Advancements in Solar Drying Technology: A Sustainable Solution for Food Preservation and Agricultural Processing

PRASHANT P BORNARE[1], DR. ADWAIT M VAIDYA[2]
[1]*Research Scholar, Kaviyatri Bahinabai Chaudhari North Maharashtra University, Jalgaon*
[2]*I/c Director, Thane Sub-Campus & Kalyan, Mumbai University, Mumbai*

Abstract—* Solar drying technology has emerged as an efficient and sustainable alternative to traditional drying methods, addressing issues of contamination, inefficiency, and high energy consumption. This paper explores the principles, classifications, and advancements in solar dryers, emphasizing their role in improving food processing and agricultural preservation. Solar drying systems are categorized based on air movement (passive, active, mixed), heat transfer modes (direct, indirect, hybrid), and innovative technologies like solar-assisted heat pumps. These systems utilize solar energy to provide controlled drying conditions, enhancing product quality while reducing operational costs and environmental impact. Hybrid and mixed- mode dryers are highlighted for their ability to combine direct and indirect drying techniques, offering superior performance for diverse applications. Furthermore, new technologies such as solar tunnel dryers and greenhouse dryers are discussed for their efficiency in preserving fruits, vegetables, and spices. Economic evaluations demonstrate shorter drying times, better product quality, and significant energy savings compared to conventional methods. This study concludes that solar drying is a viable, eco-friendly option for addressing global food preservation challenges while promoting renewable energy use.

***Index Terms-* Solar Drying Technology, Food Preservation, Renewable Energy, Hybrid Solar Dryers, Agricultural Processing**

I. INTRODUCTION

Since antiquity, free of charge and unregulated drying in the sun has been the most common way of preserving food and crops for cultivation. However, this procedure has considerable downsides, including invasion from dusty, thunderstorms, and rodents, bug infestation, and spoilage due to fungi and breakdown. These factors can degrade the product to the extent of losing its market value, adversely impacting the economy [1-4]. Additionally, uncontrolled sun drying is labour hard, lengthy, and necessitates a broad space to spread the food.

Although a mechanical curing provides a controlled alternative, it is resource pricey and raises manufacturing costs. Drying with solar emerges as a successful and sustainable answer to these problems. It enables food processing in neat, clean, and controlled conditions that meet national and international requirements, all while utilizing renewable solar energy at nil expenses for operation. This technology conserves energy, decreases drying time, takes up less room, and enhances the durability of the goods, making it a feasible alternative for small-scale companies and encouraging the use of renewable energy [1, 4-8].

Solar dryers protect produce from external elements such as flies, rain, and dust, while also being waterproof, allowing products to remain inside overnight. They also help reduce dependency on fuel, minimize environmental impact, and improve market value through better- quality products. However, solar drying systems have some limitations, such as dependency on adequate solar radiation and higher initial costs [1].

Advancements in solar drying technology have led in the creation of solutions that address these issues. contemporary sun dryers regulate drying parameters such as temperature, humidity, and airflow, resulting in higher levels of effectiveness and quality of products. Researchers have also sought to improve the effectiveness of solar heated dryers in order to satisfy the needs of certain regions, including Lebanon, which experiences fuel scarcity and economic issues. [9-12].

The objective of this study is to examine solar-powered drying technologies, classify different types of dryers, and their importance in saving the fossil fuels and particularly in reducing energy costs and CO_2 emissions, while promoting sustainable practices in food processing and agricultural preservation.

II. THE FOUNDATION OF SOLAR DRYER

A solar dryer uses heat to raise the pressure of water molecules inside the goods while lowering the humidity content of the drying air, allowing warm air to collect and transport moisture more effectively. The temperature of the drying air determines the efficiency of moisture removal; warmer air is more effective [10-11].

III. SOLAR DRYER CATEGORY

There was different category based on which classification of sun dryers are mentioned in the literatures [1-17]. This study categorizes solar dryers based on air flow method, heat transfer mode, and style of drying chamber [17]. Figure 1 shows the classifications [17,18].

3.1 Open Sun Drying

Materials are heated directly by sun radiation in open-air solar drying., a process used for centuries. This natural convection method depends on air movement caused by density differences and is divided into two types [13]:

1. Outdoor drying, where solar radiation directly heats the material.
2. Food is partially shielded from rain and other natural elements by drying under a transparent cover.

Figure 1. Schematic summary of the classification of solar dryers[16]

3.2 Direct Solar Drying

Figure 2. Open solar drying of black Corinthian seedless grapes on an outdoor threshing concrete surface [13].

Direct sun drying improves on open sun drying by enhancing hygiene and efficiency. Known as cabinet or box-type dryers, they are commonly used in areas with prolonged sunlight [14-16]. These dryers feature a transparent cover (glass or plastic) over a shallow insulated box. Food samples are placed on perforated trays to allow airflow. Solar radiation heats the interior through the greenhouse effect, where short-wavelength light penetrates the cover, converts to heat, and remains trapped [16]. Hot air is circulated using a centrifugal blower, and exhaust holes remove humid air [16].

3.3 Indirect Solar Drying

Indirect heat transfer and moisture removal are made possible by sunlight separating the drying chamber from the solar collector. Air heated by the solar collector is either passively (natural convection) or actively (fans) moved to the drying chamber [3,13,16]. The differential in moisture concentration between the air and the crop surface causes the hot air to evaporate moisture [3,13,16]. The working idea is shown in Figure 3 [16].

3.4 Hybrid Solar Drying

With the help of ventilators to circulate air, hybrid dryers combine several drying methods, such as direct sunlight with electrical power or accumulated heat. In order to improve drying efficiency and overcome the drawbacks of previous solar dryers, these dryers work in either forced convection or passive modes, depending on their application and design (Figure 4) [16]. Solar heating and other heat sources, such as gas, biomass, fossil fuels, or electricity, can be combined in hybrid systems. A lot of them have photovoltaic (PV) panels to provide electricity to run fans or other parts. For example, PV modules use solar energy to generate electricity and drive greenhouse dryers' forced air circulation. Direct, indirect, and combination processes are all supported by hybrid dryers, which increase performance and adaptability [3,16,27].

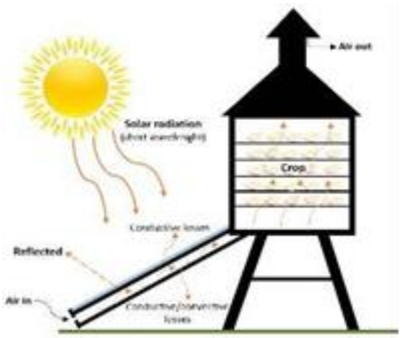

Figure 3. Schematic of working principle of indirect drying method [16].

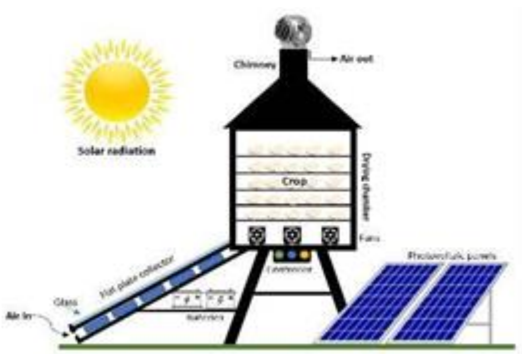

Figure 4. schematic view of hybrid solar dryer [16]

3.5 Mixed Solar Drying

Mixed solar dryers is the combination of both direct as well as indirect drying techniques [16-18]. A second solar collector warms the air before it reaches the drying chamber, which has a clear lid. The product is then immediately heated by sunlight. This design achieves higher drying rates and temperatures than other types, enabling faster moisture removal [16]. Despite its superior performance, the mixed dryer is complex and has a high initial cost [16-18].

3.6 Air Movement Mode

In terms of air movement, solar dryers can be categories as mixed-mode, which includes both passive (natural convection) and active (airflow powered by an electric fan). [18,27].

3.7 Passive Solar Dryers

Passive dryers, also called natural convection dryers, rely on air heated by radiation of sun to circulate over the goods or product surface. Different types exist within this category [3,12].

3.7.1 Direct Passive Solar Dryers

To let sunlight into the drying chamber, these dryers have a clear lid. Through evaporation and diffusion, the greenhouse effect turns the radiation into heat, which lowers crop moisture. [3,12].

3.7.2 Cabinet Passive Solar Dryers

Simple and reasonably priced, cabinet dryers are usually constructed of wood that has been coated black to capture sun radiation. For airflow, they have perforated trays that let outside air flow through the crop and remove moisture [3,12,16,19–20]. They reduce dust, insects, and weather effects while improving efficiency and product quality when compared to open sun drying.

3.7.3 Greenhouse Passive Dryers

Glass or polyethylene film are used to create the glazed roofs and walls of greenhouse dryers. They maximize airflow and sun radiation by being constructed as roof or dome kinds. Crops are positioned on trays or plastic sheets, and vents regulate the flow of air. Natural convection facilitates efficient drying because heating from sun radiation lowers air density [3,16,19,20].

3.7.4 Indirect Passive Solar Dryers

Indirect passive dryers use natural convection. Solar air heaters provide hot air, which dries the crop in the chamber and exits via vents. Crops are spread in non-overlapping trays, but airflow and heat transfer rates remain low [20].

3.8. Mixed-Mode Passive Solar Dryers

Direct and indirect airflow are combined in these dryers. The drying chamber is heated by solar radiation both directly and indirectly through collectors, providing versatility for a range of crops that need to be dried at low temperatures. [16,21].

3.9 New Technology-Based Solar Dryers

1. Cabinet Type Natural Convection Dryer: Effective for fruits, vegetables, and mushrooms, maintaining consistent product quality [23-25].
2. Multi-Stacked Natural Convection Dryer: Similar in design to cabinet dryers, ensuring product quality preservation [23-25].
3. Multi-Shelf Forced Convection Dryer: Utilizes forced airflow for enhanced efficiency and quality [23-25].
4. Solar Tunnel Dryer: Reduces drying time significantly compared to sun drying, with regulated temperature for crops like bananas [23-25].
5. Greenhouse Tunnel Dryer: An advanced version of the tunnel dryer, tested on red sweet pepper and garlic, showing improved efficiency and reduced labor costs [23-25].
6. Pineapple Drying Studies: Solar tunnel dryers achieved uniform drying for pineapple slices [23-25].
7. Sweet Pepper and Garlic Drying: Tunnel dryers explored various configurations to optimize moisture reduction over time [23-25].
8. Salted Greengages Drying: Demonstrated the versatility of solar drying for unique products [23-25].

3.9.1. Performance Evaluation

- Comparative Studies: Solar tunnel dryers showed shorter drying times and better product quality than traditional methods [23-25].
- Economic Viability: With a three-year payback period, solar dryers proved cost- effective for farmers [23-25].
- Efficiency Factors: Initial moisture, product maturity, and drying conditions significantly influenced results [23-25].

3.10. Solar Heat Pump-Based Dryers

Heat pumps and solar energy are combined in Solar-Assisted Heat Pump Drying, which improves efficiency by enabling lower temperatures to improve quality and save energy. [24-26].

1. Air Source Heat Pump Systems: Use ambient air for energy-efficient drying under controlled conditions [24-26].
2. Heat Pump Dehumidifiers: Remove moisture using latent heat, offering precise humidity control [24-26].
3. Dual System Designs: Integrate solar and heat pump technologies for better drying performance [24-26].
4. Low-Temperature Drying: Suitable for heat-sensitive products, preventing quality degradation [24-26].
5. Economic and Performance Analysis: Models predict system performance under various conditions, showcasing cost-effectiveness [24-26].
6. Aseptic Processing: Ideal for high-value foods needing strict hygiene [24-26].
7. Wide Temperature Range: Operates effectively from -20 to 100 °C, meeting diverse drying needs [24-26].

IV. CONCLUSION AND FUTURE SCOPE

Solar drying technology offers a sustainable solution to the limitations of traditional and artificial drying methods. By utilizing renewable solar energy, solar dryers provide cleaner, more efficient, and cost-effective drying processes. This study reviewed various classifications and technologies, including direct, indirect, hybrid, and solar-assisted heat pump systems. These innovations demonstrate improvements in drying efficiency, reduced environmental impact, and enhanced product quality. Hybrid and mixed-mode dryers have proven particularly effective, accommodating a wide range of crops under controlled drying parameters.

Despite their advantages, solar drying systems face challenges such as dependency on solar radiation, limited application in cloudy regions, and higher initial costs. Future studies should concentrate on creating cutting-edge materials for improved insulation, refining designs for year-round use, and incorporating smart technologies for control and monitoring in real time. The incorporation of artificial intelligence and machine learning could further improve drying performance and energy efficiency. Additionally, exploring hybrid systems that combine renewable sources like solar and biomass could enhance applicability in diverse climatic conditions. With these advancements, solar drying has the potential to revolutionize food processing, reduce carbon footprints, and contribute to global sustainability goals.

REFERENCES

[1] Umesh Toshniwal and S.R Karale, A review paper on Solar Dryer, International Journal of Engineering Research and Applications (IJERA) ,Vol. 3, Issue 2, March -April 2013, pp.896-902.

[2] M. Kumar, S. K. Sansaniwal, P. Khatak. Progress in solar dryers for drying various commodities. Renewable and Sustainable Energy Reviews 55 (2016) 346–360.

[3] A. Herez, M. Khaled, M. Ramadan, H. Bazzi. A Review on Solar Dryer - Economic and Environmental Investigation for the Lebanese Case. 10TH International Conference on Sustainable Energy and Environmental Protection 2017, 10.18690/978-961-286-061-5.49.

[4] G. Saravanapriya and R. Mahendiran. Design and development of solar tunnel dryer with control system for large scale drying of agro products. International Journal of Agriculture Sciences, 9 (2017) 4626-4631.

[5] Izhak Devid Paul, Dr. Adwait Manoharrao Vaidya, Dr. Prajitsen G. Damale, Solar Dryer Selection and its Applications for Various Household Items, International Journal of Innovations in Engineering and Science, Vol. 6 , No. 10, 2021, PP. 93 -96, https://doi.org/10.46335/IJIES.2021.6.10.19.

[6] G. Yuan. Experimental investigation of a solar dryer system for drying carpet. Energy Procedia 70 (2015) 626 – 633.

[7] A. Agarwala and R. M. Sarviyaa. Characterization of Commercial Grade Paraffin wax as Latent Heat Storage material for Solar dryers. Materials Today: Proceedings 4 (2017) 779–789.

[8] M. Bououd and A. Mechaqrane. Concentration solar dryer water-to-air heat exchanger: Modeling and parametric studies. International Journal of Hydrogen Energy 42 (2017) 8631-8643.

[9] F. Alongé and O. A. Adeboye. Drying rates of some fruits and vegetables with passive solar dryers. Int J Agrie & Biol Eng, 5 (2012) 83-90.

[10] S. Nabnean et al. Experimental performance of a new design of solar dryer for drying osmotically dehydrated cherry tomatoes. Renewable Energy 94 (2016) 147-156.

[11] M.C. Ndukwu, L. Bennamoun, F.I. Abam, A.B. Eke, D. Ukoha. Energy and exergy analysis of a solar dryer integrated with sodium sulfate decahydrate and sodium chloride as thermal storage medium. Renewable Energy 113 (2017) 1182-1192.

[12] Hisham Elhage, Amal Herez, Mohamad Ramadan, Hasan Bazzi, Mahmoud Khaled, An investigation on solar drying: A review with economic and environmental assessment, Energy (2018), doi: 10.1016/j.energy.2018.05.197

[13] V. Belessiotis, E. Delyannis, Solar drying, Solar Energy 85 (2011) 1665–1691, doi:10.1016/j.solener.2009.10.001.

[14] A.A. El-Sebaii, S.M. Shalaby, Solar drying of agricultural products: A review, Renewable and Sustainable Energy Reviews 16 (2012) 37–43.

[15] A. G. M. B. Mustayen, S. Mekhilef, R. Saidur, Performance study of different solar dryers: A review, Renewable and Sustainable Energy Reviews 34 (2014) 463–470

[16] Fernandes, L.; Tavares, P.B.A Review on Solar Drying Devices: Heat Transfer, Air Movement and Type of Chambers. Solar 2024, 4, 15–42. https://doi.org/10.3390/solar4010002.

[17] Parihar, J.S.; Kumar, S.; Kumar, L.; Kumar, Y.; Ghritlahre, H.K.; Verma, M.; Gupta, A.K.; Agrawal, S.; Shekhar, S. Development of novel cabinet solar dryer using UV sheet and its performance evaluation: An experimental study. Sol. Energy 2022, 239, 1–9.

[18] Chavan, A.; Vitankar, V.; Mujumdar, A.; Thorat, B. Natural convection and direct type (NCDT) solar dryers: A review. Dry. Technol. 2021, 39, 1969–1990.

[19] Prakash, O.; Kumar, A. Solar greenhouse drying: A review. Renew. Sustain. Energy Rev. 2014, 29, 905–910.

[20] Lingayat, A.B.; Chandramohan, V.P.; Raju, V.R.K.; Meda, V. A review on indirect type solar dryers for agricultural crops—Dryer setup, its performance, energy storage and important highlights. Appl. Energy 2020, 258, 114005.

[21] Sileshi, S.T.; Hassen, A.A.; Adem, K.D. Simulation of mixed-mode solar dryer with vertical air distribution channel. Heliyon 2022, 8, e11898.

[22] M.V. Ramana Murthy, A review of new technologies, models and experimental investigations of solar drier, Renewable and Sustainable Energy Reviews 13 (2009) 835–848

[23] Slim R, Zoughaib A, Clodic D. Modeling of a solar and heat pump sludge drying system. International Journal of Refrigeration 2008; 31:1156–68.

[24] Sharma A, Chen CR, Vu Lan A. Solar-energy drying systems: a review. Renewable and Sustainable Energy Reviews 2009; 13:1185–210.

[25] Imre L. Solar drying. In: Mujumdar AS, editor. Handbook of industrial drying. Boca Raton, FL, USA: Taylor & Francis Inc.; 2006. p. 317.

[26] Ibrahim M, Sopian K, Daud WRW, Yahya M, Alghoul MA, Zaharim A. Performance predication of solar assisted chemical heat pump drying system in tropical region. In: 2nd WSEAS/IASME international conference on renewable energy sources (RES’08); 2008.p. 122–6.

[27] Visavale, G.L., Principles, Classification and Selection of Solar Dryers. In Solar drying: Fundamentals, Applications and Innovations, Ed. Hii, C.L., Ong, S.P., Jangam, S.V. and Mujumdar, A.S., 2012, ISBN - 978-981-07-3336-0, Published in Singapore, pp. 1-50.