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Assessment of Various Solar Drying Methods for Deciding an Economical and Ecofriendly Solution for Better Quality of Dried Products

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ABSTRACT

Global issues such as energy shortages and food insecurity are intensified by a growing population and considerable losses after harvest, resulting in serious hunger levels. Solar drying presents an efficient, sustainable, and high-quality approach to food preservation, significantly contributing to the improvement of global food security. In the realms of agriculture and the food sector, dryers play a critical role in prolonging the shelf life of crops by extracting moisture, with solar thermal energy being particularly notable for its environmental advantages and widespread availability. This paper is helpful to find out the efficient and successful method for research on indirect solar drying.

The strategy is founded on research concerns and other elements that impact system performance, such as dryer forms, dryer size, food-product level of moisture, air flow rate, air temperature, and system efficiency. These types of problems have been compiled from previous research conducted on indirect solar drying. To improve the handling and storage of drying food products without sacrificing quality, all features can be divided into various categories. General, operational, application type, extra equipment and instruments employed, and other characteristics are categorized in the case of an indirect solar dryer. The drying efficiency varies from 9% to 40%, according to the current literature review using the characteristics that are currently accessible for indirect and hybrid sun drying modes. For enhancing the present quality of drying agricultural goods with reduced thermal energy storage ranges while staying within a safe maximum temperature range.

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It has been demonstrated that manufacturers, designers, and researchers may benefit from the information found in the database of research articles According to data gathered from current studies, installing a PV cell driven desiccant wheel in dryers combined with pebble bed storage is an economical and useful option since it speeds up the drying process, reduces temperature fluctuations and supplies thermal energy during off sun shine hours. It appears to be a suitable solution for addressing global warming and future nutrition rich food preservation needs.

تقييم طرق التجفيف الشمسي المختلفة لتحديد حل اقتصادي وصديق للبيئة لتحسين جودة المنتجات المجففة

سانكالب كولكارني، روناكومار شاه.

ملخص: تُساعد هذه الورقة البحثية في تحديد الطريقة الفعّالة والناجحة لأبحاث التجفيف الشمسي غير المباشر. تستند هذه الاستراتيجية إلى اهتمامات بحثية وعوامل أخرى تؤثر على أداء النظام، مثل أشكال المجفف، وحجمه، ومستوى رطوبة المنتجات الغذائية، ومعدل تدفق الهواء، ودرجة حرارته، وكفاءة النظام. وقد جُمعت هذه المشاكل من الأبحاث السابقة التي أُجريت على التجفيف الشمسي غير المباشر. لتحسين مناولة وتخزين المنتجات الغذائية المجففة دون المساس بالجودة، يُمكن تقسيم جميع الميزات إلى فئات مختلفة. تُصنف الخصائص العامة، والتشغيلية، ونوع التطبيق، والمعدات والأدوات الإضافية المستخدمة، وغيرها في حالة المجفف الشمسي غير المباشر. يُعد التجفيف مرحلة أساسية في حفظ المنتجات الزراعية.

تتراوح كفاءة التجفيف بين 9 % و 40 %، وفقًا لمراجعة الأدبيات الحالية باستخدام الخصائص المتاحة حاليًا لأنماط التجفيف الشمسي غير المباشر والهجين. يهدف هذا إلى تحسين الجودة الحالية لتجفيف المنتجات الزراعية مع تقليل نطاقات تخزين الطاقة الحرارية مع الحفاظ على نطاق درجة حرارة قصوى آمنة. أثبتت الدراسات أن المُصنِّعين والمصممين والباحثين قد يستفيدون من المعلومات الواردة في قاعدة بيانات المقالات البحثية. ووفقًا للبيانات المُستقاة من الدراسات الحالية، يُعد تركيب عجلة تجفيف تعمل بخلايا الطاقة الشمسية في المجففات مع تخزين الحصى خيارًا اقتصاديًا ومفيدًا، إذ يُسرِّع عملية التجفيف، ويُقلِّل من تقلبات درجات الحرارة، ويُوفِّر الطاقة الحرارية خلال ساعات السكون. ويبدو هذا حلاً مناسبًا لمعالجة الاحتباس الحراري واحتياجات حفظ الأغذية الغنية بالعناصر الغذائية في المستقبل.

الكلمات المفتاحية – بمجفف شمسي غير مباشر، كفاءة، سلع زراعية، جودة، اقتصادية.

1. INTRODUCTION

As part of the development of greener technologies, the food processing sector is looking at ways to reduce or eliminate the use of fossil fuels. For example, food items have been dried using a variety of renewable energy sources, such as biomass, geothermal, wind, and solar.

These days, using solar energy for many purposes is essential for a sustainable future. Numerous thermal energy applications for drying food and agricultural products may be made using solar energy. The drying of agricultural goods is an intriguing use for these renewable energy sources. This is a crucial stage in the food processing process, especially for goods that need to be dried before being processed further, such fruits, vegetables, and grains. Since this process uses a lot of energy, switching to renewable energy sources may have a big positive impact on the environment and the economy. To better understand this topic, this study will look at how well food items may be dried using renewable energy, especially solar energy. Solar energy was chosen mainly because it is widely accessible and has the capacity to provide large amounts of electricity. By demonstrating the potential advantages and viability of solar energy use in the food processing sector, we seek to support the industry's sustainability objectives.

The primary goal of drying, a crucial and complex operation in the food processing sector, is to remove moisture from a wide range of agricultural goods. These items' moisture contents might range greatly from one another, necessitating specific adaption and drying process customisation to account for these variations. As such, drying is a complicated process that must be especially adapted to the distinct qualities of every product rather than being a one-size-fits-all approach.

The sector has historically used two primary types of drying systems to meet the various requirements of various agricultural goods. These fall into two general categories: systems that function at low temperatures and systems that work at high temperatures. Depending on the needs and limitations of the product being processed, each of these methods has a unique combination of benefits and limitations. For example, high-temperature drying systems might greatly speed up the drying process. This is accomplished by subjecting the goods to high temperatures, which quickly removes the moisture content. But the main disadvantage of this approach is that it frequently lowers the calibre of the finished product. The extreme heat can change the product's flavour, texture, and appearance in addition to degrading vital nutrients. Low-temperature drying systems, however, work on an entirely different premise. By carefully and methodically venting the drying chamber, this technique helps to optimize and progressively balance the moisture content of the final product. Compared to high temperature drying, the process is slower and takes longer. The main benefit of low temperature drying, however, is that it usually tends to keep the product's quality considerably better. The product's total integrity, including its flavour, texture, and appearance, is preserved, along with its essential nutrients. Low-temperature drying is therefore frequently chosen when product quality is a crucial factor, even if it may be a slower procedure.

Low-temperature drying systems have numerous benefits, but there are still certain difficulties in putting them into practice. The need that the system's air has a humidity level below 20% is one such difficulty. A more efficient drying process results from good moisture mass transfer, which requires this lower humidity level. As a result, there have been proposals to add dehumidified air to the low-temperature drying system.

It should be noted that the dehumidification process is a complicated one that includes the vital stage of solid desiccant regeneration. This procedure is essential for eliminating moisture from the air, which speeds up the drying process. However, solid desiccant renewal requires a substantial amount of energy, which raises the drying process's energy costs considerably.

One of the primary obstacles to the use of dehumidified air in low-temperature drying systems is its high energy cost. Many in the food processing business may find it less desirable because to the higher energy expenditures, even if it promises improved moisture mass transfer and, thus, a more efficient drying process. This is a serious problem that might prevent low temperature drying systems from being widely used, necessitating further study and creativity to solve.

The goal of this review-research study is to address the issues by carefully examining the viability of using a sun-heated air stream for solar drying as a novel, alternative, and greener technique. The goal is to present a new strategy that avoids any potential compromises that could arise from using conventional drying techniques while simultaneously addressing the environmental problems associated with the usage of fossil fuels and preserving the quality of the agricultural goods.

This study is expected to provide two contributions. First of all, it suggests a more environmentally friendly method of drying agricultural products. This is accomplished by drastically lowering the food processing sector's dependency on fossil fuels and other non-renewable energy sources, which drive greenhouse gas emissions and climate change. Second, it is anticipated that the research will provide a more effective drying method that lowers the energy expenses related to the drying process while maintaining the quality of the food items.

However, the investigation of solar drying will be the only focus of this study. In this sense, solar drying is the act of powering the drying process using solar energy, a renewable and essentially limitless energy source. This restriction was put in place on purpose to keep attention on

renewable energy sources and how they may be used in the food processing sector.
The study methodology will entail a direct comparison between the suggested sun drying procedure and the conventional drying methods now in use. The influence on product quality, cost-effectiveness, and energy efficiency are just a few of the variables that will be considered in this comparison. The study intends to offer a thorough grasp of the possible advantages, difficulties, and real-world ramifications of implementing sun drying in the food processing sector through this comparative analysis.

2. PREVIOUS WORKS OF INDIRECT SOLAR DRYING SYSTEM

Solar energy may effectively dehydrate agricultural goods, as demonstrated by decades of intensive experimental investigation. Numerous small-scale solar dryer systems have been developed recently, mostly for the purpose of drying agricultural food items. These dryers may employ desiccant or thermal energy storage.
Using the same test setup, Shanmugam and Natarajan's [37] experiment revealed that green peas and pineapple slices dried consistently in all of the trays with high quality in terms of color and micro-bial deterioration when compared to pure sun drying. The flavor of the dried pineapple was decent. The desiccant material remains stable even after almost a year of continuous operation. The drier may be used to dry a wide range of agricultural items. It can improve the quality of the dried product and hasten the drying process [9].
Arun Kumar and colleagues utilized a drying process based on desiccant silica gel. [1] The airflow velocity and regeneration temperature of the dehumidifier were tuned to guarantee the least amount of food damage throughout the drying process in comparison to tray drying. The fenugreek green leaves were dried (wb) from an initial moisture content of 88.6% to 5%. Using a rotating desiccant bed dehumidifier to dry the fenugreek produced satisfactory results in terms of taste, color, and nutrient retention.
A sun drying system with a solid desiccant (silica gel) wheel was tried by Misha et al. [4]. Warm air generated by a heat exchanger heated by solar-heated water is used in desiccant regeneration. According to the results, using this hybrid solar drier with a thermo-electrical basis significantly reduced the drying time of kenaf fibers by 24%, from 20.75 to 5.75 hours, during the hours without sunshine.
Using the same test equipment, Misha et al. [5] experimented on oil palm fronds. Crushed oil palm fronds took around 30 hours and 40 minutes to dry in open sun, reducing their drying time from 69% to 29%. The drying efficiency at maximum capacity was 19%, and 65% of the energy used came from solar sources. Drying and pick-up efficiency declined as product moisture content fell and the amount of product in the drying chamber shrank. The drying air quality was enhanced by the sensible and latent efficacy of the desiccant wheel, which were 74% and 67%, respectively. Better drying air conditions, improved drying performance, and reduced electrical energy consumption were produced by the desiccant and solar dryer.
An indirect contact dehumidifier and a solar-assisted liquid desiccant cooling system were employed by Rajat Subhra Das and Sanjeev Jain [8]. Evacuated tubes served as the collectors. To avoid desiccant carryover, the system's dehumidifier uses an indirect contact heat and mass exchanger. The system's primary energy user is the regeneration process, which draws power from the sun. To reach the liquid desiccant content of 36% to 40%, hot water heated to a temperature of 60 to 70 degrees Celsius is utilized.
Govindarajulu Padmanaban et al. evaluated a desiccant aided packed bed passive solar dryer [2]. The phase-change materials (1.5 kg of paraffin wax) and desiccant within the solar air heater control humidity levels and extend heat retention, respectively. The copra was dried in 62 hours from an initial moisture content (wet basis) of around 52% to a final moisture content (wet basis) of roughly 8% using a specific moisture extraction rate of 0.82 kg/kWh. The drying time was

reduced by around forty-four hours in comparison to the conventional passive solar drier. Dryers were assessed to have an average thermal efficiency of 32%. It was determined that the finished dried product was of high quality.

M Djaeni [6] made use of an electric heater, a fluidized bed drier, and a desiccant Zeolite with tray. Paddy and onion were dried with the help of dehumidified air. As performance measures, the drying time, product quality, and heat efficiency were evaluated. The results showed that zeolite drying significantly improved performance. At working temperatures between 50°C and 60°C, the drying system's efficiency may be raised to 75% while still ensuring sufficient product quality.

In 2018, Mahdiyeh Dorouzi et al. [3] coupled a liquid desiccantassisted sun dryer with a solar panel for regeneration.The drier's experimental analysis revealed that between 0.65 and 1.4 kWh of power were needed to dry tomatoes.The maximal specific moisture extraction rate was around 0.275 kg/kW h.The primary reason for concern is the color shift toward a dark surface hue that occurs when tomato slices are dried.

Yahya et al. [7] used a solar dryer in conjunction with solid desiccant (Silica Gel) columns in a water-based solar collector. Regeneration was done using a different heater. With an average temperature of 45.4°C and a relative humidity of 25.8%, the drier decreased the moisture content of Centella asiatica L from 88.3% (wb) to 15.9% (wb) in under 12 hours. With average values of 0.594 kg/h and 0.169 kg/kWh, the rates of general moisture evaporation and specific moisture evaporation varied from 0.001 to 1.762 kg/h and 0.02-0.482 kg/kWh, respectively. The dryer's average efficiency was 15.4%, with a range of 0.62% to 30.4%.

James C. Atuonwua [12] utilized zeolite as a desiccant and a standard heater to dry pumpkin. The conclusion drawn from this work is that dehumidifying the drying air results in energy benefits, the magnitude of which varies based on the specific operating circumstances that dehumidification causes. Dehumidification dryers use the same amount of energy but stop quality degradation. Adsorption dryers and heat pumps are at the top of the hierarchy, albeit the amount of dehumidification determines the efficiency obtained. Desiccant dehumidification systems have the advantage of providing additional opportunities for beneficial heat integration.

In 2013, Wisut Chramsaard [39] utilized a silica gel bed solar drier to dry chiles. The load test findings indicate that a mass flow rate of 0.08 kg/s and a drying temperature of 600C are the optimal drying parameters for chili. This made it possible to increase the moisture content of an 8 kg dried chili from 82% (wb) to 13% (wb). The drying time of the desiccant-using system is 20.83% shorter than that of the non-using system.

Mahmut Sami Büker et al. created the parabolic trough solar air collector in 2022 [40] with a rotating desiccant system, zeolite, and a porous wheel covered in silica gel. The experimental study clearly shows that parabolic trough solar collectors can successfully supply low-medium temperature thermal energy, which is required for the regeneration process of the desiccant wheel. The findings lend credence to the idea and offer specific recommendations for the use of rotating desiccant wheel systems powered by solar heat.

Shazia Hanif et al. (2018) employed lithium chloride and silica gel as desiccants in conventional heaters [41]. Among the dried grains were corn, barley, wheat, and rice. Raising the re-generation temperature increases the air's capacity to carry more moisture, but it also uses more energy. The circumstances were found to be favorable for seed drying as long as the drying air temperature remains below the recommended temperature. In this case, LiCl has been shown to be helpful. The temperature of processed air should be raised for commercial drying. Silica gel has been proven to be effective in adjusting process temperatures while keeping regeneration temperatures constant.

In 2016, A.E. Kabeel [42] and colleagues conducted experiments on solar drying units without a desiccant wheel operating under identical conditions. They compared the results and discovered that the drying air temperature rose from 65 to 82 degrees Celsius and the humidity ratio dropped from 15 to 8.8 g water/kg dry air. when a rotary desiccant wheel was installed in the units. Additionally, the results show that the ideal desiccant wheel rotation speed is around 15 rpm, which results in the lowest humidity ratio and the maximum drying air temperature at the dryer unit's input. The average percentage increase in the system's usable heat gain when using the integrated solar drying unit with a desiccant wheel is higher 153% than when using a sun drying unit without a rotational desiccant wheel.

In 2016, Sadjad Abasi combined a drying method using dried maize kernels and a traditional heater equipped with a silica gel desiccant wheel [43]. The drying duration and rate were greatly affected by the desiccant wheel, the drying temperature, and the air flow rate. The results demonstrated that a desiccant wheel is a cost-effective and useful addition to dryers as it speeds up drying while significantly lowering energy usage.

In 2001, Hodali and Bougard employed silica gel as an indirect flat plate collector with solar regeneration [57]. The ultimate moisture content of 300 kg of apricots, which had a starting moisture level of 5.2 g/kg (db), was 0.25 g/g (db) after 44 hours. When no sorption substance was utilized, the drying time was shortened by 8 hours or15.4%.

Punlek et al. (2009) [58] used a flat plate collector with indirect forced convection for the ginger slices, using solar regeneration and silica gel as a desiccant. When no sorption material was utilized, the drying time was shortened by 50% and 4 hours.

In 2013, Chramsaard et al. conducted research on an indirect forced convection flat plate collector that used silica gel as a desiccant, dried chili, and solar regeneration [59]. The original 82% (wb) moisture content dried after 19 hours, and the final moisture level was 13% (wb). Without sorption material, the drying time was shortened by 5 hours and 20.8%.

A CaCl2 solution was used as a desiccant in an indirect forced convection flat plate collector with solar regeneration in studies carried out by Dorouzi et al. in 2018 [60]. 500 g of tomato slices with an initial moisture content of 93.6% (wb) had a final moisture level of 9.2% (wb) following 5.5 hours of drying. Drying time was 27% shorter than when no sorption material was used.

As the desiccant for a forced convection flat plate collector, Thoruwa et al. [61] employed a 6:1:2:1 mass ratio of cement, vermiculite, and bentonite. In 1996, sorption materials are also used for heat storage. Solar power helped with regeneration.

Table 1. Work done on different kinds of solar dryers.

Type of Dryer	Food	Results	Reference
Tunnel dryer	Different crops and vegetables	Compared to open sun drying, drying time and quantity losses were significantly reduced, with a 1–3-year payback period.	Lutz.et al (1987) [29]
Cylindrical collector with black interior band covered with transparent insulation.	Vegetables and Fruits	For drying agricultural products, the collector combined with a greenhouse dryer produced a temperature that was 10 °C higher than the surrounding air.	Ahmad (2001) [30]
Direct natural convection solar dryer with a simple biomass burner	Dry fruits and vegetables	With a capacity of 20–22 kg of fresh pineapple stacked in a single layer of slices that are 0.01 m thick, the overall drying efficiency was found to be 9%.	Bena and fuller (2002) [31]
Mixed mode natural convection solar dryer integrated with a biomass burner	Agricultural products	The system's drying efficiency was found to be 23% and 40%, respectively, when heat storage was present and not.	Tarigan and Tekasakul (2005) [32]

solar dryer integrated with biomass energy	coleus stem	For hybrid stems, the final moisture content was found to be 12.3%.	Gunasekaran et. al. (2012) [33]
Solar biomass hybrid system	Cashew	Drying with an average collector efficiency of 55% and a moisture removal rate of 3.6 g/h.	Dhanuskodi et al. (2013)[34]
Direct forced convection	Sliced Banana	With an expected payback period of 1.1 years, the moisture content of a 10 kg banana dried at an average temperature of 48°C dropped from 72% (wb) to 28% (wb) in just 4 days.	S. Nabnean a (2020) [10]
Indirect natural convection updraft solar dryer was designed and fabricated	Sliced apple	When compared to the initial planned drying batch size, overall efficiency increased even with a larger drying batch quantity. Because of the drying chamber's tray design layer type, appropriate air flow distribution, and chimney's high efficacy.	Maundu Nicholas Musembia (2016) [11]
Heating element	Wet product	At high temperatures and steady velocities, the evaporation rate tends to become saturated. A low water content makes evaporation more challenging. A higher evaporation rate is produced by increasing temperature and velocity. At high temperatures, the influence of temperature is less noticeable.	Raka Noveriyan Putra(2016) [13]
Hybrid mix-mode solar dryer	Freestone peach, Golden apple, Anaheim chilies	Dried products met the recommended quality standards for food products in terms of composition, total bacteria, and color. It supports the use of a hybrid mixed-mode solar dryer for a wide range of perishable agricultural products.	Arslan Afzal a(2023) [14]
Forced Convection Solar Dryer	Galangal	In terms of composition, total bacteria, and color, dried goods fulfilled the suggested quality standards for food products. It encourages the use of hybrid mixed-mode solar dryers for a variety of agricultural products that spoil quickly.	Phenphorn Nimnuan (2020) [15]
Induced draft forced convection flat plate solar air heater	Wet wool & carpet	Based on the gross area and mean temperature of the heat transfer fluid, the instantaneous efficiency and heat loss coefficient are, respectively, 5.62 W/m2·k and 0.77 W/m2·k. The findings indicate that it is possible to dry more than 320 kg of wet wool and carpet in 7.5 hours.	Guofeng Yuan et al(2015) [16]
Direct type solar dryers	Red peppers and mangoes, and meat	Food products dried in direct-type solar dryers suffer a significant loss in quality. Further, improper drying due to moisture condensation limits its application for large-scale drying	Kumar et al (2016) [17]
Hybrid solar-biomass dryer	Fish	The quality of food products dried in direct-type sun dryers is significantly reduced. Furthermore, its application for large-scale drying is limited by incorrect drying caused by moisture condensation.	T.A. Rizal (2018) [18]

Mixed Type forced convection dryer	Stevia leaves	For mixed-type forced convection solar dryers, the overall efficiency was 33.5%. Stevia leaves may be able to hold onto their flavonoid and antioxidant properties better.	Laxmi.et.al (2019) [19]
Mix Mode Solar Dryer	Pineapple	In comparison to sun drying, the dryer minimizes drying losses and has lower running costs than artificial drying.	Sristtipokakun N.et.al(2014) [35]
Indirect type forced convection solar dryer	Copra	After 82 hours of drying, it was found that the moisture content of the copra decreased from 51.8% to 7.8% and 9.7% in the top and bottom trays, respectively, with a 24% thermal efficiency. BIS 6220-1971 was used to grade dry copra based on the quality that was attained.	Mohanraj, M.et al (2008) [36]

Table 2. Work done on different kinds of solar dryers integrated with different thermal storage materials.

Type of Dryer & Thermal Storage Material	**Food**	**Results**	**Reference**
Solar Dryer cum Rockbed storage system	Peanut	With an air flow rate of 4.9 m3/s, the drying time varied from 22 to 25 hours to bring the moisture content down from 20% to the safe storage moisture level.	Butler and Troeger (1980) [20]
Solar Air Heater augmented with integral rock system	Agricultural use	Comparing the system's performance to a traditional solar air heater, it demonstrates a respectable overall efficiency boost.	Garg et al. (1985) [21]
In-built thermal-storage agro solar dryer, Thermic oil a storage material	Chillies	Greater drying air temperatures of 65.3 °C and an absorber length of 0.826 m. With a drying efficiency of 21%, it is a notable characteristic of the dryer that is absent from natural convection solar dryers: the ability to maintain uniform drying air temperature for longer periods of time.	Potdukhe & Thombre (2008) [28]
Solar crop dryer with reversed absorber plate type collector & thermal storage with natural airflow	Onions	The height of the packed bed and the width of the airflow channel determine the crop temperature. Thermal energy storage has an impact on drying during the hours when the sun isn't shining and is crucial in minimizing temperature fluctuations for drying. The suggested mathematical model is helpful in evaluating the system's performance.	Jain.et.al (2007) [27]
Solar dryer with latent heat storage with paraffin wax	Sweet Potato	Examined the viability of utilizing paraffin wax as a phase transition material in conjunction with latent heat storage to store extra solar energy during the drying process and release it when energy availability is insufficient or nonexistent, as well as the impact this would have on the kinetics of food product drying.	Devahastin and Pitaksuriyarat (2006) [26]
Tilted multi-pass solar air heater with in- built thermal storage	Grain	There is value in the suggested mathematical model. for evaluating a flat plate solar air heater's thermal performance. Predicting the moisture content, grain temperature, drying air humidity, and drying rate in the grain bed is also helpful.	Jain and Jain (2005) [25]

Solar air heater with and without thermal storage for solar drying, Three kinds of material for thermal storage were used: water, stones & sand	Various agricultural products	When using appropriate storage materials, a system's thermal performance is significantly higher than when it doesn't. It was discovered that the ideal thickness of the storage material for drying a variety of agricultural products was roughly 0.12 meters. Furthermore, the suggested mathematical model can be applied to the estimation of the flat plate solar air heater's thermal performance, both with and without thermal storage.	Aboul-Enein et al. (2000) [24]
Solar Drying system with rock bed storage	Cassava, pepper, okro, groundnuts	After being dried to a final moisture content of less than 14% (wet basis), the crops were kept fresh for a year without experiencing any degradation. The seeds were guaranteed to be viable for sowing thanks to the low-temperature drying technique.	Ayensu (1986) [23]
Rock storage chamber cum solar dryer	Wheat Crop	For the high thermal capacity of the rock bed thermal storage, reaching the steady state condition will take longer. The agricultural process is improved because of thermal storage, which lowers the maximum temperature of the drying material within a safe range.	Tiwari et al (1994) [22]
Indirect mode solar dryer with a double-pass air heater, wire mesh as the packing substrate	Lemon balm leaves	For a given range, increasing the flow rate resulted in a 20% increase in collector thermal efficiency; however, subsequent increases in flow rate had the opposite impact. From the starting moisture level of 80% (wb) to 10% (wb), the moisture content was reduced. To determine which thin layer model best described the drying behavior of lemon balm leaves, mathematical models were also examined.	Shahrbanou Shamekhi-Amiri.et.al (2018) [38]
Solar air heater with wire mesh as absorber,	Bitter gourd Slices	creation of a solar air heater that uses wire mesh as an absorber and has a nominal porosity to allow air to pass through. The primary benefit of this kind of design is that the top loss coefficient is reduced because hot air won't come into contact with the glass.	M. A. Aravindh (2014) [45]

3. DESICCANT MATERIALS FOR DRYING

The purpose of desiccant materials is to readily reactivate and hold a substantial saturation adsorption quantity. Several desiccant materials that are sold commercially are:

1. Silica gel.
2. Activated charcoal.
3. Zeolite (Types- A, X, and Y).
4. Activated alumina.
5. Molecular sieves (Types 3A, 4A, 5A, and 13 × molecular sieve).
6. Composite material.
7. Bentonite clay.

K. Venkateswarlu et.al. [62] observed that in the food ingredients having a high moisture content are particularly prone to deteriorating because of their high-water activity. Microorganisms like bacteria and yeast, which are now the primary cause of food loss, require the water activity in ordinary meals to flourish. Materials with high water activity encourage more microbes. The

minimum water activity is as low as 0.6 for fungus and at least 0.91 for bacteria.
Owing to microporous structure of interior interlocking gaps, which provides a large internal surface area, silica gel has a great adsorption capacity. Its dust particles are carcinogenic; hence it is not appropriate for direct food processing applications. It also requires a lower temperature for regeneration (almost 100°) (Luo et al., 2018).
As it is less expensive, activated carbon is a significant solid desiccant that is used extensively in the desulfurization and denitrogenating of ultraclean fuels. Because water vapours have a reduced adsorption capacity, it has fewer applications for drying.
Zeolites are desiccants that may conduct deep air dehumidification because of their capacity to absorb water vapor at low relative humidity (RH). Zeolites are marketed in a few different forms, such as A, X, and Y. Zeolites have an exceptional adsorption capability due to their unique surface chemistry and crystalline pore geometries. A temperature of renewal is produced by the zeolites' strong zeolite–H_2O interaction.
Recently, a new type of desiccant material called metal organic frameworks, or MOFs, was introduced. Due to its large surface area, pore size and shape flexibility, and adaptable composition and activity, MOFs have a significant adsorption capacity and a low regeneration temperature (around 80◦). A more comprehensive assessment of the large-scale drying applications of MOF materials is necessary, considering the adsorbent packing density and material cost.
At last, the need for environmentally friendly farming techniques has led to an increase in interest in solar dryers globally, according to the bibliometric analysis. Thematic clusters that have been found emphasize a multidisciplinary approach that integrates process optimization, thermal storage, and energy generation. To improve system efficiency, this emphasizes the necessity of doing cutting-edge research on technologies like PCMs and CFD [63]. The goal is to create climate-resilient, scalable sun drying systems that promote energy and food preservation in a sustainable manner.

Table 3. Adsorption capacities and other parameters of some adsorbents for dehumidification Wang et al. (2013) [56].

Adsorbent Regeneration temperature (°C)	**Adsorbent temperature, RH**	**Adsorption capacity g-H_2O/g-sorb**	**Regeneration temperature (°C)**	**Reference**
Silica gel	27°C, 60% 27°C, 7%	0.08–0.36 0.02–0.05	70 70	Jia et al. (2006) [52]
Silica gel	30–40°C, 60%	0.34	70–80	Li et al (2007) [54]
MCM-41	27°C, 60% 27°C, 7%	0.46 0.07	70	Jia et al. (2006) [52]
Zeolite Y (Si/Al = 5.6–220	27°C, 60% 27°C, 7%	0.02–0.30 0–0.25	250–350	Jia et al. (2006) [52]
AC Y-60	27°C, 60% 27°C, 7%	0.18–0.29 0–0.4	70	Jia et al. (2006) [52]
$CaCl_2$/silica gel SWS-1L	35°C, 4%	0.19	60–80	Jiang et al (2011)[53]
MOF-MIL-101 (Cr)	30–40°C, 60%	1.5–1.7	70–80	Seo et al (2012) [55]
MOF-MIL-100 (Fe)	30–40°C, 60%	> 0.84	70–80	Seo et al (2012) [55]
MOF-MIL-100 (Cr)	30–40°C, 60%	_ 0.84	70–80	Seo et al (2012) [55]
MOF-MIL-100 (Al)	30–40°C, 60%	_ 0.84	70–80	Seo et al (2012) [55]

Table 4. Techno economic analysis of different types of solar dryers

Dryer details	**Results**	**Reference**
Solar driers with a black stone embedded composed of glass, plastic, aluminium, and mosquito net. Fish had been dried.	Driers are superior to others because they are less expensive, dependable, safe to use, easily repairable, well-insulated, and economical. minimal costs for both development and upkeep.	Mustapha .et.al (2014) [44]
Wire mesh absorber for solar air heater with nominal porosity to allow air to pass through. Slices of bitter gourd were dried.	Evaluation of a solar matrix collector based on annualized cost, present value of yearly savings, and present value of cumulative savings for different drying applications.	M. A. Aravindh (2014) [45]
Date palm was dried and winnowed using solar PV power. In arid areas, this dryer might be used to dry a variety of fruits and vegetables in order to assess their cost-effectiveness and potential to reduce carbon emissions. hybrid method of operation for PV panels.	The dryer's high internal rate of return (IRR) of 57.4% and short payback period of 2.10 years demonstrate its cost-effectiveness. System effectively used sun energy to generate higher-quality dried date palms faster than open drying.	Poonia, S. et.al (2022) [46]
Direct Solar dryer for different fruits and vegetables	The results showed that the pay-back period (PBP), benefit-cost ratio (BCR), net present value (NPV), internal rate of return (IRR), and 225% were, respectively, 0.47 years, INR 1334026, 13.8, and 225%.	A. K. Singh .et.al (2022) [47]
In this study, the energy, energy efficiency, and environmental sustainability of hybrid solar-electric dryers (HSED) were examined. The tomato slices had dried up.	Solar and electric heat units contributed varying percentages of energy, 44.57–56.24% and 43.76–55.43%, respectively. With a short payback period of 0.72 years, HSED may save up to $1,490.33 annually, making the dryer both financially feasible and cost-effective.	Nnaemeka Nwakuba (2020) [48]
Hybrid solar dryers for high load Kenaf fibres.	As per the assessments, drying at a maximum load of 1400 kg resulted in an increase of 97.27 kg/hour, 39.86 kg/kWh, and 3.72 Malaysian ringgit (about 0.90 USD) in extracted water, actual water extraction rate, and dryer operational expenses. There was a decrease of 0.10 kWh/kg in particular energy usage and 0.05 RM/kg (0.012 USD/kg) in specific operating costs.	A. S. A. Hamid (2020) [49]
The drying trials were conducted using a new mixed mode solar greenhouse dryer (SGD) with forced convection.	In comparison to the dryer's (SGD) 20-year lifespan, the payback period was shown to be very short, 1.02 years.	Aymen, E.L(2019) [50]
Creation and evaluation of a greenhouse solar drier with a 100-kilogram capacity intended to yield premium dried goods. Like (carrot, bitter gourd, tomato)	Depending on the product to be dried, analysis indicated potential savings of up to ten times the current investment value during the dryer's lifetime. Having a 1.5–2.1-year payback time, which is short.	Nadiya Philip (2022) [51]

4. CONCLUSIONS

It is highly recommended to implement methods for food preservation utilizing renewable energy sources to meet the established sustainable development goals and solve global issues pertaining to energy shortages and food security. In this scenario, solar drying techniques are very useful because of their numerous economical, quality, and environmental advantages. The articles' goals are to compile results from various investigations, identify trends in the literature, and provide analysis and recommendations for furthering solar drying research and development. This paper also goes into detail on several performance-enhancing strategies, like using different types of solar collector plates and adding Thermal energy storage system. Also, economic analysis of various types of solar drying system. A few of this review article's important contributions are outlined below.

- Studies on a variety of solar dryer types, including hybrid, indirect, and mixed modes, indicate that drying efficiency varies between 9% and 40%.
- Studies on a variety of solar dryer types, including hybrid, indirect, and mixed modes, indicate that drying efficiency varies between 9% and 40%.
- Although a hybrid dryer is a better option, using one of them contributes to global warming because it uses either electricity or traditional fuels.
- When using sensible storage materials, the air heater's thermal performance is noticeably better than when it isn't.
- Thermal energy storage affects drying in the absence of sunlight and is crucial for reducing drying temperature fluctuations.
- A thickness of around 0.12 m for the storage material was found to be the most practical for drying a range of agricultural products. By keeping the drying material's maximum temperature within a safe range, thermal storage improves the agricultural product's quality.
- Since solar isolation fluctuates every second of the day and is not accessible at night, it is extremely challenging to guarantee consistent product drying. As a result, using energy storage units with the present system makes it more reliable and practical.
- Drying efficiency can range from 40 to 75 percent when using different combinations of solar dryers and desiccants.
- Compared to a solar drying unit without a rotary desiccant wheel, the system's useable heat gain is increased by an average of 153% when a sun drying unit and a rotary desiccant wheel are used together.
- The results demonstrated that a desiccant wheel in dryers is an economical and useful option since it speeds up drying, lowers energy consumption, and shortens drying periods.
- The drying time of the system that includes dehumidification is 20% less than that of the system that does not. The experimental investigation unequivocally demonstrates that low-medium temperature thermal energy, which is necessary for the desiccant wheel's regeneration process, can be successfully provided by parabolic trough solar collectors.
- The results also support the theory and provide particular guidance for the application of solar thermal driven regenerated aided by PV cell rotary desiccant wheel systems combined with pebble bed storage that would reduce temperature fluctuations and supply thermal energy during off sunshine hours.

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- Conceptualization: Sankalp Kulkarni and Ronakkumar Shah.
- Literature Review and Data Curation: Sankalp Kulkarni.
- Writing – Original Draft Preparation: Ronakkumar R. Shah; Sankalp Kulkarni.

- Writing – Review & Editing: Ronakkumar R. Shah; Sankalp Kulkarni.
- Visualization and Figures: Sankalp Kulkarni.
- Supervision and Final Approval: Ronakkumar R. Shah.

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