International Journal of Geography, Geology and Environment

P-ISSN: 2706-7483
E-ISSN: 2706-7491
NAAS Rating (2025): 4.5
IJGGE 2025; 7(7): 29-31
www.geojournal.net
Received: 06-05-2025
Accepted: 08-06-2025

V Sai Krishna
Assistant Professor, Department of Agricultural Engineering, Aditya University, Surampalem, Kakinada, Andhra Pradesh, India

J Laharika Surya Sai
Research Scholar, Department of Agricultural Engineering, Aditya University, Surampalem, Kakinada, Andhra Pradesh, India

D Daakshayani
Research Scholar, Department of Agricultural Engineering, Aditya University, Surampalem, Kakinada, Andhra Pradesh, India

G Durga Phanisri
Research Scholar, Department of Agricultural Engineering, Aditya University, Surampalem, Kakinada, Andhra Pradesh, India

R Uma Bharathi
Research Scholar, Department of Agricultural Engineering, Aditya University, Surampalem, Kakinada, Andhra Pradesh, India

Corresponding Author:
V Sai Krishna
Assistant Professor, Department of Agricultural Engineering, Aditya University, Surampalem, Kakinada, Andhra Pradesh, India

A comprehensive review on indirect drying using evacuated tubes

V Sai Krishna, J Laharika Surya Sai, D Daakshayani, G Durga Phanisri and R Uma Bharathi

Abstract
This review provides an overview of Evacuated Tube Solar Dryers (ETSDs), focusing on their components, working principles, and performance characteristics. The discussion highlights the role of evacuated glass tubes in improving efficiency, the functioning of solar dryers, their application in indirect food drying, and the parameters influencing their thermal efficiency. The ETSDs represent a significant advancement in the field of solar thermal energy technologies. They harness solar radiation efficiently and convert it into useful heat energy with minimal losses. The integration of evacuated glass tubes into solar dryers enhances their thermal performance, making them suitable for high-temperature applications such as food drying, space heating, and industrial processes This review concludes with insights on their potential and limitations as a sustainable energy solution.

Keywords: Solar, evacuated tubes, conduction, radiation, drying, energy

1. Introduction
Solar energy is a clean, renewable, and abundant resource that can meet a significant portion of global energy demands (Lof *et al*., 1966) [11]. Solar dryers (SAHs) are a simple yet effective technology for converting solar radiation into thermal energy, which can then be used for drying, heating, and ventilation applications (Ahmad *et al*., 2002; Wang *et al*., 2015) [3, 17]. Traditional SAHs, such as flat-plate collectors, are easy to construct and cost-effective but often suffer from high heat losses, particularly in cold or windy environments (Abene *et al*., 2003) [2].

To overcome these limitations, evacuated tube solar dryers have been developed. By incorporating evacuated glass tubes, which provide excellent insulation, ETSDs achieve higher thermal efficiencies compared to conventional systems (Wang *et al*., 2015) [17]. They can operate effectively even under adverse weather conditions, such as low ambient temperatures or diffuse sunlight (Rajagopal *et al*., 2014) [14].

The growing interest in ETSDs is driven by their suitability for various sectors, including agriculture, food processing, and industrial drying, where quality and efficiency are paramount (Manaa *et al*., 2013; Pastrana, 2014) [12, 13]. Their ability to deliver higher-grade thermal energy without relying on fossil fuels supports global sustainability and carbon-reduction goals (Yahya, 2016) [18].

2. Evacuated glass tubes
The evacuated glass tube is the heart of an ETSD system. Typically, each tube consists of two concentric glass cylinders. The inner cylinder is coated with a selective material that maximizes solar energy absorption while minimizing emissivity (Wang *et al*., 2015) [17]. The space between the inner and outer cylinders is evacuated, creating a vacuum that acts as an excellent thermal insulator by eliminating heat losses due to convection and conduction (Rajagopal *et al*., 2014) [14].

This design enables the tubes to maintain high surface temperatures, even in low ambient conditions, and to retain heat over extended periods (Benhamou *et al*., 2014) [4]. The cylindrical shape also provides an advantage over flat surfaces because it captures sunlight effectively throughout the day as the sun's position changes, ensuring a longer effective heating period (Wang *et al*., 2015) [17].

Moreover, the sealed construction of evacuated tubes protects the absorber surface from environmental degradation, such as corrosion or dust accumulation (Rajagopal *et al*., 2014) [14]. Although they are relatively fragile and can be more expensive than other collectors, their

durability in terms of thermal performance and their ability to maintain efficiency over time make them an attractive choice for solar air heating systems (Abene *et al*., 2003) [2].

3. Forced convection

In a solar dryer, the objective is to transfer the heat collected from the sun into an airflow that can then be directed to the intended application (Ahmad *et al*., 2002) [3]. In ETSDs, the absorber surface within the evacuated tubes heats up and transfers this heat to the air that passes through a manifold or duct attached to the tubes (Wang *et al*., 2015) [17]. The air picks up heat as it flows over or around the heated surfaces and exits the system at a higher temperature.

Unlike flat-plate solar dryers, ETSDs can achieve significantly higher outlet air temperatures because of the minimized heat losses and improved insulation (Rajagopal *et al*., 2014) [14]. This makes them suitable for processes where higher thermal energy is desirable. The airflow rate, duct design, and contact time with the heated surface are crucial factors that influence the performance of these heaters (Benhamou *et al*., 2014) [4].

Another advantage of ETSDs in solar air heating applications is their resilience in varying climatic conditions. Even on cloudy days or during winter, the system can produce useful heat, which expands their usability beyond just summer or sunny environments (Lof *et al*., 1966) [11]. This capability makes them a preferred choice in regions with moderate to cold climates (Manaa *et al*., 2013) [12].

4. Indirect food drying

Indirect solar food drying involves heating air with solar energy and then circulating this hot air through a drying chamber where food is placed (Ahmad *et al*., 2002) [3]. The food does not come into direct contact with sunlight, which helps preserve its nutritional value, color, and texture (Hebbar *et al*., 2004) [8]. ETSDs are particularly well-suited for this application because they can generate hot air at a consistent and controlled temperature (Rajagopal *et al*., 2014) [14].

The use of ETSDs in food drying ensures faster and more uniform drying compared to traditional open-sun or direct solar drying methods (Guarte *et al*., 1996) [7]. The absence of direct sunlight prevents surface hardening and discoloration, while the controlled airflow maintains hygienic conditions, reducing contamination by dust or insects (Elumalai, 2023) [6]. These benefits lead to higher-quality dried products with longer shelf life (Pastrana, 2014) [13].

Additionally, the higher temperatures achievable with ETSDs allow for the drying of products that require elevated temperatures, such as certain fruits, vegetables, and spices (Cardenas, 1968) [5]. This not only improves productivity but also reduces post-harvest losses, which are a major concern in many agricultural regions (Vijaykumar *et al*., 2012; Yahya, 2016) [16, 18]. The sustainable nature of solar energy further enhances the economic and environmental appeal of this technology in food processing (Manaa *et al*., 2013) [12].

5. Performance and efficiencies

The performance of an ETSD is often evaluated in terms of thermal efficiency, temperature rise, and energy output (Wang *et al*., 2015) [17]. One of the main strengths of ETSDs is their ability to maintain high efficiency even in less-than-ideal weather conditions. The vacuum insulation plays a critical role in reducing thermal losses, thereby ensuring that more of the absorbed solar energy is transferred to the air (Benhamou *et al*., 2014) [4].

Factors such as the solar irradiance, tilt angle of the tubes, airflow rate, and ambient temperature all affect the efficiency of the system (Rajagopal *et al*., 2014) [14]. Properly optimizing these parameters can lead to significant improvements in performance. For example, lower airflow rates tend to increase the temperature rise but may reduce the overall heat transfer due to limited mass flow, while higher airflow rates can deliver more heat at slightly lower temperatures (Abene *et al*., 2003) [2]. Utilization of Phase Change Material (PCM) as a Thermal Storage System has shown significant in enhancing the stability and performance of the system (Krishna *et al*, 2021; Krishna *et al*., 2024) [15, 9].

Another measure of performance is the system's ability to deliver consistent heat throughout the day. Thanks to the cylindrical shape of the tubes, which allows them to collect solar energy effectively over a wide range of sun angles, ETSDs can provide more uniform heating during daylight hours (Wang *et al*., 2015) [17]. This stability and reliability make them an attractive option for industrial and agricultural applications where predictable thermal output is essential (Manaa *et al*., 2013; Yahya, 2016) [12, 18].

6. Conclusion

Evacuated tube solar dryers are an innovative and efficient solution for harnessing solar energy, offering several advantages over traditional flat-plate systems (Rajagopal *et al*., 2014) [14]. Their superior insulation, high temperature capability, and consistent performance make them suitable for diverse applications, including indirect food drying, space heating, and industrial processes (Rajagopal *et al*., 2014; Hebbar *et al*., 2004) [14, 8]. While the initial costs and fragility of the glass components may pose challenges, the long-term benefits in terms of energy savings, product quality, and environmental impact outweigh these drawbacks (Abene *et al*., 2003) [2]. Their ability to operate effectively even in colder climates or under diffuse sunlight broadens their applicability and supports their role in promoting renewable energy utilization (Manaa *et al*., 2013) [12].

In summary, ETSDs represent a promising technology for sustainable thermal energy production, aligning well with the goals of reducing fossil fuel dependency and minimizing environmental impact (Yahya, 2016) [18]. With ongoing research and development, their efficiency, affordability, and durability are expected to improve further, making them an even more attractive choice for future energy needs.

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