Journal of Technology Research (JTR)
Volume 3, Special Issue, (2025), pp 762-769 ISSN 3005-639X
The 7th Conference of Engineering Sciences and Technology
(CEST-2025)

Enhancing Efficiency of Small-Scale Solar Food Dryers under Omani Climatic Conditions: A Study on Natural Convection and Thermal Collector Performance

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Received: 20-10-2025 | Accepted: 02-12-2025 | Available online: 25-12-2025 | DOI:10.26629/jtr.2025.71

ABSTRACT

This study evaluates the performance of five small-scale solar food dryers operated under natural convection to dry potato slices, focusing on the influence of different thermal collector materials on drying efficiency under Omani climatic conditions. The dryers, identical in size and design, differed only in the collector materials used: white marble (WM), black-painted marble (BM), gray rock (GR), granular carbon (GC), and a control black absorber floor (BAF). Results showed that darker collectors (BM and GC) achieved higher surface temperatures (50–52 °C) compared to lighter collectors (≈45 °C for WM), due to improved solar absorption and reduced reflectivity. Consequently, the highest initial drying rates were obtained using GC and BM (0.12 g/min and 0.11 g/min, respectively), while WM exhibited the slowest rate (0.035 g/min). The moisture content of the potato slices was reduced by approximately 90–93% within 4–5 hours for GC and BM, while WM required more than 7 h to achieve similar results. The findings demonstrate that both collector color and material significantly affect thermal performance and drying kinetics. However, during the later drying stage, internal moisture diffusion limited the drying rate, indicating that forced air convection could further enhance performance. This study provides a foundation for developing cost-effective, small-scale solar dryers suitable for rural food processing applications in arid regions like Oman.

Keywords: Solar dryer, natural convection, thermal collectors, moisture reduction, drying kinetics, sustainable drying.

تعزيز كفاءة المجففات الشمسية الغذائية صغيرة النطاق في الظروف المناخية العُمانية: دراسة حول الحمل الحراري الطبيعي وأداء المجمعات الحرارية

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ملخـــــــص البحـــــــث

قيّم هذه الدراسة أداء خمسة مجففات شمسية صغيرة النطاق تعمل بالحمل الحراري الطبيعي لتجفيف شرائح البطاطس، مع التركيز على تأثير أنواع مختلفة من المواد المســـتخدمة كمجمعات حرارية على كفاءة التجفيف في الظروف المناخية العُمانية. كانت المجففات الخمسة متطابقة في الحجم والتصميم، وتختلف فقط في نوع مادة المجمع الحراري المستخدمة، وهي: الرخام الأبيض(WM) ، والرخام المطلي بالأســـود(BM) ، والصـــخر الرمادي(GR) ، والكربون الحبيبي(GC) ، ووحدة تحكم بســـطح ممتص أســـود.(BAF)

أظهرت النتائج أن المجمعات الداكنة اللون BM) و GC(حققت درجات حرارة سطحية أعلى (50–52 °م) مقارنة بالمجمعات الفاتحة اللون (≈45 °م للرخام الأبيض)، وذلك بفضل زيادة امتصاصها للإشعاع الشمسي وانخفاض انعكاسها للحرارة. ونتيجة لذلك، تم تسجيل أعلى معدلات تجفيف ابتدائية باستخدام الكربون الحبيبي والرخام الأسود المطلي (0.12 و0.11 جم/دقيقة على التوالي)، بينما أظهر الرخام الأبيض أبطأ معدل تجفيف (0.035 جم/دقيقة). انخفضت نسبة الرطوبة في شرائح البطاطس بحوالي 90–93% خلال 4–5 ساعات عند استخدام GC وBM، في حين استغرق الرخام الأبيض أكثر من 7 ساعات لتحقيق نتائج مماثلة. وتُظهر النتائج أن لون المجمع ومادته لهما تأثير واضح على الأداء الحراري وحركية التجفيف. ومع ذلك، خلال المراحل المتأخرة من عملية التجفيف، كان انتشار الرطوبة الداخلي عاملاً محدداً لمعدل التجفيف، مما يشير إلى أن استخدام الحمل القسري للهواء يمكن أن يعزز الأداء بشكل أكبر. توفر هذه الدراسة أساساً لتطوير مجففات شمسية صغيرة منخفضة التكلفة، مناسبة لمعالجة الأغذية في المناطق الريفية ضمن البيئات الجافة مثل سلطنة عُمان.

الكلمات الدالة: المجفف الشمسي، الحمل الحراري الطبيعي، المجمعات الحرارية، تقليل الرطوبة، حركية التجفيف، التجفيف المستدام.

1. INTRODUCTION

Interest in solar drying as a sustainable and energy-efficient option is growing due to the need for effective food preservation in developing areas that experience significant post-harvest losses . For farmers and local food industries, small-scale solar food dryers offer a viable solution to traditional drying practices that rely on fossil fuels and are subject to weather fluctuations [1]. Traditional open sun drying is often ineffective because it exposes products to weather fluctuations and contamination, resulting in nutrient loss and reduced product quality [1,2]. Research has demonstrated that compared to open sun drying, solar dryers provide superior moisture removal efficiency and better-quality products. For example, a study on solar tunnel dryers for tomato samples demonstrated effective moisture reductions from approximately 94.42% (reduced from an initial moisture content to about 4.0%) within 31 hours, compared to longer drying times associated with open sun drying methods [3,4]. The research highlighted that solar dryers exhibited superior moisture removal efficiency, achieving significant reductions in drying time while maintaining product quality. This efficiency is attributed to uniform heat distribution and effective air circulation within the solar dryer [5]. The Short Cycle Solar Drying process has the advantages of reducing the drying time and, more importantly, enhancing the safety and quality of the dried products by protecting them from micro-organism spoilage and nutrient preservation. The design of the solar dryer is most important to its performance [1]. The use of dark-colored surfaces, such as black-painted metal, enhances thermal efficiency by absorbing more solar radiation [6]. Additionally, incorporating an air inlet at the bottom and an outlet at the top can promote natural convection, improve air circulation and increase overall drying efficiency [7].

Several studies have explored the use of greenhouse structures as solar dryers for agricultural crops in regions with warm and sunny climates. Greenhouse solar dryers have been shown to significantly reduce drying time compared with traditional open sun drying. For example, when used for drying grapes, the greenhouse dryer achieved complete drying in about 36 h, compared with 54 h required by open sun drying [8]. Quality assessments indicated that solar drying better preserved nutrients, with only a slight reduction in vitamin C content, and produced raisins with improved color and rehydration properties [9]. These findings suggest that greenhouse-based solar dryers are an effective and energy-efficient option for crop drying under climatic conditions like those found in Oman.

This study investigates the performance of five identical small-scale solar food dryers operating under natural convection, each equipped with a different thermal collector material—white marble, black-painted marble, gray rock, granular carbon, and a control unit with a plain black absorber floor. The objective is to evaluate how collector type, surface color, and material properties influence heat absorption, air temperature, and overall drying efficiency when drying potato slices under Omani climatic conditions. By comparing the thermal and moisture removal performance of these configurations, the study aims to identify the most effective collector design for improving solar dryer efficiency and supporting sustainable agricultural and food preservation practices in arid regions.

2. MATERIALS AND METHODS

2.1 Expérimental Setup

To evaluate the performance of small-scale solar food dryers under Omani climatic conditions, five identical solar dryers were designed and constructed, differing only in the type of thermal collector used. Four dryers were equipped with different collector materials, while the fifth served as a control unit with only a flat metal floor and no thermal collector. The experiment aimed to assess how collector type affects heat retention, and overall drying efficiency. Each solar dryer was rectangular in shape, constructed on a mild steel frame with base dimensions of 9 cm × 7 cm, as shown in Figure 1. The drying chamber is made from black-painted interior surface to enhance solar absorption. Inside each dryer, a wire mesh tray was fixed 3 cm above the base, creating a plenum space beneath uniform air distribution. A small open (1.0 cm × 4.0 cm) was installed on the front side for air inlet. The top of each dryer was covered with a transparent polycarbonate sheet (2 mm thick) having high solar transmittance and UV resistance to ensure durability under outdoor conditions. Each dryer included an air inlet at the bottom front side, a small open (1.0 cm × 4.0 cm), and a circular air outlet (radius = 1.0 cm) at the top rear side to promote natural convection airflow.

2.2 Thermal Collectors

Four dryers were fitted with different solar collector configurations to investigate their thermal performance:

Collector 1: White marble chips (WM)
Collector 2: Black-painted marble chips (BM)
Collector 3: Light black grain rock (GR)
Collector 4: Dark black granular carbon (GC)
Collector 5 (Control): No collector, black absorber floor (BAF)

Each collector covered the same base area as the dryer (5.0 cm × 8.0 cm). The collectors were installed beneath the drying chamber floor to preheat the incoming air before it reached the drying tray.

2.3 Experimental Conditions

All dryers were installed outdoors at the International College of Engineering and Management (ICEM), Muscat, Oman (Latitude 23.57° N, Longitude 58.28° E), positioned in the East–West orientation to maximize solar exposure throughout the day. Experiments were conducted during clear-sky conditions typical of the region's arid climate. Slices of fresh potato (2–3 mm thick) were used as the test material. Each dryer was loaded with equal mass and slice thickness to ensure uniform comparison. Key parameters—such as air and surface temperature, relative humidity, and moisture content of the samples—were recorded at regular intervals until the samples reached the desired moisture level. Comparative analysis among the five configurations was used to identify the most effective collector material for enhancing natural convection and heat retention in small-scale solar food dryers suitable for Omani conditions.

3. RESULTS AND DISCUSSION

To evaluate the thermal performance of the selected solar dryers without load, all dryers were operated under a constant airflow rate, with an average air velocity of approximately 65 km/h. During the experimental period, the ambient air temperature ranged from 34 to 38 °C, while solar radiation varied between 890 to 935 W/m^2, indicating stable weather conditions with minimal fluctuations throughout the testing day. This consistency ensured that variations in the recorded thermal performance among the dryers were primarily attributed to the design of the solar collectors rather than external climatic factors.

Figure 2 illustrates the variation of surface temperature with drying time for solar dryers equipped with different collector materials White Marble (WM), Black-painted Marble (BM), Gray Rock (GR), Granular Carbon (GC), and the control Black Absorber Floor (BAF). At the beginning of the drying process, all collector surfaces exhibited similar temperatures (around 27–30 °C), which rapidly increased during the initial 20 minutes due to the direct absorption of solar radiation. Among the tested materials, Granular Carbon (GC) and Black-painted Marble (BM) achieved the highest surface temperatures, stabilizing at 50–52 °C due to their high absorptivity and low reflectivity, which enhance solar heat retention. Gray Rock (GR) performed moderately well, reaching about 48–50 °C. In contrast, White Marble (WM) had the lowest temperature rise, stabilizing around 45 °C, attributed to its high reflectivity and low solar absorption. The control dryer (BAF), lacking a collector layer, maintained intermediate temperatures of approximately 46–47 °C, indicating that while a dark absorber base can enhance heating, it is less effective than engineered collector materials like GC or BM. The temperature stabilization observed after 40–60 minutes indicates a balance between heat gain from solar radiation and heat loss. This behavior is typical in passive solar dryers once thermal equilibrium is established. The results show that collector material significantly affects surface temperature and drying performance, with thermal efficiency ranked as follows: GC > BM > GR > BAF > WM

Figures 3 and 4 illustrate the drying behavior of the potato slices for the five collectors. Figure 3 shows the decrease in sample weight over time indicates moisture removal during drying. Systems with darker collectors (BM, GC) show faster weight reduction compared to lighter collectors (WM) and the control (BAF). Figure 4 shows the drying rate decreases with time for all configurations, with BM and GC collectors exhibiting the highest initial drying rates due to better thermal absorption and heat transfer efficiency. This behavior was consistent with the surface temperature observations in Figure 2. The surface temperature for the dryers with granular carbon (GC) and black-painted marble (BM) collectors exceeded 50–52 °C, reaching the granulated carbon drying temperature GC and BM temperature. Thus, these systems reached the quickest drying rate and the lowest moisture content within the same period drying period. Dryer with white marble (WM) maintained the lowest temperature (≈44–45 °C), characterized by high reflectivity and poor solar absorption. Slower moisture removal and longer effective drying periods resulted from these WM conditions. The other dryers, gray rock (GR) and black absorber floor (BAF), exhibited intermediate performance as expected. Their absorptivity and surface temperature were also intermediate.

The initial drying rates of the GC and BM collectors were 0.12 g/min and 0.11 g/min, respectively, while the WM collector had the lowest initial rate of 0.035 g/min. Within the first 60 to 80 minutes, during the initial drying stage, the drying rates were at their peaks, as there was excess surface moisture which made drying and evaporation more efficient. Subsequent decreases in the rate of drying were due to the diffusion of moisture retained in the material, such that internal diffusion became the predominant control mechanism.

Figure 4 shows the drying rate decreases with time for all configurations, with BM and GC collectors exhibiting the highest initial drying rates due to better thermal absorption and heat transfer efficiency.

It can also be observed that, although the selection of appropriate solar collector materials enhanced the heat absorption and surface temperature within the dryers, the drying process remained partially limited by internal moisture diffusion. At the initial stage of drying, the free water within the potato slices was rapidly removed due to the relatively high temperature and air velocity, showing a similar trend to that observed under ambient air drying. However, as drying progressed, the removal of bound water within the cellular structure required higher energy and stronger convective air movement. This indicates that forced convection plays a crucial role during the later stages of drying, as it enhances heat and mass transfer between the product surface and the surrounding air. Despite the improved thermal performance of the solar collectors, some moisture remained trapped within the slices due to diffusion-controlled mechanisms, highlighting the need for optimized airflow or hybrid systems to achieve uniform drying and prevent quality deterioration.

Future development will focus on integrating forced air convection using solar-powered fans to enhance heat and mass transfer within the drying chamber as shown in Figure 5. By coupling photovoltaic panels with low-power DC fans, the air circulation can be intensified without external electricity input, ensuring a completely sustainable system. This hybrid approach is expected to overcome the internal diffusion limitations observed in the current study, reduce drying time, and improve product quality consistency. The system can serve as a model for rural communities seeking efficient and renewable-based food drying technologies suited to the Omani climate.

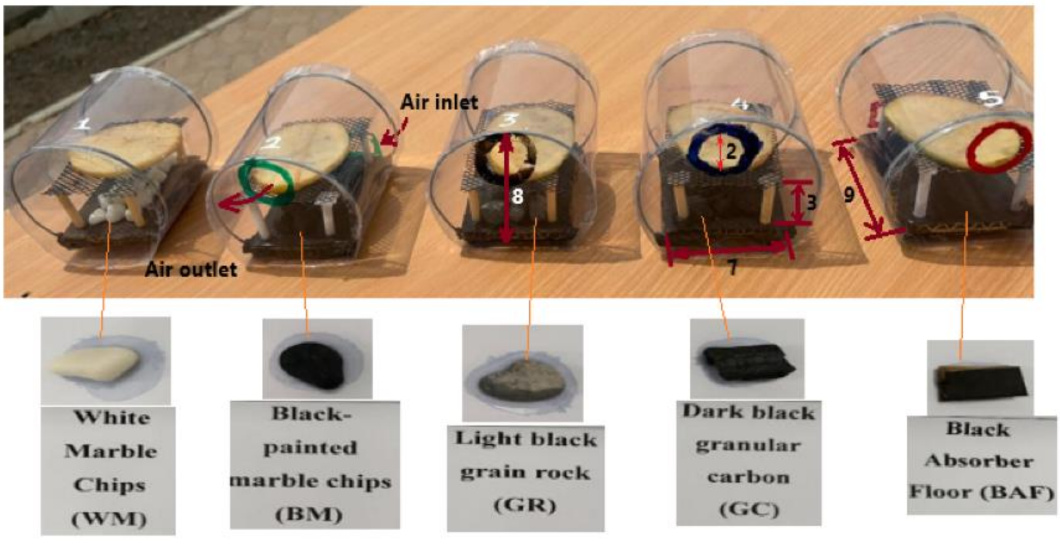

Fig 1. Overall view of the constructed solar food dryers (top), illustrating the dimensions in centimetres, and the corresponding solar collectors employed in each design (bottom).

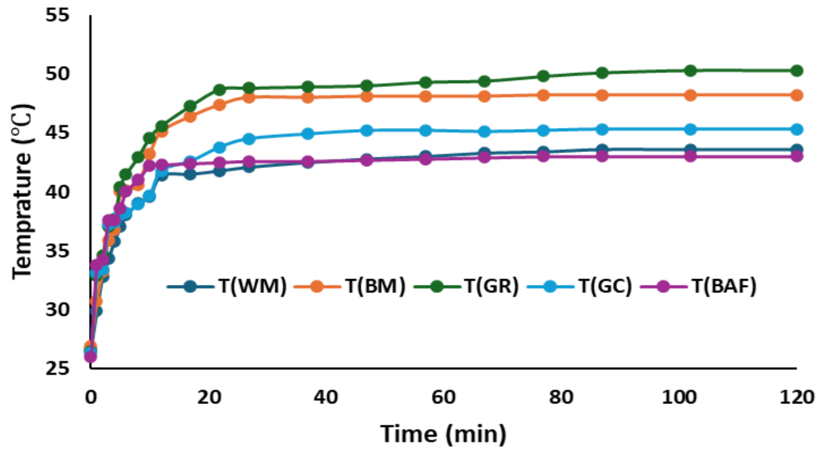

Fig 2. Variation of surface temperature with time of different materials.

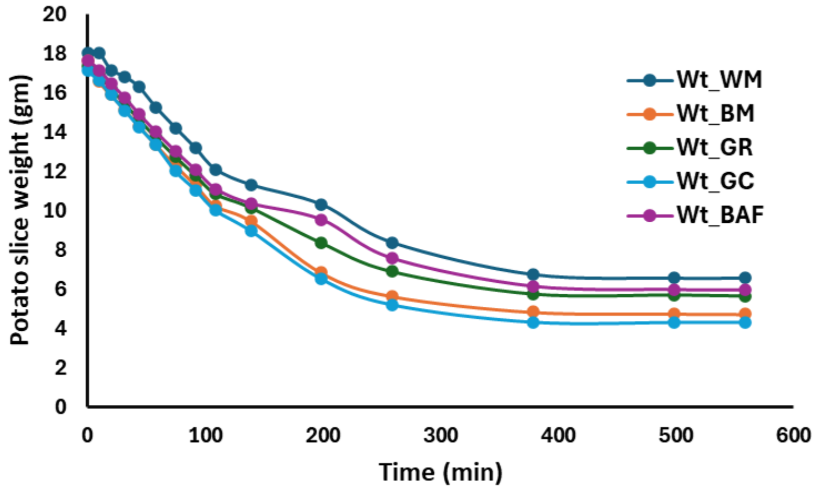

Fig 3. Variation of potato slice weight with drying time for different solar collectors.

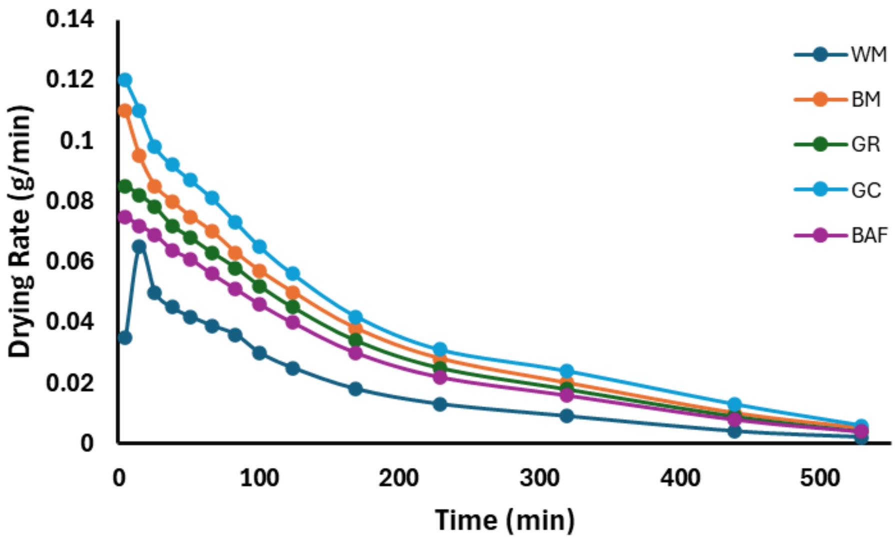

Fig 4. Drying rate of potato slices versus time under different solar collectors.

Fig 5. The hybrid solar dryers design for improved heat and mass transfer.

4. CONCLUSIONS

The study demonstrated that the efficiency of small-scale solar food dryers is highly dependent on the type and color of the thermal collector material. Among the tested designs, the granular carbon (GC) and black-painted marble (BM) collectors exhibited the best thermal and drying performance, achieving the highest surface temperatures (up to 52 °C) and the fastest moisture reduction rates. These results highlight the importance of collector absorptivity and surface characteristics in enhancing solar heat retention and promoting effective natural convection. Nevertheless, as drying progressed, moisture removal became increasingly controlled by internal diffusion, indicating that the later stages of drying were energy-limited. This suggests that, although passive natural convection is effective for initial drying, the integration of a forced convection system—powered by solar energy—would be beneficial to overcome diffusion resistance and ensure more uniform drying. Overall, the experiment confirms the potential of simple, low-cost solar dryers using locally available materials to improve food preservation and support sustainable agricultural practices in hot, arid regions.

ACKNOWLEDGMENT

The authors gratefully acknowledge the support of the Ministry of Higher education and research innovation (MOHERI), Sultanate of Oman, under the block funding research grant No. MOHERI/BFP/ICEM/2023-24/01

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