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Development and Performance Evaluation of a Novel Solar Dryer Integrated with Thermal Energy Storage System for Drying of Agricultural Products

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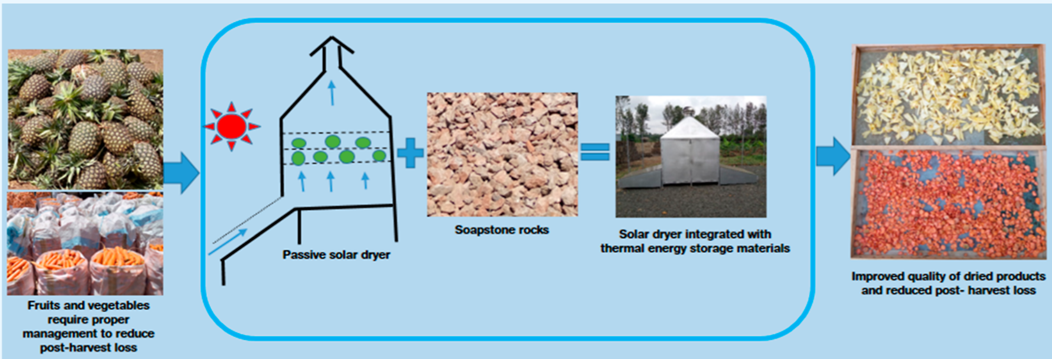

ABSTRACT: Passive solar dryers play a crucial role in reducing postharvest losses in fruits and vegetables, especially in regions like sub-Saharan Africa with low electrification rates and limited financial resources. However, the intermittent nature of solar energy presents a significant challenge for these dryers. Passive solar dryers integrated with thermal energy storage (TES) can reduce intermittence and improve the drying efficiency. Currently, phase change materials (PCMs) are popular heat storage materials in dryers, and paraffin wax dominates. The main problem with the use of PCMs is that it is necessary to closely constrain the temperature range of the process during charging and discharging. This can be a difficult condition to meet in simple solar dryers due to the variable availability of solar radiation. Instead, solid-phase materials, such as sand and rocks, are often used. Soapstone is one of the natural rocks with good thermal properties, but it has yet to be used as a TES material in solar dryers for drying agricultural products. Therefore, the main objective of the present study was to develop a novel solar dryer integrated with soapstone as a TES material and evaluate its performance. The proximate analysis to examine the quality of dried products using the developed technology was also carried out. The comparative experiments for the developed dryer were conducted in two modes: dryer with TES materials and without TES materials, and the results were compared with open sun drying (OSD) by drying 50 kg of fresh pineapple and carrot at different times. The drying times for pineapples in the dryer with TES, without TES, and OSD were 13, 24, and 52 h, respectively. However, the drying times for carrots in the dryer with TES, without TES, and OSD were 12, 23, and 50 h, respectively. Notably, the dryer integrated with TES materials could supply heat for around 3−4 h after sunset. The thermal efficiency of the dryer, collector efficiency, and storage efficiency of TES materials were calculated and found to be 45, 43, and 74.5%, respectively. Proximate analysis indicated that the dryer integrated with TES materials effectively maintained the quality of the dried products compared to OSD. Solar dryer integrated with soapstone showed great promise as sustainable and efficient solutions for reducing postharvest losses and enhancing food security in resource-constrained regions like sub-Saharan Africa.

1. INTRODUCTION

Fruits and vegetables contain essential components for human health such as proteins, vitamins, carbohydrates, fats, and minerals.[1] However, fruits and vegetables are perishable products and hence susceptible to postharvest losses. Lipinski, Hanson, Waite, Searchinger, and Lomax[2] published a working paper on reducing food waste and reported that global postharvest losses in cereal crops were about 19%, root crops about 20%, and fruits and vegetables 44%. According to the Ministry of Agriculture,[3] postharvest losses in Tanzania ranges 30−40% for cereal crops and higher for perishable crops such

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as vegetables and fruits, which lead to food insecurity and hunger.

The most common method used by farmers in reducing postharvest losses, especially in developing countries, is open sun drying (OSD). OSD is one of the oldest, cheapest, simple, and most widely used traditional methods in which products are spread on the ground and often rotated until sufficiently dried.[4] Despite its low cost and simplicity, OSD has some limitations, such as long drying time, contamination by insects, and loss of quality of dried products,[5] loss of color,[6] and the complexity of controlling drying parameters such as temperature, air velocity, and humidity.[7] Small-scale solar energy technologies such as solar dryers are being developed to address the challenges exhibited by OSD.[8] Solar dryers are specialized devices that control the drying process and protect agricultural produce from damage by insects, dust, and moisture. In comparison to drying products in the open sun, solar dryers generate higher temperatures and lower relative humidity and increase air flow across the produce, resulting in shorter drying periods, lower product moisture content, and reduced spoilage during the drying process. Solar dryers are more attractive because they can dry the product rapidly, uniformly, and hygienically to meet the required standards with zero energy costs.[9]

Depending on the mechanism of air flow, solar dryers can be divided into active and passive.[10] Active solar dyers are generally incorporated with active components such as a fan or heat pump to move the heated air from the collector to the drying chamber, hence suitable for large-scale drying operations.[11] Active solar dryers require substantial capital investments and burn significant amounts of fossil fuel,[12] making them unsuitable for rural areas, particularly in sub-Saharan Africa, where the electrification rate is low and financial resources are limited.[13] Passive solar dryers use only solar energy and do not use any active components, making them ideal for small-scale holders and agro-processors with limited resources, such as those in rural sub-Saharan Africa, due to attributes such as low capital investment and maintenance costs.[11,13] The most significant drawback of passive solar dyers is their intermittent nature, as they rely totally on the availability of sun radiation.[14] Passive solar dryers are thus ineffective during cloudy days or nighttime, demanding alternative solutions to these limitations. Passive solar dryers integrated with thermal energy storage (TES) materials can reduce the intermittent drying of agricultural products, improve the drying efficiency, and reduce the drying time.[15] TES materials store thermal energy during the day when there is enough solar energy and discharge it when sunlight is unavailable, ensuring continuous drying of agricultural products.[16] Most of the previous studies have primarily focused on the application of phase change materials (PCM) for agricultural drying applications.[17] The key issue with using PCM is that the temperature range of the process during charging and discharging must be tightly constrained. The intermittent availability of sun radiation makes it challenging to meet this need in simple solar dryers. The use of sensible thermal energy storage (STES) materials, like gravel, granite, sandstones, limestone, and soapstone, has been relatively less explored, despite their effectiveness in simple solar dryers. STES materials offer advantages, including natural availability, cost effectiveness, improved efficiency, shorter drying times, preservation of product quality, and non-toxicity.[18−21]

Soapstone, in particular, possesses good thermal conductivity and has been used for various purposes due to its thermal properties and historical availability. Kakoko, Jande, and Kivevele,[22] conducted experimental investigation of soapstone and granite as energy storage materials and found that soapstone rock performed better than granite as a TES material for solar drying technology and solar power generation applications. According to Pirinen,[23] soapstone rock has a higher density of about 2.98 g/cm^3, which is higher compared to other natural rocks, and a specific heat capacity ranging 0.9−1.1 kJ/kg °C that is about 20% more than that of other typical natural rocks. However, despite its good thermal storage properties, the application of soapstone as a TES material for agricultural product drying remains relatively understudied. Thus, this work aims to investigate the potential of soapstone integration as a TES material to reduce intermittence in a constructed passive solar dryer. A novel solar dryer integrated with soapstone as a TES material was developed and evaluated for its performance by drying 50 kg of fresh pineapples and carrots. The experiments were carried out in two modes: dryer with TES materials and dryer without TES materials, and the results were compared with that of OSD. The dryer's performance was evaluated in terms of drying parameters (temperature, relative humidity, and airflow), thermal/drying efficiency, charging and discharging of soapstone (storage efficiency), solar collector efficiency, and proximate analysis of dried products compared to open sun-dried products. This study therefore seeks to contribute to sustainable and efficient agricultural drying practices in the regions with limited resources and intermittent solar availability.

2. MATERIALS AND METHODS

2.1. Experimental Setup. A solar dryer integrated with TES materials was designed and fabricated at the workshop of the Mechanical Department, Arusha Technical College (ATC), Arusha-Tanzania. The dryer was then relocated to the Tanzania Horticultural Association (TAHA) Farmers Training Centre in Tengeru, Arusha, for experimentation and data collection. The dryer consists of three subsystems: solar collectors, drying chamber, and energy storage (soapstone), as seen in Figures 1−3. The materials used for the fabrication of

Figure 1. Photograph of the solar dryer placed at the TAHA Farmers Training Center, Tengeru-Arusha.

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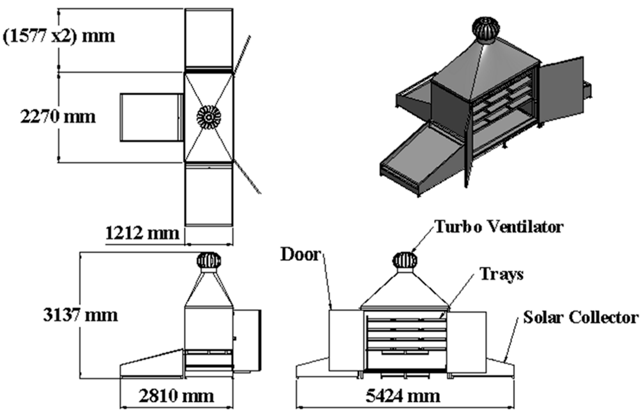

Figure 2. Schematic diagram of the developed solar dryer.

Figure 3. Photograph of a solar dryer collector with and without TES.

the solar dryer were purchased from the local market; some of the materials used are mild steel sheets of 1.5 mm thickness, aluminum sheets of 1.5 and 0.5 mm, a hollow section of 40 × 25 mm, a clear transparent glass of 6 mm thickness, a wind ventilator of diameter 400 mm, a flat bar of 25 × 3 mm, plastic mesh, gasket, reverts, bolts, and nuts, and soapstones as TES materials. Soapstones were collected from the Craton geotectonic setting in the Dodoma Region, located in the central part of Tanzania. The solar dryer, including the drying chamber and solar collectors, was made with a double-wall separated by insulation materials (fiberglass) of 2.5 cm thickness to prevent heat transfer between the inside and outside environment. For food safety measures, the interior surface of the drying chamber was made of an aluminum sheet of 1.5 mm thickness. In contrast, the exterior surface was made of a mild steel sheet of 1.5 mm thickness. The designed capacity of the solar dyer is 50 kg per batch, and the dimensions of the drying chamber were 2.27 m (L) × 1.2 m (W) and 1.5 m (H). Fifteen trays were made from an aluminum sheet of 1.5 mm to carry the drying materials. The length and width of each tray were 1.018 and 0.65 m, respectively, and each tray was designed to carry 3.4 kg of vegetables or fruits. A small chamber of 2.27 m (L) × 1.2 m (W) and 0.5 m (H) was provided below the drying chamber to allow the use of another source of energy, such as biogas or liquefied petroleum gas (LPG) during severe weather conditions, especially when sun radiation is not available for drying. To facilitate air movement inside and outside the drying chamber, a wind ventilator with a diameter of 400 mm was installed at the top of the dryer.

The solar dryer was designed with three collectors to ensure the capture of solar radiation throughout the day. The dimensions of the solar collector are 1.6 m (L) × 1.2 m (W). The inside of the solar collector was coated with black paint, enabling it to soak up solar radiation and retain thermal energy. The soapstones were positioned at a depth of 0.12 m from the bottom of the solar collector and covered with a 0.5 mm thick aluminum plate that had been coated in black paint by using tarmac/tar to effectively absorb solar radiation. The weight of the TES materials (soapstone) placed inside the solar collectors, as seen in Figure 3, was determined using a weigh scale and found to be 220 kg for each solar collector. An air vent of 0.08 m depth and 1.2 m wide with an adjustable gate that allowed airflow adjustments was positioned between the absorber plate and the collector glass of the solar collector. The design of the air vent was made according to Raju, Reddy, and Reddy,[8] who suggested at least a 5 cm air vent for hot climates. The top of the solar collector was covered by a clear glass of 6 mm thickness to transmit solar radiation to the collector. The tilt angle of the solar collector was designed to receive sufficient amounts of solar radiation according to ref 24 and was found to be 13.4°. Figures 1−3 show the photograph and sketch of the solar dryer; the summary of the specification of the solar dryer is presented in Table 1.

Table 1. Summary of the Specifications of the Solar Dryer

descriptions	unit	value
volume of the of drying chamber	m^3	3.96
thickness of the solar collector glass	m	0.006
thickness of the aluminum absorber plate	mm	0.5
insulation thickness (fiberglass)	m	0.025
capacity of the dryer	kg	50
surface area of the solar collector	m^2	1.8
volume of the collector occupied by TES materials	m^3	0.18
depth of the collector air vent (adjustable)	cm	0−8
weight of the TES in each collector	kg	220
surface area of the tray	m^2	0.65
loading capacity of the dryer	kg	4
distance between trays	m	0.24
tilt angle of the collector		13.4°

2.2. Experimental Procedure. The experiments were conducted at the TAHA Farmers Training Centre in Tengeru-Arusha Region, Tanzania. The dryer was tested for drying pineapples (*Ananas comosus*) and carrots (*Daucus carota*). Pineapples, botanically classified as fruits, and carrots as root vegetables, are essential products in Tanzania's economy and a source of nutrition. However, they are vulnerable to postharvest loss, especially during peak seasons. The fresh samples were purchased from a local market in Arusha Region, Tanzania. The carrots weighed about 65 g on average, whereas the pineapples weighed roughly 1.5 kg. Following washing, the samples were peeled and then cut into homogeneous slices approximately 3 mm thick, which is regarded as an appropriate thickness for successful drying based on previous research.[25] For carrots, a simple hand vegetable slicer was used to make circular slices with an average diameter of around 2.6 cm and a weight of about 3 g. Pineapples were cut longitudinally into four parts, and each part was manually sliced. The samples were not pretreated. A total of 50 kg of each type (carrots and pineapples) was sliced and dried using the developed solar dryer and OSD until their ultimate moisture content was less than 10% wet basis (w.b.).

The drying time, solar radiation, weight reduction, temperature, and relative humidity were recorded every 30 min. Inside the soapstone compartment, three SSN-11E USB temperature

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Table 2. Measuring Instruments and Uncertainties in Measurements

S/N	instrument	range	accuracy	resolution	error (%)	uses
1	SSN-11E USB temperature data logger meter	−40 to 125°C	±0.5°C	±0.1°C	0.01414	temperature measurement
2	SSN-22E USB temperature humidity data logger meter	0−100% RH	±0.3 RH	±0.1 RH	0.01414	humidity measurement
		−40 to 125°C	±0.3°C	±0.1°C	0.01414	temperature measurement
3	TES 132 solar power meter	2000 W/m^2	±10 W/m^2	0.1 W/m^2	0.01414	solar radiation measurement
4	kestrel 3000 wind meter	0.6−40 m/s	±0.1 m/s	0.05 m/s	0.07071	wind measurement
5	FF1976 constant digital weighing scale	0−40 kg	0.14 g	0.1g	0.01414	weight measurement

data logger probes were positioned to monitor the soapstone's temperature. At both the inlet and outlet of the solar collectors, data logger meters were placed to measure the temperature and relative humidity (SSN-22E USB temperature humidity data logger meter). Inside the drying chamber, three similar data logger meters were positioned to measure the temperature and relative humidity. A Kestrel 3000 wind meter was used to measure the airflow (inside and outside the drying chamber), and an FF1976 constant digital weighing scale was used for measuring the weight of the products. A TES 132 solar power meter was located on the solar collector for measuring the solar irradiance.

The drying experiments were conducted under two operating modes: a solar dryer with load but without TES and a solar dryer with load and TES materials. Data were collected on three consecutive days in each mode, and the average values were determined. Data collection was performed from January to March 2023.

2.3. Error and Uncertainty Analysis. In most cases, measuring instruments are subjected to errors, regardless of their precision and accuracy. The two major causes of these uncertainties are measuring devices, sometimes known as systematic errors, and measurement skills or random errors. Uncertainty assessment is crucial for designing and implementing the experiment.[26] The total errors were calculated by using eq 1 according to Gulcimen, Karakaya, and Durmus.[27] Table 2 shows the instruments used for the measurements and their uncertainty assessments

$$w_{\mathrm{th}} = \sqrt{(X_1)^2 + (X_2)^2 \ldots\ldots (X_\infty)^2} \tag{1}$$

where X = independent variables affecting measurements.

The independent variables affecting measurements were determined by using eq 2 according to AR and Veeramanipriya[28]

$$w_{\mathrm{n}} = \sqrt{(W_{\mathrm{instument}})^2 + (W_{\mathrm{reading}})^2} \tag{2}$$

The overall errors in the measurement of different parameters are given by eq 3, which is a simplified equation from eq 1

$$w_{\mathrm{total}} = \sqrt{(W_{\mathrm{temperature}})^2 + (W_{\mathrm{humidity}})^2 + (W_{\mathrm{solar\ radition}})^2 + (W_{\mathrm{wind}})^2 + (W_{\mathrm{w\ scale}})^2} \tag{3}$$

The overall uncertainties in the measuring devices and reading errors were calculated according to eq 3 and found to be ±0.0701%. This value is small compared to the acceptable range of ±10%, according to Choi, Kikumoto, Choudhary, and Ooka.[29]

2.4. Performance Analysis. The performance of the solar dryer integrated with soapstone as a TES material was analyzed by determining the sensible heat energy storage of TES materials (E), storage efficiency of TES materials (η_s) weight of water evaporated from the product (M_w), drying rate (D_r), thermal efficiency (η_t) collector efficiency (η_c), and saving of drying time (%). In addition, a comparative evaluation of drying time, temperature, and relative humidity by using TES materials, without TES materials, and OSD were conducted.

2.4.1. Amount of Sensible Heat Energy Storage. The amount of energy storage by materials is an essential parameter in selecting TES materials because it describes the amount of heat energy that can be stored in the materials at a particular time. The amount of energy storage was estimated by eq 4 according to Cetina-Quiñones, López, Ricalde-Cab, El Mekaoui, San-Pedro, and Bassam[18]

$$E = M_{\mathrm{a}} C_{\mathrm{p}} (T_{\mathrm{f}} - \mathrm{T_i}) \tag{4}$$

where E = energy storage (J), M_a = weight of storage materials (kg), C_p = specific heat capacity of soapstone (J/kg °C), T_i = temperature of the storage materials at time t (°C), and T_f = temperature of the storage material in the proceeding time (°C).

2.4.2. Storage Efficiency. The storage efficiency of TES materials (η_s) is the ratio of the discharged energy to the charging energy from the TES materials; it was calculated by using eq 5 according to Cetina-Quiñones, López, Ricalde-Cab, El Mekaoui, San-Pedro, and Bassam[18]

$$(\eta_s) = \frac{E_{\mathrm{discharge}}}{E_{\mathrm{charge}}} \tag{5}$$

2.4.3. Weight of Water Evaporated. The weight of water evaporated is the amount of water evaporated from the product during the drying process. Fruits and vegetables contain a great amount of water as compared to solids. The weight of water evaporated was calculated using eq 6 according to Fudholi, Sopian, Alghoul, Ruslan, and Othman,[30] Santanu Malakar,[31] and Suleiman, Pogrebnoi, and Kivevele[32]

$$M_{\mathrm{w}} = \frac{M_{\mathrm{o}}(M_{\mathrm{i}} - M_{\mathrm{f}})}{100 - M_{\mathrm{f}}} \tag{6}$$

where M_o = initial mass of the products, M_i = initial moisture content of the product on wet basis (%), and M_f = final moisture content of the product on wet basis (%).

2.4.4. Drying Rate. Drying rate is the ratio of moisture evaporated from the product over time. The drying rate of the products was estimated using eq 7 according to Hasibuan, Yahya, Fahmi, and Edison[33]

$$\mathrm{DR} = \frac{\mathrm{M_w}}{t} \tag{7}$$

where M_w = total mass of water evaporated from the drying products (kg), and t = drying time (h).

2.4.5. Dryer Thermal Efficiency. The dryer thermal efficiency is the ratio of energy required to evaporate water from the drying product to the energy supplied by the dryer.

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The thermal efficiency of the dryer was calculated using eq 8, as proposed by Ayyappan, Mayilsamy, and Sreenarayanan[21]

$$\eta_t = \frac{M_w h_{fg}}{A_c \times I} \quad (8)$$

where M_w is the total mass of water evaporated from the drying products (kg), h_{fg} is the latent heat of vaporization of water (kJ/kg), obtained from the saturation properties for steam temperature table, A_c is the area of the solar dyer (m^2), and I is the solar irradiance (W/m^2).

2.4.6. Collector Efficiency. The ratio of useful heat gained per unit aperture area to the average incidence radiation of the collector is the collector efficiency. The efficiency of the collector with energy storage (η_c) was calculated using eq 9 and as reported by Singh, Singh, Akhtar, and Khajuria[34]

$$(\eta_c) = \frac{M_a c_a (T_c - T_a)}{A_c I} \quad (9)$$

where M_a = mass of air flowing in the collector per unit time (kg/s), C_a = specific heat capacity of air (kJ kg^{-1} K^{-1}), A_c = collector area (m^2), and I = solar irradiance (W/m^2).

The mass of air flowing in the collector per unit time (M_a) was calculated by using eq 10 according to Singh, Singh, Akhtar, and Khajuria[34]

$$M_a = \rho_a V_a C_v \quad (10)$$

where V_a = velocity of air (m/s), ρ_a = density of air (m^3/kg), and C_v = cross-sectional area of air vent (m^2).

2.4.7. Saving in Drying Time. Saving in drying time (%) is the time saved by using a solar dyer compared to OSD. It was calculated using eq 11, according to Fudholi, Othman, Ruslan, and Sopian.[35]

$$\text{Saving in drying time (\%)} = \frac{t_{OS} - t_{SD}}{t_{OS}} \quad (11)$$

where t_{OS} = time taken in (h) to dry a product under open sun, and t_{SD} = time taken in (h) to dry a product in a solar dryer.

2.5. Proximate Analysis. Even though drying is a fundamental process for food preservation, it has been reported to slightly change the quality of the dried products, such as color, flavor, and nutrients.[36,37] However, according to Bhardwaj, Kumar, Chauhan, and Kumar,[20] drying agricultural products using solar dryers integrated with TES materials has been reported to retain the nutritional values. Therefore, proximate analysis was conducted to determine whether there was a loss of nutritional composition in the dried products in terms of moisture content, ash content, crude fiber, fats content, protein, vitamins, and minerals. The assessment was conducted for pineapples and carrots.

2.5.1. Determination of Moisture Content. Determining the moisture content helps us to understand the water level available in the product before and after drying. The gravimetric oven drying method determined the moisture content according to the Association of Official Analytical Chemist (AOAC) method.[38]

Exactly 5 g of paste sample was accurately weighed in clean and dry Petri dishes and then dried in an oven at 105 °C for 24 h until the content showed no further change in weight. The Petri dish was placed in a desiccator for 30 min to cool. After cooling, the final weight was recorded, and the moisture percentage was calculated using eq 12

$$\text{\% moisturecontents (on wet basis)} = \frac{m_i - m_f}{m_i} \times 100 \quad (12)$$

2.5.2. Determination of Ash Contents. Ash content determination is the first step in sample preparation for a particular analysis. A dry ash method was used to determine ash content according to AOAC methods.[38] A clean empty crucible was placed in a muffle furnace at 550 °C for 1 h to ensure that all possible impurities on the surface of the crucible were burned off. The device was placed in the desiccator for 30 min for cooling, and the weight of the empty crucible was recorded. Exactly 5 g of the sample was placed in the crucible and then placed in the muffle furnace. The ultimate weight was determined after the crucible and its contents had been heated in the muffle furnace for 24 h and cooled in the desiccator. The percentage of ash contents was determined by using eq 13

$$\text{\% ash content} = \frac{\text{weight of ash}}{\text{weight of sample}} \times 100\% \quad (13)$$

2.5.3. Determination of Crude Fiber. The crude fiber analysis involves two stages of digestion of acid and alkaline solutions, using the method described by the AOAC methods.[38] The percentage of fiber was calculated using eq 14

$$\text{Crude fiber (\%)} = \frac{\text{weight of residual} - \text{weight of ash}}{\text{Weight of sample}} \times 100\% \quad (14)$$

2.5.4. Determination of Protein. Protein is one of the essential foods in our body; it provides crucial elements, such as amino acids, for the growth and maintenance of our cells and tissues. When agricultural products are dried, especially in higher temperatures, they lose some nutrients.[39] Protein concentration was evaluated using the Kjeldahl nitrogen method, as defined by AOAC methods.[38] The method involves three steps: digestion, distillation, and titration. Based on this method, exactly 5 g of samples was digested by heating with concentrated sulfuric acid in the presence of the Kjeldahl catalyst to ammonium sulfate. The digested mixture was naturalized with NaOH, and nitrogen was distilled off and trapped in a boric acid solution. The amount of nitrogen was quantified by titration with an HCl solution. The percentage of nitrogen contents was determined by using eq 15. The obtained nitrogen was multiplied by conversion factor 6.25, as shown in eq 16

$$\text{Nitrogen}\left(\%, \frac{w}{W}\right) = \frac{\text{volume of acid (ml)} \times \text{molarity of acid (mol l}^{-1}\text{)} \times 14\ \text{(g mol}^{-1}\text{)}}{\text{weight of sample (g)} \times 100} \quad (15)$$

$$\text{Nitrogen (\%)} = \text{nitrogen } (\%, w/W) \times \text{protein factor} \quad (16)$$

2.5.5. Determination of Fat. Fat content was determined by Soxhlet method as described by AOAC methods.[38] A precisely 5 g sample was placed into the extraction thimble and assembled into the Soxhlet apparatus. Petroleum ether (70 mL) was used for the extraction process in three phases in a fat analyzer machine. The boiling phase was 15 min, the rinsing phase was 30 min, and the petroleum ether recovery phase was 10 min. The remaining petroleum ether was then evaporated in the oven. Preweighed cups containing fat were dried in an oven

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at 105 °C for 1 h to evaporate any remaining petroleum ether and then cooled in a desiccator for 30 min and reweighed. Percentage fat was calculated by using eq 17

$$\% \text{ fats} = \frac{\text{weight of crude fat}}{\text{weight of sample}} \times 100\% \tag{17}$$

2.5.6. Determination of Total Carbohydrates. Total carbohydrate was determined by taking the difference of the sum of all total proximate compositions from 100%.

$$\begin{aligned} &\text{Total carbohydrate \%} \\ &= 100\% - (\text{ash content \%} - \text{protein \%} + \text{fat content \%} \\ &\quad + \text{crude fiber \%+moisture content} \end{aligned} \tag{18}$$

2.5.7. Determination of Minerals. Vegetables and fruits are sources of minerals for human health. Minerals play important roles in building and maintaining bones, muscles, and brain to work properly. Mineral elements which were analyzed were calcium (Ca), sodium (Na), magnesium (Mg), potassium (K), and phosphorus (P). One gram of sample was taken in a conical flask, and 10 mL of nitric acid (HNO_3) was added. The mixture was boiled for about 20 min to almost dryness and then cooled, filtered using Whatman filter paper number 1, and diluted with 100 mg of water. An atomic absorption spectrophotometer was used to analyze the minerals separately.

2.5.8. Determination of Vitamins. Vitamins are very much essential for the growth and development of our body. In this study, vitamins A and C were determined using AOAC methods.[38]

3. RESULTS AND DISCUSSION

3.1. Evaluation of Drying Parameters. The variability of sun irradiation falling on the ground surface impacts the performance of the solar dryer. The graph in Figure 4 depicts a considerable fluctuation in the intensity of solar energy input over time. The average minimum and maximum sun irradiation levels ranged from 160 to 1140 W/m^2, respectively. The minimum irradiation was observed during the morning and evening, whereas the maximum irradiation was observed around 1.00 p.m. It can be observed that the intensity change of the solar energy input is relatively large crossing the time; this could be attributed to the prevalence of diffuse radiation and cloud cover in equatorial locations, as highlighted by Dazhi, Jirutitijaroen, and Walsh et al. (2012)[40] in their study on estimating the hourly solar irradiance using the cloud cover index. Nonetheless, the integration of TES materials within the collectors reduces the energy swings caused by solar irradiance.

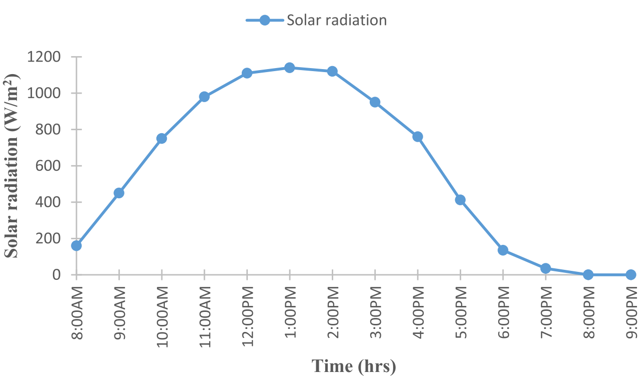

Figure 4. Variation of solar radiation with time.

Temperature plays a very important role in product drying. Figure 5 shows comparisons of temperature variation inside the drying chamber when the dryer is integrated with TES, and without TES materials, as well as ambient temperature with time. The maximum temperature was recorded at 1.00 p.m during the time of peak solar irradiance. The maximum temperature recorded for the dryer with TES materials was 62 °C, that without TES material was 61 °C, and the ambient temperature was 33 °C. The use of TES materials maintained a uniformly higher temperature in the drying chamber compared with the one without TES materials. For example, from Figure 5, at 7:00 p.m. when the ambient temperature was 28 °C, the temperature in the drying chamber with the TES material was observed to be 44 °C, and it continued to decrease gradually until 12:00 p.m. when the drying chamber temperature was 27 °C and the ambient temperature was 23 °C. TES materials prolonged the drying temperature about 3−4 h after sunset. Therefore, soapstone materials play an important role in storing solar energy during the day and release it later, hence extending the drying time. The results are in agreement with those of Bhardwaj et al. (2020) who evaluated the performance of a solar dryer integrated with the combination of STES and PCM for drying chill. In that particular research, it was found that PCM provided backup for about 6 h, whereas STE provided 2−3 h after sunset.

Relative humidity is another important parameter in the product drying process. Figure 6 shows the comparative analysis of the variation in air relative humidity inside the drying chamber for the dryer with TES materials and without TES materials as well as ambient with time. It is clear that the relative humidity inside the drying cabinet when the dryer is integrated with TES and without TES materials is relatively less compared with the ambient relative humidity. However, the relative humidity with TES materials is considerably less compared to the mode of dryer without TES materials. The average ambient relative humidity ranged from 41 to 77% during the day and night, respectively. The minimum relative humidity in all the drying methods was recorded during the day around 1:00 p.m and the maximum around 12:00 p.m during night. The relative humidity in the drying chamber without TES materials was about 25% during the day and 76% during night, whereas in the drying chamber with TES materials, it was about 9% during the day and 55% during night. It is evident that the relative humidity inside the drying chamber when the dryer is integrated with TES materials is lower than the one without TES materials and open sun. The lower relative humidity is attributed to the presence of TES materials which maintain higher temperature and hence lower relative humidity in the drying chamber. These results are in agreement with those of Cetina-Quiñones, López, Ricalde-Cab, El Mekaoui, San-Pedro, and Bassam,[18] who conducted experimental evaluation of an indirect solar dryer with sensible heat storage materials and reported that storage materials increased the drying temperature and reduced the relative humidity.

The use of TES materials involves charging of thermal materials when solar energy is available and discharging them when solar energy is not available. The amount of thermal energy stored in the soapstone during charging was determined using eq 4 and found to be 8.8 and 6.5 MJ during charging and discharging, respectively. Storage efficiency was determined

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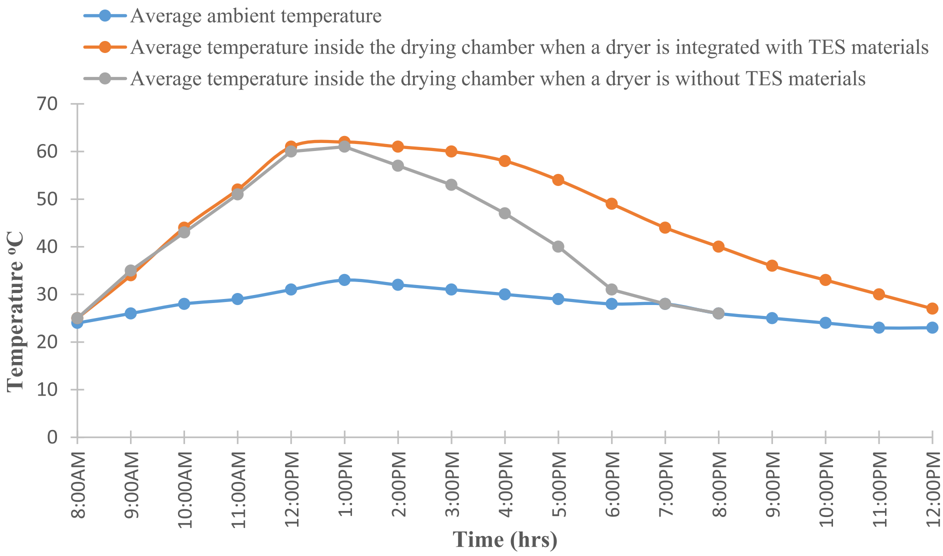

Figure 5. Variation of temperature with time.

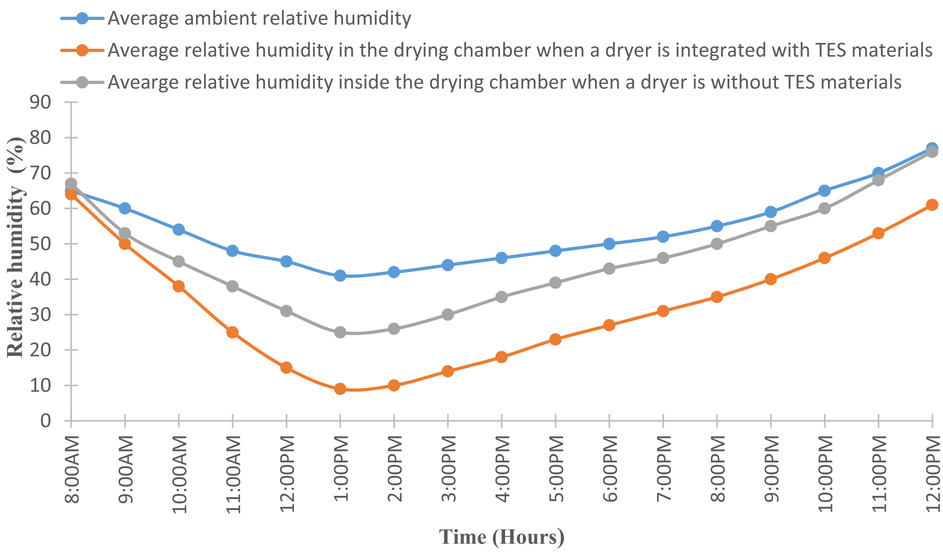

Figure 6. Variation of relative humidity with time.

according to eq 5 and was found to be 74.5%. The obtained results are in good agreement with the one reported by Cetina-Quiñones, López, Ricalde-Cab, El Mekaoui, San-Pedro, and Bassam,[18] who conducted an experimental evaluation of indirect solar dryer agricultural products using limestone and bench sand as TES materials. The charge and discharge energies for limestone were 2.4 and 2.0 MJ, respectively, whereas for beach sand, it was 5.9 MJ for charging and 4.1 MJ for discharging. The storage efficiency for limestone was 84.2%, whereas for beach sand, it was 70.3%.

3.1.1. Performance Evaluation of the Developed Dryer. The developed dryer was tested for drying pineapples (fruit) and carrots (vegetable); their initial moisture content was lowered from 90 and 88%, respectively, to 10% wet (w.b). The weight of water evaporated from 50 kg of drying products was calculated using eq 6 and found to be 44.4 kg for pineapple and 43.4 kg for carrot. The weight of dried products removed from the dryer was 5.5 and 6.6 kg for pineapples and carrots, respectively. Figures 7 and 8 show the drying curves for pineapples and carrots using solar radiation with TES materials, without TES materials, and OSD. In all of the drying methods, the drying rate was fast at the beginning and continued to decrease with time. The drying times for pineapples in the dryer with TES, without TES, and OSD were 13, 24, and 52 h, respectively, whereas the drying times for carrots in the dryer with TES, without TES, and OSD were 12, 23, and 50 h, respectively. The application of TES materials (soapstone) maintained a higher drying temperature in the range 62−30 °C in the drying chamber and a low relative humidity in the range 9−53%, which reduced the drying time. In comparison with previous studies, the result is in agreement with the findings of Ahmad and Prakash[26] who dried tomato flakes in a greenhouse dryer integrated with TES materials in which it was reported that the tomato flakes were reduced from 96 to 9.10% (wet basis) in 13 h. The results are also in good agreement with the findings reported by Kareem, Habib, Ruslan, and Saha[41] who investigated the performance of a multipass solar air heating system integrated with gravel as TES materials for drying Rosella, and the moisture content of Rosella was reduced from 85.6 to 9.2% (wet basis) in 14 h.

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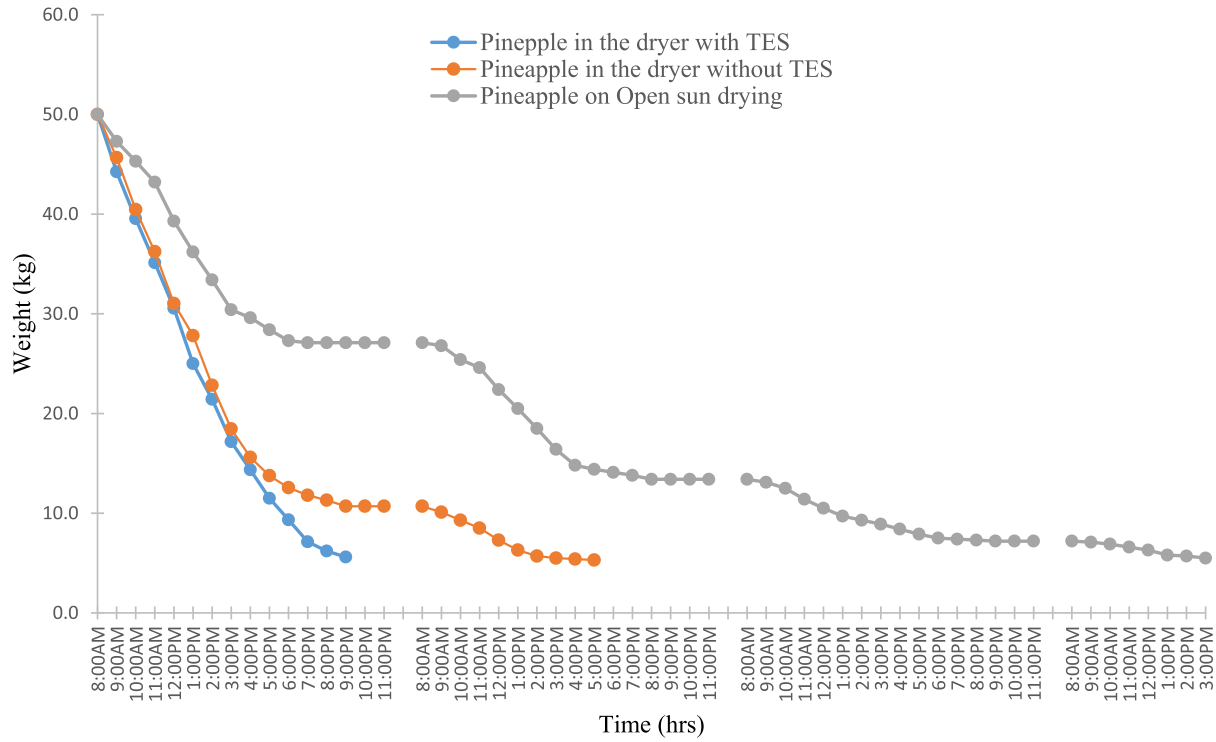

Figure 7. Weight change with time of pineapples in a solar dryer with TES materials and without TES materials and OSD.

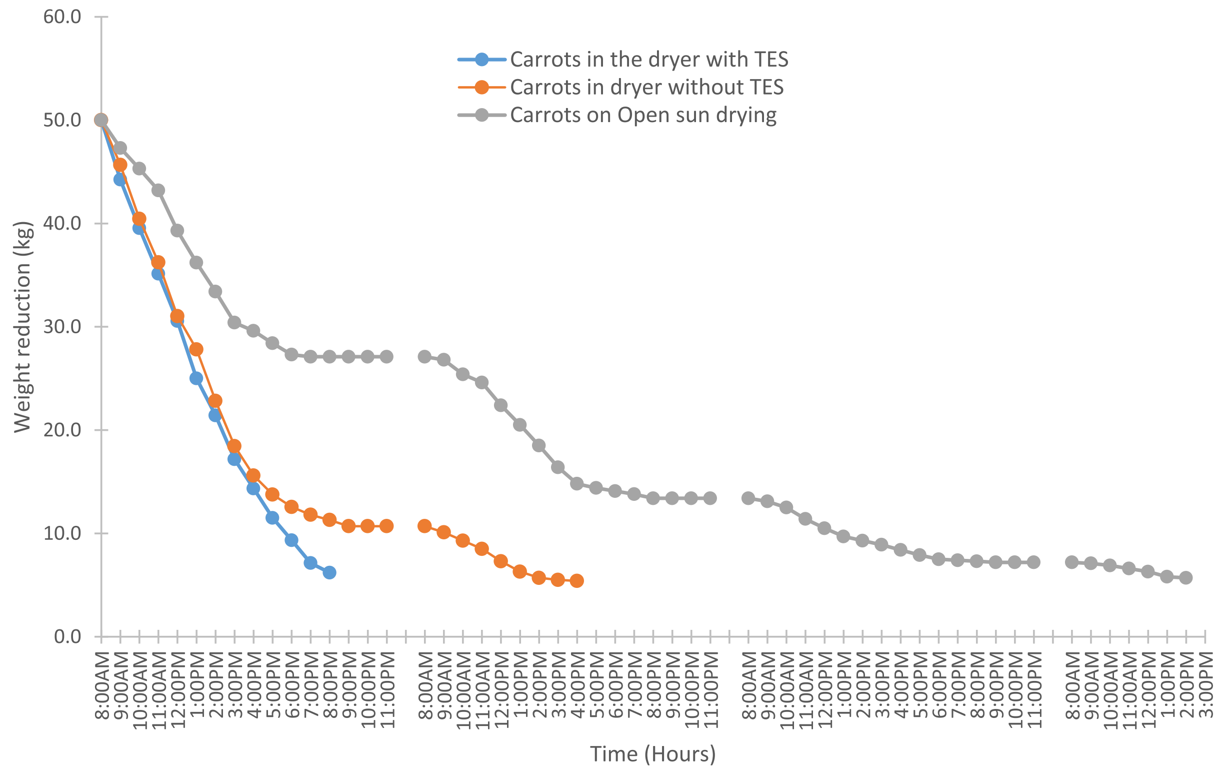

Figure 8. Weight change with time of carrots in a solar dryer with TES materials and without TES materials and OSD.

The drying rate which was calculated using eq 7 was found to be 3.4 kg/h for pineapples and 3.6 kg/h for carrots when a dryer integrated with TES materials was used, whereas for the dryer without TES materials, it was about 1.85 kg/h for pineapples and 1.88 kg/h for carrots. The drying time for ODS was 0.86 kg/h. The thermal efficiency of the dryer was calculated using eq 8 and found to be 45% with TES materials and 38% without TES materials and 25% for OSD. The results are consistent with that of Mugi, Das, Balijepalli, and Chandramohan,[16] who reported that the thermal efficiency for the majority of solar dryers combined with TES materials ranged from 9.9 to 58.2%. The collector's efficiency with TES

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Table 3. Comparison of the Performance Results of Solar Dryers with Some Previous Published Works

				drying time (h)			dryer thermal efficiency (%)			collector efficiency (%)		
S/n	types of solar dryer	loading capacity of the product	types of rock used	TES	no TES	OSD	TES	no TES	OSD	TES	no TES	references
1	hybrid solar dryer integrated with TES	2.5 kg of sliced *Carica papaya* per batch	gravel	5	6	11	34.5	30.2	19.3			28
2	multipass solar air heating collector dryer	75.2−81.3 kg of Roselle	granite	14		35	36.22			64.08		41
3	solar dryer integrated with packed bed TES system	10 kg of sliced orange	pebble	7	7.2		54.71−68.37	50.18−66.58				45
4	indirect solar dryer integrated with TES materials	0.8959 kg of tomato slices	limestone	22	25		12.57	8.41				18
		0.9641 kg of sliced tomato	beach sand	23	25		11.02	8.37				
5	solar dryer integrated with STE and PCM	9 kg of chill	gravel	21	96	150	15.62			78.02		20
6	triple-pass solar dryer	4 kg of potato	sand	4.5		5	53.57			45		42
7	indirect solar dyer integrated with TES materials	4 kgof bitter gourd	pebble	7		10	19			22		43
8	forced convection solar dryer	60 kg of copra	sand	82		168				24		44
9	greenhouse dryer	4 kg of tomato flakes	gravel	13								26
10	convectional solar dryer using TES materials	5 kg of Vitis vinifera	sand	28	53	58	40					46
		2 kg of momordica	sand	5.3	7	10	42					
11	greenhouse solar dryer integrated with TES materials	coconut	rock	53		174				11.65		21
		coconut	concrete	78		174				9.5		
		coconut	sand	66		174				11		
12	solar dryer integrated with TES materials	50 kg of pineapples and 50 kg carrots	soapstone	13	24	52	45 38	25		43	36	current study

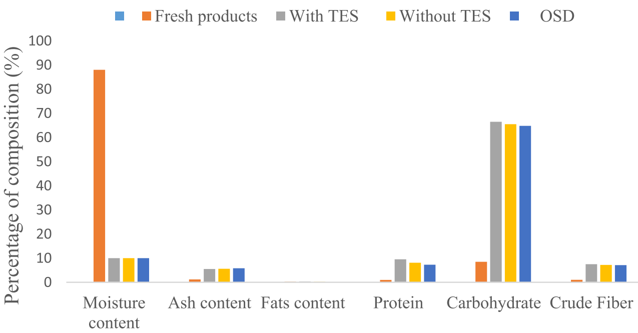

Figure 9. Graph of proximate analysis for pineapples.

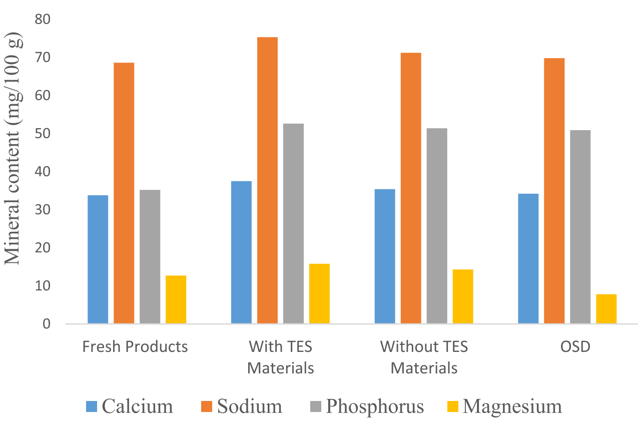

Figure 10. Graph of proximate analysis of minerals for carrots.

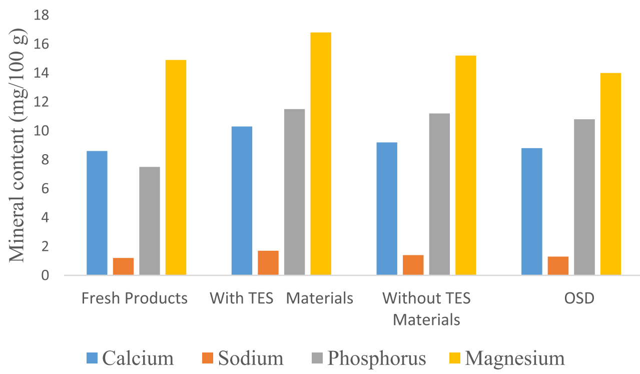

Figure 11. Graph of proximate analysis of minerals for pineapples.

materials was calculated using eq 9 and found to be 43%. The obtained efficiency agrees with that of Kesavan, Arjunan, and Vijayan,[42] in which it was reported to be 45% for a triple-pass solar dryer integrated with sand as TES material. However, collector efficiency in this research was found to be higher as compared to 22% reported by Vijayan, Arjunan, and Kumar[43] for bitter gourd drying using a solar dryer integrated with pebble as the TES and 24% reported by Mohanraj and Chandrasekar[44] who used solar dryer integrated with sand as the TES material for drying copra. The differences in the TES materials used may have contributed to the differences.

Saving in drying time (%) was calculated using eq 12 and was found to be 75%. This means 75% of time can be saved when using the developed solar dryer integrated with the TES material compared to OSD. The results of this study are slightly better as compared to that of Ayyappan, Mayilsamy, and Sreenarayanan[21] who reported that the percentage of saving time for a solar dryer integrated with TES for coconut drying with concrete was 55%, that with sand was 62%, and

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Table 4. Results of Proximate Analysis for Vitamins

parameters	fresh products (control)		with TES materials		without TES materials		OSD	
	carrot	pineapple	carrot	pineapple	carrot	pineapple	carrot	pineapple
vitamin C (mg/100 g)	5.8	47.3	5.6	45.8	5.4	43.5	5.1	40.2
vitamin A (mg/100 g)	880.5	55.7	897.2	68.1	891.8	58.2	885.6	56.5

that with rock was 69%. The difference is caused by the difference in the drying time, which took 78, 66, and 53 h when a dryer is integrated with concrete, sand, and rock, respectively, whereas OSD took 174 h.

The performance comparisons of solar dryers with TES and without TES materials and OSD from the present study and various published works are summarized in Table 3. The results of this study are in good agreement with previous studies, such as the findings reported by AR and Veeramanipriya,[28] who compared the performance of solar dryers integrated with TES, without TES, and open OSD and found that the solar dryer integrated TES materials performed better as compared to the one without TES materials and OSD.

Table 3 shows the comparison of the performance results in terms of drying time, thermal efficiency, and collector efficiency of the solar dryer integrated with different natural rocks such as gravel, granite, pebble, and sand. It can be seen clearly that the drying time, thermal drying efficiency, and collector efficiency for a solar dryer integrated with TES materials is higher compared to that without TES and OSD. For example, the drying time for pineapple from this study when a dryer uses TES materials is 13 h, that without TES materials is 24 h, and OSD is 52 h. The dryer thermal efficiency when a dryer uses TES materials is 45%, without TES materials 38%, and OSD is 25%. The collector efficiency when a dryer uses TES materials is 43% and that without TES materials 36%. These results are inconsistent with the results presented in Table 3 (previously published works).

3.2. Proximate Analysis of Dried Products. One of the most desirable aspects during the drying process is the retention of nutritional value of the dried products. Figure 9 shows a comparative analysis of nutritional contents (carbohydrate, crude fiber, protein, fats, and ash contents) for fresh and dried products using a dryer integrated with TES materials, without TES materials, and OSD. All the drying methods reduced moisture to a desirable level of about 10%, which is safe for increasing the product shelf life. The results indicate that all the drying methods increased the concentrations of nutritional value in the dried products because of the removal of water from the fresh products. This implies that a similar amount of products has more concentrated amounts of the same nutrients and calories as compared to fresh products. According to Mongi and Ngoma,[37] the drying process decreases the moisture contents which lead to an increase in the soluble concentration.

Carbohydrate showed the highest concentration in the dried products, followed by protein, crude fiber, and ash, and the least was observed in the fat contents for all the drying methods, as seen in Figure 8. With regard to the drying methods, drying products by using a dryer integrated with TES materials showed the highest concentration in nutrient composition, followed by a dryer without TES materials, and the least was observed with OSD. For example, the carbohydrate composition for the dryer integrated with TES materials was 66.5%, whereas that without TES and OSD was 65.4 and 64.8%, respectively. Likewise, for proteins, the compositions were 9.53% for the dryer with TES materials, whereas for the dryer without TES and OSD, they were 8.1 and 7.3%, respectively. This is because the integration of TES materials evaporates moisture quicker at uniform temperature.[20] This result is in agreement with previous studies by Seidu, Bobobee, Kwenin, Frimpong, Kubge, Tevor, and Mahama,[47] who studied the preservation of indigenous vegetables by solar drying technology. They found that solar drying reduced the moisture content and increased the concentration of protein, fiber, ash, and fat contents compared to fresh products. Lakshmi, Muthukumar, and Nayak[12] conducted experimental investigation on active solar dyers integrated with TES materials for drying black pepper, in which it was reported that drying reduced moisture contents and improved protein, fiber, ash, carbohydrate, and fat concentrations in the dried as compared to fresh products. Baloch, Xia, and Sheikh[48] studied proximate and mineral compositions of dried cauliflower by using OSD and cabinet dehydration. They found that drying reduced moisture contents, and the concentrations of protein, fiber, ash, carbohydrate, and minerals in the dried products were higher as compared to fresh ones.

Proximate analysis was also conducted for selected minerals such as calcium, sodium, phosphorus, and magnesium, as depicted in Figures 10 and 11 for carrots and pineapples, respectively. All the drying methods increased the concentrations of minerals as compared to fresh products because of the removal of water from the fresh sample. However, mineral concentration was relatively higher using a solar dryer integrated with TES materials, followed by the dryer without TES materials and OSD. The results align with the results reported by Mohammed,[49] who conducted proximate analysis for drying mangoes and pineapples using different solar drying technologies and found that all the solar drying methods increased the concentration of mineral contents compared to the fresh products.

The concentration of vitamin C was found to be reduced in all of the drying methods; however, a significant increase of concentration of vitamin A was observed as compared to fresh products, as shown in Table 4. For example, the concentration of vitamin C in a fresh carrot was 5.8 mg/100 g, whereas that with TES materials was 5.6 mg/100 g, without TES materials was 5.6 mg/100 g, and OSD was 5.1 mg/100 g. The reduction in the concentration of vitamin C was slightly smaller when using a solar dryer integrated with TES materials compared to the solar dryers without TES materials and OSD. The reduction in vitamin C is due to its sensitivity to heat. Vitamin C is very sensitive to heat; heat easily destroys vitamin C because it is a water-soluble vitamin (Eze and Ojike[50]).

Table 5 shows the comparison of the proximate results of the solar dryer for some agricultural products from some previous studies. It can be seen from the table that all the drying methods reduced moisture and increased the concentrations of nutritional values in the dried products because of the removal of water from the fresh products. In

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Table 5. Comparison of the Proximate Results of Solar Dryers of Some Previous Published Works

S/N	types of solar dryer	product analyzed	drying temperature (°C)	parameters analyzed	findings	reference
1	cabinet mixed-mode dryer (CMG) and tunnel dryer (TD)	mango	30–55 in CMG and 30–73 in TD	moisture, protein, fat, crude fiber, ash, carbohydrate, and minerals (Ca, Fe, K, Na, and P)	the two drying methods reduced moisture, protein, fats, crude fibers, and minerals as compared to fresh products, and more loss was observed by using the TD method; however, carbohydrates were higher in dried as compared to fresh products	37
2	OSD	raspberries and blueberries	40–60	moisture, fat, ash, protein, antioxidant activity, total phenols, and total sugar	drying reduced moisture, fat, ash, antioxidant activity, and total phenols, whereas protein and total sugar were increased in dried as compared to fresh products	51
3	OSD, shade drying, and oven drying	*Moringa oleifera* leaves	25 for shade and 60 for oven drying	moisture, fat, ash, protein, fiber, carbohydrate, vitamins, and minerals (Zn, Ca, and Fe)	the three drying methods reduced moisture, fats, and iron, whereas protein, ash, fibers, carbohydrate, vitamin, zinc, and calcium were increased as compared to fresh products	52
4	cabinet dehydration	cauliflower	70	moisture, fat, ash, protein, fiber, carbohydrate, and minerals (K, Ca, Mg, Fe, P, and Zn)	drying reduced moisture contents, however, increased protein, fiber, ash, carbohydrate, and minerals	48
5	direct solar dryer	cocoyam leaves	26.23–47.32	moisture, protein, fat, fiber, ash, and carbohydrate	drying reduced moisture and fat, however, increased carbohydrates, protein, fiber, and ash contents as compared to fresh products	47
6	air oven	tomato	70–90	moisture, protein, fat, fiber, ash, carbohydrate, and vitamin C	drying reduced moisture, protein, fats, fibers, and vitamin C, whereas it increased ash and carbohydrate contents	53
7	solar dryer integrated with TES	black pepper	47.1	moisture, protein, fats, fiber, ash, carbohydrate, and texture	drying reduced moisture contents, however, increased protein, fiber, ash, fats, carbohydrate, and texture in the dried as compared to fresh products; antioxidant activity and total phenolic content were higher in fresh black pepper as compared to the dried ones	12
8	solar dryer integrated with TES	pineapple and carrot	40–62	moisture, protein, fats, crude fiber, ash, vitamins (A and C), carbohydrate, and minerals (Ca, Mg, Na, and P)	drying reduced moisture, increased the concentration of carbohydrate, fiber, ash, minerals, and protein with a minor loss in fats	current study

most of the previous studies, an increase in concentration of carbohydrate, fats, fiber, and ash contents with minor loss in vitamin and fats when using different types solar dryers was reported. However, significant losses in nutritional composition were reported when drying on OSD. Therefore, using solar dryers integrated with TES materials significantly maintained the nutritional values of the dried products.

4. CONCLUSIONS

A solar dryer integrated with soapstone as the TES material was designed and fabricated, and its performance was evaluated by drying pineapple (*A. comosus*) and carrots (*D. carota*). The proximate analysis to determine the quality of the dried products was also carried out. The drying experiments were conducted in two modes: a dryer with and without TES materials, and the results were compared with that of OSD. During the drying process, the average initial moisture content of pineapple and carrot was reduced from 90 and 88%, respectively, to 10% wet (w.b). The drying times for pineapples in the dryer with TES, without TES, a ndOSD were 13, 24, and 52 h, respectively. However, the drying times for carrots in the dryer with TES, without TES, and OSD were 12, 23, and 50 h, respectively. This means using a dryer integrated with TES materials took less time as compared to that with OSD and when the dryer is without TES materials. It was observed that the dryer with TES materials could supply heat to the drying chamber up to 3−4 h after sunset because of the heat stored in the TES materials (soapstone). The thermal efficiency of the dryer, the collector efficiency, and storage efficiency of TES materials were calculated and found to be 45, 43, and 74.5%, respectively.

Proximate analysis was conducted for ash content, crude fiber, fat content, protein, vitamins, and minerals. It was found that all drying methods increased the concentration of carbohydrates, protein, crude fiber, ash, minerals, and vitamin A, and a greater concentration was observed using a solar dryer integrated with TES materials. However, all drying methods slightly reduced fat and vitamin C contents compared to the fresh products, and more losses were observed by using OSD, followed by solar drying without TES materials and solar drying with TES materials. Based on the performance evaluation and proximate analysis, solar dyer integrated with soapstone as a TES material can be an appropriate technology for drying agricultural products and reducing postharvest losses and improving food security, especially in rural areas. However, further studies are needed to explore the potential performance of soapstone during different weather seasons in agricultural drying application. However, further research is needed to explore the potential limitations and optimize the integration process.

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Notes

The authors declare no competing financial interest.

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