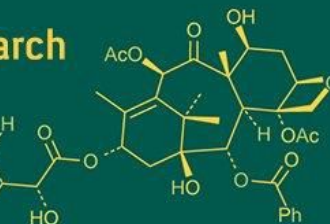


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Sustainable renewable energy approaches for food dehydration and preservation

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Abstract

Food waste across the supply chain accounts for approximately 30–40% of total global food production, thereby exacerbating hunger, increasing the burden on waste management systems, and causing significant environmental degradation. Although food scarcity remains critical in many regions, a substantial proportion of food losses occur in developing countries, primarily due to the absence of affordable and effective preservation technologies. Conventional drying methods are highly energy-intensive, largely because of inefficient control over heat, mass, and momentum transfer mechanisms. Consequently, improving sustainability in food drying processes is essential to reducing energy consumption as well as minimizing associated environmental and social impacts. In this context, sustainable food drying technologies utilizing renewable energy sources represent a promising solution, particularly for developing nations. The integration of thermal energy storage with heat pump-assisted drying systems has been shown to enhance both drying efficiency and product quality. Likewise, advanced hybrid drying configurations such as solar-assisted microwave drying and heat pump–microwave drying—offer reduced operational costs while preserving superior food quality. Furthermore, the role of resource availability and government incentive policies in promoting the adoption of renewable energy-based sustainable drying technologies is also discussed.

Keywords: Food drying, renewable energy, solar drying, microwave drying, thermal energy storage, sustainable drying.

Introduction

Post-harvest management of agricultural products proves a considerable challenge in developing countries, where insufficient infrastructure can frequently result in food losses, nutritional degradation, and insecure financial situations for smallholder farmers (Kaur *et al.*, 2024) [14]. Fruits and vegetables are extremely perishable commodities, with an average of 30% to 50% wasted due to ineffective marketing channels, inadequate post-harvest treatment, and excessive transportation costs (Hasan *et al.*, 2019; Shimpy and Kumar, 2019) [6, 32]. Meanwhile, worldwide energy demand will probably go up by as much as 50% by 2030. Drying is the predominant method of food preservation and is performed globally. Many of the emerging economies are experiencing a significant energy crisis. In addition to their energy constraints, these nations cannot afford conventional drying technology. Thus, it is important to prioritize striking a balance between food drying's cost, quality, and efficiency. In this regard, renewable energy-based drying constitutes a sustainable solution that diminishes food waste while limiting dependence on fossil fuels, reducing waste heat generation, operational cost, and negative environmental impact.

The distinctive characteristics of each particular food commodity have been associated with the trend of food waste, and each food item has certain drying requirements in order to dry foodstuffs efficiently and affordably. For instance, cereal additionally needs to be dried to a moisture content of 8-10% since it emerges with a comparatively low moisture content (25% w.b.). Furthermore, they are often produced in substantial quantities with free flow, making them ideal for batch or circulatory dryers. Fruits and vegetables are vital for human nutrition since they contain minerals, vitamins, and fiber (Duc Pham *et al.*, 2019; Pham and Karim, 2020) [5, 25]. These perishable food commodities require special cold storage facilities to keep them fresh. Unfavorably, due to a lack of access to basic energy sources like electricity, the majority of farmers still use methods like open sun drying to preserve their produce instead

of storing it in cold storage. So the long-term solution for developing countries' food preservation could be an effective drying system that uses renewable energy. Since drying is an energy-intensive process, its widespread application in industrial processes is very crucial. Increasing drying efficiency and lowering its energy usage could make this process easier as the industry faces higher demands to reduce greenhouse gas emissions and reduce its dependence on fossil fuels.

Solar drying remains one of the most widely used post-harvest processing methods for agricultural produce (Karim *et al.*, 2014) ^[13]. However, conventional solar drying systems rely heavily on intermittent solar radiation, which restricts their ability to deliver consistent and reliable drying performance. The incorporation of thermal energy storage allows solar dryers to operate continuously during periods of low solar availability, such as nighttime and overcast conditions, thereby improving system utilization (Karim *et al.*, 2018; Kant *et al.*, 2016) ^[11, 12]. To further enhance drying efficiency, several technological advancements have been proposed, including the use of phase change materials,

heat recovery strategies, and advanced thermal energy storage systems (Pandey *et al.*, 2024; Kamarulzaman *et al.*, 2021; Tomar *et al.*, 2017) ^[10, 23, 33]. In contrast to traditional solar dryers that depend solely on direct solar exposure, modern drying systems offer improved control over key operating parameters such as temperature and airflow. Among these, microwave (MW)-assisted drying technologies provide notable advantages, including reduced drying time and improved energy efficiency compared to conventional drying methods. Nevertheless, the primary limitation of MW drying systems is their high initial investment cost, which is nearly twice that of traditional drying technologies (Kumar and Karim, 2019; Kumar *et al.*, 2018) ^[17]. Recent advancements in dryer design and material selection have contributed to improvements in energy efficiency, food safety, and overall sustainability. Furthermore, hybrid drying systems that combine multiple drying technologies present a viable solution for developing countries by simultaneously enhancing energy efficiency, product quality, drying duration, and operational costs.

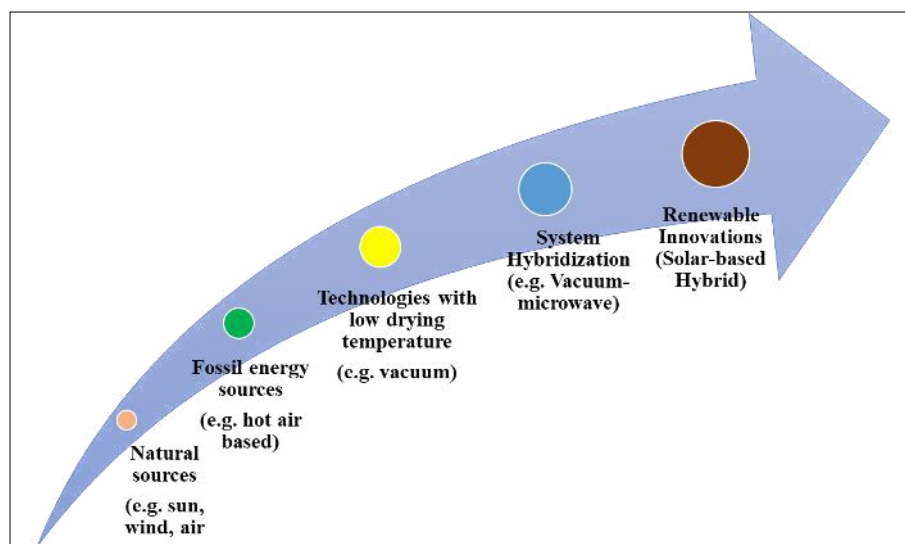


Fig 1: The development of drying techniques over time

2. Classification of existing drying technologies

Drying technologies can be categorized based on their primary energy source, including traditional fossil fuel-based systems, renewable energy-driven technologies, electrical methods, and dielectric drying techniques. Dielectric drying, which utilizes high-frequency electric fields to generate heat within food materials, includes microwave and radio frequency drying processes (Jiang *et al.*, 2016). In practice, the limitations of individual drying methods can be mitigated by integrating multiple technologies, thereby balancing their respective advantages and disadvantages. Figure 2 presents a comprehensive classification of drying technologies according to their energy sources. Conventional drying methods powered by fossil fuels have been in use since prehistoric times; however, these technologies are increasingly unsustainable

and should be replaced with more efficient drying systems based on renewable energy sources. Geothermal drying systems are highly dependent on the local availability of geothermal resources and have been successfully applied to the drying of fish, olive leaves, and tomatoes. Heat pump-assisted drying systems, while effective, tend to exhibit reduced associated with high initial investment and maintenance costs (Minea, 2013) ^[20]. Nevertheless, the performance and energy efficiency of heat pump dryers can be significantly improved through the incorporation of energy recovery mechanisms. Dielectric drying has been shown to markedly accelerate drying rates, and when combined with other drying techniques, it can enhance product quality while simultaneously reducing overall energy consumption (Rahman *et al.*, 2018) ^[29].

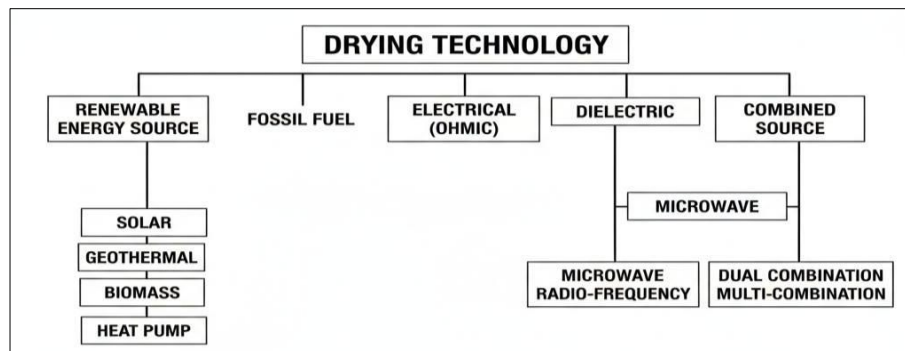


Fig 2: Classification for drying technologies by energy source

3. Sustainable energy-efficient drying technologies

Drying operations can account for as much as 25% of total energy consumption within the food processing industry, thereby contributing significantly to environmental impacts. As a result, the development of energy-efficient food drying technologies is essential for achieving long-term environmental sustainability. Among renewable energy options, solar energy remains the most extensively utilized and widely available resource for food drying applications. However, other renewable energy sources, including geothermal energy and biomass, also exhibit considerable potential for use in food drying systems (Ibrahim *et al.*, 2009; Yi *et al.*, 2020) [8, 36].

3.1 Improved solar drying with thermal energy storage (TES)

Solar drying systems offer farmers in developing countries a cost-effective and efficient alternative to traditional open-air drying methods. Incorporating an effective thermal energy storage system into solar dryers is generally more economical than installing supplementary heating units that depend on conventional fossil fuel-based energy sources. Among available storage options, latent thermal energy storage employing phase change materials (PCMs) is particularly effective, as these materials undergo repeated melting and solidification cycles, during which latent heat is absorbed and released to support continuous drying operations.

3.1.1 Thermal storage system based on phase change materials (PCM) for solar drying

Phase change material (PCM)-based thermal energy storage systems are capable of storing and releasing substantial amounts of heat through solid-liquid phase transitions. Owing to their distinctive advantages, PCMs have been extensively investigated for a wide range of thermal applications, including refrigeration and air-conditioning systems, food drying technologies, and space heating (Khan *et al.*, 2017; Abujar *et al.*, 2016) [1, 15]. The appropriate selection of PCM is a critical factor in the effective performance of solar dryer systems. Based on their composition, PCMs are broadly categorized into organic, inorganic, and eutectic types. Eutectic PCMs consist of two or more non-interacting components and exhibit a melting temperature lower than that of the individual constituents. These materials offer favorable properties such as thermophysical stability, non-toxicity, suitable heat transfer characteristics, and high volumetric heat storage capacity (Sharma *et al.*, 2009) [31]. Paraffin-based materials are the most commonly employed phase change materials (PCMs)

in hot-air drying systems, including both active and forced convection configurations. In contrast, commercially available salt hydrate PCMs typically exhibit melting temperatures in the range of 35–50 °C but often suffer from incongruent or semi-congruent melting and phase segregation during repeated freezing and melting cycles. Paraffin wax, which is non-corrosive and both physically and chemically stable, demonstrates favorable thermal performance; however, despite being combustible, it possesses relatively low thermal conductivity. To overcome these limitations, the incorporation of high-thermal-conductivity additives and fire-retardant materials has been proposed. Flat plate solar collectors remain the most widely adopted energy collection units in solar drying applications. Recent studies have demonstrated that hybrid dryers powered by renewable energy sources can achieve efficiencies approximately 20.5% higher than those of conventional flat plate solar collectors. Furthermore, the integration of geothermal and solar energy systems with PCM-based thermal storage enables dryer operation for up to 20 hours per day (Ananno *et al.*, 2020) [2]. The inclusion of fins within the air duct increases airflow turbulence, thereby further enhancing the performance of flat plate solar collectors. Similarly, the use of V-corrugated absorber plates improves heat transfer rates by increasing the effective heat transfer area. V-shaped absorber configurations also enhance solar energy absorption due to multiple internal reflections within the grooves. As a result, V-groove collectors have been reported to exhibit efficiencies approximately 12% higher than those of conventional flat plate collectors. Figure 3 illustrates an advanced solar drying system incorporating a V-groove air collector coupled with PCM-based thermal energy storage. The thermal efficiency of V-corrugated solar air collectors integrated with PCM-based thermal energy storage has been reported to be approximately 15% to 21.3% higher than that of similar collectors operating without thermal storage (Kabeel *et al.*, 2016) [9]. In such configurations, the PCM layer is positioned between the back insulation of the solar collector and the V-groove absorber plate. During periods of peak solar radiation, the thermal storage system absorbs excess heat and subsequently releases it when required. This dual modification extends the effective drying duration for food materials, thereby enhancing overall dryer efficiency and improving the quality of the dried products.

3.1.2 TES with pebble-bed solar dryer

Rock or pebble beds are among the most commonly employed packed-bed thermal storage systems for solar energy applications, owing to their high volumetric heat

storage capacity, enhanced heat transfer coefficients, low porosity, minimal pressure drop across the bed, and the low cost of both the storage medium and containment structure. Consequently, numerous studies have focused on the development of integrated rock-bed thermal energy storage systems for solar drying applications. Experimental investigations using solar dryers equipped with rock-bed storage have evaluated the drying characteristics of various

food products, including fish, pepper, and cassava chips. These studies reported that the incorporation of rock-bed storage reduced drying time by approximately 50% compared to traditional open sun drying. Furthermore, for coconut drying applications, rock-bed thermal storage demonstrated higher efficiency than alternative storage media such as concrete and sand when used within a solar greenhouse drying system.

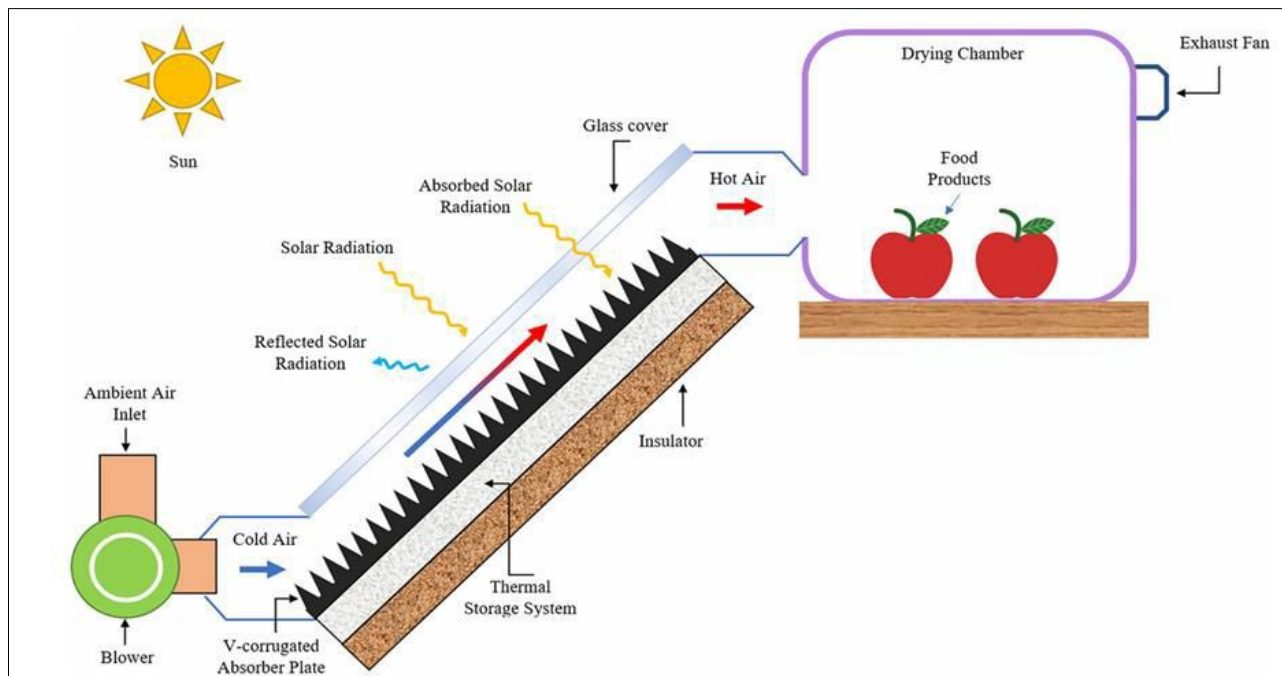


Fig 3: Diagram of solar air heater with V-groove and PCM thermal storage system for an improved dryer (Masud *et al.*, 2020) ^[19]

3.2 Drying using geothermal heat

Geothermal energy utilization is conceptually classified into near-surface and deep subsurface resources, with deep geothermal systems further categorized into high-enthalpy and low-enthalpy reservoirs. Low-enthalpy geothermal resources, operating at temperatures below 150 °C, are particularly suitable for drying applications involving fruits and vegetables. Heat is extracted from geothermal wells in the form of hot water or steam, which can be directly or indirectly utilized for drying purposes. In addition, geothermal power plants generate substantial amounts of waste heat that can be effectively recovered and applied in geothermal food drying systems. The use of geothermal energy for food drying is associated with minimal operational costs. Figure 4 presents a schematic representation of a geothermal food dryer, illustrating the transfer of heat from subsurface geothermal water through a heat exchanger to warm the drying air. The heated air is subsequently circulated through trays within the drying chamber. Several studies investigating multi-layer tray geothermal dryers for fruit processing have reported moisture reduction from approximately 80% (wet basis) to 20% (wet basis) within 24 hours. Geothermal energy has also been successfully integrated with various dryer configurations, including cabinet dryers, convective dryers, conveyor dryers, and rack-tunnel dryers (Popovska-

Vasilevska, 2003) ^[26]. Overall, geothermal drying systems have demonstrated a competitive advantage over conventional fossil fuel-based industrial dryers. Depending on the specific drying requirements of the product, operating temperatures in geothermal drying systems can be adjusted from as low as 50–60 °C to as high as 90 °C.

Rack-tunnel geothermal dryers are large-scale drying systems commonly used for fish processing, featuring multiple stacked trays. To enhance natural draft and facilitate uniform air circulation, chimneys are often incorporated into the dryer design (Van Nguyen *et al.*, 2015) ^[34]. These dryers typically have capacities ranging from 2000 to 4000 tons per unit. The drying process occurs in two stages, reducing the moisture content of fish from approximately 80% to 15% (w.b.) (Arason, 2003) ^[3]. This method is predominantly employed within the feed industry. Although geothermal energy is primarily harnessed for electricity generation, it can also be effectively utilized for food drying applications. Geothermal dryers are versatile, capable of processing a wide range of products under varying drying conditions, making them particularly suitable for large-scale operations. Consequently, countries with abundant geothermal resources, particularly developing nations, may find these dryers to be an attractive and sustainable drying solution.

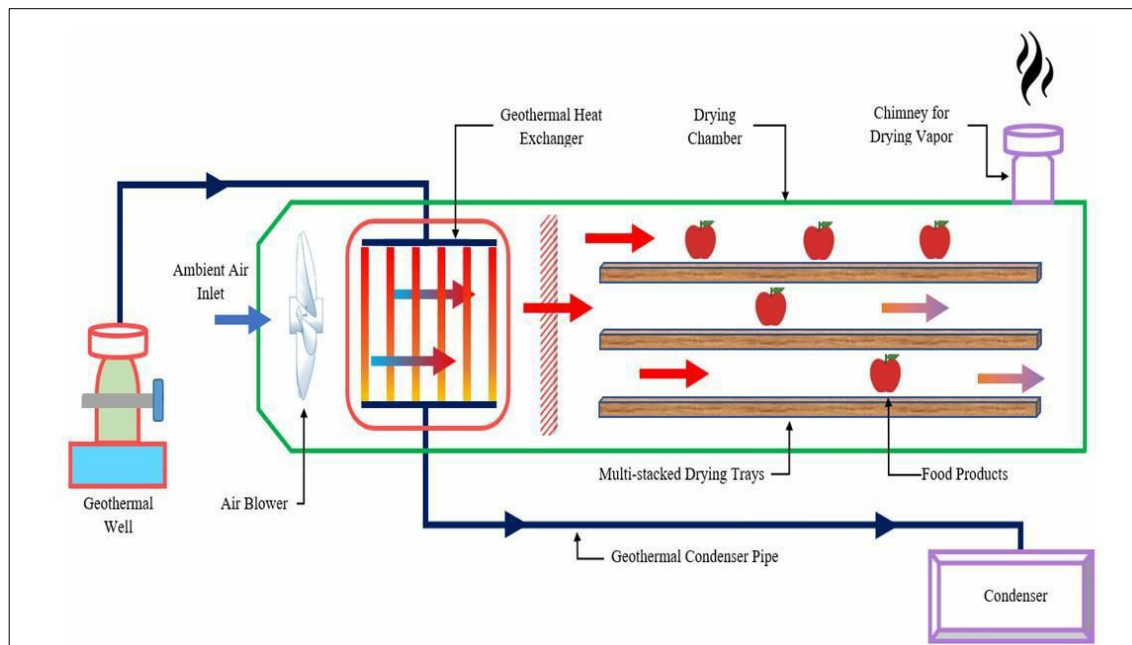


Fig 4: Diagram of geothermal dryer with multiple stacked trays

3.3 Biomass-assisted drying system

Biomass energy has been employed for centuries as a renewable thermal energy source for various drying applications. In biomass-assisted drying systems, hot air is generated through the combustion of biomass and circulated throughout the drying chamber. However, conventional biomass dryers typically suffer from low energy efficiency, primarily due to significant heat losses arising from suboptimal design. These limitations can be addressed through innovative dryer designs that minimize thermal losses, enhance heat and mass transfer rates, and improve overall product quality. Advanced biomass drying technologies, such as continuous direct-heat rotary dryers, flash dryers, and fluidized bed dryers, are recommended to overcome the drawbacks of traditional systems (Liu *et al.*, 2015) [18].

The design of an efficient fluidized bed dryer is inherently complex, as issues such as crust formation and insufficient material transport caused by plug-flow behavior can reduce drying performance. These challenges can be mitigated by increasing airflow in the feeding section and incorporating bed vibration. To protect the vibrating mechanisms from high temperatures, the vibration equipment must be installed externally to the dryer. Figure 5 presents a schematic of an improved continuous fluidized bed dryer fueled by biomass, highlighting its two main components: a biomass combustion chamber and a continuous feeding system. Additionally, biomass dryers can be integrated with solar collectors, enabling solar-assisted biomass drying systems that operate continuously, cost-effectively, and synergistically.

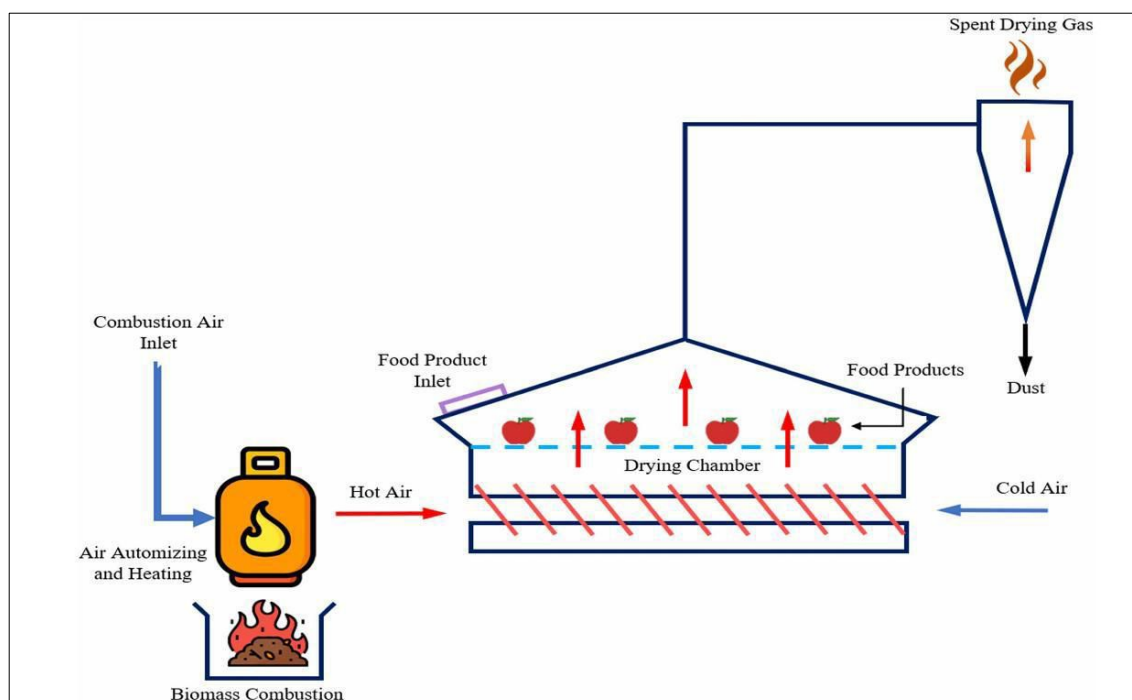


Fig 5: Fluidized bed dryer powered by biomass

4. Hybrid drying using heat pump

Heat pumps (HPs) utilize ambient heat to achieve significant energy savings. Among these, air-based heat pump dryers are the most widely employed, as air serves as an effective heat transfer medium. Heat pump-assisted convective dryers can reduce energy consumption by up to 50% compared to conventional convective dryers due to their ability to recover and reuse heat (Minea, 2018) [21]. In addition to energy savings, heat pump dryers enhance the quality of dried food products. While heat pumps are compatible with most convective drying systems, they are generally unsuitable for applications requiring very high airflow, such as spray or flash drying. Heat pump drying is particularly advantageous in developing countries with humid climates, where high ambient moisture can increase product spoilage during the rainy season. By controlling humidity throughout the drying process, heat pumps effectively mitigate this risk. Furthermore, the efficiency of heat pump dryers can be further improved by integrating them with additional heating sources, such as solar or microwave energy. These combined approaches constitute advanced hybrid drying technologies, as discussed in the following sections.

4.1 Heat pump dryers coupled with solar-assisted phase change materials

A solar thermal storage system incorporating phase change materials (PCM) can significantly reduce drying costs and enhance the operational flexibility of hybrid heat pump drying systems. By utilizing stored solar energy during periods without sunlight, hybrid systems achieve improved overall efficiency. Figure 6 presents an advanced schematic of a solar-assisted heat pump dryer integrated with PCM-based thermal storage. These systems have demonstrated both high energy efficiency and the ability to maintain superior product quality. Despite their considerable potential, research on such hybrid configurations remains limited. Qiu *et al.* (2016) [28] developed a solar-powered heat pump dryer that incorporates heat recovery and water-based thermal storage. Their study reported substantial energy savings of 40.53%, 53.39%, and 58.17% when compared to parallel solar heat pump drying, hot air drying with an open damper, and hot air drying with a half-open damper, respectively. The payback period for these systems ranged from 2 to 6 years, depending on the type of food being dried.

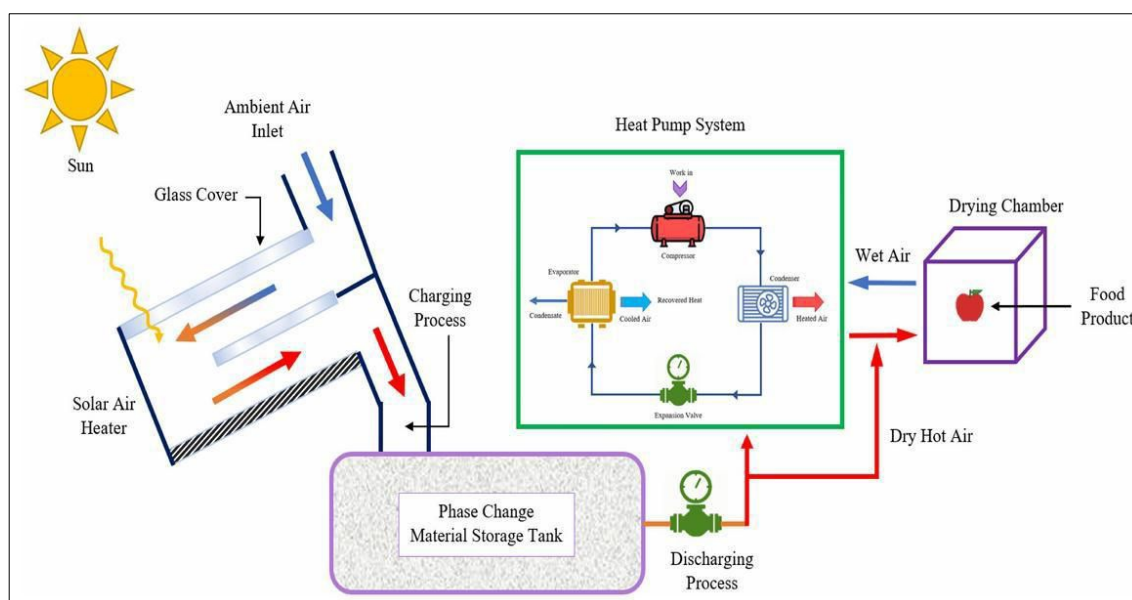


Fig 6: Enhanced PCM thermal storage for heat pump dryers

4.2 Microwave convective drying utilizing heat pump design

Heat pump-assisted drying represents a promising technology, capable of recovering 90–95% of the heat absorbed by wet materials. However, this method is relatively slow and time-intensive (Patel and Kar, 2012) [24]. The integration of microwave (MW) technology offers a solution by significantly accelerating the drying process, reducing drying time by approximately 80%. In MW drying, electromagnetic radiation penetrates the material and generates uniform volumetric heating, thereby enhancing moisture removal (Khan *et al.*, 2020) [16]. Continuous MW application, however, can lead to uneven temperature distribution, potentially compromising product quality. This issue can be mitigated through intermittent microwave-assisted convective drying (IMCD), in which MW energy is applied periodically alongside convective drying (Kumar *et al.*, 2018) [17]. By combining IMCD with heat pump-assisted

drying and optimizing MW intermittency, an energy- and time-efficient hybrid drying solution can be achieved.

Microwave-assisted convective drying has been extensively investigated for its effects on both drying rate and food quality. Studies have shown that incorporating microwave energy into convective drying can reduce drying time by approximately 50% compared to conventional convective drying methods (Bhattacharya *et al.*, 2015) [4]. In a study on lemon slices, Sadeghi *et al.* (2013) [30] reported that microwave-assisted convective drying enhanced food quality, improving parameters such as color retention and rehydration capacity relative to standard convective drying. Similarly, intermittent microwave-assisted convective drying of apple slices was found to produce superior outcomes compared to continuous microwave-assisted convective drying, including greater color changes, higher phenolic content, lower bulk density, and improved rehydration rates (Mujumdar and Xiao, 2019) [22].

4.3 Solar microwave drying using heat pumps

Solar drying has great potential as a solar thermal energy application. Solar drying, when combined with other cutting-edge drying techniques, can yield far better results. To address the present issues with food drying, one solution is heat pump-based microwave convective drying (HPMCD), which combines the benefits of solar convective heat with those of heat pump drying, including energy recovery and quick drying time without losing quality. But there are very limited studies conducted on microwave drying assisted with a heat pump.

Designing and optimizing a hybrid drying system requires careful consideration to capitalize on the benefits of each component while addressing its limitations. MW energy is recommended for heat pump drying during the falling rate period, when moisture content is typically about 20-25% and air moisture content is constant. The high price and complexity of these systems hinder their use in large-scale commercial applications. Profits must be compared to investments to determine feasibility.

5. Comparison of different drying technologies

A single energy-efficient dryer capable of handling all types of food products under varying drying conditions with multifunctional features has not yet been realized. The selection of an appropriate drying technology must therefore consider specific requirements, including the characteristics of the product, desired product quality, and the costs associated with installation, operation, and maintenance. Microwave (MW) drying is recognized as a cost-effective method for transforming low-cost raw materials into high-value products; however, a comprehensive evaluation of all relevant factors is still needed. Table 1 summarizes the key technical parameters, such as drying time and product quality, as well as economic considerations for renewable energy-based drying technologies, often in comparison with conventional drying methods (Hii *et al.*, 2012; Prakash and Kumar, 2017) [17, 27]. While renewable energy-based dryers generally entail higher initial capital investment, they benefit from lower operating costs. Consequently, it is essential to perform an economic analysis, including the calculation of payback periods based on fuel savings.

6. Government policies and incentives

Energy efficiency and environmental sustainability are among the foremost global challenges of the 21st century. The development and adoption of improved, energy-efficient drying methods based on renewable energy are likely to attract government attention, given the high energy demands of food drying processes. However, the substantial capital cost of renewable energy-based drying systems remains a significant barrier to their widespread implementation. Many developing countries, which are also major global energy consumers, have undertaken long-term initiatives to promote sustainable energy utilization. For example, India has introduced programs such as the National Energy Efficient Fan Program to enhance building energy efficiency.

Governments should prioritize the promotion of sustainable drying technologies, as food drying is one of the most energy-intensive processes in the food processing sector. Measures to support their development include (Wilkins, 2010) [35]:

- Raising awareness among stakeholders about the potential market for renewable energy-based drying

technologies.

- Offering financial incentives, such as tax breaks or duty reductions, to encourage private sector investment.
- Establishing a business-friendly environment through infrastructure development, supportive regulations, and legislation that minimize resource consumption and protect the environment.
- Engaging local communities to gather input on solutions that address their specific needs.

Among these measures, financial support from the government is particularly critical in developing countries, as it can substantially reduce initial capital costs and make renewable energy drying projects financially viable.

7. Current challenges and future directions

The future of drying technologies is expected to emphasize higher energy efficiency, reduced environmental impact, increased utilization of renewable energy, and the production of high-quality food products at lower overall costs. In developing countries, particular attention will also be given to the costs associated with system installation and operational management. However, cost assessment remains challenging, as it varies depending on the site and the specific food materials being processed.

The development of energy-efficient drying technologies is critical due to the inherently high energy intensity of drying operations. At the same time, consumers increasingly demand food products that meet high-quality standards, even when energy efficiency is prioritized. This consideration is especially relevant for high-value agricultural products, such as cash crops, where favorable market prices can offset higher production costs. Hybrid drying approaches, including intermittent microwave convective drying (IMCD) and heat pump-assisted solar drying with thermal storage, provide viable solutions that balance energy efficiency and product quality. Future research and engineering efforts should focus on identifying and addressing bottlenecks in these technologies to further enhance their performance.

Given that individual drying technologies have inherent limitations, combined or hybrid drying systems are expected to become more prevalent. Despite substantial prior research, there remains a need to develop and optimize specialized drying technologies and integrate renewable energy sources—including solar, heat pump, and microwave systems—regardless of the availability of existing dryers. Hybrid systems such as heat pump–microwave convective drying (HPMCD) demonstrate significant potential but are still at an early stage of development. Advancing renewable energy-based drying technologies will require a multidisciplinary approach that integrates technical innovation, economic feasibility, and policy considerations.

8. Conclusion

Sustainable drying technologies, including solar, geothermal, biomass, and heat pump drying, are being actively explored to mitigate nutritional deficiencies in developing countries while reducing the environmental impact of food waste. While each individual drying technology offers distinct advantages, integrated or hybrid systems are particularly promising. Heat pump–microwave convective drying (HPMCD), which combines heat pump, microwave, and solar convective drying, represents a highly

potential hybrid approach that requires further development. Microwave-assisted drying, capable of reducing drying time by up to 90% and enhancing nutrient retention, is a critical component of such combined systems. Given the complexity and high capital costs associated with these technologies, theoretical investigations provide a practical starting point for research. Solar drying systems equipped

with thermal energy storage, when integrated with heat pump drying, demonstrate superior energy efficiency and produce high-quality products. Furthermore, hybrid integrated drying systems, such as those combining solar and microwave technologies, offer additional benefits, including reduced operating costs and improved product quality.

Table 1: Comparison of renewable energy-based and conventional drying technologies

Classifications	Properties	Food products to be dried	Economic feasibility	Drying time	Quality of dried products
Convective	Most frequently, it takes long time to dry and easily forms a surface crust	Large variety of crops	Comparatively low	1-6 h	Low to medium
Microwave	Improves drying efficiency but may overheat in the last stage. Typically used in conjunction with other drying processes	Cash crops	Elevated, nearly double the hot air convection	30s- 5 min	Medium to high
Heat pump	Exhaust heat recovery leads to better product quality through precise control measures	Cash crops, heat sensitive	High investment and maintenance cost	5-60 min	Low to medium
Heat pump-based microwave convective drying	Combining heat pump, microwave, and solar convective drying to maximize the benefits of different technologies. Further study and simulations are pending	Cash crops and heat-sensitive	The possibility of attaining the cost-effectiveness by the utilization of solar heat	30 s-5 min	High
Solar	V-corrugated plates and heat storage (PCM or rock-bed) improve performance and is easily accessible resources	Large variety of crops	Possible if fuel savings can cover the additional capital cost or if government pays for it	6-10+ h	Medium
Geothermal	Utilize local resources and geothermal resources below 150 °C	Ordinary crops	-	10+ h	Low to medium
Biomass	Advanced mass and heat transfer mechanism, such as continuous fluid-bed can boost performance of this abundant and accessible resource	Ordinary crops	-	30-60 min	Low

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