very porous materials. reduced porosity in apple and banana studies	Antioxidants in moringa leaves are retained
Heat pump	When added on nuts, rosemary and parsley's brown spots take on a more vibrant hue	Compared to other drying techniques, certain plants have better structural preservation	Excellent polyphenol retention in herb drying
HPMCD	Slight color deterioration (better than CD and MD); Blackcurrant powder's color has improved	Lower bulk density than CD	In trials on chokeberries, Saskatoon berries, and sour cherries was greater than CD and MD
Solar	Excellent natural color preservation in several investigations (e.g., black mulberries)	No collapsing or shrinking, the largest porosity, elasticity loss, viscous substance, and a lower bulk density than CD	Antioxidants in moringa leaves are retained
Geothermal	Reduced pomegranate leather browning response	-	Studies on tomatoes, sweet corn, asparagus, and foods high in pomegranate pestil have all shown either a retention or improvement in antioxidant activity
Biomass	Good color retention	Positively affected	No discernible decline in kafir leaves

solar. While MD heats food using electromagnetic radiation, solar drying uses the heat of the sun to remove water from food. Table 3 compares the solar drying with MD technologies.

Table 3: Comparison of solar drying and MD technologies.

Factor	Solar drying	MD
Energy source	Sunlight	Electricity
Drying speed	Slow	Fast
Energy efficiency	Relatively efficient	Can be more efficient, especially with heat pump
Cost	Relatively low	Can be more expensive
Nutritional value	Can be preserved well	Can be damaged if drying process is not carefully controlled
Ease of use	Relatively simple	More complex

Feasibility of Sustainable Drying in the Developing Countries

The most significant global concerns of the twenty-first century are generally acknowledged to be energy and environmental issues. Because food drying requires a lot of energy, innovative and efficient drying methods that use renewable energy might get the attention of the government. However, the greatest obstacle to the successful execution of such systems is the expensive initial investment in renewable energy drying applications [38]. Most farmers and individual investors in underdeveloped nations lack enough capital and complete assistance and encouragement structures as compared to industrialized nations. Some emerging nations have undertaken sustained attempts to attain sustainable energy use, including the main worldwide energy users. According to Delina [39], Thailand wants to cut energy consumption by 30% by 2036 in comparison with 2020 levels, China is interested in lowering energy intensity by 15% from 2015 to 2020, India desires to enhance the energy performance of buildings by means of the execution of various programs, such as the National Energy Efficient Fan Program.

Future growth in integrated drying applications is predicted given the clear limits of the separate drying method. Even if there have already been a lot of studies on different dryers, scientists and engineers still have important and difficult R&D jobs to do in order to create and optimize mixtures of certain drying methods and/or renewable energy sources (such as solar, heat pump, microwave, etc.). Although HPMCD is still in its early stages of advancement and needs further theoretical investigation, it has enormous potential to accomplish its aims. The use of better energy sources that are renewable drying processes is a systematic, interdisciplinary topic that calls for attention in the fields of technology, economics, politics, the environment, and sociology.

Finally, there is a need for government support and the participation of the private sector in order to make sustainable drying feasible in developing countries. Government support can take the form of financial incentives, technical assistance, and regulatory support. The private sector can play a role in the development and implementation of sustainable drying technologies, as well as the marketing of dried food products. Overall, the feasibility of sustainable drying in developing countries is increasing. With the right combination of factors, sustainable drying can play a significant role in reducing food waste, improving food security, and promoting sustainable development in these countries.

Development of Current Drying Methods

Researchers have developed new drying methods that focus on improving the weaknesses of existing drying methods and producing high-quality products with high energy efficiency. These methods include freeze-drying, microwave vacuum, microwave-freeze drying, and spray-freeze drying [40]. Two innovative drying methods that are being discussed are superheated steam drying and refractance window drying [41]. Applying hot steam to food at a temperature over its boiling point and absolute pressure results in superheated steam drying. With this technique, the yield of total plate counts is decreased, enzyme activity is decreased, the shelf life is increased, and the food storage quality is stabilised [42].

Refractance window drying is a drying technique that transfers heat energy from hot water to the material by heating and placing a thin polyethylene film or transparent material over the water's surface. Then, the food components are equally distributed over the film and dried for a brief duration, typically 3 - 5 min. This process results in goods that retain color, vitamins, and antioxidants very well. The refractance window drying method has an advantage over other methods since it employs radiant heat transfer, which requires 5% less thermal energy overall. As a result, the drying process is more effective, and the food's quality is maintained [43]. Manga pulp, peppers, scrambled eggs, avocado powder, algae with high carotenoid content, medicinal extracts, and human nutritional supplements have all been dried using refractance windows. Additionally, it is employed in the commercial manufacture of dried fruits and vegetables [44]. Similar drying techniques include impingement drying, which dries food with hot air moving at a high speed. This method is also efficient and can preserve the quality of food [45].

Conclusions

The lack of adequate nutrition in poor countries and the environmental burden of food waste have led to interest in sustainable drying methods. These methods include solar, geothermal, biomass, and heat pump drying. This review discusses the benefits of hybrid drying technologies, which combine two or more drying methods. One promising hybrid drying technology is HPMCD, which combines solar CD, MD, and heat pump drying. MD is a promising technology because it can reduce drying time and improve nutritional retention. Theoretical research is a good place to start with HPMCD because it is a complex and expensive technology. Solar drying systems with integrated heat pump drying and TES are also promising drying technologies because they are energy efficient and produce high-quality products.

- Sustainable drying is a promising way to reduce food waste and improve food security in developing countries.
- There are a number of factors that need to be considered in order to make sustainable drying feasible in these countries.
- The availability of renewable energy sources is one of the most important factors.
- The cost of sustainable drying technologies is another important factor.
- Government support and the participation of the private sector are also important factors.

Acknowledgements

None.

Conflict of Interest

None.

References

1. Karim MA, Hawlader MNA. 2005. Mathematical modelling and experimental investigation of tropical fruits drying. *Int J Heat Mass Transf* 48(23-24): 4914-4925. https://doi.org/10.1016/j.ijheatmasstransfer.2005.04.035
2. Ghnimi S, Umer S, Karim A, Kamal-Eldin A. 2017. Date fruit (*Phoenix dactylifera* L.): an underutilized food seeking industrial valorization. *NFS J* 6: 1-10. https://doi.org/10.1016/j.nfs.2016.12.001
3. Khan MIH, Karim MA. 2017. Cellular water distribution, transport, and its investigation methods for plant-based food material. *Food Res Int* 99: 1-14. https://doi.org/10.1016/j.foodres.2017.06.037

4. Khan MIH, Farrell T, Nagy SA, Karim MA. 2018. Fundamental understanding of cellular water transport process in bio-food material during drying. *Sci Rep* 8(1): 15191. https://doi.org/10.1038/s41598-018-33159-7
5. Khan MIH, Nagy SA, Karim MA. 2018. Transport of cellular water during drying: an understanding of cell rupturing mechanism in apple tissue. *Food Res Int* 105: 772-781. https://doi.org/10.1016/j.foodres.2017.12.010
6. Karim MA, Hawlader MNA. 2005. Drying characteristics of banana: theoretical modelling and experimental validation. *J Food Eng* 70(1): 35-45. https://doi.org/10.1016/j.jfoodeng.2004.09.010
7. Nile SH, Baskar V, Selvaraj D, Nile A, Xiao J, et al. 2020. Nanotechnologies in food science: applications, recent trends, and future perspectives. *Nano Micro Lett* 12: 1-34. https://doi.org/10.1007/s40820-020-0383-9
8. Lamidi RO, Jiang L, Pathare PB, Wang Y, Roskilly AP. 2019. Recent advances in sustainable drying of agricultural produce: a review. *Appl Energy* 233: 367-385. https://doi.org/10.1016/j.apenergy.2018.10.044
9. Kumar C, Millar GJ, Karim MA. 2015. Effective diffusivity and evaporative cooling in convective drying of food material. *Dry Technol* 33(2): 227-237. https://doi.org/10.1080/07373937.2014.947512
10. Mahiuddin M, Khan MIH, Kumar C, Rahman MM, Karim MA. 2018. Shrinkage of food materials during drying: current status and challenges. *Compr Rev Food Sci Food Saf* 17(5): 1113-1126. https://doi.org/10.1111/1541-4337.12375
11. Yi J, Li X, He J, Duan X. 2020. Drying efficiency and product quality of biomass drying: a review. *Dry Technol* 38(15): 2039-2054. https://doi.org/10.1080/07373937.2019.1628772
12. Tchinda R. 2009. A review of the mathematical models for predicting solar air heaters systems. *Renew Sustain Energy Rev* 13(8): 1734-1759. https://doi.org/10.1016/j.rser.2009.01.008
13. Tsotsas E, Mujumdar AS. 2011. Modern Drying Technology, Volume 4: Energy Savings. John Wiley & Sons.
14. Joardder MU, Kumar C, Brown RJ, Karim MA. 2015. A micro-level investigation of the solid displacement method for porosity determination of dried food. *J Food Eng* 166: 156-164. https://doi.org/10.1016/j.jfoodeng.2015.05.034
15. Masud MH, Karim A, Ananno AA, Ahmed A. 2020. Sustainable Food Drying Techniques in Developing Countries: Prospects and Challenges. Springer, Switzerland.
16. Djebli A, Hanini S, Badaoui O, Haddad B, Benhamou A. 2020. Modeling and comparative analysis of solar drying behavior of potatoes. *Renew Energy* 145: 1494-1506. https://doi.org/10.1016/j.renene.2019.07.083
17. Kesavan S, Arjunan TV, Vijayan S. 2019. Thermodynamic analysis of a triple-pass solar dryer for drying potato slices. *J Therm Anal Calorim* 136: 159-171. https://doi.org/10.1007/s10973-018-7747-0
18. Nasri MY, Belhamri A. 2018. Effects of the climatic conditions and the shape on the drying kinetics, application to solar drying of potato-case of Maghreb's region. *J Clean Prod* 183: 1241-1251. https://doi.org/10.1016/j.jclepro.2018.02.103
19. Kumar PM, Mylsamy K, Saravanakumar PT. 2020. Experimental investigations on thermal properties of nano-SiO_2/paraffin phase change material (PCM) for solar thermal energy storage applications. *Energy Sources Part A Recov Util Environ Eff* 42(19): 2420-2433. https://doi.org/10.1080/15567036.2019.1607942
20. Kumar PM, Sudarvizhi D, Stalin PMJ, Aarif A, Abhinandhana R, et al. 2021. Thermal characteristics analysis of a phase change material under the influence of nanoparticles. *Mater Today Proc* 45: 7876-7880. https://doi.org/10.1016/j.matpr.2020.12.505
21. Stober I, Bucher K. 2013. Geothermal Energy: From Theoretical Models to Exploration and Development. Springer Cham.
22. Muffler P, Cataldi R. 1978. Methods for regional assessment of geothermal resources. *Geothermics* 7(2-4): 53-89. https://doi.org/10.1016/0375-6505(78)90002-0
23. Vasquez NC, Bernardo RO, Cornelio RL. 1992. Industrial uses of geothermal energy a framework for application in a developing country. *Geothermics* 21(5-6): 733-743. https://doi.org/10.1016/0375-6505(92)90026-6
24. Arason S. 2003. The drying of fish and utilization of geothermal energy; the Icelandic experience. In International Geothermal Conference, Reykjavik, Iceland.
25. Gupta HK, Roy S. 2006. Geothermal Energy: An Alternative Resource for the 21st Century. Elsevier.
26. Ambriz-Díaz VM, Rubio-Maya C, Ibarra JJP, González SRG, Patiño JM. 2017. Analysis of a sequential production of electricity, ice and drying of agricultural products by cascading geothermal energy. *Int J Hydrog Energy* 42(28): 18092-18102. https://doi.org/10.1016/j.ijhydene.2017.02.154
27. Van't Land CM. 2011. Drying in the Process Industry. John Wiley & Sons.
28. Rizal TA, Muhammad Z. 2018. Fabrication and testing of hybrid solar-biomass dryer for drying fish. *Case Stud Therm Eng* 12: 489-496. https://doi.org/10.1016/j.csite.2018.06.008
29. Dinçer İ, Zamfirescu C. 2016. Drying Phenomena: Theory and Applications. John Wiley & Sons.
30. Minea V. 2018. Industrial Heat Pump-assisted Wood Drying. CRC Press, Boca Raton.
31. Hou H, Chen Q, Bi J, Wu X, Jin X, et al. 2020. Understanding appearance quality improvement of jujube slices during heat pump drying via water state and glass transition. *J Food Eng* 272: 109874. https://doi.org/10.1016/j.jfoodeng.2019.109874
32. Ismaeel HH, Yumrutaş R. 2020. Investigation of a solar assisted heat pump wheat drying system with underground thermal energy storage tank. *Sol Energy* 199: 538-551. https://doi.org/10.1016/j.solener.2020.02.022
33. Alves-Filho M, Stranmen I. 1996. The application of heat pump in drying of biomaterials. *Dry Technol* 14(9): 2061-2090. https://doi.org/10.1080/07373939608917196
34. Qiu Y, Li M, Hassanien RHE, Wang Y, Luo X, et al. 2016. Performance and operation mode analysis of a heat recovery and thermal storage solar-assisted heat pump drying system. *Sol Energy* 137: 225-235. https://doi.org/10.1016/j.solener.2016.08.016
35. Fito P, Chiralt A, Martı ME. 2004. Current State of Microwave Applications to Food Processing. In Barbosa-Canovas GV, Tapia MS, Cano MP (eds) Novel Food Processing Technologies. CRC Press, Boca Raton, pp 547-560.
36. Hii CL, Jangam SV, Ong SP, Mujumdar AS. 2012. Solar Drying: Fundamentals, Applications and Innovations. TPR Group Publication, Singapore.
37. Prakash O, Kumar A. 2017. Solar Drying Technology: Concept, Design, Testing, Modeling, Economics, and Environment. Springer, Singapore.
38. Qu H, Masud MH, Islam M, Khan MIH, Ananno AA, et al. 2022. Sustainable food drying technologies based on renewable energy sources. *Crit Rev Food Sci Nutr* 62(25): 6872-6886. https://doi.org/10.1080/10408398.2021.1907529
39. Delina LL. 2017. Accelerating Sustainable Energy Transition (s) in Developing Countries: The Challenges of Climate Change and Sustainable Development. Routledge.
40. Wang Y, Li X, Chen X, Li BO, Mao X, et al. 2018. Effects of hot air and microwave-assisted drying on drying kinetics, physicochemical properties, and energy consumption of chrysanthemum. *Chem Eng Process Process Intensif* 129: 84-94. https://doi.org/10.1016/j.cep.2018.03.020
41. Guo XN, Wu SH, Zhu KX. 2020. Effect of superheated steam treat-

ment on quality characteristics of whole wheat flour and storage stability of semi-dried whole wheat noodle. *Food Chem* 322: 126738. https://doi.org/10.1016/j.foodchem.2020.126738

42. Raghavi LM, Moses JA, Anandharamakrishnan C. 2018. Refractance window drying of foods: a review. *J Food Eng* 222: 267-275. https://doi.org/10.1016/j.jfoodeng.2017.11.032
43. Zotarelli MF, Carciofi BAM, Laurindo JB. 2015. Effect of process variables on the drying rate of mango pulp by Refractance Window. *Food Res Int* 69: 410-417. https://doi.org/10.1016/j.foodres.2015.01.013
44. Topuz A, Feng H, Kushad M. 2009. The effect of drying method and storage on color characteristics of paprika. *LWT Food Sci Technol* 42(10): 1667-1673. https://doi.org/10.1016/j.lwt.2009.05.014
45. Bahar T, Boy V, Lemée Y, Magueresse A, Lendormi T, et al. 2018. Air impingement drying of foods: modelling coupled heat and mass transfer and experimental validation. *Chem Eng Trans* 70: 1-6.