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THE IMPORTANCE OF THERMAL ENERGY STORAGE SYSTEMS IN ENHANCING THE EFFICIENCY OF SOLAR DRYERS

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Abstract. Recent studies on solar dryer design and the integration of thermal energy storage systems are reviewed, with particular emphasis on the interrelationship between heat generation, utilization, and storage. The analysis indicates that collector modifications primarily improve solar energy capture and convective heat transfer, whereas airflow management and drying chamber reconfiguration enhance heat utilization efficiency and drying uniformity. Thermal energy storage systems enable heat retention during periods without solar radiation, thereby extending the duration of the drying process.

Keywords: heat utilization, energy storage, latent heat storage, phase change material, solar dryer.

Annotatsiya. Quyosh quritgichlarining konstruksiyasi va issiqlik energiyasini saqlash tizimlarini integratsiyalashga oid so'nggi tadqiqotlar issiqlik energiyasini hosil qilish, undan foydalanish va uni saqlash jarayonlarining o'zaro bog'liqligi nuqtayi nazaridan tahlil qilingan. Tahlil natijalari shuni ko'rsatadiki, kollektor konstruksiyasini takomillashtirish, asosan, quyosh energiyasini o'zlashtirish va konvektiv issiqlik uzatish samaradorligini oshiradi, havo oqimini boshqarish hamda quritish kamerasining konstruksiyasini o'zgartirish esa issiqlik energiyasidan foydalanish samaradorligini va quritish jarayonining bir xilligini yaxshilaydi. Issiqlik energiyasini saqlash tizimlari quyosh nurlanishi mavjud bo'lmagan davrlarda issiqlikni saqlash imkonini berib, quritish jarayonining davomiyligini uzaytiradi.

Kalit so'zlar: issiqlikdan foydalanish, energiyani saqlash, yashirin issiqlikni saqlash, fazaviy o'zgaruvchan material, quyosh quritgichi.

Аннотация. Проведён обзор современных исследований, посвящённых конструкции солнечных сушилок и интеграции систем аккумулирования тепловой энергии, с особым акцентом на взаимосвязь процессов выработки, использования и накопления тепла. Результаты анализа показывают, что совершенствование конструкции коллекторов преимущественно повышает эффективность улавливания солнечной энергии и конвективного теплообмена, тогда как управление воздушными потоками и изменение конструкции сушильной камеры способствуют более эффективному использованию тепловой энергии и повышению равномерности сушки. Системы аккумулирования тепловой энергии обеспечивают сохранение тепла в периоды отсутствия солнечного излучения, тем самым увеличивая продолжительность процесса сушки.

Ключевые слова: использование тепла, аккумулирование энергии, аккумулирование скрытой теплоты, материал с фазовым переходом, солнечная сушилка.

INTRODUCTION

The availability and rational use of energy resources are widely recognized as key indicators of socioeconomic and industrial development. Factors such as global population growth, rising energy demand associated with industrialization, climate change, the finite nature of fuel resources, and increasing challenges in transport logistics have intensified efforts to transition toward sustainable, low-carbon energy systems. Solar drying technologies have long been recognized as environmentally friendly and cost-effective drying methods, and they continue to evolve. In regions with high solar irradiance, such as Southeast Asia, Africa, and South America, abundant solar resources can be effectively harnessed to replace fossil-fuel-based drying systems [1]. Among various solar drying configurations, mixed-mode solar dryers have attracted significant attention. They combine direct solar radiation with indirect convective heating, thereby improving heat utilization, accelerating

drying rates, and enhancing overall thermal performance compared with traditional solar dryers [2].

LITERATURE REVIEW

Mixed-mode solar dryers also provide a more controlled drying environment that enhances heat and mass transfer while minimizing product loss and contamination [3]. Despite these advantages, the intermittent nature of solar energy can affect the consistency of the drying process. In this context, thermal energy storage (TES) has emerged as a key strategy for maintaining process continuity, stabilizing heat output, and enhancing the efficient utilization of solar energy in mixed-mode solar dryers [4]. Solar dryers integrated with TES facilitate continuous drying by storing energy during periods of peak solar radiation and releasing it when sunlight is unavailable, thereby reducing the mismatch between energy supply and demand [5]. From an energy systems perspective, mixed-mode solar dryers should be viewed not merely as drying technologies but as thermally integrated systems in which energy storage plays a significant role in operational stability and reliability. Consequently, TES is increasingly regarded as a key subsystem influencing drying efficiency, energy utilization, and techno-economic performance [6].

RESEARCH METHODOLOGY

Systematic analyses indicate that recent research has focused on improving the designs of mixed-mode solar dryers. Fig. 1 illustrates the basic concept of the proposed system.

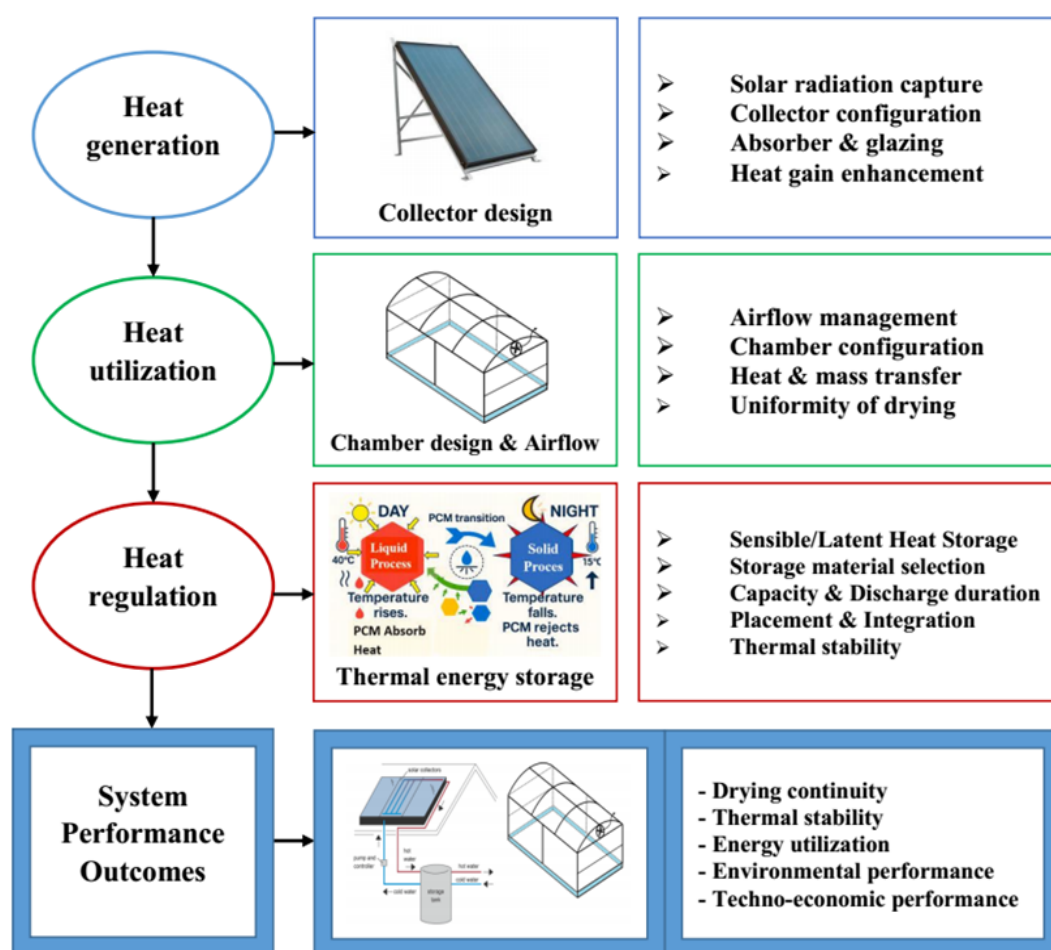


Figure 1. A system illustrating the interaction between heat generation, heat utilization, and thermal energy storage (TES) in solar dryers¹

The aim is to address ongoing challenges, such as prolonged drying times and limitations in moisture removal during periods without sunlight (e.g., at night or under cloudy conditions). Recent studies have placed

¹ Source: Developed by the author.

greater emphasis on advanced solar air collectors (SACs) featuring V-grooved, finned, and roughened absorbers, as well as forced and hybrid convection strategies, air recirculation systems, and smart control mechanisms. Modified absorber geometries and structural enhancements have been shown to improve heat transfer and collector efficiency significantly. Furthermore, the integration of thermal energy storage (TES) systems utilizing both sensible heat storage (SHS) and latent heat storage (LHS) has been investigated to extend the drying process and enhance system efficiency during periods when sunlight is unavailable [7]. Further quantitative evaluation of the relative contributions of these design modifications could help identify effective mixed-mode solar dryer configurations under different operating conditions. Furthermore, most existing TES applications rely on conventional storage media, such as stones, gravel, sand, black-painted concrete, and phase change materials (PCMs) [8], whose selection requires consideration of cost, availability, and long-term stability when used in drying systems.

ANALYSIS AND RESULTS

Solar Dryers Integrated with Solar Air Collectors and Solar Liquid Collectors/Heat Exchangers. By integrating a solar air collector into a solar dryer, it is possible to increase the air temperature inside the drying chamber and reduce drying time. The temperature required for product drying can be achieved by adjusting the collector length and airflow rate. According to the results of various studies, the maximum efficiency of solar air collectors is approximately 81%. R. Dejchanchaiwong et al. [9] dried rubber sheets in a solar dryer operating in mixed-mode (with a collector) and indirect-mode (without a collector) heat transfer configurations. M. A. Eltawil et al. [10] dried mint products of different thicknesses in an even-span hybrid solar tunnel dryer using three different airflow rates. The fan of the forced-convection system was powered by energy generated by a photovoltaic (PV) module. The energy, environmental, and economic aspects of the system were analyzed. A. El Khadraoui et al. [11] dried tomatoes under forced-convection conditions in a chapel-shaped dryer. The maximum and minimum collector efficiency values were determined. A. Khanlari et al. [12] conducted an experiment by integrating a tubular solar air collector into an even-span dryer. During the experiment, the average thermal efficiency of the collector was determined at three different airflow rates. The experimental results were compared with simulation results.

Y. R. Sekhar et al. [13] conducted experiments under natural- and forced-convection conditions in a dome-shaped (modified Quonset) dryer with an insulated north wall. Gravel was used as a heat storage material on the dryer floor. A. Djebli et al. [14] dried tomatoes cut into four different thicknesses in a single-slope mixed-mode greenhouse dryer. S. Murugavelh et al. [15] dried tomato waste in a dome-shaped (modified Quonset) mixed-mode greenhouse dryer. An analysis of the drying kinetics and exergy performance of the dryer was conducted. Z. Azaizia et al. [16] conducted an experiment using phase change material (PCM) as a heat storage medium in an even-span mixed-mode dryer. Paraffin was used as the PCM. A thin-layer drying model suitable for pepper drying was determined. R. Zachariah et al. [17] dried bitter melon in a dryer equipped with a PV-module-integrated air recirculation system. In the air recirculation system, hot air from the drying chamber was returned to the solar collector through a fan and a dedicated duct. The dryer floor was insulated, and paraffin wax was used as the PCM in pipes arranged in a zigzag configuration.

Solar dryers can utilize high-temperature fluids circulating through dedicated pipes to reduce product drying time. The use of nanoparticle-enhanced fluids in heat exchanger pipes can increase the temperature inside the dryer and improve its efficiency. High-temperature geothermal water or fluids heated in solar collectors can be used as working fluids. M. Sandali et al. [18] supplied additional thermal energy to an even-span solar dryer through a heat exchanger using geothermal water in southern Algeria. The experiment was conducted under no-load conditions and was modeled using simulation software. The maximum temperatures inside the dryer differed by up to 17 °C between configurations without and with the heat exchanger. P. Singh et al. [19] integrated an evacuated-tube solar collector into an even-span hybrid solar dryer. Tomatoes, ginger, and bitter melon were dried in the system under configurations with and without the collector. Water was used as the working fluid. A. Kushwah et al. [20] conducted experiments under no-load and loaded conditions at different water flow rates in a forced-convection dryer with a capacity of 200 L and two integrated collectors. Water was used as the working fluid during garlic drying. In a subsequent experiment, mushrooms were dried [21], and the experimental results were compared using artificial neural networks.

Thermal Energy Storage Operation, Performance, and Integration in Solar Dryers. In solar dryers, structural modifications, airflow management, and thermal energy storage (TES) function as complementary and interdependent elements governing overall system performance. Although collector and chamber modifications directly influence thermal energy absorption and utilization, maintaining drying continuity during periods of limited solar availability requires additional thermal management. TES therefore plays a significant role by buffering temporal fluctuations in energy supply and supporting drying operations beyond sunshine hours.

According to Ekka and Kumar [22], TES systems employed in solar applications are generally classified into three categories based on their energy storage mechanisms: sensible heat storage (SHS), latent heat storage (LHS), and thermochemical heat storage (THS). Each category operates according to distinct physical principles and exhibits different storage characteristics.

Table 1
Classification and Description of TES Systems²

TES type	Principle of operation	Common materials used	Key advantages	Limitations	Efficiency gains
Sensible heat storage (SHS)	Heat is stored through a temperature increase	Sand, rocks, gravel, water, bricks, waste composites, and pebbles (mostly natural and waste-derived materials)	Low cost, simplicity, and durability	Lower energy density and larger storage volume	Drying time reduction of 9–47%; thermal efficiency of up to 66%
Latent heat storage (LHS) / Phase change material (PCM)	Heat is stored and released during phase transitions	Paraffin wax, stearic acid, sodium acetate trihydrate, and hydrated salts	High energy density and stable temperature	Cost, leakage, and low thermal conductivity	Drying time reduction of up to 46%; efficiency of up to 87%
Thermochemical heat storage (THS)	Heat is stored through reversible chemical reactions	Salt hydrates (e.g., $\text{CaCl}_2 \cdot 6\text{H}_2\text{O}$ and $\text{SrBr}_2 \cdot 6\text{H}_2\text{O}$) and composites	Very high energy density and long-term storage	System complexity, cost, stability considerations, and limited scalability	Potential storage energy density exceeding 500 kWh/m^3 ; comparatively less mature technology

Srinivasan et al. presented a comprehensive review of solar dryers integrated with TES, covering direct-, indirect-, and mixed-mode configurations under both natural- and forced-convection conditions. Their analysis systematically compared SHS and LHS materials, dryer types, operating parameters, and dried products, highlighting TES as an important solution for addressing intermittent solar availability and enabling continuous drying during periods without sunlight. The study also outlined key design considerations and future research directions related to TES material selection, heat transfer enhancement, and system complexity in solar dryers.

Following this review, studies have increasingly focused on modeling and experimental validation of TES-assisted mixed-mode solar dryers. S. Tagne et al. [23] developed and experimentally validated a coupled heat and mass transfer model for a natural-convection mixed-mode solar dryer integrated with SHS using sodium chloride. A distinctive feature of the system was the relocation of sodium chloride from the collector during sunshine hours to the drying chamber during periods without sunlight, enabling extended drying operation. Close agreement between numerical and experimental results supported the model's reliability and applicability for predicting the performance of TES-assisted mixed-mode solar dryers operating under limited sunshine durations.

Dutta et al. [24] investigated the performance impact of integrating SHS into a reconfigurable active mixed-mode solar dryer designed to improve drying uniformity in multi-tray systems. The dryer allowed switching between indirect- and mixed-mode operation through movable chamber walls, while gravel embedded beneath the absorber plate served as a compact SHS medium. Comparative experiments showed that the mixed-mode solar dryer with SHS achieved the shortest drying time (10 h), compared with 26 h for the mixed-mode solar dryer without storage and 53 h for open-sun drying. Average dryer efficiency increased to 24.46% for the mixed-mode solar dryer with SHS, exceeding that of the other configurations. The enhanced performance was attributed to supplementary direct solar gain in mixed-mode operation combined with heat release from SHS during periods of low solar radiation, which increased the inlet air temperature by up to 6.7°C during the later stages of drying. These findings suggest that TES integration, when combined with mixed-mode operation, can contribute to improved thermal stability and accelerated moisture removal under the investigated operating conditions.

The relatively low energy density and shorter heat-release duration of SHS have also encouraged growing

² Source: Developed by the author.

interest in LHS systems capable of sustaining drying under extended periods without sunlight and fluctuating climatic conditions. In this context, Kalita et al. [25] investigated the integration of PCM into a mixed-mode solar dryer system to improve drying continuity under intermittently sunny and humid conditions. The study emphasized TES effectiveness in terms of temperature stabilization rather than peak temperature enhancement. PCM integration enabled sustained heat release, maintaining cabinet temperatures approximately 19.4 °C above ambient temperature and reducing drying interruptions. Drying experiments on turmeric demonstrated a reduction in drying time to 22.5 h compared with open-sun drying (OSD), with an average system efficiency of 49.28%, indicating the suitability of LHS for enhancing drying reliability in regions with variable solar availability.

Several reviewed studies have evaluated SHS and LHS separately, indicating the value of further comparative investigations to distinguish the effects of storage mechanisms from those of dryer configurations and operating conditions. To directly compare both storage mechanisms, Andharia et al. [26] conducted a controlled comparative evaluation of sensible and latent heat storage integrated into an indigenously developed small-scale mixed-mode solar dryer, using black pebble stones and paraffin wax placed within the solar air heater (SAH). Although TES integration reduced peak drying air temperatures relative to the configuration without storage, both storage modes enhanced drying continuity after sunset. The SHS unit maintained drying conditions for approximately 2 h after sunset, whereas the PCM-based LHS system sustained effective drying for up to 3–5 h, resulting in the shortest drying time (9 h) and an 18% reduction relative to SHS. The PCM system also exhibited reduced temperature fluctuations and a delayed thermal peak, supporting the suitability of LHS for stabilizing drying conditions and mitigating moisture reabsorption in mixed-mode solar dryers under intermittent solar availability.

CONCLUSION AND SUGGESTIONS

Thermal energy storage (TES) systems in solar dryers operate through cyclic charging and discharging processes governed by solar energy availability. During periods of peak solar radiation, the storage medium absorbs excess thermal energy, whereas during periods without sunlight, the stored heat is released to sustain the drying process. This temporal decoupling of energy supply and demand plays an essential role in addressing solar energy intermittency and maintaining stable drying conditions. Rather than being determined primarily by the peak drying-air temperature, TES effectiveness is largely influenced by discharge duration and temperature stability during periods without sunlight, which directly affect moisture removal kinetics. These findings have been consistently reported in solar drying systems incorporating both sensible heat storage (SHS) and latent heat storage (LHS) media.

The sizing of TES systems is a critical design parameter influencing sustained operation and overall system efficiency. Storage capacity must be matched to thermal demand during periods of low or absent solar radiation and is typically determined by climatic conditions, airflow rate, and product moisture load. Appropriate TES sizing can help maintain drying temperatures and balance capital costs with expected improvements in system performance. Therefore, optimal sizing requires balancing thermal storage capacity with operational demand and system constraints.

Based on the results of this analysis, future research should focus on five priority areas: (i) developing methodologies for determining standardized TES dimensions tailored to drying capacity, climatic conditions, and operational requirements; (ii) implementing unified reporting protocols for thermal, exergy, economic, and environmental efficiency indicators (4E analysis); (iii) experimentally evaluating alternative and low-cost storage materials under long-term thermal cycling conditions; (iv) utilizing mathematical modeling and simulation tools to optimize airflow distribution, heat transfer, and TES placement; and (v) conducting pilot tests and industrial-scale demonstrations to validate long-term efficiency, reliability, and economic viability under actual operating conditions.

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