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THE STUDY OF TURMERIC DRYING AT DIFFERENT THICKNESSES OF MODULAR THERMAL ENERGY STORAGE

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Abstract:

This research aims to study the ability of silica sand with an average diameter of 10 mm for different thicknesses of thermal energy storage to store the heat energy during the turmeric drying process. Drying is a method that uses thermal energy to remove moisture from a material. Direct sunlight or specialised electrical equipment can facilitate drying. The process for drying materials is influenced by several aspects, including the product's surface characteristics, drying temperature, airflow, steam pressure, energy supply, and the specific type of material involved. Drying rates accelerate with increased temperatures and reduced relative humidity. Regulating these parameters requires diligent supervision via the installation of numerous sensors at different positions within the dryer. Conversely, thermal energy storage applications have comparatively underutilised solid-state thermal energy storage (TES) materials like sand. Consequently, the use of silica sand is essential for thermal energy storage, mitigating the constraints of solar dryers that function exclusively during daylight hours. The highest thickness of sand has a higher drying rate compared to the lowest thickness of sand, and there is no thermal energy storage condition for turmeric drying. Additionally, the previously mentioned

amount of sand retains more heat storage compared to the lowest thickness. Therefore, it can be concluded that as the thickness of silica sand increases, the temperature of thermal energy storage also increases, which accelerates the drying process.

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Keyword:

Drying, Experimentation, Solar Dryer, Thermal Energy Storage



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Introduction

Drying is one of the most ancient techniques for preserving agricultural products like fruit, vegetables, and cotton by removing enough moisture to prevent decay and spoilage. This technique may inhibit cellular processes, including both enzymatic and non-enzymatic browning, while ensuring the optimal preservation of macronutrients (proteins, carbohydrates, and fibres), small-molecule nutrients (antioxidants and elements), and natural substances (chemical mixtures, antioxidants, and derived antioxidants) (Menon et al., 2020). Moreover, dehydration diminishes shipping and storage expenses while extending product shelf life. Despite the potential benefits of reducing product moisture content, we must address challenges like high energy requirements and extended drying times.

The swift advancement of industry has resulted in a persistent increase in worldwide energy requirements across various forms. Fossil fuels remain the primary source for fulfilling most global energy needs (Sawin, 2017), particularly for the thermal energy essential in drying processes. However, the environmental consequences associated with the use of these fuels and the progressive exhaustion of their supplies place significant constraints on their utilisation. Given the heightened awareness of environmental concerns and advancements in sustainable energy policies, renewable energy sources are crucial for attaining a more eco-friendly and safe energy future (Achkari & El Fadar, 2020). Solar dryers are an excellent example of technology that aligns with several Sustainable Development Goals (SDGs), which include goal 1, which is no poverty, solar dryers can help alleviate poverty by enabling smallholder farmers to increase the value of their crops. By preserving produce with solar dryers, farmers can avoid post-harvest losses and fetch better prices for their goods. Goal 2 is zero hunger, where solar dryers contribute to food security by extending the shelf life of perishable foods. This helps ensure a more stable food supply, especially in regions prone to food shortages or with limited access to conventional preservation methods. Goal 3 is beneficial health and well-being, where solar drying reduces the need for chemical preservatives and pesticides, leading to healthier

food products. Additionally, by reducing food waste, solar dryers can help combat malnutrition and related health issues.

Solar energy stands out as the most potent among renewable sources, characterised by its free, inexhaustible nature, widespread accessibility, and versatility, which has led to increased interest. Improving drying methods is crucial for economic and environmental reasons. Many countries continue to maintain a primarily non-renewable energy framework, making the investigation of solar energy-based drying technologies increasingly pertinent in contemporary discourse. It was emphasised that conventional dryers and kilns, reliant on fossil fuels, remain prevalent, despite their impending adverse environmental impacts (Bekkioui et al., 2020). The benefits of solar dryers exceed those of conventional kilns and dryers, extending well beyond their environmental effects. Solar dryers can potentially decrease drying expenses by as much as 80% (Jain et al., 2023). They enhance the quality of the final product, eradicate greenhouse gas emissions, and are simple to construct and operate (Jain et al., 2023). Considering the acknowledged economic and environmental benefits of solar dryers, it is imperative to undertake research aimed at enhancing the collection, conversion, and use of available solar energy. Improving solar energy dryers facilitates expedited drying and augments the capability for processing greater quantities of items while conserving the same energy consumption (Barbosa et al., 2023).

A significant challenge linked to solar energy is its immediate fluctuation. Solar energy's dependence on weather conditions implies that it is only applicable on sunny days unless integrated with conventional energy-based technology. Therefore, the effectiveness of solar energy systems depends on various factors in addition to the energy harvesting device itself. The linkage between the storage of gathered energy for extended durations and its conversion into the requisite usable energy form is intricate. Recent major publications on renewable energies emphasise that the enhancement of concentrated collectors should focus on augmenting their capacity to meet thermal demand over days, weeks, or seasons (Mehos et al., 2017; Power, 2010; U.S. Department of Energy, 2012). Consequently, thermal energy storage (TES) technologies are essential for the future advancement of solar technology. In this context, the development of solar thermal systems linked with thermal energy storage can achieve sustainable, efficient, and cost-effective applications.

Currently, research aims to optimise solar drying systems to provide high-quality final goods while minimising time and energy expenditures. A study was performed to assess the impact of various factors on the efficacy of a solar oven for wood drying (Khouya, 2020). The research assessed the impact of a heat exchanger and a latent heat storage system on the thermal efficiency of the solar oven. The study's results were encouraging. The researchers determined that employing an air heater to reclaim energy dissipated into the atmosphere (the heater utilises heat from the humid air to prepare the air entering the thermal storage) might decrease the drying time by as much as 62.4%. The deployment of the heat storage technology decreases drying time by as much as 40%. The amalgamation of these technologies led to a decrease in energy use by as much as 54%. A previous investigation documented similar findings (Khouya & Draoui, 2019). The authors noted that heat recovery and thermal storage systems could decrease drying time by as much as 47% and 26.5%, respectively. The authors achieved a peak drying efficiency of 85% with these systems.

Extensive research has been conducted over the years to gather data on developments in solar drying and heat storage systems, reflecting the subject's significance. Researchers conducted a

thorough assessment of solar dryers combined with thermal energy storage systems for the dehydration of agricultural products (Bal et al., 2010). The authors analysed various storage modes and their applications for solar drying technologies. Figure 1 presents different types of solar thermal energy storage (Baylin, 1979). The authors examined similar objectives and provided a concise analysis of how computational methods can enhance solar drying systems (Kant et al., 2016). Other researchers have conducted recent assessments of indirect solar dryers for agricultural products, as illustrated in Figure 2 (Lingayat et al., 2020).

The authors utilised a methodology that encompassed various dryer configurations and the incorporation of thermal energy storage materials into these systems. The existing literature indicates that, although there are investigations into solar dryers and thermal energy storage, there is a notable gap in comprehensive studies regarding their integrated application, performance, and numerical modelling. This renewable energy application can be adopted by both small and large-scale enterprises, as well as agricultural producers, indicating significant potential for interest in this area. This investigation outlines the drying process, classifies different types of dryers and their efficiencies, explores thermal energy storage systems, and analyses the numerical modelling associated with these processes. This investigation focuses on a relatively neglected aspect of drying studies: the role of turbulence within porous materials.

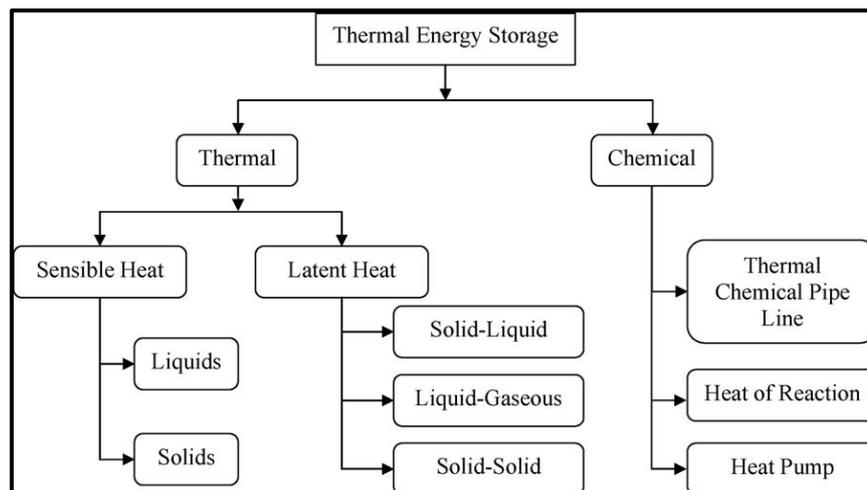


Figure 1: Different Types of Thermal Energy Storage

(Baylin, 1979).

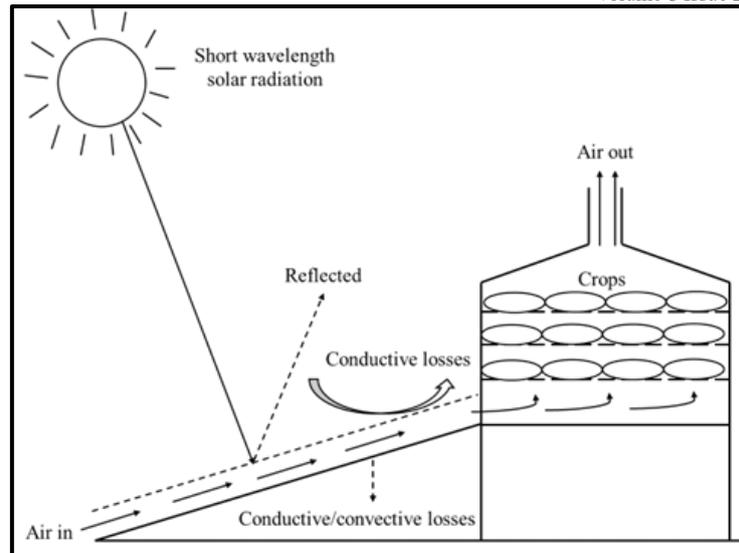


Figure 2: A Schematic Representation of The Indirect Solar Dryer

(Lingayat Et Al., 2020).

The development and evolution of solar dryers from 2010 to 2025 have been marked by significant advancements in technology, efficiency, and application, driven by the growing need for sustainable energy solutions and improved food preservation methods. Table 1 represents an overview of the key revolutions and milestones in solar dryer technology over this period.

From 2010 until 2020, the development of solar dryers focused on sustainable design and integration with Internet of Things (IoT) systems. In the 2010s, smart technology began to be integrated into solar dryers, especially with the advent of the Internet of Things (IoT) (Deokar, 2022). This made it possible to remotely monitor and control solar dryers using smartphones or computers. Automation became more prevalent, with systems adjusting airflow, temperature, and moisture content based on real-time data collected from sensors. Data-driven designs lead to more personalised solutions, allowing farmers and industries to optimise the drying process based on specific environmental conditions. The integration of energy storage systems, such as solar batteries or thermal storage materials (like molten salts), allowed solar dryers to operate 24 hours, making them suitable for industrial-scale applications. Additionally, there was a significant push toward more eco-friendly materials and hybrid systems that combined solar drying with other renewable energy sources (wind, biomass) for greater energy reliability. Solar-powered refrigeration and solar-powered dryers were developed to address both the drying and storage needs of agricultural products.

Lastly, the future with smart, modular, and highly efficient solar dryers begins from 2020 until 2025 (Gunawan et al., 2022). Recently, there has been a focus on modular solar dryers that can be scaled up or down depending on the needs of farmers or industrial users. A wider audience, particularly in developing countries, can access these systems due to their affordability and ease of installation and maintenance. Prefabricated modular solar dryers have emerged as cost-effective solutions for smallholder farmers and rural entrepreneurs. Artificial intelligence (AI) and machine learning algorithms are integrated into solar dryers to optimise drying processes, predict weather conditions, and improve energy usage. For example, AI can adjust parameters in real-time to maintain ideal drying conditions based on changing weather patterns. Moreover,

the advanced phase-change materials (PCMs) and nano-structured materials are being explored for improving the thermal storage and heat retention capabilities of solar dryers, enabling them to be more energy-efficient and weather-resistant. New heat transfer fluids and solar collector designs are being tested for greater energy capture and faster drying times. The latest solar dryers are designed with a focus on reducing carbon emissions, enhancing the efficiency of agricultural value chains, and improving the economic prospects of rural communities. These dryers are aligned with global sustainability goals, like the United Nations' Sustainable Development Goals (SDG), particularly SDGs 7, 2, and 13, which are affordable and clean energy, zero hunger, and climate action, respectively.

Table 1: Key Milestones in Solar Dryer Evolution (2010-2025).

Year	Milestone
2010 - 2020	IoT and AI-enabled smart solar dryers integrate thermal storage for continuous drying.
2020 - 2025	Modular, scalable, AI-driven, highly efficient solar dryers with eco-friendly designs and advanced storage.

Advancements in materials, energy efficiency, automation, and smart technologies have driven the solar dryer revolution from 2010 to 2025. Over the years, solar dryers have evolved from simple, passive systems into highly efficient, AI-enabled, scalable technologies that offer solutions to climate change, food security, and economic development, particularly in rural and agricultural communities. The future promises even greater advancements, including autonomous operations, innovative materials, and enhanced energy storage to make solar drying an even more powerful tool for sustainable agriculture.

The process of drying involves the movement of heat and mass between the products and the surrounding air. Therefore, favourable environmental conditions, particularly the temperature and relative humidity of the air, significantly influence the effectiveness of solar drying. The drying rate increases with higher temperatures and lower relative humidity. To ensure optimal regulation of temperature and humidity, it is essential to implement thorough monitoring by strategically placing various sensors in multiple locations within the dryer. However, solar dryers are significant only during daylight and have limited working hours (Rahman et al., 2025). Therefore, thermal energy storage systems were introduced to extend the capacity of the drying process during nighttime. On the other hand, solid-state TES materials, like sand, have not been extensively investigated for TES applications (Tetteh et al., 2024). Consequently, the use of silica sand is essential for thermal energy storage, tackling the constraints of solar dryers that function exclusively during daylight hours. To the best of the authors' knowledge, there has been insufficient investigation into silica sand as a thermal energy storage medium. This research aims to study the ability of silica sand with an average diameter of 10 mm for different thicknesses of thermal energy storage to store the heat energy during the turmeric drying process.

Methodology

The aluminium sandbox has been constructed with dimensions of 111 cm (length) x 50 cm (width) x 5 cm (height) and was placed above the solar dryer under natural convection as depicted in Figure 3. The size of the sandbox plays a critical role in the performance of solar dryers with thermal energy storage systems. It affects the energy storage capacity, efficiency,

temperature stability, and overall system cost (Shahul et al., 2023). While larger sandbox provides greater storage, they come with increased costs, space requirements, and potential efficiency trade-offs. Therefore, it is important to carefully design the system to optimise its size based on energy needs, cost considerations, and space availability to achieve the best results for the drying process. Aluminium is frequently used due to its effective heat transfer properties and cost-effectiveness compared to alternative materials (Choudhuri, 2024). Silica sand was used in the present study. Silica sand consists of a blend of coarse fragments, typically made up of different minerals and rocks. Common minerals encompass quartz (SiO_2), feldspar, and occasionally calcareous materials such as limestone. Table 2 displays the material characteristics of silica sand (Baghbani et al., 2023; Chen et al., 2021; Gu et al., 2023; Jin et al., 2024; Khalifa & Mzali, 2024; Momeni et al., 2023; Naveen & Bhat, 2024; Ran Wang et al., 2024; Ruifeng Wang et al., 2024; Ziccarelli, 2024).

Table 2: Materials Properties Of Silica Sand (Baghbani Et Al., 2023; Chen Et Al., 2021; Gu Et Al., 2023; Jin Et Al., 2024; Khalifa & Mzali, 2024; Momeni Et Al., 2023; Naveen & Bhat, 2024; Ran Wang Et Al., 2024; Ruifeng Wang Et Al., 2024; Ziccarelli, 2024).

Properties	Silica sand
Density (kg/m ³)	Bulk density = 1800
Young's Modulus (MPa)	47
Poisson's ratio (ν)	0.31
Thermal Conductivity (k)	0.2-0.4
Thermal Expansion (CTE)	$10-20 \times 10^{-6}$
Specific heat (C)	800-830
Melting point	Primary component, quartz = 1650°C
Reference temperature	20-25°C

Thermocouple connector cables are positioned at middle points inside the sandbox and outside the sandbox for ambient temperature data collection to collect accurate heat variation information through the data acquisition device (DAQ). The location of thermocouples inside the sandbox was decided by considering the sand layer thickness (Yamaguchi et al., 2023). The data-collecting system was used to record the temperature readings from the sand. Thermocouples operate as temperature sensors at their junction points. The capacity of K-type thermocouples to function across an extensive temperature spectrum necessitated their use. The DAQ data logger software sets the acquisition frequency at 10 Hz. The frequency calculation utilised in the data acquisition (DAQ) data logger software is outlined as follows, i.e.,

$$f = \frac{1}{T}. \quad (1)$$

In this context, f represents the frequency measured in hertz, while T denotes the duration required to complete a single cycle, expressed in seconds. Consequently, temperature data will be gathered at intervals of 0.1 seconds. The technique will be executed for particle sizes with diameters of an average of 10 mm, as depicted in Figure 3. The experiment will be repeated with different thicknesses of silica sand, ranging from 50 mm to 20 mm, to analyse the

temperature variations of the sand. The thermocouple-type cables linked to the gathering information section will gather and store the sand temperature. The information that results will be presented as well as portrayed on a laptop. The experiment is set to last for 13 hours, corresponding to the approximately 13 hours of everyday daylight in Malaysia (Ray et al., 2024). Upon acquiring the temperature data, the period of heat retention from the sand will be monitored and documented.

This setup was used for turmeric drying to measure the weight losses of the turmeric. Turmeric is a favourable crop choice because it is readily available, and a study would help local farmers. Furthermore, turmeric (*Curcuma longa*) are rhizomatous plants; their derivative products are widely used for food additives and folk medicines (Tian et al., 2025). The fresh turmeric is dried to prepare its derivatives, such as turmeric oil (Shahimoridi et al., 2025). The turmeric was sliced into small diameters with an initial weight of 100 g and placed above the thermal energy storage from 8 am to 12 pm, as shown in Figure 3. Slicing turmeric into small diameters increases the surface area-to-volume ratio, which enhances moisture evaporation by reducing internal resistance to mass transfer. An initial weight of 100 g is a standardised sample size used for controlled comparisons in drying experiments, allowing accurate measurements of weight loss over time to calculate drying rates. The time from 8 a.m. to 12 p.m. corresponds to the initial heating phase of the day, where solar irradiance is gradually increasing. Measurement during this period allows researchers to observe the influence of morning heat buildup on drying behaviour. Placement above thermal energy storage ensures that the turmeric receives consistent and conducted heat from the TES medium (e.g., silica sand), especially during periods with fluctuating solar intensity. TES helps maintain a stable drying temperature. The weight of the turmeric was measured for every 30-minute time interval.

The aforementioned procedure was repeated for the 1pm to 5pm and 5pm to 9pm time intervals to study different durations of the turmeric drying process. Solar radiation and ambient temperature vary significantly between morning, afternoon, and evening. Repeating the procedure during 1 p.m. to 5 p.m. (peak solar hours) and 5 p.m. to 9 p.m. (declining solar input) allows assessment of how these conditions affect drying rate, temperature profile, and energy efficiency. Moreover, segmenting time intervals helps in validating the effect of thermal energy storage media (e.g., silica sand) in releasing stored heat during low-radiation periods like late afternoon and evening.

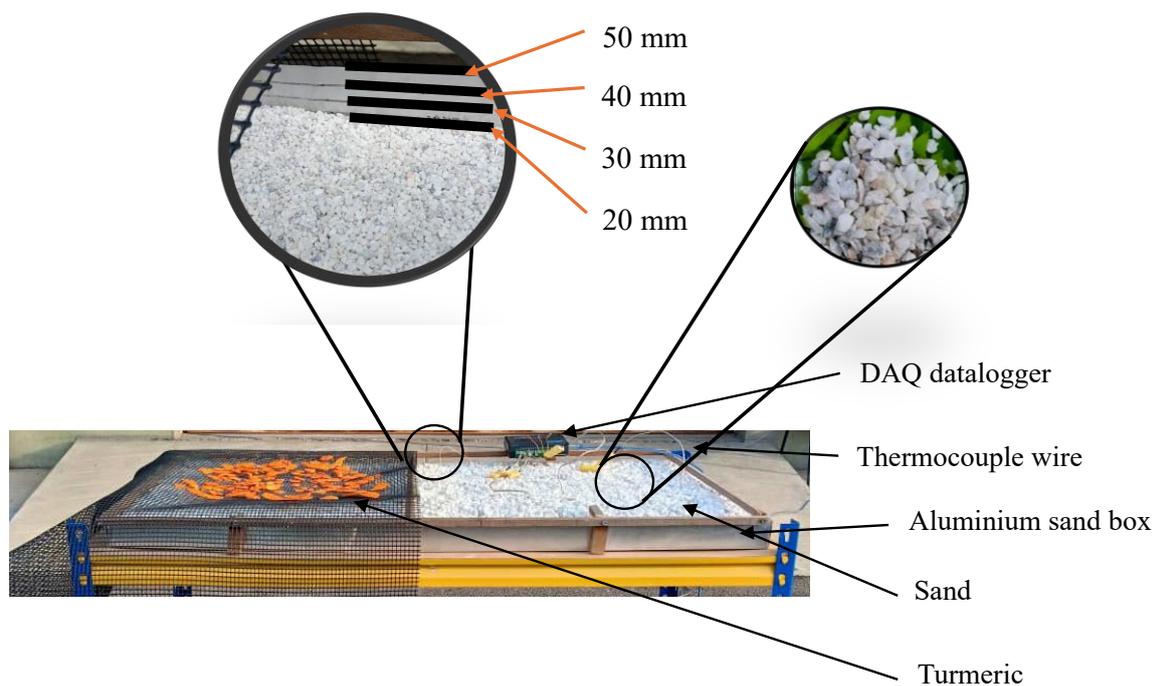


Figure 3: A Depiction Illustrating the Full Image of Turmeric Drying.

Result and Discussion

Figure 4 shows a graph of weight (g) versus drying time (h) for turmeric drying, which utilises different thicknesses of silica sand as thermal energy storage, with an average sand diameter of 10 mm during natural convection drying. The weight of the turmeric decreases linearly with the drying time in hours. This phenomenon is because the moisture content inside the turmeric decreases as the drying time decreases due to the evaporation process. The environment temperature increases with the increase of time, thus increasing the drying rate of the turmeric drying process. During turmeric drying processes, the drying rate is not linear throughout but can be approximated as linear in the constant rate period for practical analysis (Ekka, 2017; Kidane et al., 2025).

The greater the thickness of silica sand, the greater the losses of moisture content inside the turmeric. Thicker silica sand layers enhance thermal storage, improve heat transfer uniformity, reduce heat loss, and maintain higher drying temperatures, all of which contribute to greater moisture loss from turmeric during drying (AD et al., 2025; S Khaldi, S Abboudi, 2017). The turmeric drying time from 8 a.m. to 12 p.m. is slower than from 1 p.m. to 5 p.m. In the early morning (8 a.m. to 12 p.m.), the sand bed absorbs solar radiation gradually, but due to its high specific heat capacity, it takes time to heat up. Therefore, during this period, the heat transferred to turmeric is lower, slowing the drying rate. From 1 p.m. to 5 p.m., the sand has already absorbed significant thermal energy and starts to release it more effectively. Combined with peak solar radiation around 1-2 p.m., the turmeric receives more heat, accelerating moisture evaporation. The drying process slows down from 5 p.m. to 9 p.m. because the silica sand loses heat and there isn't enough heat energy to get the moisture out of the turmeric. The silica sand, acting as thermal energy storage, begins to release its stored heat once solar input stops. However, by evening, most of this energy has dissipated through natural convection and radiation, resulting in a drop in bed and air temperature. As the temperature decreases, the

vapour pressure difference between turmeric and the surrounding air is reduced, slowing the evaporation of moisture.

The 50 mm thickness has a slow drying rate from 8 a.m. until 12 p.m. compared to other drying conditions. A 50-mm-thick sand layer has higher thermal mass, meaning it absorbs more heat before its temperature rises significantly. During the early hours of the day, solar energy is not yet intense enough to heat the entire volume of the thicker layer quickly. The turmeric placed above or within the sand layer relies on conducted heat from the sand. The thicker the sand, the longer it takes for heat to reach the surface where turmeric is located. As a result, less heat is available for moisture evaporation in the early hours. In contrast, thinner layers (20, 30, 40 mm) heat up faster due to lower thermal inertia, resulting in an earlier rise in temperature and quicker onset of drying. However, the drying rate of 50mm becomes faster than others from 1pm to 5pm since the conduction process between silica sand and turmeric drying has occurred rapidly. By the afternoon (1 p.m. to 5 p.m.), the 50 mm silica sand layer has had sufficient time to absorb and store solar heat. Its thermal mass now acts as a steady heat source, maintaining a higher and more uniform temperature, which enhances the drying rate. The temperature gradient between the heated silica sand and the moist turmeric increases. As a result, thermal conduction becomes more efficient, allowing rapid transfer of heat to the turmeric and accelerating moisture evaporation. Compared to thinner layers (20-40 mm), the 50 mm layer can retain heat longer and resist rapid cooling, especially during this peak solar radiation period. This makes the drying process more consistent and intense in the afternoon.

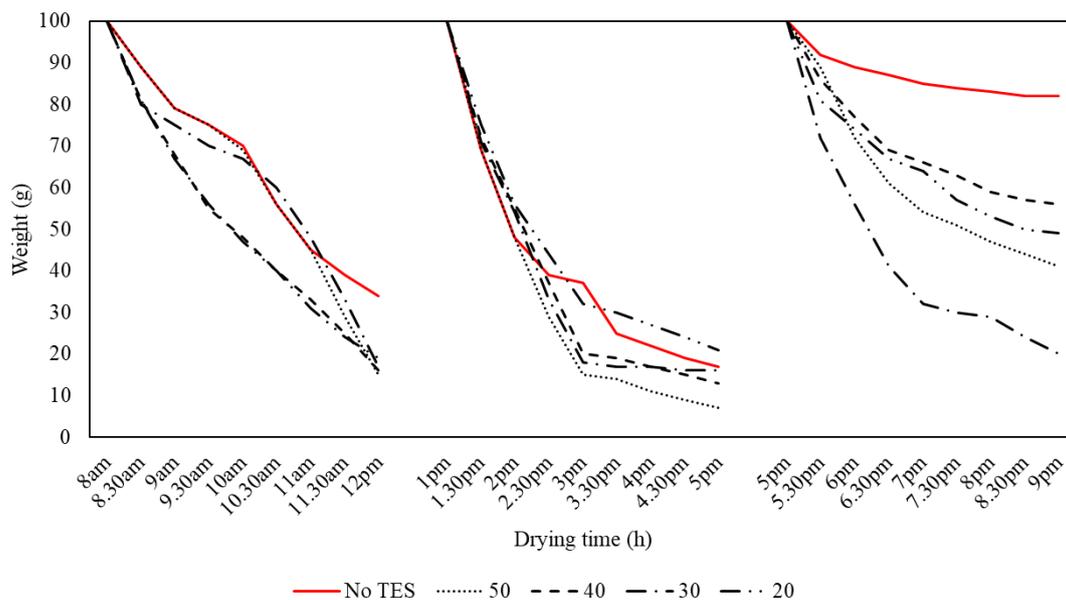


Figure 4: Weight (G) Against Drying Time (H) Graph. The Legend Represents the Thickness of Silica Sand (Mm).

Figure 5 displays the graph of the temperature ratio (temperature sand/temperature ambient) plotted against drying time (h) for the present experiment. The division of both temperatures, namely, the temperature of the silica sand and the ambient temperature, is performed to obtain a dimensionless parameter known as the temperature ratio. This ratio facilitates a standardised comparison across varying experimental conditions by eliminating the influence of absolute temperature values. In the case of the turmeric drying process without thermal energy storage, the temperature ratio remains constant at a value of 1, as the only recorded temperature is the

ambient temperature, which also serves as the drying medium. Since no additional heat is stored or supplied to the system, there is no temperature gradient, resulting in a uniform ratio indicative of a non-enhanced drying condition.

Overall, the temperature ratio is increasing from 8am to 12pm, and the highest temperature is expected to be at 2pm and begin to decrease until 9pm. Solar radiation slowly increases from sunrise (about 7-8 a.m.), which makes the temperature of the air and the surface of thermal materials like silica sand rise. Hence, the temperature ratio also increases. Solar radiation typically reaches its maximum intensity at solar noon, usually between 12 p.m. and 2 p.m., depending on location and season. This results in the highest internal temperatures in the system. After the solar peak, the sun angle decreases, and solar irradiance drops, leading to a decline in temperature from 2 p.m. to evening (~9 p.m.). Materials like silica sand may retain heat beyond peak solar hours, but the rate of heat gain is reduced, so overall temperatures start declining at 2 p.m.

The 50mm thickness received a lower temperature ratio from 8am until 12pm. A 50 mm thick layer of silica sand has higher thermal mass, which means it requires more time and energy to heat up compared to thinner layers. Between 8 a.m. and 12 p.m., solar energy is still gradually increasing and may not yet be sufficient to significantly raise the internal temperature of the thicker layer. The heat takes longer to reach deeper levels in thicker sand beds because the material acts as an insulator. This results in lower average temperatures across the depth of the sand during early hours. The temperature ratio (i.e., temperature of sand vs. ambient temperature) remains lower for the 50 mm layer in the morning hours because the heat input is primarily absorbed near the surface and has not yet conducted efficiently to the lower layers. However, from 1pm to 9pm, the temperature ratio becomes the highest among all time intervals because the heat has been fully stored in the thermal energy storage. Higher temperatures inside the sandbox can expedite the drying process as compared to the outside temperature (Fauzan & Kartika, 2023). This study indicates that the drying process above the sandbox would be significantly more effective than drying the turmeric under normal outside conditions. This finding is further supported by recent research, which demonstrated that the temperature within the solar dryer exceeded that of the external environment (Halim Ghafar, Hamid Yusoff, Sh Mohd Firdaus Sh Abdul Nasir, Kay Dora Abdul Ghani, 2025). This indicates that the temperature inside the sandbox is elevated relative to the outside temperature, which is attributable to the sand's capacity to retain heat energy as a sensible heat- solid thermal energy storage material.

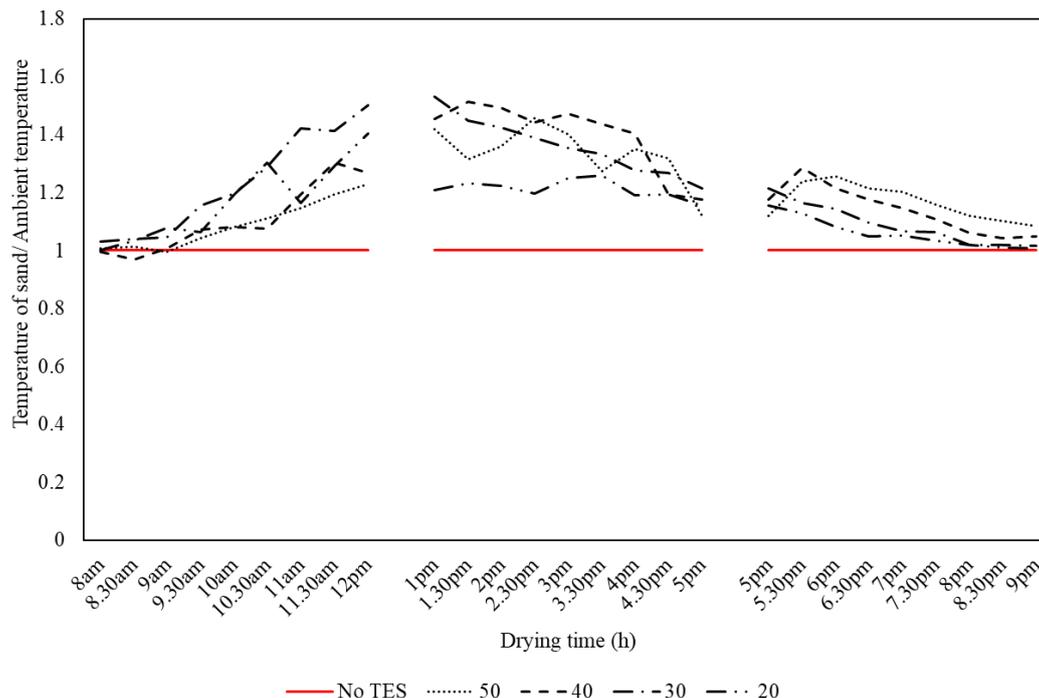


Figure 5: Temperature of Sand/ Ambient Temperature Against Drying Time (H) Graph. The Legend Represents the Thickness of Silica Sand (Mm).

Conclusion

The temperature ratio and weight loss data for different silica sand thicknesses were obtained through comprehensive experimental studies focusing on the turmeric drying process. These data were compared against a baseline condition without any thermal energy storage, allowing for a clear assessment of the impact of silica sand layers of varying thicknesses, specifically ranging from 20 mm to 50 mm. The experimental results unequivocally indicate that silica sand, with an average particle diameter of 10 mm, functions effectively as a thermal energy storage material. This capability allows the sand to absorb, retain, and gradually release heat, thereby significantly improving the heat availability within the drying chamber. As a result, the drying process of turmeric is accelerated when thermal energy storage is employed, compared to scenarios where no such storage medium is used.

The drying performance varies with sand thickness and time of day. From 8 a.m. to 12 p.m. and again from 5 p.m. to 9 p.m., the 30 mm thick silica sand layer demonstrated superior drying rates relative to other thicknesses tested, indicating an optimal balance between heat retention and transfer at this thickness during these periods. In contrast, during the peak heating period from 1 p.m. to 5 p.m., the 50 mm thickness exhibited the fastest drying rate, likely due to its greater heat storage capacity and the enhanced thermal conduction of the turmeric at higher ambient temperatures.

These observations emphasise the importance of selecting appropriate thermal storage layer thicknesses to optimise drying efficiency across different stages of the drying cycle. Moreover, these findings suggest that the thermal management of solar drying systems can be further improved by tailoring the physical properties of the thermal storage medium, such as combining sands with different particle sizes or mineral compositions. Such modifications

could result in more consistent heat delivery and further drying time reductions, thereby boosting the productivity and energy efficiency of solar dryers.

In conclusion, the integration of silica sand as a thermal energy storage medium within solar drying systems presents a promising strategy to improve drying kinetics and crop quality. Future research and development should focus on the design optimisation of such hybrid drying systems, exploring various materials and configurations to achieve greater energy efficiency and sustainability in postharvest processing.

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Ethics Statement: This study did not involve any human participants, animals, or sensitive data requiring ethical approval. The authors affirm that they conducted the research adhering to established academic integrity and ethical publishing standards.

Author Contribution Statement: All authors contributed significantly to the development of this manuscript. Alif Abni Adnan was responsible for the conceptualisation, methodology, handling data collection, analysis, interpretation of results, literature review, and drafting. Sh Mohd Firdaus Sh Abdul Nasir and Hamid Yusoff contributed to the critical revision of the manuscript and overall supervision of the study. All authors read and approved the final version of the manuscript prior to submission.

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