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PERFORMANCE EVALUATION OF MANUFACTURED SMART HYBRID SOLAR DRYER FOR DRYING VARIOUS MEDICINAL HERBS*

Ahmed Khudhayer Jabr¹

Ahmed.khudhayer@coagri.uobaghdad.edu.iq

Firas Salim khalif Al-Ani¹

fsalim@coagri.uobaghdad.edu.iq

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ABSTRACT

A Smart Hybrid Solar Dryer (SHSD) and a Traditional Hybrid Solar Dryer (THSD) were designed and manufactured to control the drying process of selected medicinal herbs and achieve the recommended moisture content, thereby extending their storage life. The dryers were tested at the Ministry of Industry and Minerals, Industrial Research and Development Authority, Renewable Energy Center.

The experiment investigated three primary factors: air discharge angle (40°, 70°, and 90°), medicinal herb type (Peppermint, Rosemary, and Sage), and dryer type (SHSD and THSD). A factorial experiment within a Randomized Complete Block Design (RCBD) with three replications was implemented to evaluate the effects of these factors and their interactions on drying performance.

Results indicated that the volumetric airflow rate increased at a discharge angle of 90°, whereas the drying efficiency peaked at a discharge angle of 40° for both dryers. The SHSD significantly outperformed the THSD due to its integrated fan system, which enabled precise control of internal temperature and relative humidity at an optimal airflow velocity of 0.65 m.s⁻¹ compared to 3 m.s⁻¹ in the THSD.

Furthermore, thermal energy loss was substantially higher in the THSD (178.60 W) than in the SHSD (157.58 W), demonstrating the superior energy efficiency and drying performance of the SHSD.

Keywords: Smart drying system, dried medicinal plants, solar panel, fan, sensors

INTRODUCTION

Agriculture-based countries play a fundamental role in global food security by producing a diverse range of fruits and vegetables that supply essential nutrients and support healthy diets. However, inadequate post-harvest handling practices and limited cold-chain infrastructure continue to cause substantial losses, estimated at 20–30% of total productivity [4, 14]. Drying remains one of the most effective preservation methods, as reducing moisture content inhibits microbial growth and slows enzymatic deterioration [16]. Hybrid solar dryers have emerged as a promising solution,

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¹ College of Agricultural Engineering Sciences, University of Baghdad. Baghdad. Iraq.

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functioning as devices that remove excess water from food products to extend their shelf life [15]. Recent studies highlight the efficiency of hybrid smart solar dryers that rely on indirect forced convection to dry medicinal herbs such as basil and sage at controlled temperatures of 30, 40, and 50°C, significantly reducing drying time compared to traditional open-air or indoor drying, while achieving up to 70% energy savings and preserving essential oil content and microbial quality [4].

Broader investigations further show that uneven global energy distribution—particularly shortages in developing countries and rural regions—contributes to post-harvest losses of nearly 30%, underscoring the need for energy-efficient drying technologies. Advanced hybrid solar dryers have demonstrated efficiencies of up to 35% at 80°C, making them suitable for high-moisture agricultural products [12]. Although natural solar drying has long been used in regions with favorable climates, modern agricultural systems increasingly require active solar dryers equipped with fans, pumps, and heaters to enhance airflow and heat transfer [5]. Hybrid solar dryers, which integrate direct solar radiation with preheated airflow from solar collectors, offer shorter drying times and superior product quality compared to open-air methods, making them particularly suitable for fast-drying, quality-sensitive crops such as herbs, cashews, mushrooms, and pineapples [20, 21].

Solar dryer designs typically consist of collectors and drying chambers and vary across direct, indirect, mixed, and hybrid configurations [18, 8]. Passive solar dryers rely on natural convection without external energy inputs, whereas active dryers incorporate sensors, controllers, and auxiliary systems to regulate temperature and humidity, thereby improving efficiency and product quality despite higher initial costs [3, 7, 11]. Additional innovations such as hybrid thermal solar dryers with phase change materials (PCM) have enhanced heat retention and improved drying performance for arid fruits [13]. Hybrid dryers have also been successfully applied in drying shrimp meat, where different pretreatments and drying modes improved drying time, energy utilization, and product appearance [1]. Overall, solar energy remains a sustainable and environmentally friendly method for drying agricultural products, especially in remote areas with limited access to electricity [2, 22]. Therefore, this research aims to determine the required moisture content of dried materials, identify the optimal air-discharge angle, and select the most suitable dryer configuration for drying medicinal herbs.

MATERIALS AND METHODS

In this study, the performance of a hybrid smart solar dryer was evaluated and compared with a traditional solar dryer that was constructed and developed specifically for experimental purposes. Both dryers were equipped with sensors in each drying chamber to monitor and control temperature and humidity. An airflow distribution system made of PVC pipes was installed in every chamber to ensure uniform air circulation. Three medicinal plants belonging to the Lamiaceae family—Peppermint (*Mentha piperita* L.), Rosemary (*Rosmarinus officinalis* L.), and Sage (*Salvia officinalis* L.)—were placed under identical climatic conditions in each chamber and dried at temperatures ranging from 30°C to 40°C.

The experiment was conducted between 27 October and 4 December at the Renewable Energy Research Center, Industrial Research and Development Authority, Ministry of Industry and Minerals, Al-Jadriya, located at 33.27°N latitude, 44.38°E longitude, and an elevation of 32 meters above sea level. Three levels of mass airflow—40°, 70°, and 90° discharge angles—were adopted as the main experimental factors, along with the three medicinal plant types.

The parameters studied included:

- 1- Efficiency of the solar collector (%)
- 2- Mass airflow rate (m^3/s)
- 3- Drying performance and quality of medicinal plants

A factorial experiment nested within a Randomized Complete Block Design (RCBD) was implemented. Data were analyzed using the Statistical Analysis System (SAS) to examine the effects of dryer type, airflow angle, and their interaction on the measured variables. Differences between treatment means were evaluated using the Least Significant Difference (LSD) test at a 0.05 significance level.

Each hybrid solar drying system consisted of three separate drying chambers, one dedicated to each plant type. The second unit of each dryer contained a flat-plate solar collector with an area of 1.125 m^2 . Each drying chamber was constructed with internal dimensions of $0.88 \text{ m} \times 0.87 \text{ m} \times 0.97 \text{ m}$ and included three equally sized shelves to accommodate the medicinal plants, as illustrated in Figure 1.

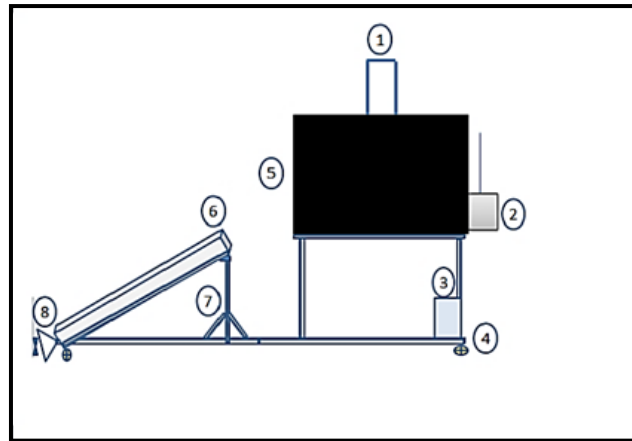


Figure 1: Shows the main components of the two Hybrid dryer. 1- Chimney 2- board electronic 3- Main board 4- frame and wheels 5- Chamber dryer 6- Solar collector 7- Stand 8- Fan and duct.

The objective of this study was to design and evaluate two hybrid solar dryers equipped with systems for controlling temperature and humidity using an Arduino ESP32 microcontroller. Electrical power for the system was supplied by a photovoltaic (PV) panel. The hybrid smart solar dryer was equipped with fourteen DHT22 sensors distributed above the shelves in each drying chamber to monitor temperature and relative humidity continuously.

The system also included an internal air fan installed within the air duct, operating on a 12-V power supply with a maximum airflow velocity of 3 m/s . The fan was programmed to operate until the chamber reached the predetermined drying temperature, at which point it automatically shut off to maintain stable conditions.

Figure 1 illustrates the main components of the hybrid dryer integrated with the solar panel, while Figure 2 presents the internal layout and arrangement of sensors, airflow pathways, and control elements used in the study. Meanwhile, Figure 3 shows Show the side view Smart Hybrid Dryer.

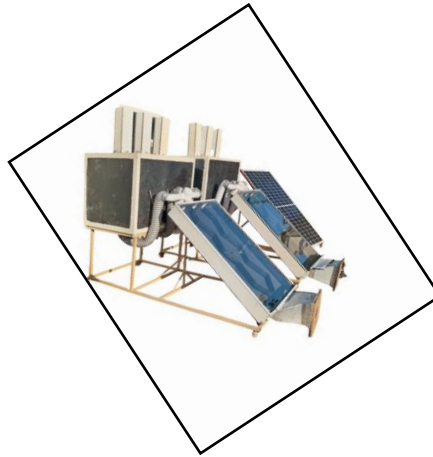
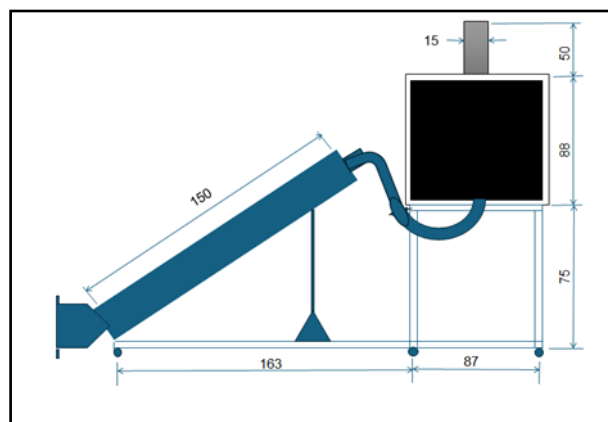


Figure 2: Shows the two Hybrid Dryer with Solar Panel

Figure 3: Show the side view Smart Hybrid Dryer
Data processing

Solar collector efficiency is defined as the ratio of the amount of energy extracted or useful energy gained by the air to the amount of solar radiation energy reaching the surface of the solar collector [6, 17].

$$\eta_c = \frac{Q_u}{I_c \times A_c} \quad (1) \quad I_c: \text{Incidental solar radiation (KWh.m}^2\text{)}. \quad A_c: \text{Solar collector area (m}^2\text{)}.$$

η_c : Solar collector efficiency (%). Q_u : Useful energy (KJ).

Q_u : Useful energy (KJ).

I_c : Incidental solar radiation (KWh.m²). A_c : Solar collector area (m²).

$$Q_u = m_a C_p (T_c - T_a) \quad (2)$$

m_a : Mass air flow rate (kg h⁻¹)

C_p : Air specific heat (KJ. Kg⁻¹. C⁻¹)

T_c, T_a : Internal and external temperature(C).

$$V_a' = V_a \times a_h \times C_w$$

$$V_a' = M_a \times \rho_a$$

V_a' : Volumetric air flow rate (m³/s).

V_a : Fan air speed (m/s), a_h : The air gap

C_w : Width of the Collection (m).

(m).

m_a : Mass flow rate (kg.s⁻¹).

ρ_a : Density of air (Kg/m³).

RESULTS AND DISCUSSION

1- Solar collector efficiency (%)

Figure 4 illustrates the effect of the air discharge angle, plant type, and dryer type on the efficiency of the solar collector. The results showed that the type of discharge angle and its averages have a significant impact on the efficiency solar collector. In the SHSD, the highest average was 45.54% while in the THSD was 43%. The angle of 40-degree best angle in solar collector efficiency in both two dryers, but the SHSD was more efficiency than of the THSD. This difference is attributed to the variation in temperature rates and airflow rates, as the smart dryer contains a fan that helps increase the airflow rate and allows for faster entry of larger quantities of air into the dryer, thereby enhancing the solar collector's efficiency.

The angle 40 degree or the smallest air discharge opening at 40 degrees provided the highest efficiency, increasing the energy extracted by the solar collector and thus its efficiency. In comparison, at angles of 70 degrees and 90 degrees, there was a gradual decrease in the useful energy inside the solar collector due to the reduced temperature difference between the smallest and largest angles. As a result, the airflow discharge at an angle of 90 in both two dryers were increased but the temperature was decreased, as well as in two dryers because it operates with forced convection, i.e., equipped with a fan that enhances the airflow entering the solar collector. This change results differences in the efficiency of the solar collector.

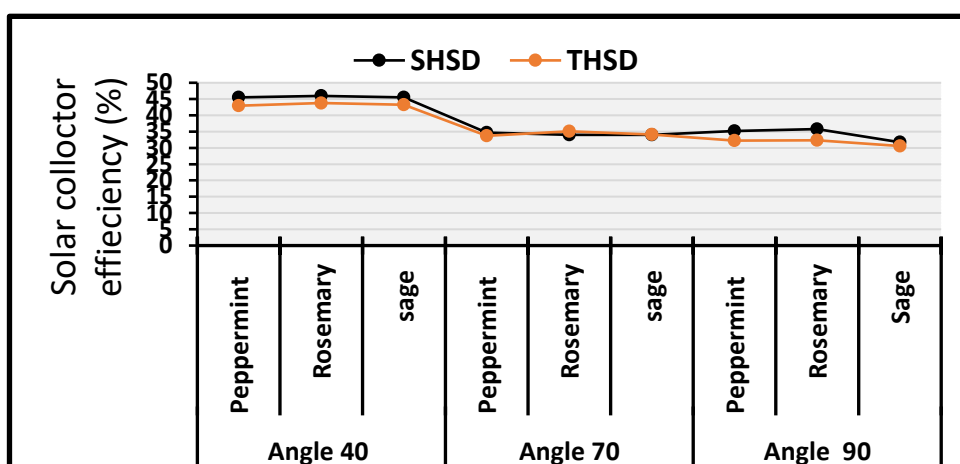


Figure 4: Impact of Air Discharge Angle, Herb Material Type, and Dryer Type on Solar Collector Efficiency (%)

2- Volumetric air flow rate (m³/s)

It seems that figure 5 Highlights the effect of the air discharge angle and the type of dryer on the air flow rate, where it is evident that increasing the discharge angle leads to a gradual increase in air flow. According to the data, the SHDT has higher efficiency compared to the THSD, as it records greater flow rates at different angles, especially at 90 degrees. It found the results: the highest average airflow was 0.030 m³/sec at a discharge angle of 90 degree in the SHSD, but it recorded 0.020 m³/sec. So, the SHSD contain on the fan was pushed the hot air into to drying room.

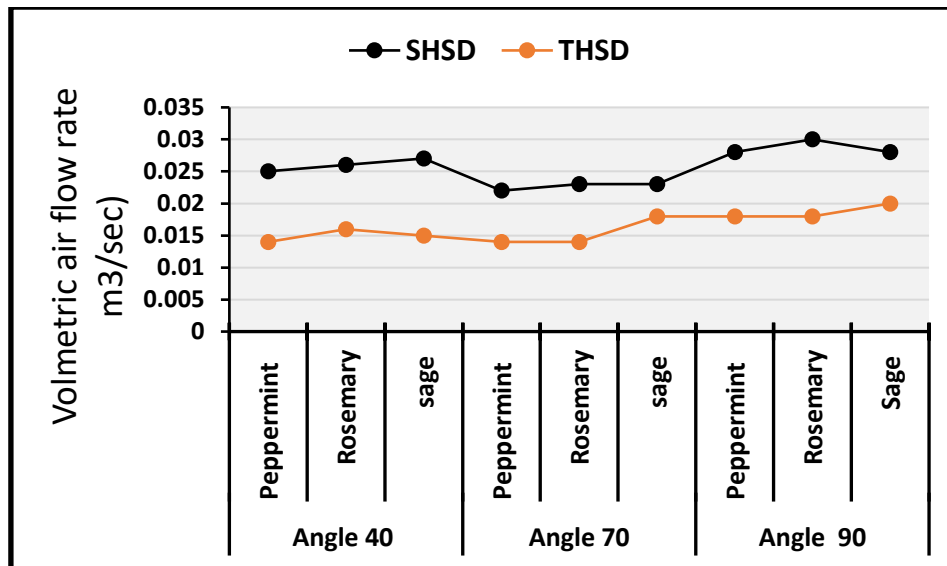


Figure 5: Shows the Effect of Angle type, Material type of plant and Dryer type on the volumetric air flow rate (m³/s)

3- West energy amount from the solar collector (J)

Figure 6 shows the effect of the air discharge angle, the drying material, and the type of dryer on the energy losses from the solar collector. The experimental results indicate significant differences between deferent angles, but in THSD was the highest average to 222.61 joule recorded at 40-degree angle for peppermint, while in SHSD the average of losses recorded to 187.14 joule. This difference is attributed to the heat loss occurring in two dryers was in the upper part of the solar collector, which is greater than in the lower part and also varies across both dryers. However, the amount of lost energy is higher in the THSD compared to with the SHSD, because the solar dryer THSD the air depends on the natural loading.

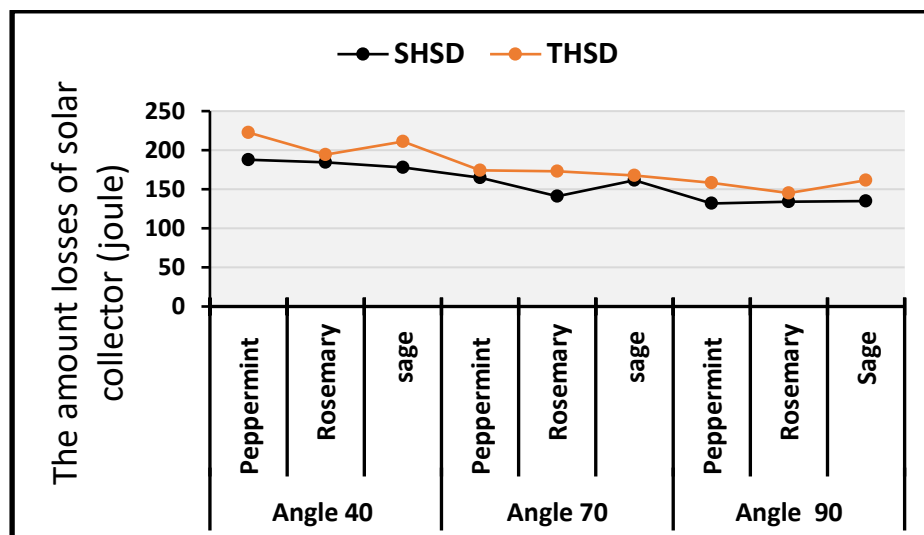


Figure 6: Shows the Effect of Angle type, Material type of plant and Dryer type on the amount of losses energy of solar collector in unit (J).

Conclusions

In this study, the Smart Hybrid Solar Dryer (SHSD) demonstrated its effectiveness as a viable and practical drying technology for small- and medium-scale agricultural applications. The system proved capable of producing high-quality dried herbs, particularly when evaluated in terms of sensory attributes and rehydration ratio, outperforming the traditional open-air drying method. The SHSD also exhibited superior energy performance, characterized by lower thermal losses, more suitable and stable mass airflow, and a significantly faster drying rate. These improvements contributed to higher overall efficiency and reduced drying time, as confirmed by the experimental results.

Given its enhanced performance, the SHSD presents a promising solution for farmers seeking to minimize post-harvest losses, improve product quality, and increase economic returns. The system's design, which allows it to operate using photovoltaic energy and low-power auxiliary components, supports its use in rural or off-grid settings. Therefore, the SHSD could be feasibly installed at the household or farm level, where it can operate with small generators or fans to effectively remove moisture from successive batches of crops or medicinal herbs. Overall, the findings suggest that hybrid solar drying technologies, such as the SHSD, offer a sustainable, efficient, and economically attractive alternative to conventional drying methods, with the potential to enhance food preservation and improve the livelihoods of agricultural producers.

Recommendations

To further enhance the performance and effectiveness of hybrid solar drying systems, several improvements are recommended. First, reducing drying time and achieving lower final moisture content can be accomplished by integrating thermal energy storage units within the dryer. Such units—particularly those based on heat-retaining materials—can store thermal energy during peak sunlight hours and release it during periods of low solar radiation, especially at night, thereby ensuring more stable drying conditions. Additionally, future designs should consider using lower air-discharge angles than those applied in this study, as smaller angles may better preserve vitamins and heat-sensitive nutrients in dried agricultural products.

It is also essential that meteorological data (Exg. solar radiation, temperature, humidity, and wind patterns) be readily accessible to users of solar energy technologies. Reliable climate information enables farmers to identify optimal drying periods, thus improving both system efficiency and product quality.

Furthermore, the study encourages students and researchers to explore the use of advanced control technologies, particularly Arduino-based systems, to automate and precisely regulate drying temperature and airflow. Developing improved programming approaches for sensors, controllers, and actuators will support precise environmental control and help preserve the nutritional and medicinal properties of dried plants, vegetables, and other sensitive materials.

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تقييم الأداء لمجفف شمسي ذكي هجين لتجفيف مختلف الأعشاب الطبية*

فراس سالم خلف العاني¹

fsalim@coagri.uobaghdad.edu.iq

احمد خضير جبر¹

Ahmed.khudhayer@coagri.uobaghdad.edu.iq

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الملخص

تم تصميم وتصنيع مجفف شمسي ذكي هجين (SHSD) ومجفف شمسي هجين تقليدي (THSD) للتحكم في عملية تجفيف بعض الأعشاب الطبية والوصول إلى المحتوى الرطوبي الموصى به لتمديد فترة التخزين. تم استخدام المجفف في وزارة الصناعة والمعادن، هيئة البحث والتطوير الصناعي، مركز الطاقة المتجددة، شملت التجربة ثلاثة عوامل: زاوية تصريف الهواء والتي مثلت العامل الرئيسي، وتم اختيار ثلاث زوايا: 40، 70، و 90 درجة. العامل الثاني كان نوع المادة النباتية الطبية (النوع، إكليل الجبل، والميرمية)، بالإضافة إلى نوعين من المجففات: المجفف الشمسي الذكي الهجين والمجفف التقليدي.

تم استخدام تجربة عاملية ضمن تصميم القطاعات العشوائية الكاملة بثلاث مكررات لدراسة تأثير نوع المادة المجففة، كفاءة المجمع الشمسي، ومعدل تدفق الهواء وتداخلها مع المعايير المدروسة.

تشير النتائج إلى أن معدل تدفق الهواء الحجمي يزداد عند زاوية تصريف الهواء 90 درجة، بينما تزداد الكفاءة عند استخدام زاوية تصريف الهواء 40 درجة في كلا المجففين، إلا أن المجفف الشمسي الذكي الهجين كان أفضل من المجفف التقليدي، لأنه يحتوي على مروحة يمكن ضبط سرعتها المناسبة عند 0.65 م.ث⁻¹ بدلاً من 3 م.ث⁻¹ للتحكم في درجة الحرارة والرطوبة داخل غرفة التجفيف. كما أن مقدار الطاقة المفقودة بلغ 178.6 واط في المجفف التقليدي مقارنة بـ 157.58 واط في المجفف الذكي، مما يدل على كفاءة وجودة المجفف الشمسي الذكي الهجين في استخدام الطاقة.

الكلمات الدالة: نظام تجفيف ذكي، أعشاب طبية مجففة، لوح شمسي، مروحة، حساسات.

* جزء من أطروحة دكتوراه للباحث الأول

¹ جامعة بغداد، كلية الهندسة للعلوم الزراعية، بغداد، العراق.

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