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Innovative Solar Drying Techniques for Sustainable Applications

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Abstract: *The increasing demand for sustainable and energy-efficient drying methods has catalyzed the development of innovative solar drying techniques. This paper explores the advancements in solar drying technologies, emphasizing their applications in agriculture, food preservation, and industrial processes. Solar drying offers an eco-friendly alternative to conventional drying methods by utilizing renewable solar energy, thereby reducing carbon emissions and operational costs. The study evaluates various solar drying systems, including direct, indirect, and hybrid solar dryers, highlighting their design, efficiency, and suitability for different applications. Additionally, the integration of advanced materials and technologies, such as phase change materials (PCMs) and photovoltaic (PV) cells, enhances the performance and reliability of solar dryers. Case studies from diverse geographic regions illustrate the practical benefits and challenges of implementing these systems. The findings underscore the potential of solar drying techniques to contribute significantly to sustainable development goals by promoting energy conservation, reducing post-harvest losses, and improving food security. This comprehensive review provides valuable insights for researchers, practitioners, and policymakers aiming to leverage solar drying for sustainable applications.*

Keywords: *Energy efficiency, Moisture removal, Direct solar dryer, Solar dryer, Comparative analysis, Drying rate.*

I. INTRODUCTION

The quest for sustainable practices in agriculture, industry, and everyday life has spurred innovation in renewable energy technologies, among which solar drying stands out as a compelling solution. Drying is a critical process in numerous industries, essential for preserving food, pharmaceuticals, textiles, and timber, among other products. Traditional drying methods often rely on fossil fuels or electricity, contributing to environmental degradation through greenhouse gas emissions and resource depletion.

In contrast, solar drying harnesses the abundant and clean energy of the sun to drive moisture removal from materials, offering a sustainable alternative that aligns with global efforts to mitigate climate change and promote environmental stewardship. By utilizing solar radiation directly or indirectly through thermal collectors, solar drying systems reduce dependency on non-renewable energy sources while minimizing operational costs and carbon footprints.

This introduction explores the evolution, principles, and applications of innovative solar drying techniques. It highlights recent advancements in technology, such as the integration of phase change materials (PCMs), photovoltaic (PV) cells, and advanced control systems, which enhance efficiency and reliability. Case studies from diverse geographic regions illustrate the practical implementation and benefits of solar drying across agricultural, industrial, and community settings.

As we delve into the intricacies of solar drying techniques, it becomes evident that these innovations not only promise sustainable solutions but also empower communities by enhancing food security, promoting economic resilience, and preserving cultural practices. By embracing solar drying, stakeholders from farmers to industrialists can contribute to a more sustainable future while safeguarding natural resources for generations to come. Recent advancements in solar drying technology have focused on enhancing the efficiency and reliability of these systems. Innovations include the incorporation of advanced materials, such as phase change materials (PCMs) and photovoltaic (PV) cells, to improve energy storage and utilization. PCMs can store excess solar energy during peak sunlight hours and release it during periods of low insolation, ensuring a continuous drying process. PV cells can be integrated to power auxiliary components like fans and control systems, further reducing reliance on external energy sources.

Additionally, design improvements such as better insulation, optimized airflow patterns, and automated control systems have significantly enhanced the performance of solar dryers. Computational modeling and simulation tools have also been employed to predict and optimize drying parameters, leading to more efficient designs tailored to specific products and climatic conditions. By systematically comparing these solar dryer designs, this study seeks to provide valuable insights that can guide the selection, optimization, and development of solar dryers tailored to specific needs in agricultural and industrial contexts. The findings are expected to contribute to the advancement of sustainable drying technologies, promoting broader adoption and further innovation in the field.

Besides that, the local as well as distributed nature of their operations, as well as technical advances, focus on providing substantial economic and environmental advantages. As of earlier civilizations, food grains have indeed been dried in India's domains by sunlight exposure.

As a direct consequence of mechanization and automation in the twenty-first century, controlled drying of several farm products, including nicotine, lumber, nectarines, resins, and several others, is becoming extremely prevalent, as components retain their flavour and aroma, quality, and attractive appearance, and thus have improved sales possibilities. To eliminate extra hydration, crops, fruits as well as veggies, and fruits are dried in a drying framework.

The solar dryer is made of abundant and cost - effective materials for construction, galvanised iron, brick, as well as particleboard. The topmost layer of the dryer is surrounded by translucent single and then double panels. It's inside the external surface is painted black to absorb radiation from the sun. Since this box is sheltered, the inside thermostat is elevated. The top of the crease has small gaps that allow air to circulate.

The free convection process removes excessive water from strawberries, fruits and veggies, as well as crops placed in containers inside the box inside as the hot air rises. To fill in the gap, fresh air is required.

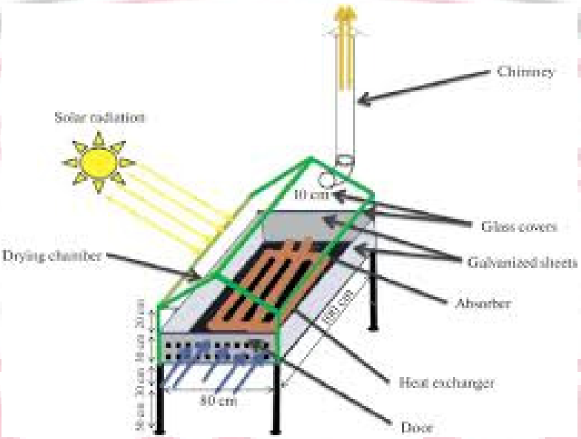

Figure 1 Solar Drying Technology

Solar dryers have numerous advantages over the traditional expanded evaporation, along with (1) a smaller area of land requisite to dry the same quantity of crop, (2) a significantly higher quality of dried crop due to the absence of insects and pests, (3) a shorter drying timeframe, (4) protection from impulsive rain, and (5) inadequate funding and operational costs.

Solar dryers having a simple extremely important backflow cost less to construct than renewable energy dryers with a distributed circulatory water system. Even though natural transfer renewable power dryers are susceptible to localised overheating and also have a slow as a whole drying temperature, a solar chimney is commonly used to speed up the rate upon which dry air tries to join by increasing the hydrostatic pressure on the air circulation.

II. LITERATURE REVIEW

To (Lamrani et al., 2019) [1] The purpose of this research is to construct a numerical method using TRNSYS systems in order to evaluate the efficacy of an implied photovoltaic power drying for woods. A sun compound parabolic concentrator (CPC) is used to create heat energy, and employee' regularly colorful simulation studies are run utilizing MoroCcan weather data. In a comparing results of both our mathematics experimentation outcome findings, the Mean Relative Error (MRE) and the Root Mean Squared Error (RMSE) are 3.9 % and 0.024 kg/kg, respectfully. The impact of some operational and design criteria on dryness kinematics, as well as the energizing of conventional drying devices, are discussed. The amount of carbon dioxide (CO2) carbon output due to incomplete combustion at the supplementary heating unit is the fºCus of an environmental assessment. The results show that incorporating a solar panel into the dryer system reduces the auxiliary heating element system's power consumption and reduces CO2 emissions by about 34% annually.

(Kuan et al., 2019) [2] In this paper, a measurement simulation for trying to predict the electricity thermal performance compressor supported solar dryer in european environments is proposed. The model is determined by the balance of energy and mass. The energy efficiency of heat pump drying systems, photovoltaic dryers, and heating system assisted solar dryers is compared. The model was conducted in Almaty, Kazakhstan, under four different climatic conditions. When opposed to ordinary solar dryers, the heating system supported photovoltaic dryer seems to be more energy efficient, according to the simulated data. It has also been confirmed that traditional solar dryers are ineffective in continental climates with intermediate temperatures.In 21 hours, the heat exchanger dryer reduces the amount of moisture of bananas (on a wet basis) from about 74 percent to about 19 percent. In 35 hours, the solar dryer diminishes the moisture levels (wet basis) from about 74 percent to about 20 percent. A heat pump facilitated solar dryer's particular humidity harvesting rate and thermal efficiency are approximated to be around 0.6 kg/kWh and 2.72, respectively.

(Lingayat et al., 2020) [3] This study describes the development of an indirect type solar dryer (ITSD) for dried apple and melons. The efficiency of the ITSD was tested, as well as the drying chamber for watermelon and apples slicing. The experimental data were used to compute the deterioration rate, surfaces transfer coefficients, and solution temperature of apples and cantaloupe. According to the results of the trials, the average temperature within the drying cabinet fluctuated over time due to frequent fluctuations in sun activity. The thermodynamics performances of the collection and dryer was 54.5 percent and 25.39 percent, respectfully, while apples drying and 56.3 percent and 28.76 percent, including both, while watermelon dryness. Watermelon water content fell from 10.76 to 0.496 kg/kg db, while apple water content declined from 6.16 to 0.799 kg/kg db. Different variants from previous studies were used to fit the dryer curves. The equilibrium moisture content diffusion coefficient average was calculated and it was 4.28 × 10−9 m2/s and 4.01 × 10−9 m2/s for apple and watermelon, respectively. Mass transfer coefficient is found to be in the range 1.584 × 10−4 to 3.158 × 10−3 m/s for apple and 5.17 × 10−4 to 4.98 × 10−3 m/s for watermelon. The heat transfer coefficients for apple and watermelon were 0.16 to 3.19 W/m2 K and 0.52 to 5.04 W/m2 K, respectfully. Apple and watermelon have activation energies of 17.34 and 18.71 kJ/mol, respective.

(Atalay, 2019) [4] The energy and and perhaps appearances of a sun drying able to integrate with a packed bed (TES) as a heat storage medium are presented in this study. The drying chamber of orange slices were studied as a case study. The goal of this research is to assess the packed bed's heat transfer possibilities by choosing to fºCus on electricity usage and entropy generation indicators. Experiments were conducted out twice daily. The results revealed that employing a solar thermal energy with a packed column reduced the moisture content of orange sliced from 93.5 percent to 10.28 percent (in the first trial) and 10.76 percent (in the second experiment) (in the second). Total usable power consumption was found to be 89.892 MJ for one status and 88.11 MJ for the other. The dryer system's power conversion efficiency ranges from 50.18 to 66.58 percent during daylight hours. The drying proCess' exergy efficiency varies between 54.71 and

68.37 % while using stored energy generation. A mathematical model is developed to forecast how well the moisture ratio of reddish sliced will change with time. According to the results of the star, the Modified Freeman and Pabis Model provided excellent specifications for determining the drying behavior of oranges sliced.

(Bhardwaj et al., 2019)[5]The laboratory experiment of an implicit forced convection dryer with sensible heat storage material (SHSM) and phase change material (PCM) in the Himalayan meteorological environment (latitude 30.91 °N) is presented in this paper. Iron scraps mixing with gravel is placed on top of the solar concentrator, with copper tubing containing engine serving as SHSM. In the drying chamber, the Paraffin RT-42 was used as a PCM. Experiments with drying Valeriana Jatamansi (a medicinal herb) were conducted, and the moisture content was reduced from 89 percent to

9 percent. When SHSM and PCM were used simultaneously, the overall drying rate was 0.051 kg/hr, just about double that of 0.028 kg/hr and 0.018 kg/hr, respectively, when no thermoelectric stºCk was used. The dryers time to reach 9 percent saturation was 120 hours, compared to 216 and 336 hours, to between, and decent quality dehydrated root system in addition to the core oil and med chem substances were obtained. Intravenous fluids capacity and total Tend to have stronger were found to be 7.11 and 3.47 percent, including both, in the experimental data, compared to 6.18 and 3.31 percent in the comparison with conventional shade drying. The ordinary energy and exergy efficiency of a solar hoarder without SHSM is 9.8% and 0.14 percent, respectively. SHSM achieves energetic and exergetic efficiency of 26.10 and 0.81 percent, respectively.

(Vijayan et al., 2020)[6]In this study, a reduced ambiguously defined forced convective heat transfer solar dryer with a highly permeable bed heat storage material was developed and tested for drying fenugreek slices throughout Coimbatore's environmental conditions. A solar panel with a surface area of 2 m2, a drying chamber, and a centrifugal blower make up the development setup. The exploratory study of an indirect forced convection dryer with sensible heat storage material (SHSM) and phase change material (PCM) in the Himalayan weather forecasting surroundings (latitude 30.91 °N) is presented in this paper. In the solar panel, iron scrap mixture with granular material is placed on the absorber tube, and brass tubes containing engine oil are used as SHSM.In the drying medium, the Paraffin RT-42 was used as a PCM. Experiments with drying azadirachta indica Jatamansi (a medicinal herb) were undertaken, and the moisture content was reduced from 89 percent to 9 percent. When SHSM and PCM were used instantaneously, the overarching rate of evaporation was 0.051 kg/hr, almost double that of 0.028 kg/hr and 0.018 kg/hr, respectively, when no thermal storage medium was used and classical shade evaporation was used. The drying time to reach 9 percent saturation was 120 hours, compared to 216 and 336 hours, to between, and decent quality dehydrated taproot in addition to the core oil and med chem substances were acquired. Moisture absorption potential and total Tend to have stronger were found to be 7.11 and 3.47 percent, including both, in the experimental data, compared to 6.18 and 3.31 percent in the comparison with conventional shade drying. The average exergy analysis efficiency of a solar concentrator without SHSM is 9.8% and 0.14 percent, respectively. To force the air, SHSM achieves energy and exergy efficiency of 26.10 and 0.81 percent, respectively.

(Sözen et al., 2020) [7] For the developing world, clean renewable energy production is a must. Solar energy is a frequently used renewable energy source that may produce both electricity and heat heat. Solar energy techniques could be employed in various of applications, include space proCess heat.. Three easy and price solar air heating systems were developed and made in this study. A hollow tube heating element is the first type of heater. The 2nd heating element will have the same basic properties as the first, but in the fluid flow, iron blended seamlessly were added to improve thermal contact area. Using Computational Fluid dynamics software, Based on the simulation results, a honeycomb tube-type heaters was developed. Both heater were equipped with a drying chamber, and drying tests were conducted at 3 different air mass flow rates (0.014, 0.011, and 0.009 kg/s). The peak energy thermal performance of an iron matrix model with various heaters was determined to be 74.71 percent. The thermal efficiency of the tube-type heaters was raised by 11% after mesh was added. Furthermore, the iron mesh customized solar aided drier had the highest average energy efficiency of the drying system, at 50.85%.This tubular SAH design, with its simple and expense structure that contains no casing, no protection function, and is manufactured from steel sheet, is promising in terms of sustainable energy hot air creation.

(Ndukwu et al., 2020) [8] The paper will compare an active mix-mode wind-powered fan solar dryer (AWPFS) to a detachable combined non-wind-powered solar drier using pre-treated potato slices (PNWPS).The two dryers were put through their paces with and without the use of glycerol as an energy storage medium. The goal was to demonstrate a non-electric sun 's energy dryer that relied solely on clean energy sources. The dryer was tested at a room temperature of 24–50 °C and a humidity of 10–52 percent. The results show that dry with AWPFS and glycerin takes much less time than drier with just AWPFS or with PNWPS. Dunking the beets in a suitable solvent and blanching for 30 seconds before dry sped up the dryers time compared to other procedures. The dry power conversion efficiency range from 2.846 to 3.686 kWh/kg, whereas electricity consumption was between 4.10 and 4.98 MJ. Exergy efficiency was improved by 25.031 percent to 31.5 percent, while dryer efficacy improved by 25.031 percent to 31.5 percent. Due to Africa's low electricity penetration, this dryer with such a naturally extractor generator will assist crop manufactures in drying their products more efficiently, saving around 15.3–290.4 $ per year at a 10%–100% consumption rate.

(Güler et al., 2020)[9]The present study designed, analysed, assembled, and checked the double indirect solar dryer (DPISD) or a double solar thermal dryer with mesh absorber modification (DPISDMA). The main goal of this research is to use iron meshes to improve thermal efficiency of the double photovoltaic panel. The experimental investigation used specimen of de pescado fruit (Solanum muricatum L.) in two thicknesses. In addition, CFD analysis of both the solar air collection and the drying chamber was performed, as well as quality measurements such as phenolic, antioxidant capacity and flavonoids content Mesh alteration has a positive effect on the collectible efficiency, according to numeric simulations and experiments. DPISDMA had the greatest average dryer efficiency of 23.08 percent for thin sample thickness. Quality evaluations revealed that the trials conducted in DPISDMA produced the best results, with the greatest values of TPC, TFC, and antioxidant activity (p 0.05). The dry information of pepino fruits for several trials was modeled using eight distinct statistical formulas. As a result, the best-fitting kinetics framework for all experimental tests was determined to be the Logarithmic model, which provided the most statistically reliable value systems.

(Vigneshkumar et al., 2021)[10]Solar dryers are crucial in the food industry for maintaining safe to eat items such as granules, veggies, fish, and other foods by removing moisture levels. They have an advantage over outdoor public drying in that they safeguard the food from soot, invertebrates, and other harmful elements. Furthermore, they are said to save more environment for future generations from deterioration. Solar dryers of the indirect type consist mainly of a solar concentrator and a space to place grated zucchini. Their water evaporation rate is high, and the end product performance would be enhanced as well. An implicit based classification natural convection solar evaporator was fabricated in this study, and petroleum distillates was used as a phase different set (PCM) in the solar concentrator to continue improving the solar dryer's performance during the off- sunshine hours. In two cases, particularly regarding, solar dryer without PCM (Plain Dryer) and solar dryer with PCM, control parameters such as water evaporation rate, hydration ratio, and dryer temperature gradient were explored for drying grated zucchini (PCM Dryer). The air flow rate was kept constant at 0.065kg/s, and the evaporator was turned on from 10 a.m. to 7 p.m. The results will be compared, and the impact of combining PCM with the drying system was investigated and presented. The presence of PCM within the solar concentrator significantly increased the drying ambient temperature 2 hours after the solar period, according to the findings. Furthermore, using paraffin, the proportion of total weight of moisture removed from potato slices was increased by 5.1 percent per day.

III. COMPARATIVE ANALYSIS

Innovative solar drying techniques for sustainable applications offer diverse approaches to enhance efficiency and reduce environmental impact compared to conventional drying methods. Passive solar drying, relying on natural convection and solar radiation, stands out for its simplicity and low operational costs, making it suitable for small-scale applications in sunny climates. However, it is limited by its dependency on weather conditions and slower drying rates. In contrast, active solar drying employs mechanical aids like fans to improve airflow and drying efficiency, resulting in faster drying times and better control over drying conditions. This method requires higher initial investments but offers scalability and suitability for larger quantities of produce. Solar greenhouse drying combines solar energy capture with controlled environmental conditions, enabling year-round operation and protection from weather fluctuations, albeit at a higher construction cost and with additional maintenance needs. Concentrated solar drying, which utilizes mirrors or lenses to intensify solar radiation onto the drying material, achieves rapid drying and high efficiency, suitable for high-value crops or industrial applications. However, it requires precise tracking systems and significant initial investments. Hybrid solar drying integrates solar energy with other sources like biomass or electricity to optimize drying efficiency and reliability, offering flexibility but at the cost of increased complexity and operational expenses. Each technique presents unique advantages and challenges, necessitating careful consideration of factors such as scale, product type, climate conditions, and budget to determine the most appropriate choice for sustainable drying applications.

IV. CONCLUSION

innovative solar drying techniques present promising solutions for sustainable agricultural practices by harnessing solar energy to reduce reliance on fossil fuels and minimize environmental impact. Each technique—from passive and active solar drying to solar greenhouse, concentrated, and hybrid systems—offers distinct advantages tailored to specific operational scales, product types, and climate conditions. Passive solar drying stands out for its simplicity and low operational costs, making it suitable for smaller-scale applications in favorable weather conditions. Active solar drying enhances efficiency through mechanical aids, catering to larger operations requiring faster drying times and precise control over drying parameters. Solar greenhouse drying extends drying capabilities year-round, offering protection from weather variability but requiring initial investment in infrastructure. Concentrated solar drying achieves rapid and efficient drying suitable for high-value products, albeit with higher upfront costs and technological complexity. Hybrid solar drying integrates solar energy with other sources for enhanced reliability and flexibility, balancing efficiency with operational challenges. Ultimately, the choice of technique should consider factors such as local climate, product requirements, economic feasibility, and environmental goals to optimize sustainability and effectiveness in solar drying applications. As technology advances and adoption increases, these techniques hold promise for transforming agricultural drying practices towards greater sustainability and resilience.

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